MECHANICAL AND VENTILATION SYSTEMS

This chapter presents guidelines for mechanical ventilation, heating, and cooling systems. This chapter also presents strategies that can enhance the effectiveness of natural ventilation when the outdoor temperature and humidity is suitable to provide improved thermal comfort during the spring and fall. Presented together in one chapter, the organization emphasizes the interrelationship between these systems. Guidelines are provided for the following technologies and design strategies:

Cross Ventilation (Guideline MV1)	Water-Loop Heat Pumps (Guideline MV15)
Stack Ventilation (Guideline MV2)	Evaporatively Precooled Condenser (Guideline MV16)
Ceiling Fans (Guideline MV3)	Dedicated Outside Air System (Guideline MV17)
Gas/Electric Split System (Guideline MV4)	Economizers (Guideline MV18)
Packaged Rooftop System (Guideline MV5)	Air Distribution Design Guidelines (Guideline MV19)
Displacement Ventilation System (Guideline MV6)	Duct Sealing and Insulation (Guideline MV20)
Hydronic Ceiling Panel System (Guideline MV7)	Hydronic Distribution (Guideline MV21)
Unit Ventilator System (Guideline MV8)	Chilled Water Plants (Guideline MV22)
Ductless Split System (Guideline MV9)	Boilers (Guideline MV23)
Evaporative Cooling System (Guideline MV10)	Adjustable Thermostats (Guideline MV24)
VAV Reheat System (Guideline MV11)	EMS/DDC (Guideline MV25)
Radiant Slab System (Guideline MV12)	Demand Controlled Ventilation (Guideline MV26)
Baseboard Heating System (Guideline MV13)	CO Sensors for Garage Exhaust Fans (Guideline MV27)
Gas-Fired Radiant Heating System (Guideline MV14)	Timers for Recirculating Hot Water Systems (Guideline MV28)

OVERVIEW

The main purposes of HVAC systems are to provide thermal comfort and to maintain good IAQ. These conditions are essential for a quality, high performance learning environment. HVAC systems are also one

of the largest energy consumers in schools, and relatively small improvements in design or equipment selection can mean large long-term savings in energy expenditures over the life cycle of the system.

The choice and design of HVAC systems can affect many other high performance goals as well. Water-cooled air conditioning equipment is generally more efficient than air-cooled equipment, but increases water consumption and maintenance. HVAC systems are the major source of outside air ventilation in schools, making their operation and maintenance mission critical for IAQ. The acoustic environment of classrooms, libraries, and other school spaces can be adversely affected by noise created by the movement of air through ducts and air diffusers and from the operation of HVAC equipment. Properly designed, installed, and operated HVAC systems and controls minimize these issues as well as provide a key component of the "buildings that teach" theme.

Integrated Design

To achieve a high performance design, it is very important to integrate the HVAC systems with the building envelope and lighting system. Integrated design creates opportunities for greater comfort, lower first costs, easier equipment maintenance, and lower operating costs. Some of the ways in which high performance can be achieved through integrated design are:

- Careful attention to shading, the locations of windows and glazing types, roof colors, building thermal mass, and enhanced natural ventilation may reduce, or even eliminate, the need for cooling in many locations, and can reduce cooling loads in all climates.
- Natural ventilation can eliminate the need for ductwork in some climates, allowing higher ceilings and more opportunities for daylighting savings.
- Under-floor air distribution allows access for future power and communication needs. The system can also be designed to work in harmony with natural ventilation.
- Attention to the radiant temperature of surfaces through careful envelope design reduces heating and cooling energy requirements. This is especially true of windows.
- Using a central heating and chilled water plant can allow for future installation of a thermal solar or geo-exchange source for heating or cooling energy, or for the use of a thermal energy storage system or other peak electric demand-reducing measures.
- Integrating HVAC, multiple light switches, and lighting occupancy sensor controls can reduce operating costs for both systems.

Thermal Comfort

Thermal comfort is affected by air temperature, humidity, air velocity, and mean radiant temperature (MRT).[1] Non-environmental factors such as clothing, gender,[2] age,[3] and metabolic activity also affect thermal comfort.

- Air temperature is measured with a normal thermometer, and most people are comfortable between about 70ºF and 76ºF. However, an individual's preferred temperature is higher in the summer and lower in the winter, mostly because of differences between summer and winter wardrobes.

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[1] MRT is the temperature of an imaginary enclosure where the radiant heat transfer from a human body equals the radiant heat transfer to the actual non-uniform temperature surfaces of an enclosure.

[2] Women generally prefer temperatures about 1° warmer.

[3] Persons over 40 generally prefer temperatures about 1° warmer.

- The relative humidity range for human comfort is between about 20% in the winter and 60% in the summer. The moisture content of air can also be expressed as the wetbulb temperature, humidity ratio, or dew point temperature.
- Ceiling fans, circulation fans, or operable windows can provide air movement, and such air movement increases the upper temperature limit of comfort by about two degrees.
- The temperature of the surfaces surrounding a person (walls, ceiling, floor, and especially windows) affects the mean radiant temperature (MRT) especially during hot and cold days. Caves have a low MRT, which makes them comfortable even when the air temperature is high. Likewise, rooms with heated floors are comfortable, although the air temperature may be cooler.

The most accepted definition of thermal comfort is ASHRAE Standard 55, but recent research is resulting in a reevaluation of this definition. Standard 55 currently defines comfort in terms of operative temperature and humidity, and represents the range of thermal conditions when 80% of sedentary, or slightly active, people find the environment thermally acceptable (see Figure 1). Operative temperature is the average of the mean radiant and ambient air temperatures, weighted by their respective heat transfer coefficients. The Standard 55 definition of comfort does not consider air movement or velocity. Most occupants do not feel comfortable when it is drafty and cold.

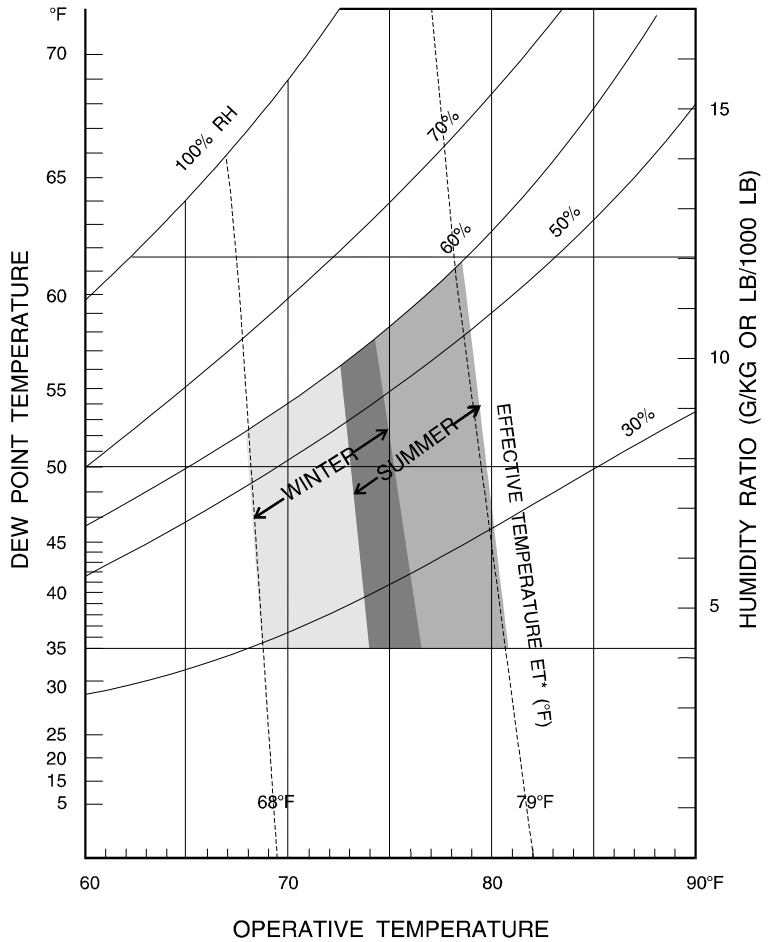


Figure 1 – ASHRAE Standard 55 Comfort Envelope

Source: 2001 ASHRAE Handbook – Fundamentals. This figure shows the temperature and humidity ranges within which about 80% of the population will be comfortable while wearing typical summer and winter clothing and being in a sedentary or slightly active state.

Much of the research on thermal comfort is based on asking people if they are hot or cold, and correlating their response to measurements of air temperature, humidity, air velocity, and MRT. The ASHRAE thermal sensation scale is commonly used for such surveys (see Table 1). Some of this research has been conducted in test environments where temperature and humidity can be tightly controlled. Other research has been conducted in workplaces.

Table 1 – ASHRAE Thermal Sensation Scale

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
-3	-2	-1	0	+1	+2	+3

Since thermal comfort is not an absolute condition but varies with each individual, statistical measures of thermal comfort are sometimes used. One statistical measure is the Predicted Mean Vote (PMV). PMV predicts the mean response of a large population on the ASHRAE thermal sensation scale (see Table 1). A PMV of +1 means that, on average, people are slightly warm. PMV can be calculated if information is known about the metabolic rate, typical clothing, and environmental conditions such as temperature and humidity. Once PMV is known, it can be translated to another statistical factor called percent of population dissatisfied (PPD).

Air movement also affects comfort. Operable windows, ceiling fans or circulation fans create or enable air movement. Too much air movement is uncomfortable, especially when it is cold. When it is hot, air velocities up to about 200 ft/minute are pleasant and enable most occupants to be equally comfortable at 2ºF higher temperatures. Air speeds higher than about 200 ft/minute should be avoided because they can create drafts and be annoying (see Table 2).

Table 2 – Effect of Air Movement on Occupants

Source: Victor Olgyay, Design with Climate, Princeton University Press, 1963

Air Velocity	Probable Impact
Up to 50 ft/minute	Unnoticed
50 to 100 ft/minute	Pleasant
100 to 200 ft/minute	Generally pleasant, but causes a constant awareness of air movement
200 to 300 ft/minute	From slightly drafty to annoyingly drafty
Above 300 ft/minute	Requires corrective measures if work and health are to be kept in high efficiency

Research by Gail Brager and others at the University of California, Berkeley, shows that students and teachers in naturally ventilated schools are comfortable in a wider range of thermal conditions than in schools that have continuous mechanical cooling. Occupants of air-conditioned schools develop high expectations for even and cool temperatures and are quickly critical if thermal conditions drift from these expectations. Occupants in naturally ventilated schools adapt to seasonal changes in mean outdoor temperature and are comfortable in a wider range of conditions. They even prefer a broader range of thermal conditions. The comfort range for naturally ventilated buildings is considerably larger than the common definition of comfort published in ASHRAE Standard 55-1992.

Research shows that part of the difference in comfort expectations is due to behavioral adaptations: occupants in naturally ventilated schools wear appropriate clothing and open windows to adjust air speeds. However, some of the difference is due to physiological factors. The human body's thermal expectations actually change through the course of a year, possibly because of a combination of higher

levels of perceived control (occupants can open and close windows) and a greater diversity of thermal experiences in the building.

Using an adaptive model of thermal comfort, instead of ASHRAE Standard 55, allows schools to be designed and operated to both optimize thermal comfort and reduce energy use. In many climates, maintaining a narrowly defined, constant temperature range is unnecessary and expensive. Brager's research is the foundation of changes currently being considered to ASHRAE Standard 55.

Potential for Natural Ventilation

Natural ventilation is an effective and energy-efficient way to provide outside air for ventilation and to provide cooling in many climates during certain times of the spring and fall. In the winter, the challenge is to temper the cold ventilation air as it is brought into the classroom. Humidity is the challenge in the warm portions of the season. Schools that are operated throughout the year should have some means of dehumidification or air conditioning. Historically, schools have not been air conditioned and natural ventilation (cooling with outside air) has been the only means of cooling. Prior to the widespread availability of mechanical cooling, the classic classroom had high, large operable windows to provide both natural ventilation and daylighting.

In most climates, natural ventilation is a useful strategy only during the spring and fall. When any significant number of operable windows are utilized, the building as a system must be carefully designed to minimize glare and heat gain from the sun shining in through the glass, and to maintain a safe and secure facility while still allowing air to enter and escape. Use of ventilation in the off-hours must be approached very carefully as the humidity load from damp nighttime air can lead to moisture problems in some climates. This is especially important if some areas of the facility are mechanically cooled or have any cold surfaces that might be below the dew point of the damp nighttime air.

Figure 2 through Figure 8 contain weather data and analysis of the seven national climates. The figures include data from a typical school year: Monday through Friday, from 7 am to 3 pm, September through June. These figures show drybulb temperature on the vertical axis and relative humidity on the horizontal axis. The figures in the cells are the number of hours during the year when a particular combination of relative humidity and drybulb temperatures exist. The preferred humidity and temperature ranges (30% to 55% and 68°F to 77°F) are shaded gray. The overlapping area indicates when outdoor temperature and humidity are within the ASHRAE 55 Comfort Zone.

Natural ventilation is an effective and energy-efficient way to provide outside air for ventilation and to provide cooling in many climates. However, in climates with extreme cold and/or humid weather, the challenge is to temper the cold ventilation air as it is brought into the classroom during the winter months. Humidity is the challenge in the warm portions of the season. Historically, schools have not been air conditioned and natural ventilation has been the only means of cooling. The classic classroom has high windows to provide both natural ventilation and daylighting.

Seattle, WA
September - June
7 am - 3 pm, weekdays

Dry Bulb Temp	20%-25%	25%-30%	30%-35%	35%-40%	40%-45%	45%-50%	50%-55%	55%-60%	60%-65%	65%-70%	70%-75%	75%-80%	80%-85%	85%-90%	90%-95%	95%-100%	>100%	Total
98-102	1																	1
93-97	2																	2
88-92		1	2															3
83-87				7	2													9
78-82		1	1		3	1	1	1										8
73-77		2	1	7	4	3	5	6										28
68-72		1	5	5	11	15	12	11	6	2								68
63-67		2	4	6	14	6	19	17	30	12	8	2						120
58-62		4	2	2	12	28	30	28	31	38	24	21	10	19	1			250
53-57			2	5	5	10	20	35	19	15	16	37	56	30	23	2	3	278
48-52		4	1	3	5	4	11	15	23	32	27	17	29	41	39	6	3	260
43-47		1	2	7	10	8	13	15	27	21	71	66	19	52	42	8	3	365
38-42	2	3	1	5	8	6	12	10	14	23	3	52	79		34	7	12	271
33-37	1				3		5	2	8	6	7		21		10	18	7	88
28-32						3		1		2		9		3		4	4	26
23-27												3		1			3	7
Total	6	19	21	47	77	84	128	141	158	151	156	207	214	146	149	45	35	1784

Relative Humidity

Total Hours
ASHRAE 55 Comfort Zone 68

Figure 2 – Climate Analysis, Temperate and Mixed (Seattle)

Denver, CO
September - June
7 am - 3 pm, weekdays

Dry Bulb Temp	<15%	15%-20%	20%-25%	25%-30%	30%-35%	35%-40%	40%-45%	45%-50%	50%-55%	55%-60%	60%-65%	65%-70%	70%-75%	75%-80%	80%-85%	85%-90%	90%-95%	100%	>100%	Total
88-92	22	1																		23
83-87	22	9	3	1																35
78-82	49	16	5	4																74
73-77	58	21	12	11	7	5			1											115
68-72	34	14	22	12	15	19	4	4	1	3	1									129
63-67	21	30	12	8	10	8	9	14	5	5	5	1								128
58-62	37	28	12	18	17	6	1	7	8	13	10	5	3		1	1				167
53-57	46	34	18	14	21	14	6	10	6	4	3	9	4	5	1		1			196
48-52	25	27	18	20	23	12	8	8	5	4	10	8	1	1	2	3	1			176
43-47	21	13	23	10	12	16	10	7	6	7	6	1	6	12		2	1		2	155
38-42	5	7	9	17	18	15	12	9	10	9	7	10	1	5	6		2			142
33-37	4	7	11	6	14	11	18	17	10	5	13	8	7		7		5		1	144
28-32	2	1	9	1	8	4	5	8	6	16		17		14		16		3	3	113
23-27		1	1	1	3	16	1	3	11	2	15		4	4		19		2	3	86
18-22		1			1	1	6		4	8		8	14		1	2			2	48
13-17											6	5			5					16
<13			1		2	2	1	2	5	2	4		4	13					1	37
Total	346	210	156	123	151	129	81	89	78	78	80	72	44	54	23	43	10	5	12	1784

Relative Humidity

Total Hours
ASHRAE 55 Comfort Zone 56

Figure 3 – Climate Analysis, Cool and Dry (Denver)

Phoenix, AZ
September - June
7 am - 3 pm, weekdays

Dry Bulb Temp	<15 %	15%-20%	20%-25%	25%-30%	30%-35%	35%-40%	40%-45%	45%-50%	50%-55%	55%-60%	60%-65%	65%-70%	70%-75%	75%-80%	80%-85%	85%-90%	90%-95%	>100 %	Total
108-113	10																		10
103-107	28	15	2																45
98-102	37	13	14	2															66
93-97	36	20	12	7	7	2	1												85
88-92	66	40	18	11	12	8	3	2											160
83-87	65	45	39	19	11	5	7	5	6	1									203
78-82	44	47	23	27	13	7	2	2	3		7								175
73-77	25	28	49	24	25	14	7		6		2	2	2						184
68-72	15	28	35	29	15	22	9	5	3	1		1	1	1	2	2			169
63-67	6	12	24	24	33	12	11	12	5	5	2	2	2		1				151
58-62	4	8	17	22	15	38	19	11	11	2	3	4	2		2	3			161
53-57	3	10	8	6	12	14	18	21	12	8	6	4	4	6	3	5	2		142
48-52	1	2	6	6	13	7	7	8	10	9	16	11	4	2	2	2	6		112
43-47		4	5	5	3	3	3	5	4	9	6	3	8	5		4	3		70
38-42			2	2	2	2	3	1	4		2	7	1	7			3	1	37
33-37				1	2			1	1	1		1	2		2				11
28-32						1				1									2
23-27									1										1
Total	340	272	254	185	163	135	90	73	66	37	44	35	26	21	12	16	14	1	1784

Relative Humidity

Total Hours
ASHRAE 55 Comfort Zone 106

Figure 4 – Climate Analysis, Hot and Dry (Phoenix)

Minneapolis, MN
September - June
7 am - 3 pm, weekdays

Dry Bulb Temp	20%-25%	25%-30%	30%-35%	35%-40%	40%-45%	45%-50%	50%-55%	55%-60%	60%-65%	65%-70%	70%-75%	75%-80%	80%-85%	85%-90%	90%-95%	95%-100%	>100%	Total
93-97			1															1
88-92				3	1	2	4	4										14
83-87	2	1		1	7	4	2	3	3	1								24
78-82	3	5	6	5	10	9	6	9	3	5	1							62
73-77	3	3	2	9	9	6	19	11	10	6	3	2	1	1				85
68-72	1	1	3	12	7	17	7	7	12	5	8	5	2	4	1			92
63-67			3	5	6	13	16	11	8	12	21	11	16	15	2			139
58-62		2	9	12	11	14	14	19	9	8	5	12	5	14	2			136
53-57		4	5	10	8	14	13	27	3	8	5	7	5	3	5			117
48-52		10	9	8	15	15	7	16	17	13	6	2	3	6	11			138
43-47		3	6	3	6	5	10	15	7	2	15	8	1	3	2	2		88
38-42			1	1	4	3	17	17	8	19	4	14	15		18	1	1	123
33-37					1	8	15	10	14	10	26		30		18	10	15	157
28-32					1	6		18		28		36		18		6	2	115
23-27						3	7	3	23		32	15		18		3	5	109
18-22				2	8		11	10		22	29		21	13		3	3	122
13-17					5	8	4		29	19			24			1	3	93
<13		1	1	7	10	23	21	21	16	24	18	18				6	3	169
Total	9	30	46	78	109	150	173	201	162	182	173	130	123	95	59	32	32	1784

Relative Humidity

Total Hours

ASHRAE 55 Comfort Zone **91**

Figure 5 – Climate Analysis, Cold and Humid (Minneapolis)

Boston, MA
September - June
7 am - 3 pm, weekdays

Dry Bulb Temp	15%-20%	20%-25%	25%-30%	30%-35%	35%-40%	40%-45%	45%-50%	50%-55%	55%-60%	60%-65%	65%-70%	70%-75%	75%-80%	80%-85%	85%-90%	90%-95%	95%-100%	>100%	Total
88-92					4	2	1												7
83-87				2	2	7	6	7	4										28
78-82		1	1	12	7	5	3	7	13	5	1								55
73-77		1	3	4	4	3	10	9	14	6	12	8	5	1					80
68-72			1	4	6	14	12	10	8	11	6	8	15	7	15	2	1		120
63-67				3	10	10	15	17	14	6	11	21	13	6	8	8		1	143
58-62			1	6	12	6	15	8	13	10	6	10	12	15	21	10	1	1	147
53-57	1	2	8	13	7	13	12	11	8	11	5	4	1	10	13	24			143
48-52		2	2	7	11	11	14	11	11	13	10	12	1	5	29	26	3	2	170
43-47		3	12	10	11	19	19	22	18	14	2	10	28	4	16	23	3	5	219
38-42			2	13	12	14	11	20	12	4	10	1	12	18		7		4	140
33-37			8	16	20	19	15	18	15	10	10	18		26		20	3	5	203
28-32		1	3	16	16	17	33	4	28		23		14		6		3	1	165
23-27	2	1	5	3	14	7	11	11	4	11		3	6					2	80
18-22			5	5	13	11		7	9										50
13-17			3	4		6	3	4		2									22
<13				1	1	4	3	2	1										12
Total	3	11	54	119	150	168	183	168	172	103	96	95	107	92	108	120	14	21	1784

Relative Humidity

Total Hours
ASHRAE 55 Comfort Zone **76**

Figure 6 – Climate Analysis, Cool and Humid (Boston)

Atlanta, GA
September - June
7 am - 3 pm, weekdays

Dry Bulb Temp	10%-15%	15%-20%	20%-25%	25%-30%	30%-35%	35%-40%	40%-45%	45%-50%	50%-55%	55%-60%	60%-65%	65%-70%	70%-75%	75%-80%	80%-85%	85%-90%	90%-95%	95%-100%	>100%	Total
93-97						1														1
88-92						2	9	3												14
83-87				1	4	6	8	14	23	10	4									70
78-82			2	4	9	5	10	16	15	26	25	20	6	6						144
73-77			3	1	8	10	13	16	17	15	8	28	32	13	6	5	2			177
68-72	3	1	1	3	5	11	12	24	10	14	12	8	13	20	14	24	13	14	1	203
63-67		7	5	10	11	16	9	19	11	13	9	9	20	14	20	32	25	1		231
58-62	1	3	6	6	7	14	9	16	17	9	6	12	5	9	15	19	31	2	7	194
53-57		1	7	8	9	14	10	7	8	11	12	8	7	13	10	16	19	6	2	168
48-52			5	6	9	10	7	8	4	8	13	11	10	8	9	8	16	3	2	137
43-47		3	2	3	5	5	9	3	8	7	11	3	17	7	4	18	21	9	7	142
38-42		1	4	10	8	6	6	12	7	3	4	9	3	5	2		8	6	7	101
33-37		3	1	4	5	9	9	10	7	3	4	4	15		7		11	13	4	109
28-32		1	2	1	4	2	3	7	1	7		3		2		12		3		48
23-27		1	2	1	5	1	1	1	7	1	5			1		1				27
18-22				1	2	2			1	2			1		1	1				11
13-17								1	2		2	1								6
<13										1										1
Total	4	21	40	59	91	114	115	157	138	130	115	116	129	98	88	136	146	57	30	1784

Relative Humidity

Total Hours
ASHRAE 55 Comfort Zone 126

Figure 7 – Climate Analysis, Temperate and Humid (Atlanta)

Orlando, FL
September - June
7 am - 3 pm, weekdays

Dry Bulb Temp	15%-20%	20%-25%	25%-30%	30%-35%	35%-40%	40%-45%	45%-50%	50%-55%	55%-60%	60%-65%	65%-70%	70%-75%	75%-80%	80%-85%	85%-90%	90%-95%	95%-100%	>100%	Total
93-97				2	3	1	4												10
88-92			1	7	6	23	14	26	25	2									104
83-87				2	7	26	44	57	44	66	48	28	3	1					326
78-82			5	2	9	21	34	37	22	39	51	30	67	30	2	1			350
73-77		2	7	6	13	13	27	31	34	22	31	31	25	26	31	15	4		318
68-72		2	13	3	10	12	15	28	21	26	10	15	19	7	20	15	16		232
63-67	1	1	3	7	5	6	12	17	10	10	9	13	12	22	13	18	4	4	167
58-62		2	4	1	4	4	5	6	8	6	12	12	20	20	15	13	1	1	134
53-57		4	1	1		4	3	5	4	5	5	2	8	5	11	7	1	1	67
48-52			1	1	1	1	5		8	5	3	2	2	1	7	5			42
43-47				1	1	1	1	5	4		1	4	2						20
38-42						1		4	2	3	1		1						12
33-37							1							1					2
Total	1	11	35	33	59	113	165	216	182	184	171	137	159	113	99	74	26	6	1784

Relative Humidity

Total Hours
ASHRAE 55 Comfort Zone 158

Figure 8 – Climate Analysis, Hot and Humid (Orlando)

Outside Air Ventilation

Classrooms and other school spaces must be ventilated to remove carbon dioxide and other pollutants from breathing, odors, and other pollutants. The national consensus standard for outside air ventilation is ASHRAE Standard 62.

If outside air is provided through natural ventilation, then all spaces within the room must be within 20 ft of a window, door, or other ventilation opening, and the total area of ventilation openings must be greater than 5% of the floor area. For a typical 960-ft² (30 ft x 32 ft) classroom, the minimum free ventilation area must be at least 48 ft². The 20-ft rule would also require that ventilation openings be provided on two sides of the room; otherwise some portions of the classroom would be further than 20 ft from a window.

If outside air is provided through a mechanical system, then at least 15 cubic feet per minute (cfm) of outside air must be provided for each occupant. A typical classroom with 30 people requires a minimum of 15 x 30 or 450 cfm per occupant. Other spaces in schools require differing levels of outside air ventilation, based on the expected occupant density of the space and the recommended ventilation rate of 15 cfm/occupant.

The number of occupants is highly variable in some school spaces such as gyms, auditoriums, and multi-purpose rooms. Many codes require systems to vary the quantity of outside air ventilation in these spaces based on the number of occupants. One technique for addressing this issue is to install carbon dioxide (CO_2) sensors that measure concentrations and vary the volume of outside air accordingly. If an auditorium fills up for a school assembly, CO_2 concentrations will increase, the HVAC system will be signaled, and outside air volumes will be increased accordingly. This type of control can both save energy and significantly improve IAQ.

Systems must also be designed to provide at least three air changes per hour, or the required ventilation rate indicated above for the hour prior to normal occupancy of the building. This requirement ensures building-related contaminants that may have built up overnight while the system was shut down are flushed out.

The location of ventilation air intakes and exhausts is a critical aspect of integrated building design and sometimes difficult to coordinate or optimize. Outside air intake dampers must be carefully located to avoid pollution from sources such as parking lots, loading docks, adjacent roadways, sewer vents, or boiler exhaust fumes. Patterns of air movement around buildings can be quite complex and dynamic. Designers are advised to consult ASHRAE Fundamentals Chapter 15 airflow analysis models for exhaust stack reentrainment modeling. If major sources of industrial pollution exist nearby, more sophisticated models are often used for predicting downwind concentrations of pollutants. In the extreme case of urban settings with multiple building heights, designers should consider building scale models for testing in wind tunnels.

IAQ is also affected by the selection of interior finishes and materials. These issues are discussed in the Resource-Efficient Building Products chapter. The design of air distribution ducts and fan systems can also have a significant effect on IAQ. Exposed fiberglass and other porous or flaking materials should never be used on the interior of ducts, unless they are encapsulated with a surface finish that is robust, will not break down from atmospheric ozone exposure (smog), and can be cleaned with a mechanical brush without releasing particles.

Load Calculations

Properly sizing HVAC systems in schools is critical to both energy efficiency and cost effectiveness. The compressors in oversized packaged air conditioners or heat pumps cycle frequently and overall efficiency drops with each cycle. Frequent cycling also reduces the efficiency of boilers, furnaces, and many other types of equipment. Properly sized equipment, with multiple firing rates and stages of cooling, reduces cycling and helps maintain efficient operation, but smaller, properly sized equipment that is matched to the building load is also often less expensive and can reduce initial construction costs.

Many computer programs and calculation methodologies can be used for load calculations. The assumptions used about infiltration rates, lighting levels, equipment, and occupant loads are often more important than the actual software that is used in the calculations. Engineers should take care to make assumptions that are consistent with the energy-efficient recommendations made in other chapters of the Best Practices Manual. An efficient building shell and lighting system should result in significant HVAC equipment size reductions and reduce cost.

Environmental Considerations

In terms of environmental performance, the HVAC system primarily affects energy usage, acoustic comfort, the life of building materials, and indoor environmental quality. Other environmental considerations are relevant, such as using materials efficiently, employing energy recovery devices for heating or cooling, conserving water, using materials that can be readily recycled, and avoiding ozone-depleting refrigerants. The following specific measures can be used to reduce the environmental impact of HVAC systems.

- A well-designed building with integrated building systems will significantly reduce the requirements for heat and cooled air distribution. In addition to energy savings, significantly less equipment, or smaller equipment, is needed.
- A well-designed HVAC system always provides easy access for cleaning and repair, enhancing long-term ability to provide good IAQ and thermal comfort.
- Selection of equipment and materials play a part as well. Strategies and considerations include:
    - Specifying low-toxic (water-based) mastic to seal ducts, or in cases where round ducts are used, specify internal gasketed duct joint systems so that duct sealants are not needed.
    - Selecting durable long-life equipment with hinged access doors that allow for equipment service and that can be easily refurbished.
    - Limiting the use of equipment that uses CFC or HCFC refrigerants.
    - Consider alternatives to cooling towers, which use significant amounts of water.
    - Metal components of HVAC systems can be recycled. Suggest recycling equipment at the end of its life cycle. In addition, metal components of HVAC equipment typically include recycled content, although data is not readily available as to the amount.
    - Energy recovery equipment should always be considered for the ventilation system since heating and cooling the ventilation air accounts for the majority of the load that is placed on the systems in a well-designed facility. Payback periods for energy recovery are often 10 years; however the school systems are designed to last 30 to 50 years.
    - Consideration needs to be given to renewable energy heating and cooling sources such as geothermal standing column wells.

Commissioning

Commissioning is the process of ensuring that the intent of the project program is properly reflected in the design and that the design intent is properly executed during construction and operation. Commissioning tasks start at the very beginning and continue throughout the project, even into the occupancy period. Experience has shown that most energy-efficient designs do not achieve intended savings without the oversight and testing provided by a commissioning process.

For larger facilities, the project manager should consider including an independent commissioning agent in the early planning process. A commissioning plan should be developed during schematic design and updated at each project phase. Typical elements of a commissioning process include:

- Commissioning plan development
- Documentation of design intent
- Design review
- Submittals review
- Inspections and system functional testing
- Enhanced operating and maintenance documentation, including hands-on training of the staff operating and maintaining the equipment
- Post-occupancy testing and operation evaluation.

For small schools with relatively simple mechanical systems, a detailed commissioning process may not be feasible. However, some form of a testing of the equipment and controls is essential to ensure systems are operating properly and at peak efficiency before, or soon after, occupancy.

Specific commissioning issues are discussed in each of the guidelines below. A number of sample commissioning plans and guidelines are also available. A good source is the Portland Energy Conservation Inc. at http://www.peci.org/. Other resources include the U.S. Department of Energy at http://www.energy.gov/, the American Society of Heating, Refrigerating and Air-Conditioning Engineers at http://www.ashrae.org/, and the Sheet Metal and Air Conditioning Contractors' National Association at http://www.smacna.org/.

Design Tools

In addition to general energy simulation programs, many useful tools for optimizing mechanical design exist. Heating and cooling load calculation programs that are widely available from equipment manufacturers and commercial vendors are most commonly used. Other programs integrate with CAD software and aid the design of piping and duct systems. Many of these tools also have cost estimating capabilities, which are very helpful in design optimization and budget review.

Computational fluid dynamics (CFD) software can help in studies of natural and mechanical ventilation and is very useful in creatively integrating mechanical and architectural design. Historically, this type of analysis is expensive. Many manufacturers of air distribution equipment can now provide CFD graphic representation of the air distribution delivered by their products.

Controls

HVAC, lighting, water heating, signal/communication wiring, and other systems need to be operated and controlled efficiently and effectively. With integrated design, the effective control of one system may depend on how another system is being operated. Building management systems offer integrated control of HVAC, lighting, outside air ventilation, natural ventilation, building security, and water heating systems. Energy can be saved through efficient control that turns off or slows down systems when they are not needed. In general, slowing down most fans by 25% cuts the electric energy the fan uses by 50%. Building management systems can also provide information for students and faculty to understand how the building is working and how much energy it is using. Building management systems should always be equipped with easy-to-use graphic interfaces to facilitate their proper use.

System Selection

Figure 9 illustrates a few important questions that help narrow the choice of HVAC system for each space. This decision tree leads to one of several categories of system types. There are three main questions:

1. Can natural ventilation meet all reasonable cooling needs? For many locations this is possible, especially with careful attention to architectural design. If cooling is unnecessary, then several heating-only options exist.
2. Can outdoor air ventilation be provided naturally or is mechanical ventilation required? This affects the system choice regardless of whether it is heating only, or heating and cooling. If fans are not required for ventilation, the design should allow them to be off for much of the year, saving fan energy.
3. If cooling is required, can an efficient evaporative cooling system be used? If not, compressor cooling, either with a direct expansion or chilled water system is required.

There are, of course, many other considerations in system selection. This chapter provides guidelines for most of the common HVAC system types used in schools. Table 3 provides an overview of what systems are most applicable to each climate zone.The choice of optimal system type for a specific school is a complex decision based on many factors. Many tradeoffs are involved, especially price versus performance. Other important considerations are:

- Noise and vibration
- IAQ ventilation performance
- Thermal comfort performance
- Operating costs and energy efficiency
- Maintenance access, costs, and needs
- HVAC equipment space requirements (in the classroom, on the roof, in mechanical rooms)
- Durability and longevity
- The ability to provide individual control for classrooms and other spaces
- The type of refrigerant used and its currently understood ozone-depleting potential.

Table 4 compares system types using these criteria and others. More information regarding the applicability of each system type is discussed in the individual guidelines.

Phasing of construction projects also influences the decision between central systems and distributed systems. If a large facility is to be constructed in several phases, then it may be difficult to afford the upfront investment in the central plant option.

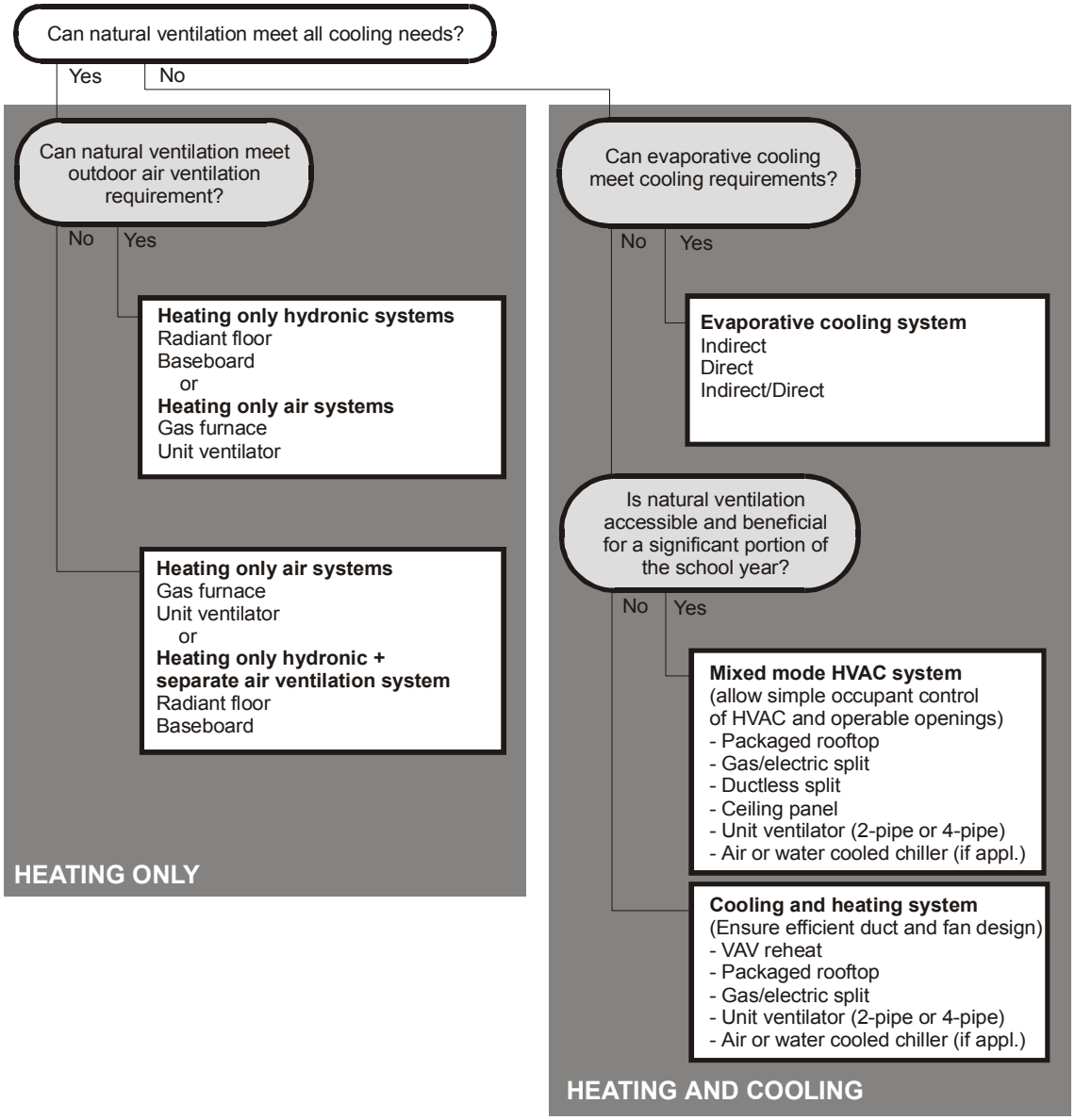


Figure 9 – HVAC System Selection Decision Tree

Table 3 – Climate Zone Applicability for HVAC Guidelines

Guideline	Temperate and Mixed	Cool and Dry	Hot and Dry	Cold and Humid	Cool and Humid	Temperate and Humid	Hot and Humid
MV1: Cross Ventilation	●	●	○	●	●	◉	○
MV2: Stack Ventilation	●	●	◉	●	●	◉	○
MV3: Ceiling Fans	●	◉	◉	●	●	◉	○
MV4: Gas/Electric Split System	○	◉	●	○	◉	●	●
MV5: Packaged Rooftop System	○	◉	●	○	◉	●	●
MV6: Displacement Ventilation System	◉	●	◉	○	●	●	◉
MV7: Hydronic Ceiling Panel System	◉	●	◉	◉	●	○	○
MV8: Unit Ventilator System	●	●	◉	●	◉	◉	◉
MV9: Ductless Split System	◉	●	◉	●	◉	◉	○
MV10: Evaporative Cooling System	○	●	●	◉	◉	○	○
MV11: VAV Reheat System	◉	◉	●	○	○	●	●
MV12: Radiant Slab System	●	●	○	●	●	◉	○
MV13: Baseboard Heating System	●	●	○	●	●	◉	○
MV14: Gas-Fired Radiant Heating System	●	●	◉	●	●	◉	◉
MV15: Water-Loop Heat Pumps	●	●	○	●	●	◉	○
MV16: Evaporatively Precooled Condenser	○	◉	●	○	◉	●	◉
MV17: Dedicated Outside Air Systems	◉	●	○	●	◉	◉	○
MV18: Economizers	●	●	●	●	●	●	◉
MV19: Air Distribution Design Guidelines	●	●	●	●	●	●	●
MV20: Duct Sealing and Insulation	●	●	●	●	●	●	●
MV21: Hydronic Distribution	◉	◉	●	◉	◉	●	●
MV22: Chilled Water Plants	◉	◉	●	◉	◉	●	●
MV23: Boilers	●	●	●	●	●	●	●
MV24: Adjustable Thermostats	●	●	●	●	●	●	●
MV25: EMS/DDC	●	●	●	●	●	●	●
MV26: Demand Controlled Ventilation	●	●	●	●	●	●	●
MV27: CO Sensors for Garage Exhaust Fans	●	●	●	●	●	●	●
MV28: Timers for Recirculating Hot Water Systems	●	●	●	●	●	●	●

Legend: ● Best Applicability ◉ Mid-Range Applicability ○ Worst Applicability

Table 4 – HVAC Selection Criteria

Selection Criteria		Gas/Electric Split System	Rooftop Packaged System	Displacement Ventilation	Ceiling Panels	Unit Ventilator (4-pipe)	Unit Ventilator (2-pipe)	Ductless Split System	Evaporative Cooler	VAV/Reheat.	Radiant Floor	Baseboards	Gas-Fired Radiant System for Gyms	Chiller – Water Cooled	Chiller – Air Cooled
First Cost		◉	●	○	○	○	◉	◉	◉	◉	○	◉	◉	○	◉
Maintenance Cost		◉	◉	◉	◉	◉	◉	◉	●	◉	◉	◉	◉	◉	◉
Cooling Effectiveness		◉	◉	●	●	◉	◉	○	◉	●	N/A	N/A	N/A	●	●
Heating Effectiveness		◉	◉	○	○	◉	○	○	N/A	◉	●	●	●	N/A	N/A
Energy Operating Cost		◉	◉	●	●	◉	◉	◉	●	◉	●	◉	●	●	◉
Durability		◉	◉	◉	●	◉	◉	◉	◉	●	●	●	◉	●	◉
Life-Cycle Cost		◉	○	●	◉	○	○	◉	●	◉	◉	◉	◉	●	◉
Noise (Acoustic Environment)		◉	◉	●	●	○	○	○	◉	◉	●	●	●	○	○
Roof Space Required		●	○	◉	●	●	●	●	○	○	●	●	●	N/A	N/A
Water Consumption		●	●	●	●	●	●	●	○	●	●	●	●	◉	●
Classroom Control		●	●	●	◉	●	●	●	●	●	◉	◉	●	N/A	N/A
Multi-Zone Capability		○	○	○	◉	○	○	○	○	●	◉	◉	◉	N/A	N/A
Ozone Depletion		○	○	◉	◉	◉	◉	○	●	◉	◉	◉	◉	◉	◉
Outside Air Ventilation		◉	◉	●	○	◉	◉	○	●	◉	○	○	○	N/A	N/A
Thermal Comfort		◉	◉	●	●	○	○	○	◉	●	●	◉	◉	N/A	N/A
Natural Ventilation (Mixed Mode Method)	Compatibility (poor/fair/good)	◉	◉	◉	●	◉	◉	◉	◉	○	●	◉	●	N/A	N/A
	Change-Over (yes/no)	●	●	●	○	●	●	●	●	●	○	○	○	N/A	N/A
	Concurrent (yes/no)	○	○	○	●	○	○	○	○	○	●	●	●	N/A	N/A
Indoor Air Quality		◉	◉	●	●	◉	◉	◉	◉	◉	●	●	●	N/A	N/A

Legend: ● Better than average (better performance or lower cost) ◉ Average ○ Worse than average (lower performance or higher cost)

Selection Criteria		Gas/Electric Split System	Rooftop Packaged System	Displacement Ventilation	Ceiling Panels	Unit Ventilator (4-pipe)	Unit Ventilator (2-pipe)	Ductless Split System	Evaporative Cooler	VAV/Reheat.	Radiant Floor	Baseboards	Gas-Fired Radiant System for Gyms
Spaces Applicability (black, gray or clear)	Classrooms	●	◉	●	●	◉	◉	○	◉	◉	●	◉	○
	Library	◉	◉	◉	○	○	○	○	◉	●	◉	◉	○
	Multi-purpose	◉	◉	◉	○	○	○	○	●	◉	◉	◉	●
	Gym	◉	◉	○	○	○	○	○	●	◉	◉	○	●
	Corridors	◉	◉	○	○	○	○	○	●	◉	◉	◉	○
	Admin	◉	◉	●	●	○	○	◉	●	●	◉	●	○
	Toilets	◉	◉	○	◉	○	○	◉	◉	◉	◉	◉	○
	Other	◉	◉	◉	◉	◉	◉	◉	◉	◉	◉	◉	◉
Possible Cooling Sources	DX	●	●	◉	○	◉	◉	●	○	●	N/A	N/A	N/A
	CHW	○	○	●	●	●	●	○	○	●	N/A	N/A	N/A
Possible Heating Sources	HP	○	●	●	○	◉	◉	●	○	○	○	○	○
	HW	○	◉	●	●	●	●	○	◉	●	●	●	○
	Furnace	●	●	●	○	○	○	○	◉	●	○	○	○
Optional Energy Efficient Features	Air Economizer	◉	●	●	○	●	●	◉	●	●	○	○	○
	Evaporative Precooler	●	●	●	○	○	○	●	○	●	○	○	○
	Variable Speed Fan	◉	◉	◉	○	◉	◉	◉	●	●	○	○	○
	High Efficiency Motors	●	●	●	●	●	●	●	●	●	●	●	○

Legend: ● Better than average (better performance or lower cost) ◉ Average ○ Worse than average (lower performance or higher cost)

GUIDELINE MV1: CROSS VENTILATION

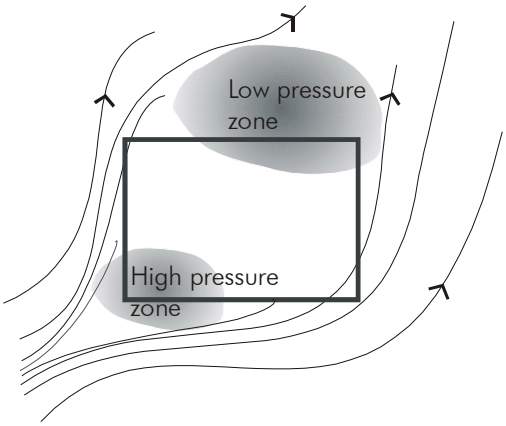
Recommendation

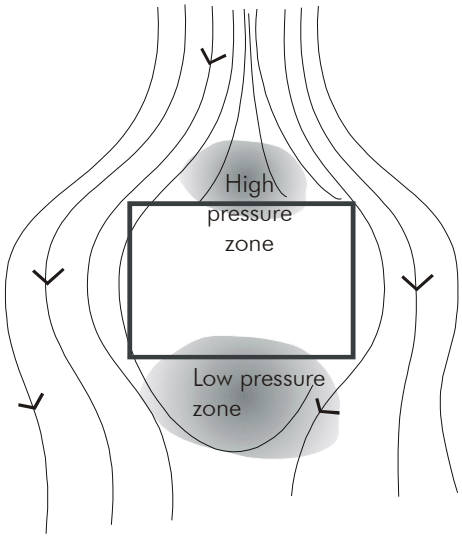
Provide equal area of operable openings on the windward and leeward side. Ensure that the windward side is well shaded to provide cool air intake. Locate the openings on the windward side at the occupied level.

Description

Wind-driven ventilation is one of two methods of providing natural ventilation. All natural ventilation strategies rely on the movement of air through space to equalize pressure. When wind blows against a barrier, it is deflected around and above the barrier (in this case, a building). The air pressure on the windward side rises above atmospheric pressure (called the pressure zone). The pressure on the leeward side drops (suction zone), creating pressure stratification across the building. To equalize pressure, outdoor air will enter through available openings on the windward side and eventually be exhausted through the leeward side.

Pressure is not uniformly distributed over the entire windward face, but diminishes outwards from the pressure zone. The pressure difference between any two points on the building envelope will determine the potential for ventilation if openings were provided at these two points. The airflow is directly proportional to the effective area of inlet openings, wind speed, and wind direction.

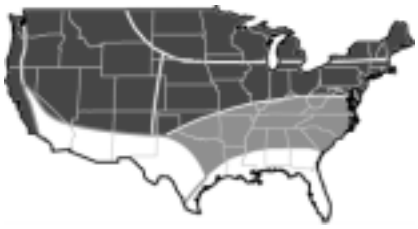




Applicability

Cross ventilation is a very effective strategy for removing heat and providing airflow in mild climates. In coastal climates, the need for a cooling system may be eliminated by a carefully designed natural ventilation system. In most other climates, it can alter interior conditions only modestly. Hybrid systems work best in such situations. In humid climates, natural ventilation cannot replace the moisture-removing capabilities of air conditioning (although desiccant systems that remove moisture from the space can be used for more effective natural ventilation). Introducing humid air (even if it is relatively cool) into a space will add a substantial load on the cooling system in hybrid systems. However, even extreme climates experience moderate conditions during spring and fall, and natural ventilation should be designed to take full advantage of these conditions.

Applicable Climates



Applicable Spaces

Classrooms	■
Library	■
Multi-Purpose	■
Gym	■
Corridors	▒
Administration	■
Toilets	▒
Other	■

When to Consider

Programming	□
Schematic	■
Design Dev.	■
Contract Docs.	□
Construction	□
Commissioning	□
Operation	■

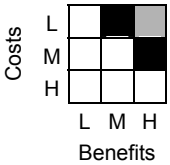
This strategy relies heavily on two parameters that may change continuously: wind availability and wind direction. Consequently, it is a somewhat unreliable source for thermal comfort. Spaces, like computer rooms and laboratories, that need strict maintenance of indoor temperature and humidity should definitely use hybrid systems for both cooling and ventilation. Introducing natural ventilation in a building may cause increased levels of dirt, dust, and noise, which could also be a serious limitation for certain types of spaces.

Cross ventilation has to be an integral part of the design schematic and design development phases. An effective natural ventilation design starts with limiting space sizes to facilitate inward flow of air from one face and outward flow from the other — architectural elements can be used to harness prevailing winds. This may alter building aesthetics and needs to be addressed early in the design phase.

Integrated Design Implications

- **Design Phase.** Cross ventilation can (or should) very strongly influence building aesthetics and site planning. Natural ventilation codes will dictate space widths and minimum opening sizes. To maximize the effectiveness of openings, the long façade of a building should be perpendicular to the prevailing wind direction. Narrow and woven plans with more surfaces exposed to the outside will work better than bulky plans with concentrated volumes. Singly loaded corridors will provide better air flow than doubly loaded ones. An open building plan with plenty of surface area exposed to the outside will work well for cross ventilation. Architectural elements like fins, wing walls, parapets, and balconies will enhance wind speeds and should be an integral part of cross ventilation design.
- **Thermal Mass.** Cross ventilation should be combined with thermal mass to take advantage of large diurnal temperature swings. Mass walls can act as heat reservoirs, absorbing heat through the day and dissipating it at night. At night, natural ventilation can be used to increase the quantum of dissipated heat as well as to accelerate the process of dissipation (see section on Energy-Efficient Building Shell for details). This will reduce the load on the cooling system by pre-cooling the building. A large diurnal temperature swing (as in desert areas) will ensure that the building is more effectively "flushed."
- **Integration with Daylighting and View Windows.** The apertures for cross ventilation will also serve as view windows and luminaires for side lighting. All architectural elements intended to enhance one strategy should also work for the other. Orientation that works for ventilation (openings on the windward side) may not be the ideal direction for bringing in daylight. West orientation for windows will increase heat gain and cause glare, but may be the best orientation for bringing in outside air in the coastal areas. Prioritize the needs of the space based on function and climate. For instance, benefits of daylighting in a cold climate outweigh those of cross ventilation, therefore orient the building based on daylighting considerations.
- **Integration with HVAC.** Natural ventilation may be intended to replace air conditioning entirely or, as is more often the case, to coexist with mechanical systems in a "hybrid mode." Also, natural ventilation may occur in "change-over" (windows are shut when mechanical system is on) or "concurrent" modes. Fewer systems are compatible with the concurrent mode. These factors need to be carefully considered before selecting a system (for more information on system selection see this chapter's Overview).

Cost Effectiveness



Low to moderate. Buildings that use natural ventilation may have higher initial costs, due to the higher cost of operable windows. Operable windows typically cost 5% to 10% more than fixed glazing. Based on average installed cost for metal frame, double-glazed, fixed windows of $20/ft^2 to $30/ft^2, the operable window should cost $48 to $72 more per classroom for buildings that meet their ventilation needs through natural ventilation only (based on code-prescribed minimum area of operable glazing per classroom). For "hybrid" buildings, the cost will be more modest because the operable window area can be less than the code prescribed minimum (5% of floor area). In buildings where natural ventilation is designed to occur concurrently, the initial costs may be higher due to limitations in system selection.

Benefits

Moderate to high. This varies significantly depending on climatic conditions and natural ventilation design.

- In a moderate climate, wind-driven ventilation can meet the cooling loads most of the time. In such climates, the simple payback period will vary between 8 to 12 years. At times, a good natural ventilation design may completely eliminate the need for a cooling system. This design will result in huge savings that offsets the cost of installing operable windows and lowers the simple payback period to one to four years.
- Buildings located in harsher climates will use “mixed-mode” systems. In such climates, natural ventilation may have limited application resulting in higher payback periods of 12 to 15 years.
- Cross ventilation alleviates odors and quickly exhausts contaminants from a space.
- Increased airflow in a space results in higher thermal comfort levels and increased productivity.
- Operable openings at the occupied level instill the occupants with a sense of individual control over the indoor environment.
- An intangible benefit of natural ventilation is the establishment of a connection with the outdoors (both visual and tactile), weather patterns, and seasonal changes. This results in higher tolerances for variations in temperature and humidity levels.
- Natural ventilation systems are simple to install and require little maintenance.

Design Tools

Opening areas may be derived using spreadsheet-based calculations. These estimates use approximation techniques but are good numbers to start with. The following algorithm shows the rate of wind-induced airflow through inlet openings:

$$Q = C_4 C_v A V$$

where,

Q = airflow rate, cfm
C_v = effectiveness of openings (C_v is assumed to be 0.5-0.6 for perpendicular winds and 0.25 to 0.35 for diagonal winds)
A = free area of inlet openings
V = wind speed, mph
C_4 = unit conversion factor= 88.0

The following algorithm calculates the required airflow rate for removal of a given amount of heat from a space (see section on Load Calculations for estimating the amount of heat to be removed):

$$Q = \frac{60q}{c_p \rho (t_i - t_o)} \qquad Q = \frac{\text{Btu/h}}{1.08 \Delta T}$$

where,

Q = airflow rate required to remove heat, cfm
q = rate of heat removal, Btu/h
C_p = specific heat of air Btu/lb°F (about 0.24)
ρ = air density, lb_m/cf (about 0.075)
t_i-t_o = indoor-outdoor temperature difference, °F

Many computer programs are available for predicting ventilation patterns. Some that use the “zonal” method may be used to predict ventilation rate (mechanical and natural), magnitude and direction of air flow through openings, air infiltration rates as a function of climate and building air leakage, pattern of air flow between zones, internal room pressures, pollutant concentration, and back drafting and cross-contamination risks. These models take the form of a flow network in which zones or rooms of differing

pressure are interconnected by a set of flow paths. This network is approximated by a series of equations representing the flow characteristics of each opening and the forces driving the air flow process. Widely available codes include BREEZE and COMIS.

A computational fluid dynamics (CFD) program is a more accurate and complex tool for modeling airflow through a space based on pressure and temperature differentials. These programs can simulate and predict room airflow, airflow in large enclosures (atria, shopping malls, airports, exhibitions centers, etc.), air change efficiency, pollutant removal effectiveness, temperature distribution, air velocity distribution, turbulence distribution, pressure distribution, and airflow around buildings. FLUENT is a sophisticated analysis technique that can, among other things, model and/or predict fluid flow behavior, transfer of heat, and behavior of mass. This software is particularly geared towards ventilation calculations including natural and forced convection currents. It also accurately calculates air density as a function of temperature and predicts the resulting buoyancy forces that can give rise to important thermal stratification effects. Important outputs from FLOVENT are user variables, such as the comfort indices of predicted mean vote, percentage of people dissatisfied, mean radiant temperature, dry resultant temperature, and percentage saturation, including a visualization of their variation through space. A summary of minimum, maximum, mean, and standard deviation for all calculated variables is also available.

Design Details

- Orient the building to maximize surface exposure to prevailing winds.
- Provide the inlets on the windward side (pressure zone) and the outlets on the leeward side (suction zone). Use architectural features like wing walls and parapets to create positive and negative pressure areas to induce cross ventilation. Air speed inside a space varies significantly depending on the location of openings (see table below). As far as possible, provide openings on opposite walls. Using singly loaded corridors will facilitate provision of openings on opposite walls. Limit room widths to 15 ft to 20 ft if openings cannot be provided on two walls. Windows placed on adjacent walls also perform very well due to the wall-jet phenomenon wherein the inflowing air moves along the nearest wall surfaces. This positioning should be limited to smaller spaces (less than 15 ft x 15 ft).
- Air inlet and outlets should be designed to minimize noise transfer from the exterior to the interior and to adjacent occupied spaces.

Table 5 — Average Indoor Air Velocity as a Percentage of the Exterior Wind Velocity for Wind Direction Perpendicular to and 45° to the Opening

Window Height as a Fraction of Wall Height	1/3	1/3	1/3
Window Width as a Fraction of Wall Height	1/3	2/3	3/3
Single Opening	12%-14%	13%-17%	16%-23%
Two Openings on Same Wall	-	22%	23%
Two Openings in Adjacent Walls	37%-45%	-	-
Two Openings on Opposite Walls	35%-42%	37%-51%	46%-65%

Source: Givoni, Baruch; Man, Climate, and Architecture*, London: Applied Science, 1976.*

- A free ventilation area of 1.5% to 2% (of the floor area), which is the recommended minimum area for operable windows only, will meet the ventilation requirements. Daylighting considerations will require a larger window area. Also, if the space is solely dependent on natural ventilation then code requirements will set the minimum operable window area to 5% of the floor area. Although this area will meet the ventilation requirements of a space during mild climatic conditions, larger window areas should be provided for occupant cooling through increased air movement. For cooling purposes provide 5% to 8% of the floor area as free ventilation area. Equal inlet and outlet areas maximize airflow, whereas outlets that are 2% to 5% larger than inlets produce higher air velocities.The inlet location affects airflow patterns far more significantly than outlet location. Inlet location should be a higher priority (if faced with a choice), as a high inlet will direct air towards the ceiling and will almost bypass the occupied level. Locate inlets at a low or medium height.For natural ventilation to function

properly, solar gains should be minimized. Direct sunlight penetrating into the space during periods of natural ventilation may make it difficult or impossible to achieve comfortable conditions with natural ventilation alone. Use shading devices such as overhangs, awnings, and fins to control solar gains.

- The incoming air may be cooled through good site planning, landscaping, and planting strategies. If a water body is planned for the site, place it on the windward side to pre-cool the incoming air through evaporative cooling. Planting tall deciduous trees on the windward side will lower the temperature of the inflow and shade the openings.
- Provide windows with shutters that can be opened or shut in increments. This allows the occupants to vary the inlet and outlet areas according to seasonal variations.
- Use features like overhangs, awning windows, eaves, and porches to protect the openings from rain and to minimize excess heat gain from direct sunlight. Awning windows work very well for cross ventilation because they provide more airflow than double-hung windows (for the same glazed area) and also provide protection from rain. Casement windows provide maximum airflow in both perpendicular and oblique wind conditions.
- Ensure that vents and windows are accessible and easy to use. Avoid blocking windows with exterior objects such as shrubs and fences, but do not eliminate shading.
- Provide inlets for cross ventilation openings at the occupied level. Stagger the outlet openings both vertically and horizontally by a few feet to achieve longer air paths. Concentrate ventilation openings in spaces most likely to require cooling.
- Use overhangs, porches, and eaves to protect windows and vents from rain to extend the amount of time that natural ventilation can be used.
- Ensure that openings can be tightly sealed in winter or when using air conditioning or dehumidification systems.
- HVAC systems should be designed to work in harmony with natural ventilation. The objective of a concurrent natural ventilation system is to meet the outside air requirement using the least possible opening area. The objective of a change-over natural ventilation system is to meet the outside air requirement as well as provide cooling. The HVAC and natural ventilation system are mutually dependent. See the Overview for a detailed discussion.

Operation and Maintenance Issues

This strategy is largely dependent on manual operation for its success. Automated operation may make sense for very large commercial buildings, but not for schools.

- Encourage students and teachers to open/close openings regularly.
- The mechanisms for operable inlets and outlets should be well maintained and clean.
- Periodically clean windowsills, panes, fins, screens, and louvers to ensure healthy air intake for the space.
- Assign responsibility of ensuring that openings are shut during cold weather and the hours of operation of the mechanical system. Also ensure adequate opening area is available for nighttime ventilation in hot dry climates.

Commissioning

None.

References/Additional Information

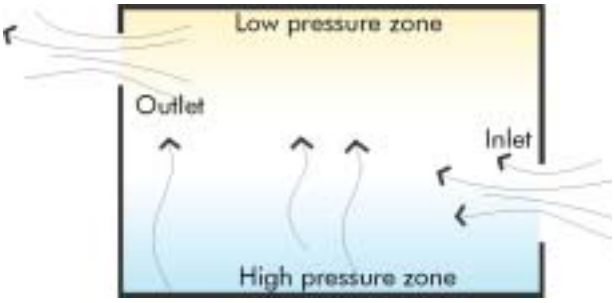
Cook, Jeffrey, Ed. *Passive Cooling*. Cambridge: MIT Press, 1989.

Brown, G.Z. *Sun, Wind, and Light*. New York: John Wiley & Sons, 1986.

GUIDELINE MV2: STACK VENTILATION

Recommendation

Use inlets and outlets of equal area and maximize the vertical distance between these two sets of apertures. Place inlets close to the floor or at the occupied level. Locate the outlets closer to the ceiling on the opposite wall. To facilitate varying summer and winter strategies, provide incrementally operable shutters.



Description

Stack ventilation is one of two methods of providing natural ventilation. Stack ventilation utilizes the difference in air densities to provide air movement across a space. At least two ventilation apertures need to be provided; one closer to the floor and the other high in the space. Warmed by internal loads (people, lights, equipment), the indoor air rises. This creates a vertical pressure gradient within the enclosed space. If an aperture is available near the ceiling, the warmer air at the upper levels will escape as the lower aperture draws in the cool outside air. Higher indoor temperatures are essential for causing a pressure difference such that the upper openings act as the outlet and cool air intake is induced at the lower opening.

Applicable Climates

Applicable Spaces		When to Consider	
Classrooms	■	Programming	□
Library	■	Schematic	■
Multi-Purpose	■	Design Dev.	■
Gym	■	Contract Docs.	□
Corridors	▒	Construction	□
Administration	■	Commissioning	□
Toilets	▒	Operation	■
Other	■		

The airflow induced by thermal force is directly proportional to the inlet-outlet height differential, the effective area of the aperture, and the inside-outside temperature differential.

Applicability

Pressure-differential-driven natural ventilation is an effective strategy for meeting minimum airflow requirements, especially during winter, when the inside-outside temperature differential is at a maximum. It is also appropriate for providing cooling during mild weather conditions when direct outside air is still sufficiently cool to meet interior space cooling requirements.

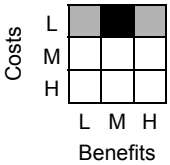
Integrated Design Implications

- **Design Phase.** Using the stack effect for ventilation requires an integrated design approach. Stack ventilation will affect building mass and aesthetics. Vertical airshafts for providing stack ventilation also need to be considered early in the design phase.
- **Thermal Mass.** Nighttime ventilation coupled with thermal mass is a very effective strategy for heat removal in hot, dry climates.
- **Integration with Daylighting and View Windows.** Apertures for stack ventilation need to be located close to the floor and ceiling for best results. The high apertures can couple as clerestories or side-lighting luminaires. Benefits of daylighting and natural ventilation need to be considered in conjunction with each other to arrive at the ideal location and size for openings.
- **Integration with HVAC.** Stack ventilation will be used for meeting the outside air requirement in most climates other than Hot and Dry (where stack ventilation will also be used for nighttime cooling).

Carefully integrating this strategy with HVAC system selection and operation will maximize its benefits. For details, see the Overview section.

Cost Effectiveness

Low to moderate.



Stack ventilation may not add to overall costs significantly if integrated with view windows, high side lighting, and other daylighting strategies. However, an additional cost of $2/ft^2 may be associated with ensuring that all openings are operable. Adjustable frame intake louvers may cost up to $25/ft^2 (this includes installation costs). Additional cost of installing windows high in the space will range from $15/ft^2 to $30/ft^2.

Benefits

Low to moderate.

The benefits depend largely on weather conditions (indoor-outdoor temperature differential) and the design of openings.

- In a moderate climate, a combination of wind-driven and stack ventilation strategies can meet the cooling loads most of the time. In more extreme climates (with a large diurnal range of temperature), stack ventilation can operate in “mixed-mode” systems and reduce the peak demand through nighttime flushing, resulting in lower utility bills and first costs. In such climates, the simple payback period will be 8 to 12 years. For most other climates, the simple payback period will be 10 to 14 years.
- Stack ventilation apertures can also double as side and high side lighting strategies.
- Stack ventilation effectively removes contaminants and pollutants from space.

Design Tools

The airflow (cfm) required can be reasonably estimated using spreadsheet-based calculations. The following algorithm defines the airflow as it varies with the area of openings, indoor temperature, outdoor temperature, and location of the inlet and outlet:

$$Q = 60 C_D A \sqrt{2 g \Delta H_{NPL} (T_i - T_o) / T_i}$$

Q = airflow rate, cfm

C_D = discharge coefficient for opening

ΔH_{NPL} = height from mid-point of lower opening to Neutral Pressure Level (NPL) ft

T_i = indoor temperature, °F

T_o = outdoor temperature, °F

Use this algorithm to estimate the aperture area for a particular hour of a day (with Q equal to 15 cfm).

Several computer tools are available for simulating pressure driven airflow. Refer to Guideline MV1: Cross Ventilation for details.

Design Details

- Provide equal inlet and outlet areas to maximize airflow. Airflow will be dictated by the smaller of the inlet and outlet areas.
- The width to height ratio of openings should be more than one as far as possible (i.e., orient openings horizontally).
- The free ventilation area of the inlet and outlet should be at least 1% of the total floor area of the room (4.8 ft^2 each per classroom, based on 32 ft x 30 ft x 9 ft-6 in. classrooms). This is adequate to meet outdoor air requirements with perpendicular wind speeds as low as 2 mph and low temperature differentials that occur during summer months. Lowering the air intake of these openings during

winter or completely shutting some of these openings may avoid uncomfortable winter conditions. For extreme climates, all the available operable openings may remain open only for limited periods.

- Allow for at least a 5-ft center-to-center height difference between the inlet and the outlet. Increasing the height differential further will produce better airflow.
- Use stairwells or other continuous vertical elements as stack wells by providing adequate apertures. Such spaces may be used to ventilate adjacent spaces because of their ability to displace large volumes of air (because of greater stack height).
- Carefully control and minimize solar gains. For details see Guideline MV1: Cross Ventilation.
- Combine stack ventilation with cross ventilation elements. Set the inlet openings for cross ventilation lower in the wall so that they can double as inlets for stack ventilation.
- Use louvers on inlets to channel air intake. Use architectural features like wind towers and wind channels to effectively exhaust the hot indoor air.
- HVAC systems should be designed to work in harmony with stack ventilation (see the Overview section for a discussion).
- Air inlet and outlets should be located or designed to minimize noise transfer from the exterior to the interior and to adjacent occupied spaces.
- Large openings may require installing security grills to limit potential points of entry.

Operation and Maintenance Issues

This strategy is largely dependent on manual operation for its success:

- Openings should be appropriately operated according to indoor-outdoor temperature differentials.
- The mechanisms for operable inlets and outlets should be well maintained and clean.
- Windowsills, fins, screens, and louvers should be periodically cleaned to ensure healthy air intake for the space.
- Assign responsibility of ensuring that openings remain shut during the mechanical system's hours of operation unless the ventilation is designed to work concurrently.
- Ensure that adequate opening area is available for nighttime ventilation in hot, dry climates.

Commissioning

None.

References/Additional Information

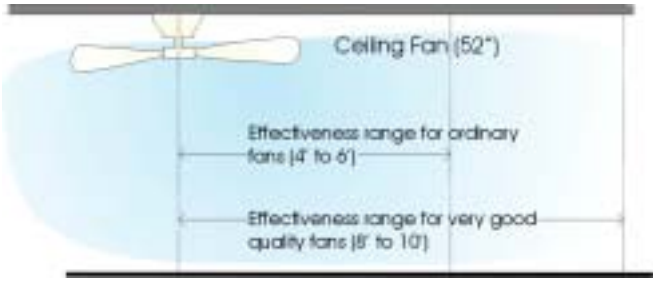
Cook, Jeffrey. *Passive Cooling*. Cambridge: MIT Press, 1989.

Brown, G.Z. *Sun, Wind, and Light*. New York: John Wiley & Sons, 1986.

GUIDELINE MV3: CEILING FANS

Recommendation

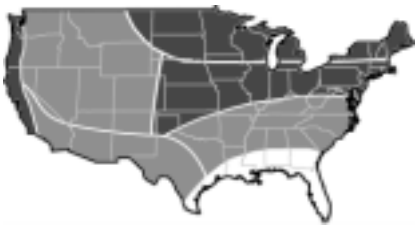
Use ceiling fans in classrooms to provide enhanced thermal comfort for occupants through higher air velocity. Use the ceiling fans instead of air conditioners in mild coastal climates. In more extreme climates, use ceiling fans as a supplement to cooling systems.



Description

A ceiling fan is a device for creating interior air motion. It is a permanent fixture operated by a switch or a pull string. Acceptable comfort levels can be maintained above the customary comfort zone for air speeds exceeding 50 fpm by using a ceiling fan. Generally, for speeds above 30 fpm, most people will perceive a 15 fpm increase in air to be equal to 1°F decrease in temperature. This phenomenon is commonly called "chill factor." Outside air can be introduced into a space through openings using a fan when outside air cannot enter the space on its own, because it is either too humid or too hot. A fan can also re-circulate air within a space. Fans also cool by increasing evaporation of moisture from the skin (skin moisture vaporizes using body heat to change phase).

Applicable Climates



Applicable Spaces		When to Consider	
Classrooms	■	Programming	□
Library	■	Schematic	□
Multi-Purpose	■	Design Dev.	■
Gym	□	Contract Docs.	□
Corridors	□	Construction	▒
Administration	■	Commissioning	□
Toilets	□	Operation	■
Other	▒		

In a high ceiling space, ceiling fans can help "destratify" the warm air layer, which collects near the ceiling, and distribute it to the lower part of the space for thermal comfort. As a result, heating thermostats need not be set as high.

The interior air motion caused by ceiling fans varies as a function of fan position, power, blade speed (measured in rpm), blade size, and the number of fans within the space. Moreover, air speeds within a space vary significantly at different distances from the fan.

The normal current draw will range from approximately 15 W at low speed to 115 W at high speed.

Applicability

Ceiling fans are appropriate for classrooms and administration areas. They may not be suitable for gyms because of the potential for rapid skin cooling (more skin moisture is secreted during intense physical activities). Nor are they appropriate for toilets as the space may be too small for a ceiling hung fan. Noise produced by ceiling fans may be an issue in auditoriums or classrooms if fans turn at too high a velocity.

Ceiling fans are suitable for most climates that require cooling. Combined with other passive strategies they may eliminate the need for air conditioning in the Temperate and Mixed region. They are not very useful in humid climates.

Ceiling fans should be considered in the design development stage due to electrical wiring and ceiling height issues, although adding fans to existing spaces is feasible too.

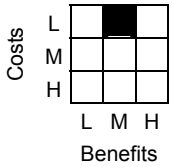
Integrated Design Implications

Using ceiling fans does not significantly impact other design decisions, except when a displacement airflow design is being considered.

- A minimum ceiling height of 9 ft must be provided to accommodate a fan such that its blades are at a distance of 8 ft from the floor and 1 ft from the ceiling.
- Ceiling fans should be combined with natural ventilation strategies for best results.

Cost Effectiveness

Ceiling fans cost between $75 and $200. The typical cost of a professionally installed fan is about $250. Fans with features such as light fixtures, reverse or multiple speed settings, and extended warranties may cost more. Some ceiling fans are very economical to operate as they consume very little energy. Others have very inefficient motors and add considerable heat to the room. Careful selection should be made.



Benefits

- Moving air extends the comfort range and allows occupants to feel comfortable at higher temperatures. It also helps occupants feel dry. Wind speed is one of the six factors that affect thermal comfort indices like the predicted mean vote (PMV). Increasing air speeds results in PMVs that fall in the comfort zone (for detailed discussion, see this chapter's Overview section).
- Temperature settings for mechanical cooling equipment can be higher and an energy savings greater than the energy consumption of the fans can be realized. According to the Texas Energy Extension Service, for a three-ton cooling system costing $550 per season, raising the thermostat from 75°F to 80°F can reduce the operating cost by $151. Operating a ceiling fan 10 or more hours a day may cost less than $3/month. For example, a typical fan operating at high speed uses approximately 100 W of power. Assuming that the fan is operated five hours/day with an energy cost of $0.08/kWh, the cost of operation will be $0.04/day. At lower speeds this operating cost will be even less. This low operating cost and the potential reduction in cooling and heating cost make the ceiling fan one of the better energy-saving devices on the market. As a rule of thumb — each degree rise in a thermostat setting (beyond 78°F) results in a 3% to 5% saving on cooling energy. If the ceiling fan is supplementing air conditioning, the thermostat of the air conditioning unit may be raised a full 4°F above the standard 78°F setting while still maintaining comfortable space conditions.
- In the heating season, ceiling fans can help bring the warmer air that stratifies near the ceiling down to where the occupants are located. A low speed that does not create a significant breeze is best for this heating season application. Again, the thermostat set point may be lowered by nearly 2°F.

Design Tools

Use the following charts to size ceiling fans according to largest room dimension and room area:

Table 6 — Fan Diameter Selection Based on Space Dimensions

Largest Dimension of Room	Minimum Fan Diameter
12 ft or less	36 in.
12 - 16 ft	48 in.
16 - 17.5 ft	52 in.
17.5 - 18.5 ft	56 in.
18.5 ft or more	2 fans needed

Table 7 — Fan Diameter Selection Based on Space Area

Room Area	Minimum Fan Diameter
100 ft^2	36 in.
150 ft^2	42 in.
225 ft^2	48 in.
375 ft^2	52 in.
400+ ft^2	2 fans needed

Sources: Consumer Guide to Home Energy Saving (1995) by the American Council for an Energy Efficient Economy.

Design Details

- Use ceiling fans in frequently occupied spaces.
- Use “Quiet Type” energy-efficient fan and motor assemblies.
- A larger fan provides a greater range of airflow settings and ventilates a larger area at lower velocities, with less noise, and only slightly more power than similar smaller units. Use two 48-in. fans in classrooms (based on 30 ft x 32 ft classrooms). These will move air most effectively in a 4 ft to 6 ft radius, and somewhat less effectively for another 3 ft to 4 ft radius. At the level of seated occupants, this will achieve air speeds ranging from 50 fpm to 200 fpm. Beyond 30 fpm, every additional 15 fpm results in a perceived 1°F drop in temperature. The more blade surface, the more air it will catch.
- Ceiling fans work best when the blades are 8 ft to 9 ft above the floor and 10 in. to 12 in. below the ceiling. Placing fans so the blades are closer than 8 in. to the ceiling can decrease the efficiency by 40%. Fans also require at least 18 in. of clearance between the blade tips and walls. Two types of mountings are available for ceiling fans — rod and hugger. In rod fans, the motor housing is suspended from the mounting bracket by a rod. With hugger fans, the motor housing is mounted directly to the ceiling box. Hugger fans are not as efficient as rod fans in the down motion, especially at higher speeds. The blades will starve themselves for air when they are too close to the ceiling.
- Use ceiling fans to supplement air movement in natural ventilation strategies.
- Select a fan with at least a two-speed control for better regulation of air movement. Variable-speed fans are preferable so that the lowest speed can be used in the heating season to accomplish destratification without causing excessive draft. If using a reversible fan, ensure that the fan has a setting low enough to circulate the air without creating too much of a breeze. These fans are best for rooms that tend to build up heat.
- Fans should be on only when the space is occupied; otherwise the movement of the motor is also introducing some heat in the room without any cooling benefits. Remember that ceiling fans cool people, not spaces. Consider using an occupancy sensor.

Operation and Maintenance Issues

- Ceiling fans should be operated only when the rooms are occupied. A motion sensor or a clear policy of operating ceiling fans only when using the room is needed. In the destratification mode, starting the fans several hours before occupancy would be beneficial for getting ceiling accumulated heat down.
- Ensure that all blades are screwed firmly into the blade holder and that all blade holders are tightly secured at the fan. This should be checked at least once a year.
- It is important to periodically clean the fan, as the blades tend to accumulate dust on the upper side. An anti-static agent can be used for cleaning, but do not use any cleaning agents that can damage the finish. Never saturate a cloth with water to clean the ceiling fan.
- For a fan to perform efficiently, it is very important that the blade be aerodynamically shaped to increase its efficiency, similar to an airplane propeller. "Balanced" blades; that is, blades that are electronically matched at the factory; are sold as balanced four- or five-blade sets, depending on the design of the fan. For this reason, never interchange blades between fans.

- Use durable fans with longer warranties. Use fans with metal motor housings — these may require annual lubrication while plastic motor housings will not.

AIRBASE (database of over 7,000 abstracts of international papers on infiltration and ventilation), Air Infiltration and Ventilation Centre, Sovereign Court, University of Warwick Science Park, Sir William Lyons Road, Coventry, CV4 7EZ, U.K. Tel: 44-203-692050, Fax: 44-203-416306.

American Society of Heating, Refrigerating and Air Conditioning Engineers. *ASHRAE 62-Ventilation for Acceptable Indoor Air Quality.* 1791 Tullie Circle NE, Atlanta, GA, 30329-2305. Tel:(404) 636-8400; Fax:(404) 321-5478.

Bower, John. *Understanding Ventilation: How to Design, Select, and Install Residential Ventilation Systems.* The Healthy House Institute, 430 N. Sewell Rd., Bloomington, IN 47408.

The Home Ventilating Institute. *The Certified Home Ventilating Products Directory.* 30 West University Dr., Arlington Heights, IL 60004-1893. Tel:(708) 394-0150.

GUIDELINE MV4: GAS/ELECTRIC SPLIT SYSTEM

Recommendation

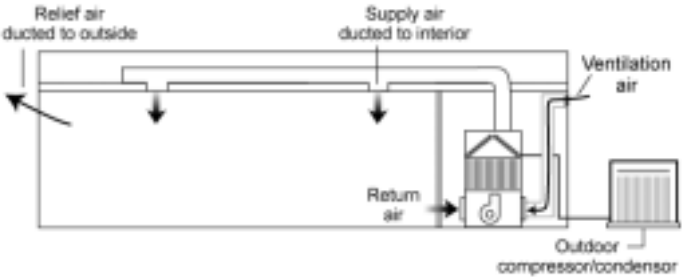
When specifying a gas/electric split system, consider an add-on economizer, two-speed blower/furnace/compressor, high-efficiency furnace (AFUE 90+), and high-efficiency cooling (SEER 14+).

Description

This system is similar to a typical residential heating and cooling system. The components include an indoor fan unit and outdoor compressor and condenser package. The indoor unit usually includes a cooling coil and furnace section, although the furnace can be omitted if the compressor is also used for heating in heat pump mode. The indoor and outdoor sections are connected via refrigerant tubing and control wires.

Supply air from the indoor unit is typically ducted to several supply diffusers in the ceiling. Return air may be ducted or returned directly to the unit through a grill.

While most residential systems recirculate indoor air only, an outside air duct is essential to supply ventilation air that is mixed with return air for schools.



Basic gas/electric split system.

Applicable Climates

Applicable Spaces		When to Consider	
Classrooms	■	Programming	☐
Library	☐	Schematic	■
Multi-Purpose	☐	Design Dev.	☐
Gym	☐	Contract Docs.	☐
Corridors	☐	Construction	☐
Administration	☐	Commissioning	☐
Toilets	☐	Operation	☐
Other	☐		

Variations and Options

An economizer is not standard with split systems but is available as an aftermarket option. The additional equipment includes a mixing box with outdoor and return air dampers and the associated controls. Check with split system manufacturer for control compatibility.

For climates where cooling is unnecessary, the system can be used for heating only, or for heating and ventilating. Eliminating the cooling coil and outdoor compressor unit reduces the cost significantly. An economizer may be installed to provide free cooling if the space design does not allow for convenient natural ventilation cooling (due to drafts, outdoor noise, dust, or similar problems).

Indoor units are available for either horizontal or vertical installation. Horizontal units are typically installed above the ceiling. Vertical units may be installed in a mechanical closet with flow direction either upwards or downwards.

A high-efficiency, condensing furnace is available as an option for most split systems. Annualized fuel utilization efficiency (AFUE) is 90% to 96%, compared to about 80% for standard units.

High-efficiency cooling is also an option provided by most manufacturers. Systems are available with efficiencies greater than seasonal energy efficiency ratio (SEER) 14, compared to typical units with SEER 10 to 11.

A two-speed blower and variable output furnace is an option that can provide significant fan energy savings and improve comfort through less on-off cycling.

Two-speed compressors are available that can be controlled together with a two-speed indoor fan for better comfort and humidity control.

Heat pump heating is an option for locations without convenient natural gas access. In cool climates, a supplementary electric resistance heating element may be necessary, especially to handle relatively high ventilation air requirements for classrooms.

Natural gas engine-driven heat pumps are available; however, they are more expensive. These units use a reciprocating natural gas engine rather than an electric motor to drive the compressor and provide heating and cooling.

Applicability

This system type is appropriate for classrooms or other single zone spaces up to about 2,500 ft^2. Minimum cooling efficiency is SEER 10.0 for split systems smaller than 65,000 Btu/h of cooling capacity. Minimum heating efficiency is 78% AFUE for gas furnaces smaller than 225,000 Btu/h. These efficiency requirements are federal regulations.

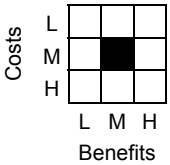
Integrated Design Implications

Location of the indoor and outdoor units needs to be considered early in the architectural design to ensure optimal performance. See Design Details below for important considerations. Similarly, the location of ducts and supply registers should be considered when making structural and lighting system decisions.

System controls should be specified so they integrate with natural ventilation design. Use automatic interlock controls to shutoff the system when windows are opened or allow manual fan shutoff. If the space is designed for good natural ventilation, then an economizer may not be necessary.

Try to place ducts within the conditioned envelope to minimize the impact of leakage and conduction losses, which can be very significant. Insulate under the roof deck rather than on top of a suspended ceiling. If possible, place the indoor unit within the conditioned envelope as well. Ensure, however, that combustion air is properly vented.

Cost Effectiveness



Overall system cost for a gas/electric split system ranges from \$10/ft^2 to \$12/ft^2.

A high-efficiency (condensing) furnace adds roughly \$700, compared to a standard efficiency unit with a base installed cost of about \$550. However, the extra cost may also cover multi-speed fan control and variable furnace output, in addition to better efficiency.

An efficient three-ton air conditioner with 13 SEER costs roughly \$2,500, compared to \$1,700 for a SEER 10. The incremental cost is roughly \$800.

An outside air economizer adds about \$300 to \$500.

For a 960-ft^2 classroom, incremental cost for combined measures is about \$2,000, or \$2/ft^2 of floor area.

High-efficiency cooling is generally cost effective in warm regions. A high-efficiency, condensing furnace should be cost effective in cool climates, especially considering construction cost savings due to more flexibility in locating the low temperature flue vent.

Benefits

Advantages

- High heating and cooling efficiencies are available. (By contrast, efficient heating options are seldom available for packaged rooftop units.)
- Two-speed fan and compressor options improve partial load efficiency, comfort, and humidity control.

- Numerous system capacities are possible with combinations of furnace units, cooling coils, and compressors.
- An economizer can be added to take advantage of outdoor air for free cooling.
- Outdoor unit is relatively small.
- It is possible to keep all ducts within the insulated building shell to minimize impact of duct losses.
- Moderate initial cost.
- This can be installed as a heating-only system at a lower cost. A cooling coil and outdoor condensing unit can be added later if desired. However, their ductwork and air distribution system would need to be sized for greater cooling airflow requirements.

Disadvantages

- Space within the building shell is required for the indoor unit, either above the ceiling or in a closet.
- An indoor unit may create noise in the space if not carefully designed and installed.
- Air ducts are required, which can be leaky and inefficient if not installed properly.
- High-efficiency units have a significant cost premium.
- Limited multi-zone capability.
- Poor dehumidification control (better with two-speed compressor and fan).
- Higher maintenance cost for large facilities compared to central VAV system.

Design Details

Indoor unit location considerations:

- To reduce noise, isolate the unit from the occupied space, and provide appropriate noise control measures at the intake and discharge and adequately sized ducts and registers to avoid excessive air velocity.
- Make sure that filters and coils are easily accessible for maintenance.
- Provide easy access for the outdoor air inlet, minimizing length of ducts and eliminating turns from ductwork if possible.
- Allow access to outdoors for furnace combustion air and provide a vent for flue gas as recommended by the manufacturer.
- Minimize the number of duct turns necessary to reach supply diffusers and return grilles, and minimize duct length (second priority compared to number of turns). At the same time, however, ensure that noise transmission through the ducts is controlled.
- Consider that cooling coil condensate must drain to a proper receptacle and condensate pan overflow should drain to a visible location.
- Provide adequate vibration isolation. Manufacturer may provide standard vibration isolation package.
- See also MV19: Air Distribution Design Guidelines for information about choosing locations for supply and return registers to minimize noise and maximize performance.

Outdoor unit location considerations:

- Typically, the unit is placed on a concrete pad alongside the building. However, rooftop installation is possible as well.
- To reduce noise, keep the unit away from operable windows and doors.
- Remember that outdoor units face the potential for vandalism and design accordingly.
- Provide access for maintenance.

- Try to choose a shaded location with the lowest possible ambient air temperature to improve cooling efficiency. Be especially careful to avoid direct exposure to afternoon sun.
- Provide adequate clearance around the outdoor unit to prevent airflow obstructions.
- If the outdoor unit is mounted on the rooftop, then consider using a reflective white roof membrane to reduce temperature and improve system performance. Standard roofs exceed 150°F on a sunny day, while white roofs can be 50°F cooler.

Match the compressor and indoor fan units for proper performance. See manufacturers' literature for combinations and their efficiency ratings.

Be sure to allow for furnace condensate drainage for high efficiency units, and provide condensate drainage for cooling coils.

Design the air distribution system to minimize pressure drop and set blower fan motor to low or medium speed to reduce fan energy consumption and minimize noise (see MV19: Air Distribution Design Guidelines).

Do not oversize heating and cooling capacities (see the topic Load Calculations in this chapter's Overview section).

If choosing a system with a multiple-speed fan as well as variable heating and cooling capacity, then specify a thermostat with those control capabilities.

Operation and Maintenance Issues

Maintenance requirements for a gas/electric split system are very similar to other system types. However, all compressor cooling systems require additional maintenance skills and cost more to maintain compared to heating-only systems.

Recommended maintenance tasks include:

- Replacing filters regularly
- Cleaning indoor and outdoor coils regularly
- Checking refrigerant charge
- Cleaning the cooling coil condensate pan and drain
- Lubricating and adjusting the fan as recommended by manufacturer.

Commissioning

Measure total supply airflow with a flow hood or comparable measuring device. Make sure that airflow is within 10% of design value. If airflow is low, then check ducts for leaks and constrictions, and check that filters and coils are free of obstructions. Larger ducts, or shorter duct runs, may be necessary. Reduce the number of duct turns to a minimum. If airflow is high, then reduce fan speed if possible according to manufacturer's instructions.

If an economizer is installed, then verify proper operation (see MV18: Economizers).

References/Additional Information

MV18: Economizers; MV19: Air Distribution Design Guidelines.

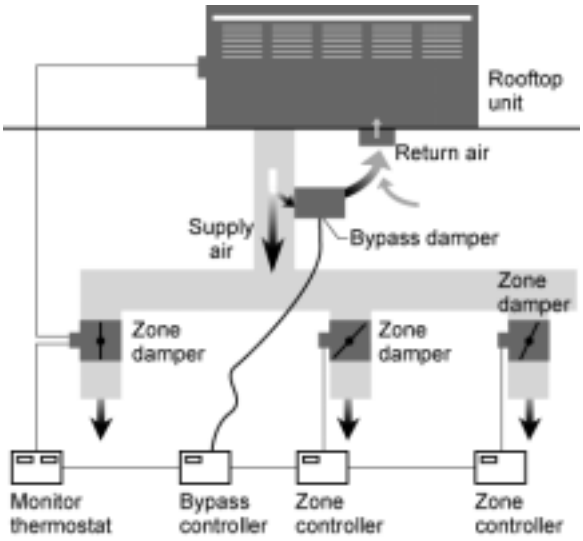
GUIDELINE MV5: PACKAGED ROOFTOP SYSTEM

Recommendation

If choosing a packaged rooftop system, specify a high-efficiency unit with an integrated economizer and design the duct system to allow proper airflow at low or medium fan speed.

Description

A packaged rooftop system is fully self-contained, and most consist of a constant volume supply fan, direct expansion cooling coil, heating (when required) with gas furnace, filters, compressors, condenser coils, and condenser fans. Units are typically mounted on roof curbs but can also be mounted on structural supports or on grade. Packaged rooftop single-zone units are typically controlled from a single space thermostat with one unit provided for each zone. Supply air and return air ducts connect to the bottom (vertical discharge) or side (horizontal discharge) of the unit.



Packaged rooftop system.

Applicable Climates

Applicable Spaces		When to Consider	
Classrooms	■	Programming	□
Library	■	Schematic	■
Multi-Purpose	■	Design Dev.	□
Gym	■	Contract Docs.	□
Corridors	■	Construction	□
Administration	■	Commissioning	□
Toilets	■	Operation	□
Other	■		

Variations and Options

Economizers are often standard, cost-effective options for rooftop units (see MV18: Economizers).

High-efficiency cooling with seasonal energy efficiency ratios in the range of 12 to 13 is commonly available.

Units can be purchased as heat pumps for use in areas without convenient access to natural gas for heating.

An evaporative precooler can be added to the condenser to increase capacity and efficiency during hot weather.

A “single zone” rooftop unit can condition multiple zones when equipped with special controls and hardware. This type of system includes an automatic damper in the ductwork for each zone, which modulates to control temperature. If some zones require cooling while others need heating, then the controller switches the rooftop unit between both modes and the zone dampers will open or close as appropriate. This system also includes a bypass damper between the supply and return that is opened to maintain constant airflow through the rooftop unit when one or more zone dampers are closed.

Applicability

A packaged rooftop unit is applicable for spaces that require heating and cooling. However, due to their relatively low cost and expected short life (less than 30 years), they are sometimes installed where only heating is required.

Due to the constant-volume fan, this system is most applicable where loads and ventilation requirements are relatively constant, such as in classrooms, administration areas, and libraries. The system is less applicable for intermittent occupancies such as assembly areas.

Packaged rooftop units are available in capacities from 2 tons to more than 100 tons and can be used for single zones from 600 ft^2 to more than 30,000 ft^2.

Multiple zones where the zone loads are not too different can be handled with special controls. There is no theoretical limit to the number of zones possible, and commercially available controllers will serve 32 or more. However, in practice, these controls should be used for no more than a handful of zones. For larger systems, variable air volume (VAV) controls will be more effective and efficient.

See Table 8 for minimum cooling efficiency requirements. For units smaller than 65,000 Btu/h, these efficiency requirements are federal regulations.

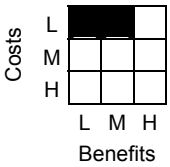
Integrated Design Implications

Rooftop units can have a significant visual impact and can create concern regarding noise level at adjacent properties. Their location should be considered early in the architectural design process to allow for efficient duct layout. In addition, location of ducts and supply registers should be considered when making lighting system decisions.

System controls should be specified so they integrate with natural ventilation design. Use automatic interlock controls to shut off the system when windows are opened or allow manual fan shutoff. If the space is designed for good natural ventilation, an economizer may not be necessary.

Try to place ducts within the conditioned envelope as much as possible to minimize the impact of leakage and conduction losses, which can be very significant. This is only recommended, however, where approximately the first 20 ft of duct runs above spaces that are not sensitive to noise. Insulate under the roof deck rather than on top of a suspended ceiling.

Cost Effectiveness



The overall cost for a packaged rooftop system can be as low as \$15/ft^2 to \$20/ft^2 (installed cost, including ductwork and controls).

The unit cost alone ranges from about \$1,500 for a two-ton unit to around \$2,000 for a five-ton unit. High-efficiency package units (when available) cost about 10% more than standard efficiency models and have paybacks of around three to four years in warm climates.

Packaged rooftop systems are often the lowest first-cost alternative when both heating and cooling are required. However, they are relatively costly to maintain, energy costs are higher than average, and life expectancy is less than 30 years.

Benefits

Advantages

- Low initial cost.
- No inside mechanical equipment space is used.
- An added economizer can take advantage of outdoor air for free cooling (see MV18: Economizers).
- Systems are widely available.

Disadvantages

- Fewer efficiency options exist compared to gas/electric split systems (e.g. condensing furnace, two-speed fan, high efficiency cooling).
- Systems are relatively large and require roof space.
- Air ducts, which can be leaky and inefficient if not installed properly, are required.

- Systems have limited multi-zone capability.
- Poor dehumidification control can occur compared to VAV systems (due to compressor cycling).
- Higher maintenance costs occur for large facilities compared to central VAV systems.
- Systems have typically shorter lifetimes than central VAV systems.

Design Details

Most packaged systems have several fan speed options that can be selected in the field when the unit is installed. Careful design of the air distribution system can reduce pressure drop and provide significant savings if the fan is wired for low or medium speed (see MV19: Air Distribution Design Guidelines).

The incremental equipment cost for packaged rooftop equipment is not too large to increase size from, say, two to four tons. Therefore, the temptation is strong to specify the larger unit for safety's sake. However, there are performance penalties for oversized systems. Bigger is not always better. Do not rely on rules of thumb to select airflow, cooling capacity, or heating capacity. See this chapter's Overview section for a discussion of load calculations and the impact of cooling capacity oversizing.

Table 8 lists recommended minimum efficiencies for packaged rooftop equipment.

Vibration isolation is often provided internally. Internal isolation should be reviewed for proper spring type and static deflection. If internal isolation is not provided, or is unacceptable, external spring isolators should be utilized. Refer to 1995 ASHRAE Handbook Chapter 43 for recommended vibration isolation. If external isolation is used, all internal spring isolators should not be released from their restraining bolt.

The unit should be located above unoccupied spaces (i.e. storage, stairwells, etc.).

Provide appropriate intake and discharge noise control consistent with meeting the Noise Criteria.

Table 8 – Recommended Minimum Efficiencies for Air-Cooled Packaged Rooftop Equipment

Capacity	Recommendation
< 65,000 Btuh	12.0 SEER
65,000 – 135,000 Btuh	11.0 EER
135,000 – 240,000 Btuh	10.5 EER
> 240,000 Btuh	10.0 EER

Operation and Maintenance Issues

Maintenance requirements for a packaged rooftop system are very similar to other system types. However, all compressor cooling systems require additional maintenance skills and cost more to maintain compared to heating-only systems.

Recommended maintenance tasks include:

- Replacing filters regularly
- Cleaning indoor and outdoor coils regularly
- Checking refrigerant charg.
- Cleaning and draining cooling coil condensate pan, and specify pans that are pitched to drain continuously under all operating conditions
- Pitch and properly trap drain pan and drain condensate to a roof drain, not over the side of a building
- Lubricating and adjusting fan as recommended by the manufacturer.

Commissioning

Measure total supply air flow with a flow hood or comparable measuring device. Make sure that airflow is within 10% of design value. If airflow is low, then check ducts for constrictions and check that filters and coils are free of obstructions. Larger ducts or shorter duct runs may be necessary. Reduce the number of

duct turns to a minimum. If airflow is high, then reduce fan speed if possible, according to manufacturers' instructions.

If an economizer is installed, then verify proper operation (see MV18: Economizers).

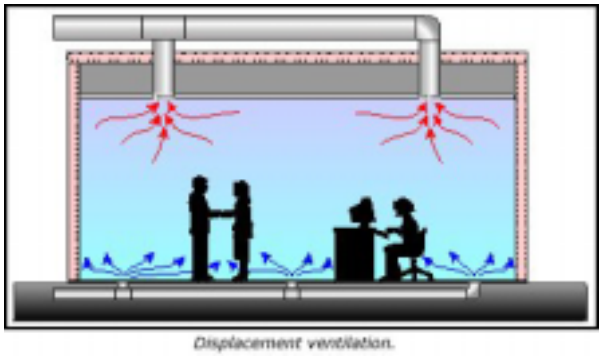
References/Additional Information

Guideline MV18: Economizers; Guideline MV19: Air Distribution Design Guidelines.

GUIDELINE MV6: DISPLACEMENT VENTILATION SYSTEM

Description

Displacement ventilation systems are different from most other HVAC systems for schools and offer a number of advantages. With displacement systems, air is delivered near the floor, at a low velocity, and at a temperature from 63ºF to 65ºF (compared to around 55ºF for conventional air distribution cooling). The goal of displacement systems is not to cool the space, but to cool the occupants. Cool air flows along the floor until it finds warm bodies. As the air is warmed, it rises around occupants, bathing them in cool fresh air. Air quality improves because contaminants from occupants and other sources tend to rise out of the breathing zone rather than being mixed in the space. Similarly, cooling loads decrease significantly because much of the heat generated by occupants, lights, and computer equipment rises directly out of the occupied zone and is exhausted from the space. This is especially true in classrooms designed for 100% outside air with total energy recovery.



Ventilation system.
(source: http://www.advancedbuildings.org)

Applicable Climates

Applicable Spaces		When to Consider	
Classrooms	■	Programming	■
Library	■	Schematic	■
Multi-Purpose	■	Design Dev.	□
Gym	■	Contract Docs.	□
Corridors	□	Construction	□
Administration	■	Commissioning	□
Toilets	□	Operation	□
Other	□		

Variations and Options

There are several supply air distribution options:

- Access floor.
- Low wall outlets.
- Infloor outlets.

The best cooling source for a displacement ventilation system is a chilled water coil. The control valve in a hydronic system allows supply of constant 63ºF to 65ºF air. A typical direct exchange (DX) system is designed to provide colder 50ºF to 55ºF air while the compressor is running and cycles on and off to meet space loads. This lower temperature and temperature fluctuations would create a comfort problem in displacement ventilation when it comes in contact with occupants. However, larger DX systems with several compressors and temperature reset capabilities can be used as an alternative to a chilled water system. For example, a packaged rooftop VAV system serving 10 or more classrooms should be able to provide the necessary supply air temperature control.

Evaporative cooling is also a potential source because it typically produces higher air temperature than a DX system.

Applicability

Displacement ventilation is most appropriate for spaces with ceiling height of at least 10 ft to permit stratification. Systems that utilize 100% outside air design with enthalpy energy recovery are very suitable for high occupant density areas like classrooms and auditoriums. This distribution type is also a great choice where raised access floors are desired for flexibility of power and communication wiring (although access floors are not required for displacement ventilation).

Integrated Design Implications

Supply air outlets must be coordinated with the location of furnishings and space usage. The outlets may be integrated with cabinets or seating.

There is an excellent opportunity to integrate electrical and communication wiring with the air distribution either under the floor or along the baseboard.

A displacement system can eliminate the need for a suspended ceiling and allow the ceiling to be clear of supply diffusers.

If the ceiling is high enough, displacement ventilation can be integrated into portable classroom design, where space for ducting exists in the crawlspace beneath the floor.

Slab floors may be designed with integral ducts or troughs for air distribution.

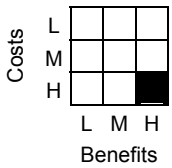
Consider using variable-speed heating and cooling sources to minimize the on-off cycling and variations in supply air temperature.

Ceiling fans are not recommended with displacement ventilation because they are designed to mix air in a space and will disrupt the stratification created by the displacement ventilation system.

Cost Effectiveness

There is not a great deal of experience with displacement ventilation in classrooms, but it is growing in popularity for new commercial buildings. For the near future, costs are likely to be higher than standard overhead air distribution.

A displacement ventilation system will probably not provide a short payback based on energy savings alone. However, the system provides additional comfort and air quality benefits.



Benefits

Advantages

- Significantly lower cooling loads (1/3 lower) result from thermal stratification.
- Significantly low system capacities will be needed if enthalpy energy recovery is used in combination with this vertical displacement approach.
- Air quality will improve per cfm moved compared to systems that mix space air.
- Can provide equal or better air quality with less outdoor air due to stratification.
- Lower fan energy with lower static pressure may result (depends on distribution type and outlet type).
- Ceiling remains clear of supply registers, except for exhaust/return grills.
- Raised access floor systems are typically made up of 1-in. to 1.5-in.-thick concrete sections. This provides advantages from the standpoint of controlling duct noise breakout and/or radiated noise from VAV or fan powered boxes.

Disadvantages

- Heating performance may be worse than systems providing air at greater velocities. Mixing (i.e., destratification) is desirable for heating.
- First cost may be higher with raised floor systems.
- Some floor area or low wall area is required for supply air outlets.

Design Tools

All manufacturers of sidewall displacement diffuser and floor systems offer design assistance and computational fluid dynamics (CFD)-generated graphics that depict air supply patterns with defined supply air temperatures and air flows.

CFD software that now runs on personal computers can help predict airflow patterns within a room, as well as help with the selection and location of supply outlets.

Design Details

Provide 20 cfm to 30 cfm per occupant (0.6 cfm/ft² to 0.9 cfm/ft²) for classrooms depending on cooling loads. At this relatively low airflow rate, 100% outside air may be necessary.

Deliver supply air at 63ºF to 65ºF.

Design for air velocity at supply outlets no greater than 25 ft/minute to 50 ft/minute. Therefore, displacement ventilation requires significantly larger supply outlets than an overhead distribution system. However, the system would be typically delivering close to half the airflow rate of a conventional mixed air system.

Try to place sidewall outlets at the corners of the room. Try to avoid situations where occupants are more than 15 ft from the nearest supply outlet.

Use barometric relief dampers to exhaust the 100% outside air.

Minimum ceiling height is about 10 ft for adequate stratification.

In choosing cooling capacity, consider that loads from lighting, computers, and occupants will be reduced by about one-third compared to a system type that mixes indoor air.

Higher air velocity is desirable in heating mode, so consider a design that reduces supply air outlet area (either manually or automatically) when the system provides heating, or that uses VAV in cooling and full airflow in heating. This is especially important in large halls, such as a gymnasium with sidewall supply. Consider demand control and variable frequency drive (VFD) in gyms, auditoriums, and cafeterias.

Operation and Maintenance Issues

Operating and maintenance requirements are similar to overhead air distribution systems.

Commissioning

Check for proper supply air temperatures. Ensure that air velocity at supply outlets is not too high for comfort. Verify that total airflow meets design requirement. Verify proper control operation and temperature reset for heating or cooling. Verify VAV or VFD operation if demand control is incorporated into an area such as a gym.

References/Additional Information

Boscawen School, NH implemented this type of system. H. L. Turner Group, Architects.

GUIDELINE MV7: HYDRONIC CEILING PANEL SYSTEM

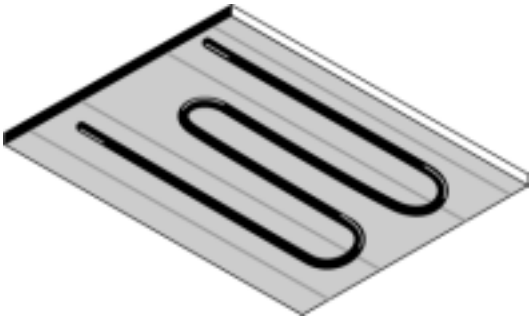
Recommendation

Install radiant cooling ceiling panels in arid areas needing significant cooling.

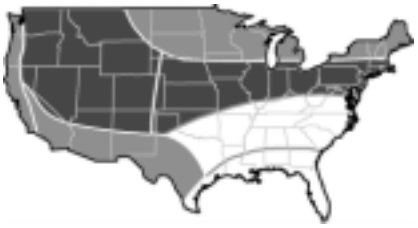
Description

A hydronic ceiling panel system provides thermal comfort predominately through radiation heat transfer with objects and occupants. Basic ceiling panel design consists of a metal sheet with copper tubing attached to the upper side and covered with insulation/acoustical inlay material. Applications can take the form of modular panels or wall-to-wall linear design. The system can be suspended, recessed, or placed in a grid configuration. A ceiling panel heating/cooling system involves the following:

- Ceiling panels
- Support system
- Control system
- Hydronic distribution system
- Hot/cold water source.



Applicable Climates



Applicable Spaces		When to Consider	
Classrooms		Programming	
Library		Schematic	
Multi-Purpose		Design Dev.	
Gym		Contract Docs.	
Corridors		Construction	
Administration		Commissioning	
Toilets		Operation	
Other			

Applicability

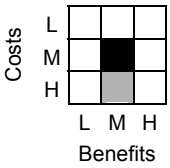
Most applicable in areas with low latent heat load, but can also work in more humid climates with a proper dehumidifying system. Panels can also be used for heating, generally as a substitution for radiators around building perimeter.

Integrated Design Implications

Extruded Aluminum Linear Panel. NREL/PIX 11422

- Hydronic ceiling panel systems provide no outside air ventilation so fresh air must be supplied with either operable windows or an air-handling system.
- Choosing any hydronic cooling system affects hot and chilled water decisions (solar thermal, chiller, boiler, etc.).
- Placement of system components affects requirements of the hydronic distribution system. Try to make these decisions early to create a hydronic distribution layout that minimizes piping materials (pipes, bends, etc.) and head loss.
- Depending on regional weather characteristics and required panel water temperature, an air-conditioning system may be required to remove excess latent heat load and avoid condensation.
- Possibly integrate the system with building sprinkler systems to lower installation costs. Check with the fire marshal to ensure this does not violate fire code regulations.
- Use a heat pump or possibly a cooling tower to attain required temperatures.
- Acoustic properties of the panels need to be considered.
- If the system is to be used for both heating and cooling, a choice between a two-pipe and four-pipe system must be made. This decision will affect the hydronic distribution system.
- Use heavy-duty ceiling grid and provide space in plenum for hangar support.
- System can be integrated into a facility-wide hydronic heating and cooling system, including baseboards and radiant slabs.
- Effectiveness of panels relates to architectural and daylighting decisions regarding ceiling height. Performance of panel system degrades with increasing ceiling height.

Cost Effectiveness



Price for installed panels is roughly $18/ft^2 of active ceiling area. This does not include costs for control system, hot/cold water supply, or hydronic distribution. Installed cost for modular and linear panels is roughly equal.

- Suppliers report that 10-year savings are substantial. Operation and maintenance costs are low. Fuel costs are lower due to increased efficiency compared to air handling systems. The system is generally most cost effective when part of a facility-wide hydronic heating and cooling system.

Benefits

- Hydronic systems can decrease or eliminate the need for mechanical air-handling systems.
- The water pumping system does not create as much internal heat as air fans do.
- Aluminum panels present the possibility for high recycled-content material use.
- Added cooling comfort results from lower perceived temperature.
- The system's low noise makes it a good choice for classrooms.
- Energy demand is significantly lower than that for air systems due mostly to savings in fluid transport systems.
- Quick response time.

Design Tools

- RADCOOL is a software program developed by the Lawrence Berkeley National Laboratory for modeling buildings with radiant cooling systems.
- Design and sizing procedure is documented in Chapter 6 of the 2000 ASHRAE Systems and Equipment Handbook.
- Additional tools are available that provide AutoCAD-based programs for layout design and Microsoft Excel-based spreadsheets for sizing calculations. Other software programs cover design for floor, ceiling, and baseboard radiant systems.

Design Details

- If the panels are to be used for heating and cooling, a two- or four-pipe system can be used. A two-pipe system is less expensive and will work for applications with infrequent changeover from one mode of operation to another. If frequent changeovers occur, it is best to use a four-pipe system.
- Panel performance is dependent upon room air, panel water temperatures, and thermal resistance of the panel. Cooling performance for modular panels is generally around 27 Btu/h ft^2 with an 18°F temperature difference between room air temperature and mean water temperature. Extruded linear panels absorb from 40 Btu/h ft^2 to 50 Btu/h ft^2 with the same temperature difference. In either case, performance degrades with increasing ceiling height. Heating performance ranges from 40 Btu/h ft^2 to 200 Btu/h ft^2 for mean water temperatures of 120°F and 180°F and a 70°F room temperature.
- Cooling water temperatures are generally between 58°F and 65°F, depending on dewpoint.
- Heating water temperatures are usually between 120°F and 180°F.
- Panels located above occupants should not exceed a 95°F surface temperature for comfort reasons. Higher temperatures may be used for panels that do not extend more than 3 ft into the room. These high temperature panels can be used in lieu of baseboard radiators to heat glass surfaces and exterior walls to decrease downdrafts.
- Water temperature should be kept at least 1°F higher than the dewpoint temperature at all times.
- Temperature rise for cooling systems should be less than 5°F and temperature drop for heating systems less than 20°F.

- Be sure the water flow rate is in the proper range. Rates too high can cause noise and those too low can result in a significant decrease in heat transfer rate due to laminar flow.
- Panels can be perforated and installed with a special inlay material to improve acoustical properties.
- To avoid condensation, a control system must be used. The system can either use flow control or temperature control. A flow control system uses humidity sensors, temperature sensors, and control valves. It is an on-off system; as soon as the water temperature reaches the dew point temperature, the control valve closes. This system is cheap and simple, but can make the system useless for extended periods. A temperature control system uses similar sensors and a two- or three-way valve to adjust water temperature and avoid condensation. This system is more complex, but it allows for system operation when humid conditions exist.

Operation and Maintenance Issues

Normal hydronic operation and maintenance issues include checking pumps, valves, pipe leaks, chemical water treatment, and water quality/pipe fouling (important for sustaining maximum heat transfer and minimum pressure drop in open systems). Significant maintenance does not appear to be an issue. The ceiling panels have a life expectancy in excess of 30 years.

Commissioning

Commissioning should be performed throughout planning, design, construction, and operation to ensure proper installation, set-up, and integration with other facility components. The ceiling panel array(s) should be documented with an infrared camera during testing, adjusting, and balancing work to guarantee even cooling and/or heating.

References/Additional Information

Preparation room in the Challenger Learning Center, Phoenix, AZ, uses 2 ft x 4 ft REDEC CBA-C modular panels for 15/16 in. T-Grid with micro perforation and sound absorbing mats.

GUIDELINE MV8: UNIT VENTILATOR SYSTEM

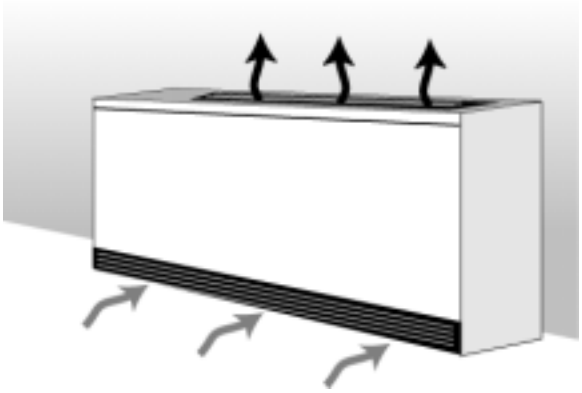
Recommendation

If choosing a unit ventilator system, specify units with multiple-speed fans, two-way control valves, and economizer controls. Also specify variable-flow chilled water and hot water distribution systems.

Description

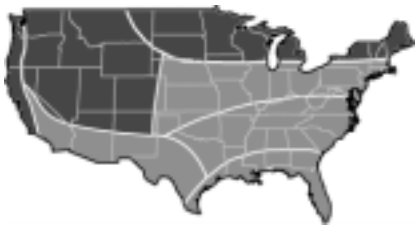
Unit ventilators, sometimes called classroom ventilators, provide heating, cooling, and ventilation for a single space. The units consist of constant volume fans, chilled water and hot water coils (typical), filters, and outdoor and return air dampers, all enclosed in a heavy gauge metal housing. Ventilation and/or economizer air is drawn from adjacent openings in the outside wall. Relief is either by gravity or powered exhaust remote from the unit.

A unit ventilator can be mounted in a vertical or horizontal position. A typical installation is a vertical discharge unit on the floor against an exterior wall. However, horizontal discharge units may be suspended from the ceiling or hidden above the ceiling.



Unit Ventilator, aka Classroom Ventilator

Applicable Climates



Applicable Spaces		When to Consider	
Classrooms	■	Programming	□
Library	■	Schematic	■
Multi-Purpose	□	Design Dev.	□
Gym	□	Contract Docs.	□
Corridors	□	Construction	□
Administration	□	Commissioning	□
Toilets	□	Operation	□
Other	□		

Variations and Options

A unit ventilator may be part of a two-pipe or four-pipe hydronic distribution system.

A two-pipe system (i.e., one supply pipe and one return pipe) is also known as a changeover system, if it provides both heating and cooling. The same piping is used for both hot water and chilled water, and the central plant produces either one or the other. During mild weather periods, the system may be required to switch from heating to cooling as the day warms up. Therefore, two-pipe systems must be designed to account for the potential thermal shock to the equipment. Two-pipe systems likely need supplemental natural ventilation to accommodate swing seasons.

Four-pipe systems can circulate hot water and chilled water throughout the facility simultaneously. The advantage is better zone control because some zones may be heating while others are cooling. The main disadvantage is higher initial cost.

The control valve within a unit ventilator may be a two-way or three-way valve. In both cases, the valve modulates the flow of water through the coil. The difference is how the valve affects flow in the rest of the distribution system. A three-way valve provides a bypass so total flow through the unit ventilator is constant even though flow through the coil changes. A two-way valve modulates the total flow through the unit ventilator. A distribution system with two-way valves will have variable flow and potentially lower pumping energy consumption, especially if pumps are controlled with variable-speed drives.

Economizer controls are an option for some units. An actuator controls the integral outdoor air and return air dampers to take advantage of free cooling when it is available.

Direct expansion cooling may be an option in place of a chilled water-cooling coil.

Alternatives to hot water heating include steam coils and heat pumps.

Some unit ventilators offer a heat recovery option that uses exhaust air to either preheat or precool the outdoor ventilation air. Options for this heat recovery function include an air-to-air heat exchanger and a heat pipe.

Some manufacturers offer matched cabinetry to make the unit ventilator look like part of the furnishings.

Applicability

Systems are applicable for classrooms and other spaces with exterior wall access.

The systems should also be used in facilities with central chilled water and hot water distribution. These are typically large schools that are fairly centralized (to minimize length of chilled water and hot water distribution piping).

In spaces where ceiling height is restricted, these systems can be useful because ducts are unnecessary.

Integrated Design Implications

A unit ventilator requires more coordination with classroom space planning than most other system types. Casework systems are available to integrate the unit with classroom fixtures. An exterior wall with clean outdoor air must be available for unit ventilator installation.

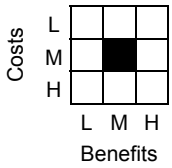
Hydronic distribution may free up space normally reserved for ducts, permitting lower floor-to-floor heights or enabling higher ceilings and better daylighting performance. Hydronic piping should not be run in floor trenches as they are impossible to clean and often grow mold, which can impact indoor air quality since the unit ventilator always pulls some air from the trench.

With unit ventilators as well as other hydronic system types, pay attention to site planning and building layout to minimize the length and complexity of piping between the central plant (chiller and/or boiler) and the terminal units.

As with other system types, controls should be designed to allow simple manual or automatic interlock with natural ventilation systems. In addition, economizer controls may be unnecessary if the space is designed to encourage occupants to use operable ventilation openings during mild weather.

Cost Effectiveness

A system consisting of unit ventilators, a chiller, boiler, and two-pipe distribution costs roughly $14/ft^2$ to $16/ft^2$ of floor area served. Cost for a four-pipe system is $17/ft^2$ to $18/ft^2$, similar to central-type systems with energy recovery.



A unit ventilator system may be cost effective in specific cases, but in most cases other system types will be either lower cost and/or higher performance.

Benefits

Advantages

- Fan energy savings increase, as duct friction losses are avoided.
- Cooling can be very efficient if water-cooled chillers and a well-designed pumping system are installed.
- Constant, or slowly varying, supply air temperature (through modulation of control valves).
- Multiple-speed fans are available in some units.
- Provides flexibility for heating or cooling different parts of the building.

Disadvantages

- Poor air distribution, subject to drafts.

- Noise, particularly for student sitting adjacent to unit.
- Vulnerable to student abuse.
- Subject to turning-off or blocking air output by teachers.
- Air intakes can gather pollutants from mowing, rain intrusion, and vehicle exhaust.
- Relatively high first cost.
- Relatively inefficient fans.
- Console units take up floor space within the room.
- Significant maintenance needed in each classroom.
- Typically limited to poor air filtration.
- Energy recovery difficult or expensive.
- Multiple controls and valves located in every classroom.

Design Details

Ensure that the outdoor air intake area is free from potential pollution sources. Assure that buses will not be staged in areas with unit ventilators. Do not plant shrubs at unit ventilator air intakes. Also make sure to locate the unit to minimize drafts indoors. Air from the units must not be discharged on the occupants, and seating should never be immediately adjacent to the unit. The top of the unit should not be used for storage.

Specify the lowest possible noise levels. If possible, specify a unit with multiple-speed fan control so that normal ventilation occurs at low fan speed. For chiller, boiler, and hydronic distribution system design details, see those individual guidelines. Specify two-way valves in all unit ventilators and variable-flow chilled water and hot water systems.

Load calculations are important, but oversizing of cooling and heating capacity, as long as it is not excessive, is less of a concern with unit ventilators (and with most other hydronic system terminal units) because control valves can modulate output rate. On/off cycling and partial load efficiency degradation is less of a concern, especially with variable-speed fan control. Note, however, that overall facility load calculations are still very important for central plant equipment sizing, where oversizing penalties do occur.

Two-pipe systems should be avoided in climates where heating and cooling may be needed on the same day (or even the same week). The switch from heating to cooling wastes energy and can take a long time. In some cases, the cooling tower and a heat exchanger are used at switchover to cool the loop. The chillers are engaged once the loop has dropped to a tolerable temperature.

Operation and Maintenance Issues

Unit ventilator maintenance is significant, and requires a high skill level for all the controls that are involved in keeping discharge temperatures correct. They are often difficult to access due to classroom arrangements. Furniture should not be pushed up against the unit. Chiller and boiler maintenance requires a relatively high skill level.

Maintenance tasks include:

- Cleaning cooling coil condensate pans to prevent mold growth
- Replacing filters at least three times a year
- Cleaning coils to prevent mold growth
- Cleaning outdoor air intake louvers
- Lubricating fans if required by manufacturers

- Lubricating and adjusting outdoor air and return air dampers.

Commissioning

Check fan speed setting and airflow. Check control valve operation and thermostat operation. Confirm staging of fan speed if applicable. Check coil connections for proper water flow direction. Check outdoor air supply, economizer operation, and economizer airflow. Make sure the outside air duct boot is sealed to the building shell and that water will not enter into it.

References/Additional Information

Guideline MV18: Economizers; Guideline MV21: Hydronic Distribution; Guideline MV22: Chilled Water Plants; Guideline MV23: Boilers.

GUIDELINE MV9: DUCTLESS SPLIT SYSTEM

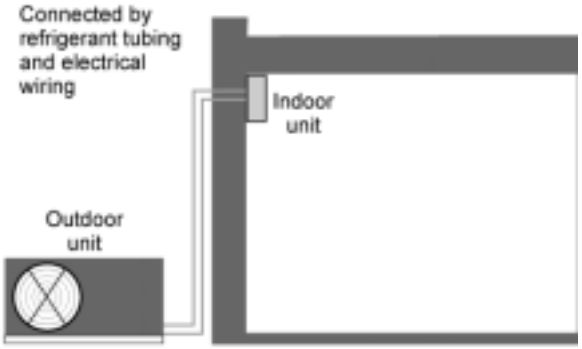
Recommendation

For ductless split systems, specify high efficiency, multiple fan speed, and low noise.

Description

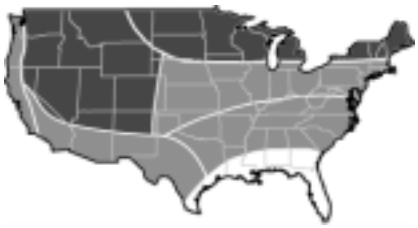
A ductless split system consists of two matched pieces of equipment: an indoor fan coil unit and an outdoor condenser and compressor unit connected by refrigerant tubing and control wiring run through the wall or roof. The indoor unit contains a cooling coil, fan, and filter. The outdoor unit includes compressor(s), condenser coil, and condenser fans.

In its simplest form, a ductless split system recycles 100% indoor air. However, on many units, ventilation air can be supplied with an optional duct attachment that passes through the wall.



Ductless split system.

Applicable Climates



Applicable Spaces		When to Consider	
Classrooms	■	Programming	□
Library	□	Schematic	■
Multi-Purpose	□	Design Dev.	□
Gym	□	Contract Docs.	□
Corridors	□	Construction	□
Administration	■	Commissioning	□
Toilets	□	Operation	□
Other	□		

Variations and Options

The indoor unit is available in several forms: high wall mount, ceiling mount, and above-ceiling mount. The high wall mount may be least costly but is usually limited in peak capacity to about two tons. Capacities up to five tons are available with suspended ceiling units. The above-ceiling units typically fit in a 2 x 2 suspended ceiling system and resemble a typical supply diffuser from below.

Many of these systems can be supplied with a heat pump option to provide heating as well as cooling. Alternatively, heating can be provided through a separate system such as a radiant floor.

Variable-speed fans are common and desirable to minimize cycling and reduce noise.

Economizers are typically not available for most ductless split systems.

Systems are available that allow two indoor units to be connected to a single outdoor unit, which can increase system capacity up to four tons.

Applicability

A ductless split system can serve spaces up to about 1,000 ft^2, or perhaps 2,000 ft^2 if multiple units are installed. They are most useful for buildings with indoor and/or outdoor space constraints, where rooftop space is unavailable or space for ducts is limited.

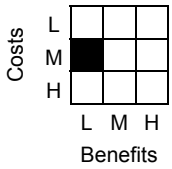
Ductless split systems are good choices when integrated with natural ventilation that can provide free cooling. For sealed spaces without operable openings, a split system is less desirable because it does not typically have capability to provide 100% outdoor air for free cooling.

This system is also applicable for retrofits where ducts do not currently exist.

Integrated Design Implications

A ductless split system is a good complement to radiant heating for spaces where cooling is also necessary but infrequent.

Cost Effectiveness



In North America, ductless split systems are usually more expensive than packaged rooftop systems due to higher equipment cost. The unit price for a typical two-ton unit is $4,000 to $5,000.

Due to the extra cost, a ductless split system will probably be cost effective only where space constraints prohibit the use of ducted system types.

Benefits

Advantages

- Systems can be utilized where outdoor space is limited.
- Equipment is compact.
- No duct losses.
- Simple installation.
- Multiple-speed fans are commonly available.

Disadvantages

- Does not provide good outside air ventilation.
- Relatively poor indoor air distribution and higher potential for drafts.
- Systems have limited capacity to handle ventilation air.
- Heating option is limited to heat pump.
- System use is less common in North America, where equipment cost is relatively high.

Design Details

Place the indoor unit on an external wall for ventilation air access and for minimum distance to the outdoor unit. Follow manufacturers' recommendations for positioning the indoor unit to provide maximum air distribution and avoid drafts.

Pay attention to security, noise, and ambient temperature when positioning the outdoor unit.

Specify high efficiency units if they are available. Specify low-noise units.

- Fan coils should be isolated from occupied spaces. Locate rooftop units above unoccupied spaces.
- Provide appropriate intake and discharge noise control consistent with meeting the Noise Criteria.

Outdoor units should be located away from noise sensitive areas and windows.

Be very careful not to oversize the unit to avoid excessive cycling, which reduces humidity control and irritates occupants. Manufacturers even recommend choosing a system slightly smaller than peak load for these reasons.

Insulate suction and liquid refrigerant lines separately during installation. Otherwise, one heats the other causing capacity and efficiency loss.

Water may condense on the indoor cooling coil. Therefore, a condensate pump may be required to remove water from the condensate drain pan to an approved receptacle. Overflow from the drain pan must be routed to a visible location.

Operation and Maintenance Issues

Maintenance requirements and operator skills are similar to gas/electric split systems and rooftop packaged systems.

Commissioning

Verify proper multiple-fan-speed control operation and thermostat operation.

References/Additional Information

None.

GUIDELINE MV10: EVAPORATIVE COOLING SYSTEM

Recommendation

Consider evaporative cooling for spaces with high outside air ventilation requirements.

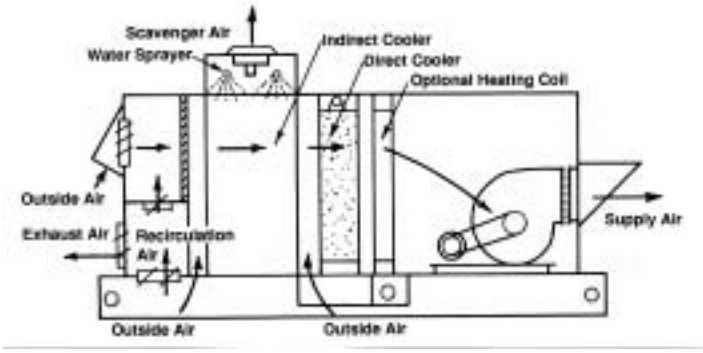
Description

Evaporative cooling is an alternative way to provide air conditioning. Lower energy costs result because no compressor is needed, only a fan and pump.

Evaporative cooling can be "direct" or "indirect." In a direct evaporative cooling system, the water is exposed to the supply air stream. Usually the water flows over a special medium designed to maximize the surface area of water in contact with air, and the air is cooled by the evaporation. The effectiveness can reach 80% to 90%, meaning that the drybulb temperature drops by 80% to 90% of the difference between the drybulb and wetbulb temperature of the entering air. For example, if entering air temperature is 80°F drybulb and 50°F wetbulb, then the leaving air is cooled to 53°F to 76°F drybulb.

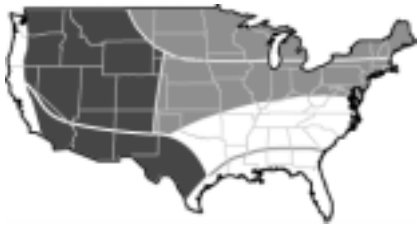
Indirect evaporative cooling is not as effective as direct evaporative cooling, but adds no moisture to the supply air. In some systems, the air passes through a heat exchanger that is wetted on the outside, where cooling takes place in a secondary air stream. In other systems, air passes through a cooling coil supplied with water from a remote cooling tower. Indirect evaporative cooling can be approximately 60% effective in reducing the dry bulb temperature of the entering air to its wet bulb temperature. While direct cooling provides 72°F to 74°F air in the example above, indirect cooling could provide 78°F air.

Combining indirect and direct evaporative cooling (as shown in the figure above) further reduces the supply air temperature. When air passes through the indirect cooler first, then drybulb and wetbulb temperature is reduced through sensible cooling. Due to the lower wetbulb temperature, the direct cooler can achieve even cooler temperature for the supply air.



Evaporative Cooling System

Applicable Climates



Applicable Spaces		When to Consider	
Classrooms	■	Programming	■
Library	□	Schematic	■
Multi-Purpose	■	Design Dev.	□
Gym	■	Contract Docs.	□
Corridors	■	Construction	□
Administration	■	Commissioning	□
Toilets	□	Operation	□
Other	□		

Variations and Options

Packaged evaporative coolers are available in a wide range of sizes, approximately 3,000 cfm to 20,000 cfm. They are typically roof mounted to supply outside air for the indirect cooling stage.

Packaged air handlers are available that incorporate both indirect and direct evaporative cooling. The evaporative cooling system has an economizer that uses 100% outside airflow during cooling mode, and minimum outside airflow during heating mode. This allows the use of return air during the heating season to keep heating costs equivalent to a standard system. These package units can have hot water coils or duct furnaces installed to provide heating.

If evaporative cooling alone does not satisfy cooling loads, then it can be combined with packaged rooftop cooling by adding direct and/or indirect coolers onto the outside air intake of the packaged unit or it can be integrated directly into the mixed air stream (outside + return) of the packaged unit. Evaporative cooling reduces the load on the direct expansion (DX) cooling coil, allowing the compressor size to be reduced, and peak power to be reduced.

Alternatively, a combination of cooling tower and heat exchanger could be used with cooling coils and standard air handlers.

Some indirect evaporative cooling systems are designed to use exhaust air rather than outside air as the secondary air stream, providing heat recovery.

Other systems combine evaporative cooling with a desiccant wheel and/or enthalpy wheel as a method of precooling the outdoor air and increasing cooling capacity.

Applicability

Evaporative cooling is most effective in hot, dry climates but it can also be used to completely replace compressor cooling in cold and coastal areas. For areas with higher design wetbulb temperatures, such as Phoenix, AZ (100°F/70°F), evaporative cooling can produce most of the space cooling needs. However, if evaporative cooling is used exclusively, space temperatures may rise above 80°F during design conditions a few hours each year. Direct evaporative cooling is only marginally applicable in the Cool and Humid and Cold and Humid climates. Indirect evaporative cooling may be a better approach in these climate zones.

Evaporative cooling is especially appropriate for spaces with high outside air ventilation requirements such as showers, locker rooms, kitchens, or shops. Compressor cooling is often too expensive to operate for these applications.

Integrated Design Implications

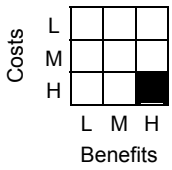
Evaporative cooling is a good match for displacement ventilation systems, which are designed for higher supply air temperature than a typical overhead air distribution system. However, the design will need to accommodate higher airflow that could disrupt stratification. Therefore, careful attention is necessary in locating and sizing supply outlets.

Larger ducts are required compared to a typical compressor cooling system, and duct size may be a consideration in the architectural and structural design.

Direct evaporative cooling may not be appropriate for spaces with materials such as wood floors that might be damaged by high humidity.

These systems require regular maintenance and are difficult to seal against air infiltration in cold climates.

Cost Effectiveness



Installed costs are typically greater than for typical packaged air-conditioning equipment.

Evaporative cooling is usually cost effective in warm and dry climates as long as somewhat higher indoor temperatures are acceptable during hot periods.

Benefits

Advantages

- Lower electricity consumption and lower peak electric demand result.
- Systems typically use 100% outside air in cooling mode, providing better air quality.
- Smaller electrical supply.

Disadvantages

- Regular maintenance is more critical than for compressor cooling systems.

- Higher airflow requirements lead to increased fan energy.
- Cooling unit requires water supply.
- On-site water consumption increases.
- Cooling requirements in some climates may not be completely satisfied.
- Direct evaporative cooling increases space humidity.
- First cost is higher.

Design Details

An evaporative cooling system requires higher airflow due to higher supply air temperature. Therefore, special attention to duct design and sizing is required to avoid high fan energy costs. The appropriate airflow depends on design conditions for the school's location.

A variable-speed or two-speed fan is a good idea to allow lower airflow in heating mode.

In warm climates, try to use exhaust air as the secondary air stream for indirect evaporative cooling systems.

Vibration isolation is often provided internally. Internal isolation should be reviewed for proper spring-type and static deflection. If internal isolation is not provided, or is unacceptable, external spring isolators should be utilized. Refer to 1995 ASHRAE Handbook Chapter 43 for recommended vibration isolation. If external isolation is used, all internal spring isolators should not be released from their restraining bolt.

- Locate rooftop units above unoccupied spaces.
- Provide appropriate intake and discharge noise control consistent with meeting the noise criteria.

Operation and Maintenance Issues

Evaporative coolers demand more maintenance than a typical compressor-based system, so they should be specified only for facilities with qualified maintenance staff or with a qualified outside service company.

To minimize maintenance requirements, specify adequate bleed-off rates to prevent mineral buildup (without causing excessive water consumption). Also specify controls that periodically flush the evaporative medium with water to remove dirt and scale. Finally, specify materials to minimize potential for corrosion.

Commissioning

Check for correct airflow.

Check for correct water flow rate over the evaporative media.

Check the bleed-off rate of water from the evaporative system to ensure that it is adequate to prevent mineral buildup but not too large to cause excessive water consumption.

Verify all modes of operation.

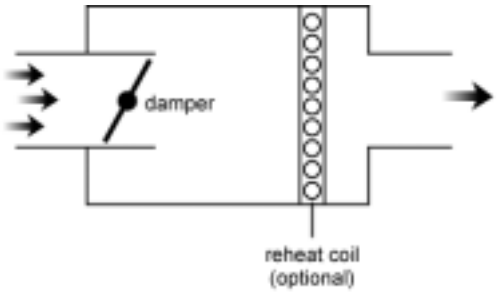
References/Additional Information

None.

GUIDELINE MV11: VAV REHEAT SYSTEM

Recommendation

Choose a VAV reheat system for large administration or classroom facilities, especially multi-story buildings. Specify variable-speed fan control, low face velocity cooling coil, bypass damper, monitored/measured outdoor air supply, supply air temperature reset control and supply duct pressure reset control and graphic-displayed direct digital controls (DCC).



VAV Box

Applicable Climates

Applicable Spaces		When to Consider	
Classrooms	■	Programming	■
Library	■	Schematic	■
Multi-Purpose	■	Design Dev.	□
Gym	□	Contract Docs.	□
Corridors	□	Construction	□
Administration	■	Commissioning	□
Toilets	□	Operation	□
Other	□		

Description

VAV is a general term for a type of HVAC system that supplies only the amount of air needed to satisfy the load requirements of a building zone and can supply different volumes to different zones at the same time. The result is that the total supply of cool air changes over the course of the day, depending on the heat gains in different building areas at different times.

In a VAV system, a central supply fan sends air through medium-pressure ductwork to terminal units (VAV boxes) throughout the building. The airflow to each zone — a space or group of similar spaces — is controlled by the VAV box (a “smart damper”), which varies the airflow in response to the space temperature. As cooling loads in the zone drop, the damper continues to close until it reaches a minimum position. The minimum position provides the occupants of the zone with adequate ventilation air. Some VAV boxes, especially those in perimeter zones, contain a reheat coil for times when the minimum airflow provides too much cooling. The reheat coil — typically hot water — prevents zones from being overcooled. The reheat coil also provides winter heating, typically during a morning warm-up period prior to occupancy when the outdoor air dampers are closed.

A duct-mounted pressure sensor that decreases the fan output as the VAV box dampers close controls the main system fan.

Variations and Options

VAV air handlers may be purchased as factory-fabricated units or may be assembled from components in the field (built-up). In either case, cooling can be provided with a chilled water coil or a direct expansion refrigerant coil.

- A common choice for schools is the packaged rooftop VAV air-conditioning system. The self-contained unit consists of a variable-volume supply fan; direct-expansion cooling coil; heating (when required) with gas furnace, hot water, or steam; filters; compressors; condenser coils; and condenser fans.
- Facilities with a central chilled water plant often use factory-fabricated air handlers with chilled water coils. In this case, the unit includes a supply fan, cooling coil, filters, and perhaps a heating coil.

VAV systems usually include economizer controls. Several VAV box types are available and some can be combined within the same system:

- Most common for new buildings are pressure-independent boxes with DDC-controlled actuators.
- Fan-powered mixing boxes recirculate room or plenum air and are available in two types: series fan or parallel fan. The series fan box requires the fan to operate at all times. The parallel fan box fan activates only when reheat is required.
- Dual-duct VAV boxes contain two dampers controlling a cool duct inlet and a warm duct inlet. Typically, the warm duct damper is closed during cooling periods. When cooling load drops and the cool duct damper reaches its minimum position, then the warm duct damper begins to open to prevent overcooling in the space.

A dual-fan, dual-duct VAV system is an alternative to VAV reheat and requires less reheat energy. The warm duct recirculates indoor air and adds heat if necessary. The cool duct provides ventilation air and cooling. Rather than using a reheat coil to avoid overcooling at minimum ventilation position, the dual duct system mixes warm return air to offset cooling.

Applicability

VAV systems are appropriate for administration buildings or large classroom buildings with peak cooling load greater than 20 tons. The minimum size for a packaged VAV system is about 20 tons.

The overall efficiency of VAV systems depends on the diversity of zone heating and cooling loads. If a particular building has very similar zones and constant loads (such as classrooms with identical occupancy schedules in an extremely well-insulated building), the potential for savings from a VAV system are reduced.

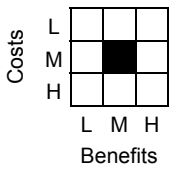
Integrated Design Implications

VAV systems require space for ductwork and should be considered early in the design process.

Requirements for fire separations can affect duct layout and architectural design. Fire separation is less of an issue with single-zone systems because all the ductwork is typically within a single fire zone.

Shaft space may be required in multi-story buildings to deliver air to the lower floors.

Cost Effectiveness



A typical VAV reheat system costs $16/ft^2 to $18/ft^2 of floor area. This cost is greater than packaged single-zone systems and roughly equal to a unit ventilator system, but offers far greater performance and control.

A VAV system is usually cost effective for larger buildings. It is the most common system type for new multi-story commercial facilities.

Benefits

Advantages

- Better comfort control results from steady supply air temperature (vs. single-zone systems that are constant volume and variable temperature).
- Moderate initial cost for buildings that require multiple zones.
- Better dehumidification control than packaged single zones.
- Energy efficiency of variable air volume.
- Larger and more efficient fans than single-zone systems.
- Centralized maintenance for coil cleaning and filter replacement.
- Relatively simple to add or rearrange zones.

Disadvantages

- Sometimes higher fan pressure occurs than with variable-speed, single-zone systems, depending on load matching of design. This may lead to higher energy consumption.
- Requires more sophisticated controls than single-zone systems.
- VAV box can generate noise that radiates out of the sheet metal walls (radiated noise), and travels down the supply duct (discharge noise).

Design Details

Although several methods are possible, a variable-speed fan is the recommended approach to controlling duct air pressure in a VAV system. Variable-speed drives are the most efficient and have the added advantage of limiting current inrush for startup of large motors ("soft-start" feature). Other, less effective, duct pressure-control devices are variable inlet vanes, inlet cones, sliding covers, and discharge air dampers.

For direct-expansion VAV systems, multiple-step unloading or variable-speed compressors should be specified, which prevents frosting of the evaporator coil at low cooling loads (particularly important for units equipped with economizers). Greater numbers of unloading steps also improves supply air temperature control by allowing a smaller throttling range.

Supply air temperature reset. Specify controls that will adjust the supply air temperature according to demand for cooling. As cooling demand drops, supply air temperature may be increased so that compressors operate more efficiently, and outside air can provide a larger fraction of cooling. However, more airflow is required with higher supply air temperature and, at some point, the extra fan energy exceeds the cooling energy savings. Carefully consider the characteristics of a specific building when choosing a supply air reset schedule. Computer simulations can help to determine optimal settings.

Supply air pressure reset. Consider controls that will also minimize the supply air pressure required to meet all zone loads. Typically, the supply fan is controlled to maintain a constant static pressure of around 1.5 inches water column in the duct upstream of the VAV boxes. However, lower pressure may satisfy airflow demands at many times of the year and can save fan energy. Automatic reset controls can monitor damper position in all VAV boxes and lower the supply duct pressure when all dampers are partially closed.

Ventilation air control can be tricky in a VAV system due to varying supply airflow. One option is to modulate the outdoor air damper based on measurement of outdoor airflow. This modulating damper method can also allow demand ventilation control to reduce airflow when spaces have low occupancy (see Guideline MV26: Demand Controlled Ventilation). Another option is a separate outdoor air fan that injects a constant volume of ventilation air into the supply air stream when the system is not in economizer mode.

To minimize reheat energy consumption, set the minimum flow on each VAV box as low as possible. In many cases, reheat would be unnecessary if the minimum flow were zero. However, the need for ventilation air usually requires some minimum damper position. In some systems, heating occurs at minimum airflow. Therefore, heating load can also be a constraint on the minimum flow. In these situations, reverse acting damper control is recommended. As heating load increases, the damper reopens.

The zone thermostats should have separate setpoints for heating and cooling with a deadband in between. This control also helps to minimize reheat energy.

Zone controls should also be tied to a central energy management and control system (EMCS). An EMCS reduces operation and maintenance cost by allowing remote monitoring and control.

To minimize air pressure drop across the cooling coils, limit the face velocity to 300 fpm, which requires a larger coil as well as larger equipment and floorspace. Also consider specifying a bypass damper that opens when the cooling coil is not needed, such as in economizer mode. Both measures help reduce fan energy consumption.

Rather than installing a return air fan, consider using a relief fan or barometric relief dampers to minimize fan energy.

Design duct systems to minimize pressure drop and leakage. For recommendations on duct design, see Guideline MV19: Air Distribution Design Guidelines.

VAV boxes should not be located over noise-sensitive areas (i.e., classrooms) when an acoustical tile ceiling system is being used. A gypsum board ceiling will do a better job of reducing VAV-radiated noise than a typical ceiling tile system. For this reason, most VAV boxes can be located above noise-sensitive areas where a gypsum board ceiling, which has all penetrations and joints well sealed, is installed.

Oversizing VAV boxes is one way to reduce radiated and discharge noise levels. This has to do with the velocity of air as it enters the box and passes by the damper.

Static pressure drop across the VAV box also has an impact on the amount of noise generated. Designing the system so that the damper does not produce more than 0.5 in. of static pressure drop will minimize noise.

Operation and Maintenance Issues

VAV system operation requires a skilled commissioning staff to ensure that controls operate efficiently. However, maintenance is relatively simple once the system is operating. Maintenance is centralized for boilers and chillers rather than being distributed to individual units. Many tasks are centralized and take less time than for a system with single-zone units.

VAV boxes typically have DDC interfaces allowing space conditions to be monitored from a central building management system. The information and remote control capability helps reduce maintenance costs.

Commissioning

Calibrate zone airflow sensors, and confirm minimum and maximum flow for each VAV box.

Calibrate all system temperature and pressure sensors. Confirm supply air temperature, reset supply pressure, and reset control operation.

Calibrate outside airflow measurement (if one is installed) and ensure that minimum ventilation airflow is provided under varying conditions.

Confirm proper functioning of all valves and dampers.

References/Additional Information

None.

GUIDELINE MV12: RADIANT SLAB SYSTEM

Recommendation

Install radiant slab-on-grade systems in rooms with heating demand. When conditions permit, use a solar thermal, geothermal system, and/or recovered thermal energy for the hot water supply.

Description

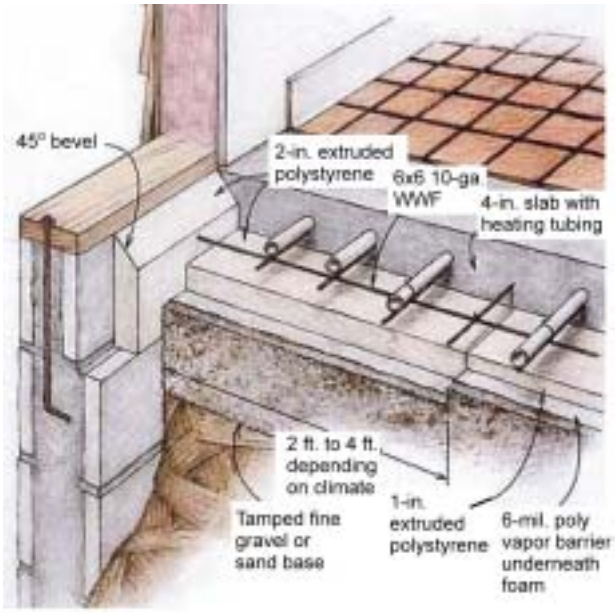
A radiant slab heating system consists of the following:

- Hydronic distribution
- Hot water source (boiler, solar, geothermal heat pump, etc.)
- Control system.

Like all radiant heating systems, radiant slab systems provide thermal comfort to building occupants predominantly through radiation heat transfer. In other words, the system heats or cools room objects and occupants, rather than the surrounding air. Two basic configurations exist for hydronic radiant slab heating and/or cooling. The first option involves the placement of pipes in the foundation slab itself, referred to as slab-on-grade. The second, called thin-slab, consists of piping placed in a thinner slab layer that is situated on top of the foundation slab or on suspended floors. Each consists of a loop of tubing (normally cross-linking polyethylene, PEX) that is imbedded in concrete or a similar material, such as gyp-crete. Hot water is passed through the tubing, which heats the slab, and in turn, the room.

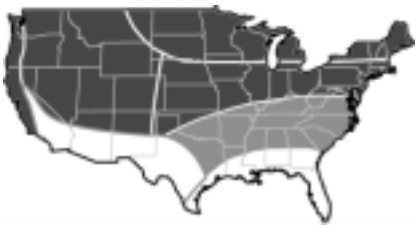
Applicability

The use of radiant slabs for heating is applicable in all regions with a heating demand. However, due to condensation concerns, the use of radiant slabs for cooling should be limited to areas with a low latent cooling load.



Radiant slab

Applicable Climates



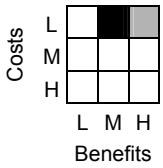
Applicable Spaces		When to Consider	
Classrooms	■	Programming	□
Library	▒	Schematic	▒
Multi-Purpose	▒	Design Dev.	■
Gym	▒	Contract Docs.	■
Corridors	■	Construction	■
Administration	■	Commissioning	■
Toilets	▒	Operation	■
Other	■		

Integrated Design Implications

- Choosing any hydronic heating system affects boiler decisions (heat pump, solar, etc.).
- All radiant hydronic systems provide an alternative to large-scale air-handling systems. This impacts many aspects of the building design including the required plenum sizing, boiler/chiller sizing, and ducting, among other things.
- The slab system is a low-temperature application and is complemented well by alternative water heating methods including geothermal heat pumps and solar thermal systems. Typical hydronic heating systems, such as baseboard radiators, use water temperatures of 140°F to 200°F, whereas radiant floor heating uses temperatures between 90°F and 120°F.

- Consider framing strength when installing suspended-floor, thin-slab systems. It is much more cost effective to consider this during design rather than reinforcing the framing during construction.
- This system can be integrated into a facility-wide hydronic heating and cooling system including baseboards and ceiling panels.
- Placement of system components affects requirements of the hydronic distribution system. Try to make these decisions early to create a hydronic distribution layout that minimizes piping materials (pipes, bends, etc.) and head loss.

Cost Effectiveness



- The installed cost of the slab only ranges from $2/ft^2 to $20/ft^2 depending upon application. PEX tubing costs around $0.65/lin ft retail.
- Operation and maintenance costs are low. Fuel costs are lower due to increased efficiency compared to air-handling systems.
- The system is generally most cost effective when part of a facility-wide hydronic heating and cooling system.

Benefits

Advantages

- Hydronic systems can decrease or eliminate the need for mechanical air handling systems.
- Quiet operation.
- Better perceived comfort. Radiant slabs heat occupants from the bottom up and are purported to increase comfort. Allows for lower thermostat settings.
- Lower boiler temperatures of 90°F to 120°F compared to 140°F to 200°F for other heating systems. These temperatures can be accomplished by a geothermal heat pump or solar thermal system.
- Can provide fuel savings when compared to forced air systems.
- Aesthetically pleasing; no heat registers or visible radiators.

Disagvantages

- Hard to set back temperatures because of lag.
- Ground losses can reduce efficiency if insulation is not properly installed.

Design Tools

- Using a CAD-based program to design the layout of the tubing will save time, materials, and money.

Design Details

- Install edge insulation around radiant slab.
- Older installations used copper or other metal tubing, but these materials can react with the concrete and corrode if not properly treated. Copper has excellent heat transfer characteristics, but its short coil length and incomplete compatibility with concrete has caused a switch to polymer or synthetic rubber tubing. Most modern installations use cross-linked polyethylene (PEX) tubing. PEX tubing is usually layered with an oxygen diffusion barrier to extend the life of system components. Some installers use stainless steel components in lieu of the diffusion barrier. Another option is PEX-aluminum (PEX-Al-PEX) composite tubing, where the aluminum acts as a nearly perfect diffusion barrier. PEX-Al-PEX is also easier to bend than standard PEX.
- Any PEX tubing outside of the slab should be protected from sunlight to prevent corrosion.
- Tubing must be routed through the sub-soil or in a protective sleeve when passing through expansion joints.

- Before pouring the concrete, tubing should be laid out and pressurized to 100 psi for 24 hours to ensure no leakage. The tubing should remain pressurized throughout the pouring and curing process.
- Water should be delivered to the slab at a temperature that can maintain surface temperatures between 80°F and 85ºF. The required inlet water temperature is dependent upon the thermal resistance of the slab and any floor finishing material.
- Tubes should be spaced between 6 in. and 15 in. apart, depending on application.
- Use tighter spacing for slabs with wood floor finishing. Even temperatures are critical to avoiding varying levels of expansion and contraction in wood floors.
- Early planning, including an accurate estimate of the load requirements in the rooms to be heated and cooled, is key for these systems. Due to the nature of the system (in the foundation slab), the earlier the decision is made the better.
- High quality control systems should be used that monitor both indoor and outdoor temperatures. The slab is a large thermal mass and care must be taken to avoid under or over shooting the prescribed temperature.

Operation and Maintenance Issues

- The slab system consists of a large thermal mass and thus takes a significant amount of time to respond to changes in control settings. The response time of the system can be through proper operation and maintenance practices that serve to avoid severely over or under shooting the desired temperature.
- Modern radiant slab systems require little maintenance and do not have the leakage concerns of earlier systems.

Commissioning

Commissioning should be performed throughout planning, design, construction, and operation to ensure proper installation, set-up, and integration with other facility components. Proper installation and management of the control system for a radiant slab are particularly important. Be sure indoor and outdoor sensors are sited correctly and functioning properly.

References/Additional Information

None.

GUIDELINE MV13: BASEBOARD HEATING SYSTEM

Recommendation

Use baseboard heating in areas experiencing periods of at or below-freezing temperatures, especially under areas of glass.

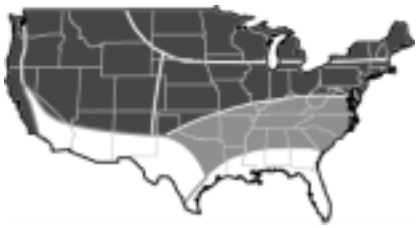
Description

Hydronic radiant baseboard heating is a common application that has been used for over 50 years in the United States. The most common types are the finned-tube convector and radiant convector, both of which heat cold air at the floor of the room and induce an upward convective current. This is extremely effective in reducing downdrafts at cold facades and under windows. These models provide heat through a combination of convection and radiation. Another model is the panel, or flat pipe, radiator. Panel radiators are common in Europe and provide thermal comfort predominately through radiation heat transfer. A baseboard heating system requires the following:

- Baseboard heaters (convector or panel)
- Hydronic distribution system (piping, pumps, valves)
- Control system (sensors, thermostats)
- Hot water source (boiler, solar thermal, recovered thermal energy, geothermal heat pump)

Baseboard heaters such as this are commonly used as an effective way to reduce downdrafts experienced at cold facades and under windows. NREL/PIX 11423

Applicable Climates



Applicability

These systems are applicable in all areas experiencing extreme cold, and are especially effective in areas of significant heat loss, such as entryways or under windows.

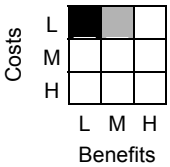
Integrated Design Implications

Applicable Spaces		When to Consider	
Classrooms		Programming	
Library		Schematic	
Multi-Purpose		Design Dev.	
Gym		Contract Docs.	
Corridors		Construction	
Administration		Commissioning	
Toilets		Operation	
Other			

- Baseboards are a good compliment for displacement ventilation systems. They can operate independently to maintain space temperature and to recover from night cool down.
- Choosing any hydronic heating system affects boiler decisions (heat pump, solar, etc.).
- All radiant hydronic systems provide an alternative to large-scale air-handling systems. This impacts many aspects of the building design including the required plenum sizing, boiler/chiller sizing, ducting, etc.
- The systems can be integrated into a facility-wide hydronic heating and cooling system including radiant slabs and ceiling panels.

- They can be the main heat source, or integrated with another system and used primarily to reduce downdrafts at cold walls or glass, and can provide off-hours heating without running fans.
- Placement of system components affects requirements of the hydronic distribution system. Try to make these decisions early to create a hydronic distribution layout that minimizes piping materials (pipes, bends, etc.) and head loss.

Cost Effectiveness



Baseboard heaters cost $10/lin ft to $25/lin ft.

- Operation and maintenance costs are low. Fuel costs and electric pumping costs in a well-designed system are lower due to increased efficiency compared to air-handling systems.
- The system is generally most cost effective when part of a facility-wide hydronic heating and cooling system.

Benefits

- Hydronic systems can decrease or eliminate the need for mechanical air-handling systems.
- These well-understood systems have been used for over 50 years.
- The systems are low maintenance.
- They can be more fuel efficient than air systems and use less power to move heat through the facility.
- Since they are quiet, these systems are good for classrooms.
- Cold downdrafts at outside walls and windows are stopped.
- Systems should be configured to allow for individual room control.

Design Tools

- The *Advanced Installation Guide for Hydronic Heating Systems*, available from the Hydronics Institute, includes a design and sizing procedure for baseboard heating.
- *Hydronics Design Toolkit* software is available from the Radiant Panel Association.

Design Details

- Baseboard systems can use zone control or individual room control. Zone control uses one thermostat to regulate several spaces in a single hydronic loop. This system is simple and cheap, but often involves large temperature drops and can be difficult to balance. Individual room control uses thermostatic radiator valves (TRV) to independently control baseboard elements in each space. The TRV allows educators to control the thermal environment of their own classroom.
- Flow rate must be controlled to ensure turbulent flow. If the flow rate is in the laminar regime, the heat transfer rate will be dramatically lower and more sensitive to flow rate changes causing difficulties in maintaining intended thermal conditions. Too high a flow rate can cause pipe noise.
- Proper water flow design is especially important if low temperature water will be used for heating, such as with a geothermal heat pump design.
- Increases in altitude can decrease the performance of finned-tube and radiant convectors.
- Painting panel radiators can affect performance. Aluminum and bronze paint can reduce total heat output by up to 10%.
- Make allowances for pipe expansion during installation to decrease audible disturbances.
- Water should be delivered to baseboard radiators between 140ºF and 200ºF.
- Care should be taken to ensure baseboard surface temperatures do not reach levels dangerous to young children.

- Output ranges from 300 Btu/hr/ft to 800 Btu/hr/ft depending on inlet/outlet temp and flow rate.
- Temperature drop across heater should not exceed 20ºF to insure uniform heating.
- Be sure not to inhibit convective flow patterns when arranging furniture near baseboard heating elements.
- “Quiet Type” baseboard heaters (ie., heaters designed to produce less operating noise) should be specified for occupied areas.

Operation and Maintenance Issues

Operation and maintenance issues for baseboard heating systems are minimal. Heat transfer surfaces should be kept clean and free of dust. If the system is open to the potable water supply, some internal cleaning may be necessary to avoid fouling. Pipe fouling can lower efficiency by decreasing the heat transfer rate and increasing the pressure drop.

Commissioning

Commissioning should be performed throughout planning, design, construction, and operation to ensure proper installation, set-up, and integration with other facility components.

References/Additional Information

"Advanced Installation Guide for Hydronic Heating Systems." Available from Hydronics Institute. Berkeley Heights, NJ 07922.

Radiant Panel Association, PO Box 717, Loveland, CO 80539-0717. Phone: (800) 660-7187 or (970) 613-0100. Fax: (970) 613-0098. Email: info@rpa-info.com.

GUIDELINE MV14: GAS-FIRED RADIANT HEATING SYSTEM

Recommendation

Consider gas-fired radiant heating for spaces with high ceilings and potentially high infiltration, or in large spaces with spot heating needs such as workshops or gymnasiums.

Description

This class of radiant heaters burns gas to heat a steel tube or a ceramic surface. The heated surface emits infrared radiation that is absorbed by occupants, furniture, floor, and elements of the building in view of the heating element. Those objects then heat the air in the space through convection. An advantage to this type of radiant heating in high traffic areas is that the objects in the space remain warm even if cool air is introduced.

Applicable Climates

Variations and Options

- Several configurations of gas-fired radiant heaters are available. Some are linear units consisting of a long steel pipe with a reflector above. Another option is a smaller unit with heated ceramic surface design to cover a rectangular area of floor.

Applicable Spaces

Classrooms	☐
Library	☐
Multi-Purpose	■
Gym	■
Corridors	☐
Administration	☐
Toilets	☐
Other	■

When to Consider

Programming	☐
Schematic	■
Design Dev.	☐
Contract Docs.	☐
Construction	☐
Commissioning	☐
Operation	☐

Applicability

Radiant heating is appropriate in spaces with high ceilings because it helps to overcome thermal stratification. Much of the heat is delivered directly to objects and occupants at floor level.

As mentioned earlier, radiant heating is also useful in areas with high traffic where infiltration can be a problem.

Appropriate spaces include gyms, shops, greenhouses, and high-traffic entrances or lobbies.

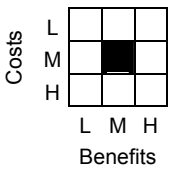
Radiant heaters can provide spot heating in large open spaces such as workshops or warehouses.

Integrated Design Implications

Consider the need for combustion air and flue gas venting when choosing the location for a gas-fired radiant heater. Also allow for adequate clearance around the unit, as recommended by the manufacturer.

Cost Effectiveness

Gas-fired radiant heaters are usually a cost-effective choice for spot heating in large open spaces. They may also be cost effective for general heating in spaces like gymnasiums when energy savings are considered.



Benefits

Advantages

- Equal comfort with lower indoor air temperatures results in lower heating energy consumption.
- Fan energy and/or pumping energy required for heating distribution is eliminated.

Disadvantages

Occupants may experience some discomfort due to warm heads and cool feet.

Design Tools

None.

Design Details

Provide protection for units installed in gymnasiums to prevent contact with sports equipment.

Follow the manufacturers guidelines for clearance above and to sides.

Provide an outdoor combustion air source and vent flue gas to outdoors.

“Quiet Type” unit should be specified.

Operation and Maintenance Issues

Gas-fired radiant heaters are relatively low maintenance systems.

Commissioning

None.

References/Additional Information

None.

GUIDELINE MV15: WATER-LOOP HEAT PUMPS

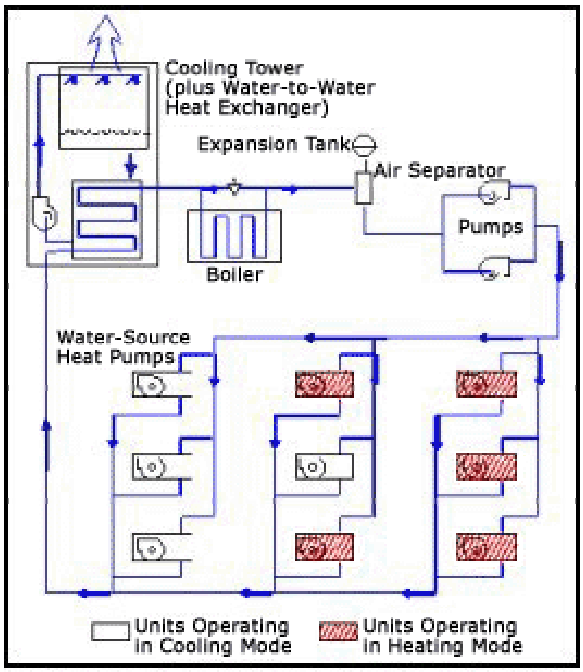
Recommendation

Consider using water-loop heat pumps if the building requires simultaneous heating and cooling, and has a minimum cooling capacity of 35 to 50 tons.

Description

A water-loop heat pump system provides space heating and cooling for individual building zones. Each building space contains a separate heat pump connected to a single circulating water loop. The piping system adds or removes heat to the circulating water. When most of the pumps are working to cool building spaces, heat must be removed from the loop via a cooling tower or other means. If most of the pumps are heating building zones, a boiler must generate added heat for the loop.

When heat is being removed from some zones (i.e. certain heat pumps are working in cooling mode and rejecting heat to the loop) as well as being delivered to other spaces (i.e. other heat pumps are working in heating mode and using heat from the loop), the water loop remains within the desired temperature range without the addition or removal of heat.



Typical commercial water source heat pump system

(Source: AdvancedBuildings.org)

Applicability

This system is applicable to all interior school spaces. It is most effective in schools where simultaneous heating and cooling is required in different areas of the building.

This system offers limited benefits where cooling loads are small or non-existent.

Applicable Climates

Applicable Spaces

- Classrooms ■
- Library ■
- Multi-Purpose ■
- Gym ■
- Corridors ■
- Administration ■
- Toilets ■
- Other ■

When to Consider

- Programming □
- Schematic ■
- Design Dev. □
- Contract Docs. □
- Construction □
- Commissioning □
- Operation □

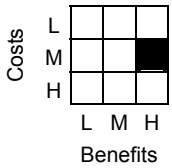
Integrated Design Implications

Water-loop heat pumps can be used as part of geothermal heat pump systems (See Guideline RE5).

Cost Effectiveness

The cost of a water-loop heat pump system is generally more than a two-pipe fan/coil system, but less than a four-pipe fan/coil system.

Benefits



Advantages

- Ability to use unwanted heat from one zone to heat another zone.
- Provides easy temperature control for building spaces. Units in areas not requiring heating or cooling can be turned off and bypassed.
- Provides high reliability for both heating and cooling modes.

- Do not require wall openings to reject heat from air-cooled condensers.
- Have a longer service life since they are not exposed to the weather.
- Failure of an individual water-source heat pump does not cause the entire system to fail.

Disadvantages

- Failure of a loop pump, heat rejection device, or secondary heater can affect system operation.
- Increases electrical load in the winter.
- Requires a central boiler and cooling tower.

Design Tools

See this chapter's Overview.

Design Details

Water in the loop needs to be kept within a temperature range of 60°F to 90°F.

Due to the limited operating range, insulation is not required on the water loop.

Changes to building spaces can generally be accommodated by adding or removing individual pumps.

Heat pumps must be specified for the proper operating temperature. Do not use electric boilers for the auxiliary heating.

Operation and Maintenance Issues

Typical life cycle for water-loop heat pumps is 15 to 20 years, depending on quality of maintenance. Regular cleanings of heat exchanger coils and regular air filter changes are required. This system can have higher maintenance costs because of the multiple compressors and fans.

Commissioning

Flushing the loops will ensure the system is in good operating order.

References/Additional Information

Advanced Buildings Technologies and Practices. http://www.advancedbuilding.org/.

Cooling System Alternatives. Tri-State Generation and Transmission Association. http://www.tristate.apogee.net/.

International Ground Source Heat Pump Association, Oklahoma State University, Stillwater, OK. http://www.igshpa.okstate.edu/.

Geothermal Heat Pump Consortium. http://www.geoexchange.org/.

GUIDELINE MV16: EVAPORATIVELY PRECOOLED CONDENSER

Recommendation

Specify an evaporatively precooled condenser for larger packaged units (10 tons or greater) in warm climates.

Description

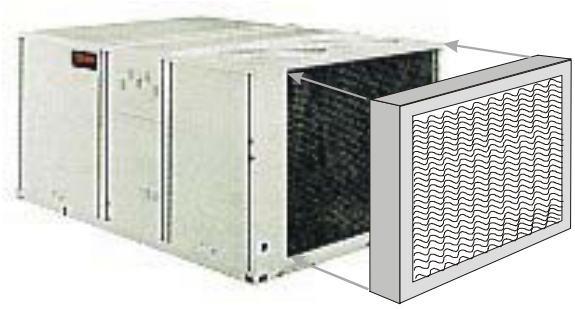
An evaporative precooler is an option available for some packaged air conditioners that cools the air entering the unit's condenser coils. The precooler reduces the temperature at which the condenser operates and increases the efficiency and capacity of the packaged unit.

The evaporative precooler consists of an evaporative medium several inches thick that replaces the inlet grill that typically protects the condenser coils. The medium is wetted using a recirculating system or a "once-through" system. Air drawn over the medium by the condenser fan is evaporatively cooled to a point close to the wetbulb temperature of outside air.

Precoolers are also available for outdoor units of some split systems.

Applicability

These condensers are applicable for larger units, especially those serving spaces used in summer. They should be used in facilities with skilled maintenance staff.



Evaporatively precooled condenser.

Applicable Climates

Applicable Spaces		When to Consider	
Classrooms	■	Programming	□
Library	■	Schematic	■
Multi-Purpose	■	Design Dev.	■
Gym	■	Contract Docs.	□
Corridors	■	Construction	□
Administration	■	Commissioning	□
Toilets	□	Operation	□
Other	□		

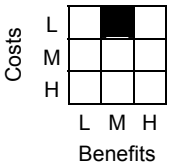
Integrated Design Implications

An evaporative precooler increases the capacity of air conditioners under hot conditions. Therefore, a smaller unit can be installed that will run more efficiently under normal partial load conditions. Water supply piping is required.

Cost Effectiveness

Evaporative precooled condensers add about 10% to the cost of the equipment and can pay for themselves in two to three years.

An evaporatively precooled condenser is generally cost effective for units over 10 tons.



Benefits

Condensers increase capacity and efficiency of packaged direct exchange air conditioners. They can also reduce summer demand peaks.

Design Tools

None.

Design Details

Evaporative precoolers are typically controlled to operate only at higher outdoor air temperatures, approximately 80°F and above. At lower temperatures, less benefit occurs.

When sizing the packaged rooftop system, reduce the design outdoor drybulb temperature assuming that the evaporative precooler is about 50% effective. For example, in a climate with summer design conditions of 100°F drybulb and 70°F wetbulb, use an outdoor drybulb of 85°F for selecting the system capacity. This smaller system will run more efficiently at part load and have a smaller peak electric demand.

The addition of the evaporative precooler will reduce condenser airflow due to extra pressure drop. Check with the unit's manufacturer to make sure that airflow will be adequate.

Ensure that the precooler medium is properly designed and sized to prevent carry-over of water onto the condenser coils.

Operation and Maintenance Issues

To minimize maintenance requirements, specify adequate bleed-off rates to prevent mineral buildup (without causing excessive water consumption). Also specify controls that periodically flush the evaporative medium with water to remove dirt and scale. Finally, specify materials to minimize potential for corrosion.

Specify periodic cleaning of evaporative medium and periodic inspections of water circulation rate and bleed-off rate.

Commissioning

Check that the precooler is activated when system runs and outdoor air exceeds the minimum setpoint (typically 80°F).

References/Additional Information

None.

GUIDELINE MV17: DEDICATED OUTSIDE AIR SYSTEMS

Recommendation

Install dedicated outside air ventilation systems to supplement or replace natural ventilation. Install systems to provide dehumidification of outdoor air supply with or without air conditioning.

Description

Dedicated outside air systems typically provide 100% outside air and deliver approximately 450 cfm to each classroom.

Outside air systems can be designed with ducted return or with relief dampers to outdoors. Systems with ducted return air can recover exhaust heat with an air-to-air heat exchanger. Systems without a heat exchanger usually need some means to temper the outside air, especially during winter.

Small systems are available that can serve individual rooms, while larger systems can serve an entire building. With larger centralized ventilation systems, evaporative cooling or waste heat recovery may be economical for tempering outdoor air.

Rooftop air-to-air heat exchangers are useful in systems with ducted return air for recovering exhaust heat.
NREL/PIX 11424

Applicable Climates

Applicable Spaces		When to Consider	
Classrooms	■	Programming	□
Library	■	Schematic	■
Multi-Purpose	■	Design Dev.	□
Gym	■	Contract Docs.	□
Corridors	□	Construction	□
Administration	□	Commissioning	□
Toilets	□	Operation	□
Other	□		

Applicability

This design strategy applies mainly to classrooms, or other areas with expected high occupant density, but can be used for spaces where hydronic heating systems and natural ventilation are appropriate. This design strategy is not as applicable for spaces that have conventional air conditioning, since outside air ventilation would be provided by the air-conditioning system.

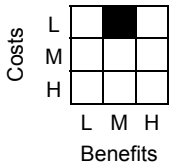
Dedicated outside air ventilation is especially appropriate in combination with baseboard or radiant heating systems, where a fan is not required for heating. However, even with forced-air heating systems, a separate ventilation system may be appropriate if access to clean outdoor air is difficult from each individual room. In these cases, a central air handler can supply tempered ventilation air to each room, while each space heater recirculates indoor air and runs only when there is a demand for heating. Alternately, a separate baseboard system can be used to provide well-controlled heating in each zone.

A dedicated ventilation system may also be appropriate where natural ventilation access is difficult because of noise, extreme temperatures, dust, security, or lack of physical access to the outdoors.

Integrated Design Implications

Special attention to controls is important to make sure that the ventilation system works together with the heating and/or cooling system. As with any ducted HVAC system, architectural coordination is important in locating relief dampers and routing ventilation ducts.

Cost Effectiveness



A dedicated outside air system may add cost to the overall HVAC system, but when combined with a well-designed displacement system in a coordinated building, it would be expected to be competitive with a well-designed, high-quality conventional HVAC system.

The U.S. EPA has created the School Advanced Ventilation Equipment Software (SAVES) that uses DOE-2 and code by the Florida Solar Energy Center and others to show that dedicated outdoor air supply systems with energy recovery ventilation components have a payback of under seven years in most areas (except the Hot and Dry and Temperate and Mixed climates).

Benefits

These systems, especially when combined with enthalphy energy recovery, will reduce energy costs in most regions. In addition, they ensure proper ventilation, improving air quality and occupant well being.

Design Tools

Most popular energy simulation programs, such as DOE-2, do not have the capability to directly model dedicated outside air distribution systems or 100% outdoor air systems with enthalpy energy recovery. However, there are some tricks that can give an approximation of the energy use, and some manufacturers of enthalpy energy recovery equipment can provide modeling.

Design Details

- In both hot and cold climates, consider using an enthalpy air-to-air heat exchanger to precondition outside air that is brought into the building. This will also reduce winter dryness.
- In hot climates, evaporation can be used to lower the temperature of air that is delivered to the space.
- Provide VAV dampers that can automatically minimize and shut off ventilation air to each classroom if it is not occupied. Consider using a motion sensor already installed for lighting as a control.
- Consider variable-speed controls for central ventilation fans, so that airflow can be reduced when some rooms are unoccupied.
- Use gravity type or automatic relief dampers in each classroom, unless exhaust air is ducted to a central unit for heat recovery.
- Size the system to provide at least 15 cfm per person in classrooms and other spaces. If a classroom is expected to have 30 students, 450 cfm should be delivered. If a classroom is expected to have 24 students, 360 cfm is appropriate.
- Use filters to remove dust and other particles from outside air.
- Isolate unit from occupied spaces. Provide appropriate intake and discharge noise control consistent with meeting the Noise Criteria. Locate rooftop units above unoccupied spaces and away from pollution sources on the roof.

Operation and Maintenance Issues

Replace filters on a regular basis.

Commissioning

Provide documentation regarding the design intent to contractors and building operators to ensure that the system gets implemented properly. Systems should be balanced and controls commissioned so that adequate air is delivered to each classroom.

References/Additional Information

None.

GUIDELINE MV18: ECONOMIZERS

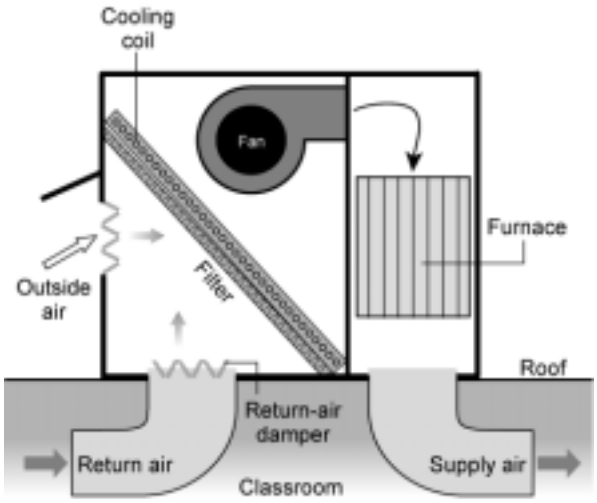
Recommendation

Incorporate integrated economizer dampers and controls on HVAC systems that utilize return air. For units under five tons, use non-integrated economizers with two-stage cooling controls

Description

Economizers consist of three sets of dampers with interlinked controls: an exhaust damper that relieves space return air to offset ventilation air brought in; an outside air damper that controls the amount of ventilation air brought into the system; and a return damper that balances the return and outside air portions of the economizers. At low outside air temperature (below 65°F), the economizer dampers modulate to minimum ventilation position unless more outside air is needed for cooling. This minimizes the heating load and protects the cooling coils from frosting at low loads. At high outside air temperature (above about 75°F), the economizer dampers return to this low ventilation position. At these temperatures, the recirculated space air takes less energy to cool. Between these points, the economizer dampers modulate from minimum ventilation to 100% outside air, acting as a first stage of cooling in an attempt to maintain the desired supply air temperature.

Integrated economizers allow simultaneous economizer and mechanical cooling. Non-integrated economizers first attempt to cool with outside air; if that does not satisfy the load, the economizer dampers return to minimum position and mechanical cooling is initiated.



Components of an economizer.

Applicable Climates

Applicable Spaces		When to Consider	
Classrooms	■	Programming	□
Library	■	Schematic	■
Multi-Purpose	■	Design Dev.	■
Gym	■	Contract Docs.	□
Corridors	■	Construction	□
Administration	■	Commissioning	□
Toilets	■	Operation	□
Other	■		

There are three common control methods:

- **Fixed temperature setpoint** economizers close to minimum position when outdoor air exceeds a fixed temperature setpoint, typically 72° to 74°F.
- **Differential temperature** economizers will operate whenever the temperature of the outside air is below the temperature of the return air.
- **Differential enthalpy** economizers compare the enthalpy of the outside air and return air streams and operate whenever the outside air has less heat content. Enthalpy economizers are most important in humid climates.

For moderate climates, economizers can be a significant means of minimizing space-conditioning costs, because outside air will be within the comfort range for much of the school day throughout the year.

Applicability

Economizers make the most difference for systems serving spaces with low occupant density, such as libraries, administration, and other areas. In those spaces, the normal ventilator rate is fairly low and little free cooling occurs without an economizer. In classrooms and assembly areas, where high occupant density will dictate a large minimum position on the outside air damper (30% or above), economizer controls will have less impact. However, they will still be cost effective due to higher cooling loads in these spaces.

On many existing systems, economizers can be added as a retrofit.

Economizers will not be as useful for spaces designed to use natural ventilation for cooling. In those cases, the cooling system may run only during hot periods when an economizer would be at minimum position anyway.

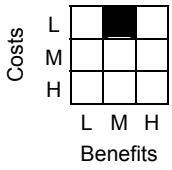
Economizers should not be installed in facilities that do not receive maintenance because a failure can increase energy consumption.

Integrated Design Implications

Economizers are especially valuable with displacement ventilation systems because the higher supply air temperature may allow an economizer to provide 100% of the cooling demand for a greater number of hours each year.

An economizer may be unnecessary in spaces with exterior walls and good natural ventilation design.

Cost Effectiveness



The cost premium is $200 to $500 to add an economizer to a small packaged rooftop system.

Economizers are very cost effective for spaces without natural ventilation.

Design Tools

None.

Design Details

Economizers should be factory-installed or specified to be factory-designed if they are to be field-assembled. Improper installation may cause coil and/or compressor damage.

Differential temperature control is recommended for most climate areas. However, in humid climates a differential temperature economizer could actually increase the system energy use by imposing a latent cooling load during economizer operation. A differential enthalpy economizer is ideal for humid areas, but enthalpy sensors require maintenance and can be unreliable. Therefore, a fixed temperature economizer with a setpoint around 72°F is a good choice for coastal areas where mild temperatures are accompanied by fairly high humidity.

For retrofit applications, care must be taken to protect the direct exchange coil and compressor from damage during low loads. With existing direct exchange systems, either non-integrated economizers should be installed or controls should be added to prevent compressor cycling and cutout on low evaporator temperatures. Economizer retrofits are likely to be cost effective only for larger systems (above 7.5 tons).

Operation and Maintenance Issues

Clean and lubricate dampers and control linkages. Maintenance is critical to ensure that economizers work properly for the lifetime of the system.

Commissioning

A functional test is critical to ensure that economizer controls are operating properly. With the system running during mild weather (outdoor cooler than indoor air), set the space thermostat to a low value to call for cooling and check that the outside air dampers are completely open. Then use a heat source, such as a hot-air gun, to warm the outside air temperature sensor and check that the outside air damper closes to its minimum position. Remove the heat source and check that the damper reopens (after the sensor has cooled).

For integrated economizers, also check that the outside air dampers remain completely open when the compressor is running and outdoor air is cool.

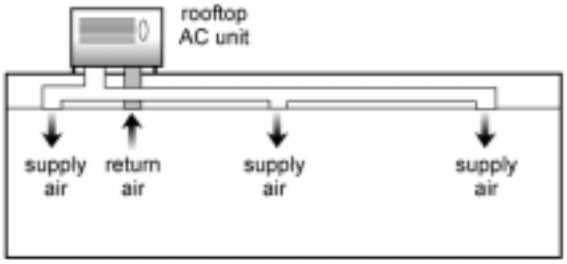
References/Additional Information

None.

GUIDELINE MV19: AIR DISTRIBUTION DESIGN GUIDELINES

Recommendation

Design the air distribution system to minimize pressure drop and noise by increasing duct size, eliminating duct turns, and specifying low-loss duct transitions and plenums. Use lowest possible fan speed that maintains adequate airflow. Pay special attention to the longest or most restricted duct branch. (See Guideline MV11: VAV Reheat System for information on variable volume systems.)



Basic air distribution system.

Applicable Climates

Applicable Spaces		When to Consider	
Classrooms	■	Programming	□
Library	■	Schematic	■
Multi-Purpose	■	Design Dev.	■
Gym	■	Contract Docs.	■
Corridors	■	Construction	■
Administration	■	Commissioning	■
Toilets	■	Operation	□
Other	■		

Description

Optimal air distribution system design is fairly complicated. An optimal design balances the need for comfort and low noise with overall HVAC system cost, energy cost, and long-term maintenance and replacement costs. Many factors affect performance: diffuser type, number of diffusers, diffuser size, duct size, duct material, plenum type and size, fitting types, length of ducts, number of turns, type of turns, location of duct system (e.g., unconditioned attic or within conditioned space), priority for heating performance vs. cooling performance, and fan characteristics (pressure vs. airflow).

Due to the complexity of design, a detailed analysis is common for small systems. Typically, designers and contractors rely on experience or rules of thumb in choosing system components. Even if design calculations are performed, however, decisions are not always the best, in terms of energy efficiency and acoustic performance.

This guideline addresses small, constant-volume duct systems that are common in schools. It covers design targets for air velocities and pressure loss that help ensure an efficient and quiet system.

Applicability

All ducted air systems.

Integrated Design Implications

Air distribution design options are closely tied to the architectural design. The choice of duct type is often limited by space availability, but acoustics should be considered. Round ducts with no internal glass fiber lining tend to keep noise inside and not let it be reduced as it travels away from the noise source (i.e., fan). Rectangular ducts with no internal glass fiber lining allow more sound to escape than circular ducts, but can be problematic if the noise level traveling through the sheet metal walls of the duct is too high.

Ducts may be located outside, in unconditioned space, or within the conditioned space. The most energy-efficient option is usually within conditioned space, but excessive noise may require that the first section of duct to be attenuated over unoccupied areas for a considerable distance. More expensive sheet metal ducts are usually required, but they need not be insulated. If ducts are located in an unconditioned attic, then the roof must be insulated and/or equipped with a radiant barrier to reduce heat gain to the ducts. Outdoor ducts should not be used unless no other option is feasible, as they almost always get wet and become mold sites.

Location of supply air outlets must be coordinated with lighting design (if located in ceiling) or space plan and furniture (for wall or floor outlets).

Cost Effectiveness

Sometimes extra costs for low-loss fittings or larger ducts are necessary to achieve a high performance design. However, these costs can often be offset by carefully sizing the heating and cooling system to reduce overall system size. In addition, many air distribution improvements have little or no extra cost, such as proper installation of flex duct that should be limited to the last 5 ft to 6 ft due to higher internal pressure drop.

Design Tools

Numerous duct-sizing computer programs are commercially available.

Design Details

These guidelines are intended to cover typical, small, single-zone systems. Additional criteria appropriate for multi-zone air distribution systems are not covered here.

Airflow

System cooling airflow. Total system airflow should generally fall between 350 cfm/ton and 450 cfm/ton for systems with cooling. If airflow is greater, condensation might blow off the cooling coil. If airflow is less than 350 cfm/ton, the cooling capacity and efficiency drop. The capacity loss due to low airflow is worst in dry climates where latent cooling loads are low.

System heating airflow. For heating-only systems, a good target is 25 cfm per kBtu/h of heating capacity, providing about 105°F supply air. Heating airflow should not be lower than 15 cfm per kBtu/h because supply air temperature will exceed 135°F. If the airflow is low, supply air will be too warm and air velocity too low, and poor mixing occurs in the room. Excessive airflow during heating creates more noise and can cause uncomfortable drafts.

Airflow adjustment. After system installation, airflow can be adjusted by either changing the fan speed or altering the duct system. To reduce airflow, lower the speed of the fan rather than install dampers. Try to use the lowest fan speed possible because fan energy consumption drops rapidly as fan speed decreases. If possible, specify a variable-speed or multiple-speed fan. To increase airflow, try to modify the duct system rather than increase the fan speed. Possible measures include replacing the most restrictive ducts with larger sizes, improving duct transitions to reduce pressure loss, and eliminating duct turns or constrictions (especially in flex duct).

Supply diffuser. Most diffusers also have a minimum velocity, both for proper mixing and to avoid dumping cool air on occupants. Refer to manufacturers' guidelines for specific types of supply diffusers. When choosing diffusers based on Noise Criteria (NC), remember that manufacturers' data are usually at ideal conditions (long, straight duct attached to diffuser) and actual noise level is likely to be higher. To account for this, diffusers should be selected for 5 to 10 NC points below the NC criteria of the room. Refer to Table 9 below for suggested air velocities.

Table 9 – Air Velocities for Supply Outlet and Return Inlet

	Design Criterion NC or RC(N)	Neck Air Velocity (fpm)
Supply Outlet	45	625
	40	560
	35	500
	30	425
	25	350
	20	300
Return Inlet	45	750
	40	675
	35	600
	30	500
	25	425
	20	375

(Source: 1999 ASHRAE APPLICATION HANDBOOK)

Return grille. The return air grille(s) must be larger than the total supply air diffuser area to avoid excessive noise. Refer to table above for suggested air velocities.

Duct. Air velocity should not exceed 700 fpm in flex ducts and 1,200 fpm in sheet metal ducts above occupied areas. Higher flow creates excessive turbulence and noise. There is usually a practical lower limit to duct air velocity, where the duct becomes too large and expensive.

Cooling coil. Air velocity through the cooling coils should be minimized to reduce pressure loss. A good target is 300 fpm. However, designers seldom have a choice of coil area in small packaged HVAC units, though it is possible to compare airflow and fan power data from different manufacturers to identify units with lower internal pressure loss.

Duct type

Flex duct. Flexible ducts are widely used. They offer several advantages when properly installed, but also have some disadvantages.

Flex ducts are most popular for their low cost and ease of installation. In addition, they attenuate noise much better than sheet metal ducts, but allow noise to escape into the ceiling plenum, which may not be acceptable if noise levels at the flex duct are excessive. Flex duct also offers lower air leakage, are usually pre-insulated, and provide some flexibility for future changes.

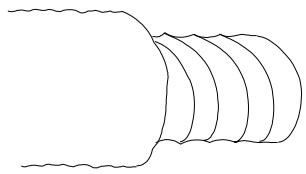
On the down side, pressure loss is greater in flex ducts, even when they are properly installed. They are also prone to kinking, sagging, and compression, which are problems that further reduce airflow and create noise. And since they are flexible, flex ducts are usually installed with more turns than sheet metal ducts. Actual performance of flex ducts in the field is often poor due to these installation problems. As a final disadvantage, flexible ducts are typically warranted for only about 10 years and will need replacement more often than a sheet metal equivalent.

If flex duct is used, several important points to consider are:

- The duct must be large enough for the desired airflow (see Table 10 below).
- The ducts must be properly suspended according to manufacturer guidelines without compressing or sagging.
- All ducts must be stretched to full length (see table notes below).
- Keep flexible duct bends as gentle as possible; allow no turns of more than 45°.
- Fasten all flex ducts securely to rigid sheet metal boots and seal with mastic (see Guideline MV20: Duct Sealing and Insulation).

- Limit duct lengths to no longer than about 5 to 10 ft to facilitate drop in ceiling designs (otherwise pressure loss may be too high).

Table 10 – Minimum and Maximum Airflow Values



Flex Duct Diameter (in.)	Minimum Airflow (cfm)	Maximum Airflow (cfm)
4	20	60
5	40	100
6	60	140
7	90	190
8	130	240
9	175	310
10	230	380
12	380	550

Table Notes:

- Maximum airflow limits correspond to velocity of 700 fpm. Higher flows create turbulence and noise in flex ducts.
- Minimum airflow corresponds to a design friction rate of 0.06 in./100 ft.
- The airflow values in the table assume that the flex duct is stretched to its full length. Airflow resistance increases dramatically if flex duct is compressed in length. Pressure loss doubles if the duct is compressed to 90% of its full length and triples if it is 80% compressed.

Sheet metal duct. The advantages to sheet metal ducts are lower pressure loss, longer life, greater durability, and the potential for reuse or recycling at the end of the system's life. They are the only option for long duct runs or medium- to-high-pressure duct systems. In addition, sheet metal ducts may remain exposed in conditioned spaces.

Disadvantages to sheet metal ducts are higher cost, higher sound transmission (sometimes they require noise attenuation measures that offset some of the pressure loss advantage), insulation requirement, and potentially greater leakage (though leakage is not an issue if they are properly sealed).

From a pressure loss standpoint, round sheet metal ducts are preferred over rectangular when adequate space is available. Round sheet metal ducts keep noise inside better than rectangular ducts. This may be preferred if the ducts are running over a noise sensitive space, and duct noise breakout is a concern. However, because round ducts do not allow noise to escape as easily as rectangular ducts, noise will not be reduced as quickly as the noise travels down the duct system. When ducts cannot be lined with internal glass fiber, rectangular ducts are preferred to allow low frequency noise to escape the duct before reaching the diffuser. Rectangular ducts are susceptible to noisy drumming at high airflow.

Reducing pressure loss

Several measures may be taken to reduce pressure loss and improve airflow. Knowledge of the following simple principles may help the designer improve airflow:

- **Air resists changing direction.** The pressure drop of a turn can be reduced dramatically by smoothing the inside and outside radius. When possible, avoid sharp turns in ducts and never allow kinks in flexible ducts. Turning vanes are another option to reduce the pressure drop in a sharp turn.

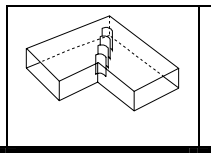
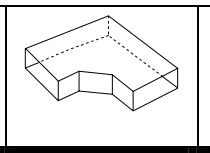
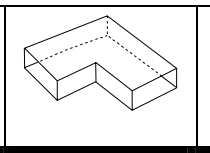
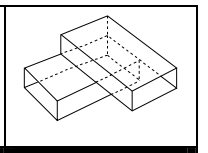
				
	BEST	**GOOD**	**FAIR**	**POOR**
Relative Pressure Loss	1.0	X 1.3	X 4.7	X 13.0

Figure 10 – Pressure Loss for Duct Turns

Note: Total pressure loss calculated at 800 fpm air velocity.

- **Airflow into branch ducts will be improved by using angled transitions (or conical taps) rather than typical straight connections.** The angled transition is especially useful for critical branches that are not getting enough air.

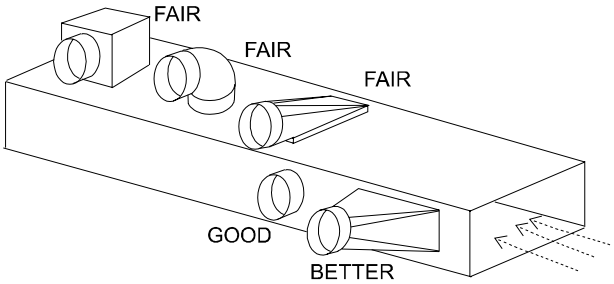


Figure 11 – Various Connections for Branch Ducts

From a pressure loss standpoint, the fewer turns the better. However, turns help reduce noise, particularly at high frequencies, as it travels through the duct system. For example, a side branch takeoff provides less flow resistance than a top branch takeoff because the top takeoff requires the air to turn twice.

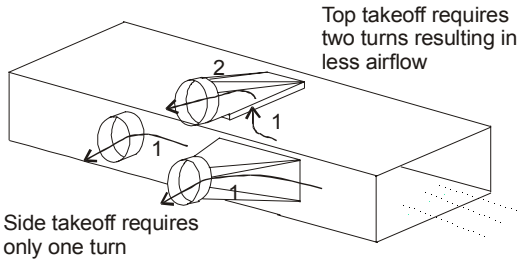


Figure 12 – Side Takeoff Vs. Top Takeoff

Reducing noise

Noise reaching the space via the duct system is either transmitted from the air-conditioning unit or generated by air turbulence within the air distribution system.

There are several measures available to reduce noise as it travels through the duct system, such as sound absorbing duct liner, flex duct, duct turns, and sound attenuators (silencers). Each of these elements has different noise reduction characteristics that need to be considered when analyzing the system for noise. Duct lining thickness and duct dimensions control the amount of noise reduction per linear foot of duct. Thicker glass fiber lining will reduce noise faster. Length and diameter controls the amount of noise reduction across flex duct. Duct dimensions and the way in which the duct turns (i.e.,

turning vanes, radiused elbow, etc.) impacts the amount of noise reduction. Please bear in mind that noise reduction is frequency dependant. Noise reducing elements (i.e., elbows, flex duct, etc.) may reduce noise effectively at high or low frequencies, but seldom have the same amount of noise reduction across the audible frequency range.

The first three measures mentioned above are the most feasible for small, single-zone systems because they are not prohibitively expensive and do not necessarily cause excessive pressure loss (small packaged systems usually do not have a lot of pressure to spare). Careful design is important to balance noise attenuation benefits vs. additional pressure loss.

Limiting air velocity as described earlier in this guideline controls noise generation with the ducts, or at grilles and diffusers.

Other Design Issues

Pay special attention to the duct branch with the greatest pressure drop, either the longest branch or the one with the most constricted turns. For longer branches, either larger duct size or low-loss duct transitions will be required to achieve proper airflow.

Do not place balancing dampers directly behind diffusers. If they are necessary, dampers should be located as close to the fan as possible to minimize noise and air leakage in the supply duct.

Connections to ceiling diffusers should have two diameters of straight duct leading into the diffuser. Otherwise noise and pressure drop can increase significantly.

Avoid placing ducts in a hot attic. The roof can reach 150°F on a sunny day and the radiant heat load on the duct is significant. If ducts are above the ceiling, insulation must be installed on or under the roof or a radiant barrier must be installed under the roof deck.

In many cases, if the pressure loss in the air distribution system can be reduced by as little as 0.15 in. SP, fan speed can be reduced and fan power decreases significantly. In the case of a three-ton rooftop packaged unit, energy savings can be $200 to $300 over a 10-year period. Manufacturer's data for a typical three-ton unit shows that the fan can supply 1,100 cfm at 0.8 in. w.c. external static pressure, if the fan is set to high speed. The fan can provide the same airflow at 0.65 in. w.c. at medium speed. Therefore, if the duct system is carefully designed and installed, it may be possible to run at medium speed. The fan power then drops from 590 W to 445 W. For typical operating hours and electricity rates, the savings are about $30/year.

Operation and Maintenance Issues

Filters must be replaced regularly to maintain airflow. Fans and drives must be lubricated to maintain proper operation.

Commissioning

Measure supply airflow and external static pressure to compare with design values. If airflow is low, take measures to reduce restrictions in duct system rather than increasing fan speed.

References/Additional Information

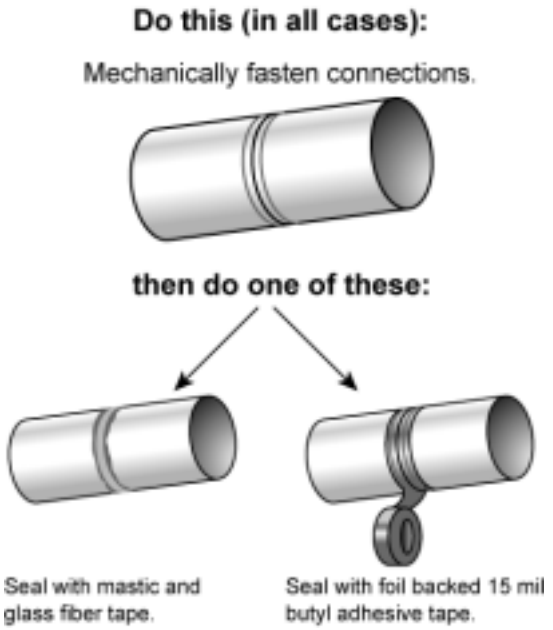
American Society of Heating, Refrigeration and Air Conditioning Engineers. *ASHRAE Handbook - 2001 Fundamentals*. Atlanta, GA.

Sheet Metal and Air Conditioning Contractors National Association. *HVAC Systems Duct Design*. Chantilly, VA.

GUIDELINE MV20: DUCT SEALING AND INSULATION

Recommendation

Create strong and long-lasting connections by mechanically fastening all duct connections and using mastic to seal connections and transverse joints (those perpendicular to airflow). If choosing pressure-sensitive tape as a sealant, then specify foil-backed tape with 15-mil butyl adhesive. Internal gasketing at joints is an excellent choice for round ducts.



Description

Duct leakage has a big impact on system efficiency and capacity. Studies of residential systems conducted by the Lawrence Berkeley National Laboratory show that 20% loss is common.[4] Similar problems exist in commercial duct systems.

Other studies have shown that some types of pressure-sensitive tape fail quickly in the field. Therefore, duct sealing systems must be specified carefully for longevity as well as strength and air-tightness.

Depending on duct location, insulation also plays a critical role in ensuring system efficiency and capacity.

Supply and return air plenums must be sealed as well. These are usually the areas of greatest pressure in the air distribution system, and small holes create significant leaks.

Applicable Climates

Applicability

All ducted air systems.

Applicable Spaces	
Classrooms	■
Library	■
Multi-Purpose	■
Gym	■
Corridors	■
Administration	■
Toilets	■
Other	■

When to Consider	
Programming	□
Schematic	□
Design Dev.	■
Contract Docs.	■
Construction	■
Commissioning	□
Operation	□

Integrated Design Implications

Duct leakage problems can be avoided by placing ducts within the conditioned envelope or by eliminating them altogether (e.g., hydronic heating and cooling).

Cost Effectiveness

Using mastic for duct sealing may increase material costs, but many find that labor costs drop compared to sealing with tape. Therefore, good duct sealing should not have a significant cost impact.

Costs \ Benefits	L	M	H
L			■
M			
H			

Benefits

Careful duct sealing and insulation application will allow use of smaller cooling and heating equipment or at least allow the use of smaller safety margins in sizing calculations. Lower equipment cost may be a result.

[4] http://www.lbl.gov/Science-Articles/Research-Review/Highlights/1998/v3/EES_duct.html.

Lower cooling and heating costs result. Other benefits include improved system performance, potentially better comfort, and reduction in infiltration and potential moisture problems within envelope components.

Design Tools

None.

Design Details

Do not rely on sealants, such as tape or mastic, to provide a mechanical connection. Specify screws, draw bands, or other mechanical fastening devices as appropriate for the duct type.

As a first choice, use mastic to seal all connections and transverse joints. Mastic is a liquid applied sealant that can also be used together with a mesh or glass fiber tape to provide added strength or to span gaps of up to about ¼ in. Specify mastic in a water-based solvent with a base material of polyester/synthetic resins free of volatile organic content.

If choosing pressure-sensitive tape as a sealant, specify foil-backed tape with 15-mil butyl adhesive. Butyl tape has been found to have greater longevity in the field. Avoid using tape with rubber or acrylic adhesive.

Flexible ducts must be mechanically fastened with draw bands securing the inner and outer plastic layers to the terminal boot. Specify that the draw bands be tightened as recommended by the manufacturer using an adjustable tensioning tool.

Seal both supply and return ducts and plenums.

Commissioning

Inspect duct connections.

Test duct leakage with smoke testing or pressure testing.

References/Additional Information

None.

GUIDELINE MV21: HYDRONIC DISTRIBUTION

Recommendation

Consider using a variable flow system with variable-speed drive (VSD) pumps, but be careful to keep turbulent flow in the fintube during cold weather. Insulate exposed hydronic heating/cooling piping. Make early decisions regarding the placement of heating/cooling components (radiators, ceiling panels, slab floors, boilers, chillers). Use this information to create a system layout that minimizes piping material (pipes, bends) and head loss. When possible, use larger pipe diameters and smaller pumping equipment to conserve energy.

These loop water pumps and piping are part of a geothermal heat pump system being used by Nebraska schools to save money and energy on heating and cooling. NREL/PIX07415

Description

Significant amounts of energy must be used to distribute water for heating and cooling. Proper design can result in substantial economic and energy savings. Unfortunately, hydronic distribution design is often governed by *past* practices and not necessarily *best* practices. This factor makes the design process quick and easy, but not always the most economical or energy efficient. A hydronic distribution system consists of pipes, fittings, tanks, pumps, and valves.

Applicable Climates

Applicability

Applicable in all areas. However, the system is most applicable to the Hot and Dry, Hot and Humid, and Temperate and Humid regions.

Integrated Design Implications

Hydronic distribution is related to nearly all aspects of building design and construction. It is crucial that the HVAC piping contractor be involved throughout the design and construction process to maximize the efficiency and cost effectiveness of the hydronic distribution system. Simply laying out heating and cooling elements (baseboards, ceiling panels, chillers, boilers) in such a way that minimizes the required pipe material and maximizes straight-running pipe can save significant amounts of energy. Maximizing the amount of straight-running pipe also simplifies the insulating process.

Applicable Spaces		When to Consider	
Classrooms	■	Programming	■
Library	■	Schematic	■
Multi-Purpose	■	Design Dev.	■
Gym	■	Contract Docs.	■
Corridors	■	Construction	■
Administration	■	Commissioning	■
Toilets	■	Operation	■
Other	■		

Cost Effectiveness

Initial cost for hydronic distribution depends on the quantity, size, and type of piping, valves, and pumps. Initial cost can be minimized through proper planning, sizing, and placement of each.

When doing life-cycle cost analysis, compare incremental cost of increased pipe diameter to energy savings, and savings from decreased size and cost of pumping system.

Benefits

- A properly sized and installed system will provide quiet, efficient, and virtually maintenance-free operation at minimal cost.

- Properly insulating all exposed piping will save energy and money, which can be cost effective at levels beyond code requirements.
- Increasing piping diameter significantly decreases the pumping power required. Pressure head loss due to friction drops the fifth power with pipe diameter.
- Oversized piping allows for increases in load requirements from add-ons or renovations without complete system overhaul.

Design Tools

- Use a CAD-based program to design pumping layout.
- ASHRAE Handbook - Fundamentals outlines the process for determining pressure drop through piping layout.
- Pipe diameter selection involves balancing the following:
- Location of pipe in the system
- First costs of installed piping
- Pump costs (capital and energy)
- Erosion considerations
- Noise considerations
- Architectural constraints
- Budget constraints.

Design Details

Piping Circuits

There are four general types of piping circuits: series, diverting series, parallel direct-return, and parallel reverse-return. The series circuits are one-pipe circuits and are the simplest and lowest-cost design. Both the series and diverting series involve large temperature drops; however, only the latter allows for control of individual load elements.

The advantage of parallel piping circuits is that they supply the same temperature water to all loads. Direct-return networks are sometimes hard to balance due to sub-circuits of varying length. Reverse-return networks are designed with sub-circuits of nearly equal length. Parallel circuits are two-pipe systems.

Piping attached to vibration-isolated equipment (typically within the first 25 ft to 30 ft from the equipment) should be supported with vibration isolators, similar in type and static deflection to the vibration isolation being used for the associated equipment.

Fluid flow should be limited to 4 fps in 2-in. diameter pipes and below. For larger pipes a flow velocity of 6 fps is recommended.

Maintain a maximum of 50 psig water pressure at plumbing fixtures.

Valves

In general, either two-way or three-way control valves are used to manage flow to the load. A two-way valve controls flow rate to the load through throttling, which causes a variable flow load response. Three-way valves are used in conjunction with a bypass line to vary flow to the load. Because the water that does not go to the load simply passes through the bypass line, three-way valves provide a constant flow load response. Significant energy savings can be realized when two-way control valves are used in conjunction with VSD pumps.

It is recommended that ball valves or butterfly valves be used for all isolation and balancing valves. These valves are reliable and offer a low-pressure drop at a low cost.

Pumps
Centrifugal pumps are most commonly used in hydronic distribution systems. The use of VSD pumps can save significant amounts of energy and simplify the distribution system. Pump power falls at a cubed rate with speed; thus, a VSD pump can be extremely cost effective for systems with significant load variations. Also, variable flow networks with VSD pumps use a simple two-way valve and do not require balancing valves. For systems that use supply air temperature reset controls, specify a clamp on the speed of the pump to avoid excessive energy use during system startup.

Refer to 1995 ASHRAE Handbook Chapter 43 for recommended vibration isolation.

Dual-Temperature Systems
When a space requires both heating and cooling, either a two-pipe or four-pipe system can be used. In a two-pipe system, all the loads must be either heating or cooling congruently. Two-pipe systems cannot be used when some spaces on the piping network need cooling, while others need heating. Switching from one mode of operation to the other increases overall energy usage and can be a fairly time-consuming process. A four-pipe system is more complex, but it allows for heating and cooling on the same network and is more convenient than a two-pipe system when frequent changeovers are required.

Expansion Chamber
- Closed systems should have only one expansion chamber.
- Expansion tanks open to the atmosphere must be located above the highest point in the circuit.

Air Elimination
Measures such as manual vents and air elimination valves should be taken to purge any gases from the flow circuit. Failure to do so can lead to corrosion, noise, and reduced pumping capacity.

Insulation
The insulation process becomes significantly easier when the piping network is laid out properly. Install all valves with extended bonnets to allow for the full insulation thickness without interference with valve operators. It may be cost effective to insulate pipes beyond code requirements.

Water Treatment
Care should be taken to avoid scaling and biological growth within the distribution system. Significant fouling resulting from either source is detrimental to system performance. The degree to which scaling can occur is dependent upon temperature, pH level, and the amount of soluble material present in the water. Scale formation can be controlled through several means including filtration and chemical treatments.

Biological growth is generally a larger problem for cooling systems. Heating systems typically operate at temperatures high enough to prohibit substantial biological growth. Chemical treatments with biocides such as chlorine and bromine have traditionally been used to control this growth. Alternatives to these chemicals include ozone and UV radiation. Ozone itself is toxic; however it readily breaks down into non-toxic compounds in the environment. UV radiation is completely non-toxic, but is only effective when turbidity levels are low. Mechanical methods such as blow downs can also be utilized to control fouling and decrease chemical use, but these methods increase water usage.

Operation and Maintenance Issues

- Water quality should be checked on a regular basis to ensure fouling due to scaling or biological growth is not occurring.
- Periodically check piping insulation. Insulation adhesive can fail and expose piping.
- Check pressures, pumps, and valves on regular basis to ensure system is performing as intended.

Commissioning

Commissioning should be performed throughout planning, design, construction, and operation to ensure proper installation, set-up, and integration with other facility components. Water flow should be measured and adjusted accordingly. System head should be measured and compared to design system head.

References/Additional Information

American Society of Heating, Refrigerating and Air Conditioning Engineers. *ASHRAE Handbook - HVAC Systems and Equipment*. 2000.

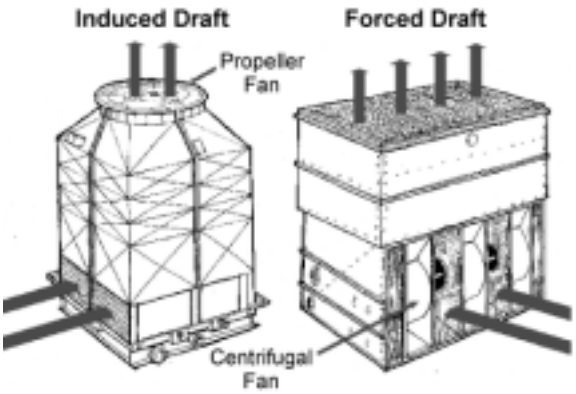
CoolTools: Chilled Water plant Design Guide. Available from Pacific Gas and Electric, P.O. Box 770000, B32. San Francisco, CA 94177.

Hydronics Institute, Berkeley Heights, NJ 07922. Phone: (908) 464-8200.

GUIDELINE MV22: CHILLED WATER PLANTS

Recommendation

Use high-efficiency, water-cooled, variable-speed chillers. Use chiller heat recovery if there is a reliable hot water demand. Install oversized induced-draft cooling towers with axial propeller fans. Use low approach temperatures and variable-speed fan control.



Cooling Towers

Applicable Climates

Applicable Spaces	When to Consider
Classrooms	Programming
Library	Schematic
Multi-Purpose	Design Dev.
Gym	Contract Docs.
Corridors	Construction
Administration	Commissioning
Toilets	Operation
Other	

Description

Chillers

There are two basic chiller classifications, air-cooled and water-cooled. Water-cooled chillers cost more (when considering the cooling tower and condenser water loop), but are more energy efficient. Several chiller types exist within the classifications, including electric (centrifugal, reciprocating, screw or scroll), gas-fired (engine-driven or double effect absorption), and steam absorption.

Towers

A cooling tower provides heat rejection for a water-cooled chiller by exposing as much water surface area to air as possible to promote the evaporation of the water and thus cooling. Cooling towers come in a variety of shapes and configurations. A “direct” tower, also known as an “open” tower, is one in which the fluid being cooled is in direct contact with the air. An “indirect” tower, or “closed-circuit fluid cooler,” is one in which the fluid being cooled is contained within a heat exchanger or coil, and the evaporating water cascades over the outside of the tubes. The tower airflow can be driven by a fan (mechanical draft) or can be induced by a high-pressure water spray. The mechanical draft units can blow the air through the tower (forced draft) or can pull the air through the tower (induced draft). The water invariably flows vertically from the top down, but the air can be moved horizontally through the water (cross flow) or can be drawn vertically upward against the flow (counterblow).

Applicability

These towers are applicable for a small percentage of schools in areas needing significant amounts of chilled water and space cooling.

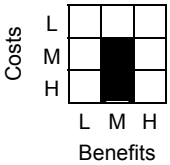
Equipment should perform in accordance with efficiency guidelines in ASHRAE 90.1-2001. The energy performance requirements set forth by ASHRAE 90.1-2001 state that heat rejection devices must supply ≥ 38.2 gpm/hp for axial fan towers and ≥ 20.0 gpm/hp for centrifugal fan towers. The U.S. Environmental Protection Agency codes chemicals (usually chlorine) used for cleaning. Methods using ozone for cleaning are also an option, but this can lead to increased corrosion of internal systems.

Integrated Design Implications

Chiller and tower decisions are related to many aspects of building design and construction including space considerations, cooling/heating choices, and the hydronic distribution system layout. Tower performance is related to facility layout and orientation. The tower should be sited properly to minimize recirculation of saturated air.

The placement of chilled water plant components affects requirements of the hydronic distribution system. Try to make these decisions early to create a hydronic distribution layout that minimizes piping materials (pipes, bends, etc.) and head loss.

Cost Effectiveness



Installed estimates for chillers fall between $575/ton and $781/ton, depending on efficiency and drive choice. Installed tower cost estimates are between $133/ton and $178/ton.

As a general rule, air-cooled chillers are more cost effective if the chiller plant is less than 300 tons. Water-cooled are more cost effective above 300 tons. However, many factors affect operating costs for a chilled water plant, and the best choice of type, size, efficiency, and controls is difficult to generalize. First-cost premium, when improving from an efficiency of 0.7 kW/ton to 0.6 kW/ton, is $70/ton. This number increases to $136/ton for variable-speed chillers. Simple payback periods vary from 3 to 11 years.

Increasing the cooling tower's size and efficiency is generally cost effective with a four- to seven-year payback. Annual energy savings are between $0.01/ft^2 and $0.04/ft^2. Incremental costs are between $0.08/ft^2 and $0.12/ft^2, depending upon climate.

Design Tools

- CoolTools: Chilled Water Plant Design Guide available from Pacific Gas and Electric.
- The use of chillers with various efficiencies can be modeled using DOE-2 and VisualDOE.

Design Details

Vibration Isolation

Refer to 1995 ASHRAE Handbook Chapter 43 for recommended chiller and cooling tower vibration isolation.

Chiller Type

The best choice among electric, gas, and steam chillers (or some combination thereof) is largely site specific. If a reliable source of free or very low cost steam is available on site, then steam absorption makes the most sense.

Gas versus electric or hybrid gas/electric will depend on utility rates. Gas-fired chillers can cost two times more than electrically driven machines and will require a larger cooling tower and condenser water pump. Gas engine chillers are more energy efficient than absorption machines and have high temperature heat readily available for recovery; however, are more maintenance intensive than absorption machines.

Chiller type has a significant impact on the level and quality of noise produced. Historically, rotary screw compressors produce very high levels of noise, which typically contain an annoying tonal component. Centrifugal compressors are usually quieter than screw chillers and do not contain a tonal component. Scroll compressors are the most quiet of the three, but are usually air-cooled. The predominant source of noise from air-cooled scroll compressor chillers is generated by the cooling fans. VSDs can reduce the amount of noise being generated by slowing the flow of refrigerant through the compressor.

The most cost-effective type of electric chiller is primarily a function of chiller size. General decision guidelines are listed in Table 11.

Table 11 – Recommended Electric Chiller Types

Chiller Size	Recommendation
<= 100 tons	1st choice: reciprocating 2nd choice: scroll 3rd choice: screw
100 – 300 tons	1st choice: screw 2nd choice: scroll 3rd choice: centrifugal
> 300 tons	1st choice: centrifugal 2nd choice: screw

Number of Chillers

As a general rule:

- If the peak chilled water load is less than 300 tons, then a single chiller is usually most economical.
- If the load is greater than 300 tons, use two chillers. This offers better low-load capability and operating efficiency and offers some redundancy should one of the chillers fail.

Having one smaller or pony chiller (as opposed to two or more equally-sized chillers) can improve part-load efficiency of the plant. However, some operators prefer if all the machines are the same size due to familiarity and parts interchangeability.

Unloading Mechanism

Centrifugal chillers typically use inlet vanes to control the chiller output at part-load. Using hot gas bypass as a means to control the chiller at very low loads should be avoided, if at all feasible, as this strategy results in significant energy penalties. Using a VSD instead of inlet vanes allows the compressor to run at lower speed at part-load conditions, thereby reducing the chiller kW/ton more than inlet vanes. The energy savings from a VSD chiller can be quite significant if the chiller operates many hours at low load. To capture the potential savings of VSD chillers, it is important that the condenser water temperature is reset when ambient conditions are below design conditions. This can be accomplished either by using a fixed setpoint (e.g., 70°F) that is below the design condenser water temperature (e.g., 85°F) or using wetbulb reset control, which produces the coldest condenser water the tower is capable of producing at a particular time. A gas engine chiller is also capable of unloading by decreasing engine speed.

Chiller Efficiency

The ratings in Table 12 should be considered as upper bounds. Lower efficiencies are available and are often the lowest lifecycle cost option.

Table 12 – Recommended Chiller Rated Efficiency

Condenser Type	Compressor Type	Min Tons	Max Tons	Recommended kW/Ton	Recommended IPLV	Recommended C.O.P.
Water-Cooled	Scroll	1	80	0.79	0.78	
Water-Cooled	Screw	1	150	0.76	0.70	
Water-Cooled	Screw	151	300	0.72	0.70	
Water-Cooled	Screw	301	& up	0.64	0.61	
Water-Cooled	Reciprocating	1	80	0.84	0.75	
Water-Cooled	Reciprocating	81	& up	0.82	0.75	
Water-Cooled	Gas Engine	501	2000			1.80
Water-Cooled	Absorption (SE)	150	1000			0.65
Water-Cooled	Absorption (DE)	150	1000			1.00
Water-Cooled	Centrifugal	1	150	0.62	0.62	
Water-Cooled	Centrifugal	151	300	0.60	0.61	
Water-Cooled	Centrifugal	301	& up	0.56	0.56	
Air-Cooled	Scroll	1	80	1.25	1.10	
Air-Cooled	Absorption (SE)	1	& up			0.60
Air-Cooled	Screw	1	& up	1.21	1.00	
Air-Cooled	Reciprocating	1	& up	1.15	1.15	
Air-Cooled	Centrifugal	1	& up	1.30	1.30	

Heat Recovery Chiller

Heat rejected from the condenser of a chiller can be recovered and used to drive a desiccant system or for preheating domestic hot water by routing the condenser water through a double-wall heat exchanger that is either an integral part of a storage tank or is remotely located with a circulation pump to the storage tank. Heat recovery chillers are typically used only for a portion of the total cooling load, because of the need to match hot water load and cooling load and because of the lower efficiency of heat recovery chillers. Heat recovery chillers are not typically piped in parallel with other chillers but rather are either piped for “preferential” loading or in series with other chillers, allowing the cooling load on the heat recovery chiller to be matched to the hot water load. Waste heat can also be recovered from the engine jacket and exhaust of gas engine-driven chillers.

The energy savings from chiller heat recovery are reduced when using economizers (air-side or water-side) because chillers are often not needed when the weather is mild or cold. Chiller heat recovery cannot eliminate the need for a DHW boiler but it can eliminate the need for some of the cooling towers at a site.

Chiller Staging

For a plant composed of single-speed chillers, control systems should be designed to operate no more chillers than required to meet the load. A plant composed of variable-speed chillers should attempt to keep as many chillers running as possible, provided they are all operating at above approximately 20% to 35% load. For example, for the typical variable-speed chiller plant, it is more efficient to run three chillers at 30% load than to run one chiller at 90% load. The use of hot gas bypass at very low loads should be avoided, if at all feasible, as this strategy results in significant energy penalties.

Tower Fan Speed Control

Two-speed (1,800 rpm/900 rpm) or variable-speed fan control is always more cost effective than single-speed fan control. For plants with multiple towers or multiple cells, provide two- or variable-speed control on all cells, not just the “lead” cells. The towers are most efficient when all cells are running at low speed rather than some at full speed and some off. For instance, two cells operating at half speed will use about 15% of full power compared to 50% of full power when one cell is on and the other is off.

Tower Oversizing
The tower and fill can be oversized to reduce pressure drop, thereby allowing the fan to be slowed down, which reduces motor power and noise. Tower heat transfer area should be oversized to improve efficiency to at least 60 gpm/hp to 80 gpm/hp at CTI conditions.[5] The energy savings should outweigh the added cost to oversize the tower and to accommodate the larger tower footprint and weight.

A larger tower can also produce cooler water, allowing chillers to run more efficiently. Selecting towers for a 4% or 5% approach will generally be cost effective relative to a more typical 10%. Cooling towers are available with as low as 3% approach temperature, but the tower cost increases as the degree of approach drops. A life-cycle cost analysis should be performed to compare the extra cost to the energy impact on the tower, chiller, and pumps.

Tower Performance
The performance of a cooling tower is a function of the ambient wetbulb temperature, entering water temperature, airflow, and water flow. The drybulb temperature has an insignificant effect on the performance of a cooling tower. "Nominal" cooling tower tons are the capacity based on a 3 gpm flow, 95°F entering water temperature, 85°F leaving water temperature, and 78°F entering wetbulb temperature. For these conditions, the range is 10°F (95°F-85°F) and the approach is 7°F (85°F-78°F).

Table 13 – Cooling Tower Design Considerations

	Energy	Noise	Height	Chiller Fouling	Cost	Application
Packaged Induced Draft, Axial Fan	Lower	Higher	Higher	Higher	Medium	Best for most plants.
Field-Erected Induced Draft, Axial Fan	Lowest	Higher	Higher	Higher	Higher	Very large plants.
Forced Draft, Centrifugal Fan	Higher	Lower	Lower	Higher	Lower	Best if noise or height constrained or large external static pressure (e.g., tower located indoors).
Closed Circuit Evaporative Cooler, Axial Fan	Higher	Higher	Higher	Lower	Highest	Appropriate for heat pumps, not most chillers.
Closed Circuit Evaporative Cooler, Centrifugal Fan	Highest	Lower	Lower	Lower	Highest	Appropriate for heat pumps, not most chillers.
Spray Towers	Lowest	Lowest	Higher	Higher	Lowest	Seldom used due to high maintenance and variable condenser water flow.

Operation and Maintenance Issues

Periodic blow downs and scrubbing of cooling towers must be performed to avoid scaling of internal systems and biological growth. The condition of cooling tower fill is critical to performance. It should be inspected every year and the chemistry of the tower water should be maintained to minimize fouling.

Commissioning

For chillers to operate efficiently, they must be properly commissioned. Part of this process is making sure that sensors (such as chilled water flow, chilled water supply and return temperatures, and chiller electric

[5] Tower efficiency (as defined in ASHRAE Standard 90.1-1999) is the ratio of the maximum tower flow rate (gpm) to the fan motor horsepower (hp) at standard CTI rating conditions (95°F to 85°F at 78°F wetbulb). Standard efficiency is about 35 gpm/hp to 40 gpm/hp efficiency.

demand), are specified and properly calibrated. Sensor data should be permanently stored by the energy management system and easily visualized graphically. Not only is this data valuable for insuring that the design intent is met in the construction process, but also for maintaining energy efficiency over the life of the chiller. For example, by monitoring the approach temperatures in the condenser and evaporator heat exchangers (as the heat exchanger surface becomes fouled, the approach temperature increases), maintenance can be scheduled when needed, as opposed to too often, which wastes maintenance resources, or too infrequently, which wastes energy. A detailed account of commissioning issues specific to chilled water plants can be found in the CoolTools design guide (see the References section below).

References/Additional Information

CoolTools: Chilled Water Plant Design Guide. Available from Pacific Gas and Electric, P.O. Box 770000, B32, San Francisco, CA 94177.

STD-201 (November 1996) Certification Standard for Commercial Water Cooling Towers. Available from Cooling Tower Institute, Post Office Box 73383, Houston, Texas 77273. Phone: (281) 583-4087.

GUIDELINE MV23: BOILERS

Recommendation

Consider medium-to high-efficiency gas-fired boilers or medium efficiency oil-fired boilers for space heating and domestic hot water. If demand is large and variable, install several smaller modular boilers instead of one large unit.

Description

Boilers are pressure vessels that transfer heat to a fluid. They are constructed of cast-iron, steel, aluminum, or copper. There are two basic types, fire-tube and water-tube. Fire-tube configurations heat water by passing heated combustion gases through conduit that is submerged in the water. This system generally uses natural gas or oil as the combustion fuel. Water-tube configurations pass water in pipes through the heated combustion gases and can use natural gas, oil, coal, wood, or other biomass. The air needed for combustion can be supplied by either mechanical or natural means. Hot water boilers are generally classified as either low temperature (less than 250°F) or high temperature (250°F to 430°F), and are rated by their maximum working pressure. All boiler systems have the following components in common:

- **Fuel supply:** natural gas, oil, wood, or other biomass.
- **Burner:** The burner injects a fuel-air mixture in the combustion chamber.
- **Combustion chamber:** Location in boiler where combustion occurs.
- **Heat exchange tubes:** Tubes within the boiler that contain water for a water-tube model and combustion gases in a fire-tube unit.
- **Stack:** The stack is the chimney through which combustion gases pass into the atmosphere.
- **Hydronic distribution system:** Supplies feed water to the boiler and distributes hot water to the facility.

This central, high-efficiency boiler supplies hot water to two insulated storage tanks, providing hot water to six baths and a radiant floor heating system. NREL/PIX07925

Applicable Climates

Applicable Spaces	When to Consider
Classrooms	Programming
Library	Schematic
Multi-Purpose	Design Dev.
Gym	Contract Docs.
Corridors	Construction
Administration	Commissioning
Toilets	Operation
Other	

Applicability

Applicable in any situation where a significant amount of space heating and/or water heating are required.

The boiler should comply with the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. This includes codes regarding suggested maintenance. Stack placement should adhere to ASHRAE 62 standards. Stack emissions must conform to requirements set forth by the Clean Air Act under jurisdiction of the applicable air quality district. The stack will produce transmit vibration and

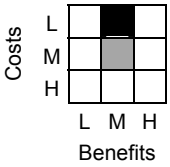
noise if the stack is not decoupled from the building structure. Ensuring that the stack is isolated from the building structure is particularly important when the stack is close to occupied areas.

Integrated Design Implications

A certain amount of hot service water will always be needed for restroom facilities. Any additional need is dependent upon the choice of space heating system (air or hydronic) and whether or not the building design includes a swimming pool and/or commercial sanitation and food preparation equipment. The actual heating load is dependent upon climate and decisions regarding fenestration, hydronic distribution, building envelope, indoor equipment, and building orientation. The placement of boiler affects requirements of the hydronic distribution system. Try to make these decisions early to create a hydronic distribution layout that minimizes piping materials (pipes, bends, etc.) and head loss.

If a central cooling plant is being considered for the facility, the possibility of using recovered thermal energy should be considered. Using this technique could affect many aspects of design including chiller choice.

Cost Effectiveness



Total installed costs between $35/kBtuh and $52/kBtuh, depending on efficiency. Maintenance costs exists, but they will be less in comparison and can save huge future costs.

Condensing boilers cost from 30% to 60% more than standard units up to 500 kBtu/hr. Incremental costs for more efficient boilers range from $0.23/ft^2 to $0.35/ft^{2}depending on climate. The more efficient boilers realize a simple payback period of 5 to 10 years.

Benefits

- Longer life span than standard storage water heaters.
- Can be more efficient than a furnace, but not always.
- Gas boilers burn significantly cleaner than oil-, coal-, and wood-fired units.

Design Tools

The use of boilers with various efficiencies can be modeled using DOE-2 and VisualDOE.

Design Details

- Large systems between 75% and 85% efficient.
- New condensing gas-fired boilers are up to 96% efficient.

Boiler Energy saving add-ons:

- Economizers preheat feed water with energy from stack gases before it goes to the boiler.
- Air preheaters preheat the air that is mixed with the fuel for combustion leaving more energy to heat the water.
- Turbulators increase the convective heat transfer rates in fire-tube boilers by inducing higher levels of turbulence.
- Oxygen trim controls measure and adjust oxygen levels in the inlet air before combustion.
- Boiler reset controls automatically change the high-limit set point based on changes in outdoor temperatures.
- Since boilers are generally most efficient at their rated capacity it is better to have several smaller boilers rather than one large unit that is rarely used at its most efficient setting.

- Condensing boilers produce acidic condensate that is corrosive to some materials such as steel or iron. Make sure to account for proper condensate drainage and follow manufacturers specifications for exhaust flue design if specifying a condensing boiler.
- Refer to 1995 ASHRAE Handbook Chapter 43 for recommended boiler vibration isolation.

Operation and Maintenance Issues

Performing basic operating and maintenance practices on boilers is very important. Regular inspection of boiler system components ensures safe and efficient operation. Proper maintenance can lead to energy savings of 10% to 20%, reduce harmful emissions, and increase the lifespan of the system.

High efficiency boilers (<90% efficiency) need meticulous maintenance to keep them working correctly.

Fire-side maintenance:

- Minimize excess combustion air and monitor stack gas O_2 and CO_2 to ensure proper percentages. Too little air can cause increased CO and particulate emission, while too much can lower efficiency.
- Clean heat transfer surfaces.

Water-side maintenance:

- Perform regular 'blow downs" to reduce the level of total dissolved solids (TDS) in the system. High TDS levels cause pipe fouling that reduces the heat transfer rate and increases the pressure drop.
- Insulate boiler walls and piping.

Commissioning

Commissioning should be performed to ensure proper installation and operation. It is particularly important to properly train maintenance operators. The safety and efficiency of a boiler system is highly dependent upon the duties performed by boiler personnel.

References/Additional Information

American Society of Mechanical Engineers. *Boiler and Pressure Vessel Codes.* New York: ASME, 1998.

GUIDELINE MV24: ADJUSTABLE THERMOSTATS

Recommendation

Specify thermostats or temperature sensors that will allow classroom teachers control over comfort conditions in their classroom including temperature (within limits) and noise.

Description

Teachers find it helpful to have control over conditions in their classrooms because different conditions may be appropriate at different times. For example, cooler temperatures may be appropriate after recess or for a more active group. It may be appropriate to turn off mechanical ventilation for certain activities requiring acute hearing or when windows are open. Where an energy management system is not used for temperature control, programmable thermostats can allow implementation of energy-saving and comfort-enhancing measures, but only if programmed and maintained properly. Care should be taken to select a model that is very easy to program. Otherwise, it is likely to be overridden or set for continuous operation.

Adjustable thermostats allow the user to have control over the conditions of the room, which can improve overall comfort and create a better learning environment. NREL/PIX04899

Applicable Climates

Cost Effectiveness

$50 to $200 premium for programmable thermostat.

Programmable thermostats are highly cost effective. For a relatively small incremental increase over conventional thermostats, a carefully selected and programmed model will provide teachers with control over their classroom environment while combining time-of-day and override functions. DDC system sensors with adjustable set point have a greater incremental cost impact over plain sensors, but the benefits of giving teachers control should not be underestimated.

Applicable Spaces		When to Consider	
Classrooms	■	Programming	□
Library	■	Schematic	□
Multi-Purpose	▒	Design Dev.	■
Gym	▒	Contract Docs.	■
Corridors	□	Construction	■
Administration	■	Commissioning	■
Toilets	□	Operation	■
Other	▒		

Benefits

Improved comfort and sense of control may foster a better attitude and teaching environment. Some energy savings may be realized due to stopping mechanical ventilation when windows are open. Service requests may be reduced compared to situations where teachers must request a set point change from operations and maintenance personnel. Programmable thermostats replace time clocks, eliminating associated first and maintenance costs.

Costs \ Benefits	L	M	H
L	▒	■	□
M	□	□	□
H	□	□	□

Design Tools

None.

Design Details

- Specify programmable thermostats for control, adjustment, time clock, and override functions when no DDC system will be used for temperature control.

- Sensors with set point control and fan/unit on-off control should be specified for temperature control of classrooms using a DDC system. Also specify limits within which the set point may be varied and the time period after which an overridden value or state will revert to the standard “automatic” (default) value or state.
- If it is necessary to have thermostat covers that lock, provide a means for faculty access.
- Place the thermostat on an interior wall in a location out of direct sun and away from heat sources such as copiers or computers. A point close to the return air or exhaust air inlet is often a good choice.

Operation and Maintenance Issues

Faculty may require repeated training on programmable thermostat operation. Unlike DDC system temperature sensors with adjustable set point, which can be programmed to revert to standard operation after a specified period, programmable thermostats may allow the HVAC system to be switched off, rather than overridden. This can defeat morning warm-up, resulting in comfort problems and complaints. Specify that simplified one-page instructions be provided by the installing contractor and kept on file at school office with copies distributed to teachers for adjustable sensors or programmable thermostats. Programmable thermostats may require periodic replacement of back-up battery.

Commissioning

Proper functioning of any thermostat or temperature sensor must be verified prior to acceptance of the installation. Programmable thermostats and temperature sensors with adjustable set points necessitate a slightly more involved verification procedure.

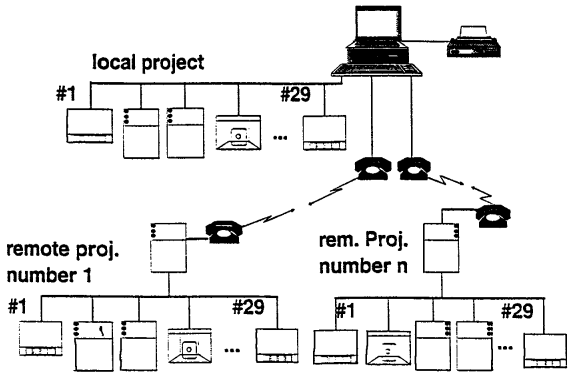
References/Additional Information

None.

GUIDELINE MV25: EMS/DDC

Recommendation

Use a graphic-interfaced, DDC system to integrate multiple components of HVAC and other building systems and manage them from a single (local and/or remote) location.



Description

Automatic control of multiple pieces of HVAC equipment and other systems may be integrated using computerized systems known variously as DDC, energy management systems (EMS), energy management and control systems (EMCS), building management systems (BMS), or building automation systems (BAS). The added expense and complexity may be justified by the equipment optimization and increased convenience of maintenance possible with such a system.

Applicable Climates

Applicable Spaces	When to Consider
Classrooms	Programming
Library	Schematic
Multi-Purpose	Design Dev.
Gym	Contract Docs.
Corridors	Construction
Administration	Commissioning
Toilets	Operation
Other	

DDC systems generally perform three functions: equipment on/off control, space temperature control, and equipment status monitoring. A single system can control lighting, security, central plant equipment, and space conditioning equipment. Systems may be specified to allow local override and temperature adjustment at selected space temperature sensors. Graphical user interfaces may be custom configured with different levels of access to allow limited adjustment of schedules and other system parameters by various personnel. While a DDC system will permit the implementation of energy- and cost-saving measures not otherwise possible, the advantages will only be realized if the system is initially programmed correctly and checked periodically by adequately trained personnel.

DDC systems consist of individual controllers that communicate with one another over a network linked by two-conductor cable or other means. Each controller is wired directly to relays, valve and damper motors, and temperature sensors to control and monitor specific equipment. Controllers generally require line voltage power to control panels containing one or more controllers. All other wiring is generally low voltage. The systems may connect directly, via a local-area network (LAN) or modem to a desktop or laptop computer for monitoring and adjustment. A “user-friendly” graphical interface is desired. Systems may be programmed to retain and plot temperature and other status data for performance analysis over limited periods, but retention of historical data requires optional software and additional storage media.

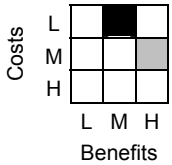
Applicability

DDC systems may not be appropriate for small schools with very simple HVAC systems. Their applicability increases with the size of the facility, the complexity of the HVAC system, and the size of the district.

Integrated Design Implications

Coordination between mechanical and electrical consultants is necessary for supplying power to a DDC system. If the system is to integrate control of lighting and other building systems, significantly greater coordination will be required. It may also be desirable to have the DDC system use the building (or district-wide, if available) LAN for communications between controllers and with users. These decisions must be made early in the design phase to allow for coordination throughout the design.

Cost Effectiveness



$0.50//ft^2 to $1.50/ft^2. $300 to $500 per input or output "point." Special operation and maintenance training is required to operate, maintain, and troubleshoot DDC systems. Periodic recalibration of sensors may be required for precise control. Software upgrades are periodically required, and life expectancy of major system components may be as low as 8 to 10 years due to the rapid pace of computer technology development.

Cost effectiveness can be very high, with simple paybacks commonly estimated at 4 to 15 years. However, benefits will only be realized when certain conditions are met: the system must be programmed carefully, checked out thoroughly, and maintained actively. If operation and maintenance personnel are not comfortable with the system, it is likely to be bypassed, so good training is critical. Many school districts find that the greatest benefit of a DDC system is as a maintenance tool, allowing remote adjustment and troubleshooting of equipment.

Benefits

Energy savings may be realized from a DDC system that is correctly installed and actively maintained. Additionally, comfort conditions may be more easily and consistently attainable, and improvements can be made in operation and maintenance resource utilization, through the use of the DDC system for fine tuning, analysis, and trouble shooting.

Peak electric demand savings are possible through load management controls. A DDC system can be programmed to shutoff or reduce power to specific loads during times of high peak demand charges. The savings can be significant, especially if implemented throughout a district.

Comfort improvements and energy savings may be achieved through such features as adaptive optimum start programs that learn when to start morning warm-up to achieve comfort at occupancy time for different operating conditions such as Monday mornings (when the building may have cooled off more than on other mornings).

DDC systems can also offer remote monitoring of system status from a central office and help reduce time spent on maintenance and trouble calls.

DDC systems have the added benefit of eliminating the air compressors required for pneumatic control systems, together with associated maintenance costs, failures, etc.

Design Tools

Control system manufacturers and their representatives are usually eager to assist with the design process (or take it over, if possible). This resource should be used with care, so as to not overlook the design engineer's responsibility to specify a well-engineered system. Close attention to the development of operation sequence is always worthwhile. Software is available, both commercially and from control manufacturers, to chart sequences of operation in block diagrams or flow charts.

Design Details

- Keep controls as simple as possible for a particular function. They will generally be operated (or bypassed) to the lowest level of understanding of any of the operation and maintenance personnel responsible for the HVAC system.
- Rooftop units are often available with optional factory-installed control modules that will interface with the DDC system as an independent "node," allowing a high level of monitoring and control.

- Discharge air temperature sensors are necessary for troubleshooting, even if not required for control.
- Specify temperature sensors with adjustable set point to give teachers control.
- Specify training. Because operation and maintenance personnel will “inherit” the system, and its performance will ultimately depend on them, involve them as much as possible in design decisions.
- Specify at least a one-year warranty, including all programming changes.
- By specifying the configuration of specific data trend logs (not just the capability to collect them) and their submittal for review and approval at system completion, some system commissioning may be accomplished by the design engineer and/or other owner’s representatives.
- Specify all software necessary for efficient system operation by operation and maintenance personnel to be provided as part of the system installation.
- Local DDC contractors will usually be willing to provide design assistance or even a “complete” design package. Great care should be taken in such collaboration, for it is unlikely that thorough engineering will be applied to the design. The control system should be carefully specified by the design engineer, and details left up to the installing contractor only after careful consideration.
- Control algorithms that may be specified to increase energy efficiency include: optimal start time calculation based on learned building behavior; operation of central equipment based on zone demand, including supply temperature or pressure reset; night purge ventilation to cool building interiors with cool nighttime air in hot climates; heating and cooling system lockouts based on current or predicted outside air temperature; or heating and cooling lockout when windows or doors are opened for natural ventilation (using security system sensor switches).
- Automatic alternation of redundant and lead/lag equipment based on runtime should be accomplished by the DDC system, with provision for operator override.

Operation and Maintenance Issues

Calibrating critical points is required annually or semi-annually. Alternating redundant or lead/lag equipment for even wear may be triggered automatically or manually. Operation and maintenance requires special training, particularly in the case of software, and consistency with existing systems may be desirable. Permanent software changes should be carefully limited. Periodic checkout is necessary.

Commissioning

Careful commissioning is critical for the success of DDC system installations, and proper control operation is necessary for proper equipment operation. Since DDC software may be somewhat esoteric, lack of commissioning may mean that this important aspect of the contractor’s work may never be inspected and may never be finished to the desired level. Therefore, it is a very good idea to provide for some commissioning of the control system by an independent party or organization representing the owner’s interests. Submittal and review of contractor’s input and output point verification test documentation should be required. Field calibration of any temperature sensors that must be accurate for proper control is necessary. (Factory calibration is adequate only for non-critical sensors, such as room temperatures with adjustable set points.) One minimal but effective commissioning method is to specify submittal of trend data logs, showing system operation in specified modes, for review by the design engineer. User interfaces including graphics (when specified) should also be reviewed.

References/Additional Information

None.

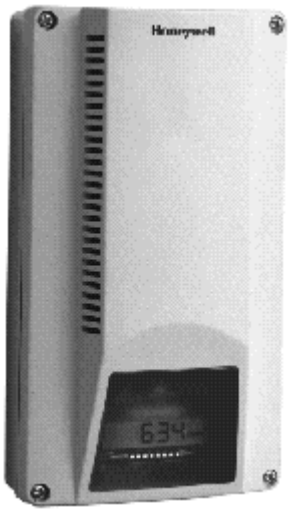
GUIDELINE MV26: DEMAND CONTROLLED VENTILATION

Recommendation

Specify controls to adjust ventilation rate for spaces with varying occupancy to prevent unnecessary cooling or heating of large quantities of outside air, and insure that adequate ventilation *is* provided when needed.

Description

Many spaces in schools require high ventilation rates due to dense "design" occupancy, but experience this occupancy level sporadically or occasionally. The outdoor air required may represent a very large heating or cooling load, depending on the season and climate. Therefore, reducing the amount of ventilation during those times the space is partly occupied or unoccupied may save substantial amounts of energy and wear on equipment, but temperature needs to be maintained. This may be accomplished using occupancy sensors or air quality (CO_2 concentration) sensors to control the quantity of ventilation air. This may be done either in conjunction with a DDC system or by independent controls.



CO_2 sensors help indicate building occupancy levels, allowing for better control of the quantity of ventilation air needed. NREL/PIX 11425

Applicable Climates

Applicability

For variable air volume, variable airflow with constant volume, multi-zone or small packaged unit zones, occupancy sensors may be applied but must be enabled/disabled to meet any pre-occupancy ventilation requirements. For larger intermittently occupied spaces such as multi-purpose rooms, auditoriums, cafeterias, and gyms, the energy savings may justify the added first cost, maintenance cost, and complexity of a CO_2-sensing system that modulates the outside air quantity down from the design level when interior air CO_2 levels indicate partial occupancy.

Applicable Spaces	
Classrooms	■
Library	■
Multi-Purpose	■
Gym	■
Corridors	■
Administration	□
Toilets	□
Other	▒

When to Consider	
Programming	□
Schematic	□
Design Dev.	■
Contract Docs.	■
Construction	□
Commissioning	■
Operation	■

Cost Effectiveness

Each CO_2 sensor costs approximately $400.
Installation, testing, and adjustment ranges from $500 to $1,500 per system. A hand-held CO_2 sensor for calibration costs $500.

Generally, cost effectiveness for occupancy sensor-based controls will be very high for larger systems. For CO_2 sensor-based control, it will depend on the climate being "severe" enough, and the required ventilation rate being large enough, so that the heating and cooling load reduction saves enough energy costs to offset the first cost of the CO_2 sensing equipment.

Costs \ Benefits	L	M	H
L	■	□	□
M	□	□	▒
H	□	□	□

Benefits

- Reduced energy consumption.
- Reduced wear on equipment.
- Confirmed/documented interior air quality.

Design Tools

None.

Design Details

- Demand-controlled ventilation responds to human occupancy only. Other sources of internal pollutants must be addressed with per-area baseline ventilation, targeted ventilation, etc. This should be considered very carefully before applying this type of control, especially to classrooms, where various odor sources may be used. Demand-controlled ventilation always results in worse interior air quality than a properly adjusted system constantly delivering ventilation for rated occupancy.
- CO_2 sensor-based ventilation control uses the measured CO_2 level as an indicator of the current occupancy level, so the ventilation rate may be adjusted accordingly. This is an important difference from using the CO_2 sensor as a direct indication of air quality.
- In areas where outdoor air CO_2 concentration is relatively constant, ventilation may be controlled by a single return air sensor to maintain a fixed CO_2 limit. Otherwise, outdoor and return air sensors should be used.
- The setpoint must be calculated based on occupancy and activity level. For example, the CO_2 concentration for an office space designed at 15 cfm per person (sedentary adult) can be calculated at 700 ppm above ambient.

Operation and Maintenance Issues

Calibration is required.

Commissioning

Review system operation under varying occupancy. Correlate with balance report data for minimum and maximum outdoor air damper positions. Verify acceptable levels of CO_2 concentration in space when occupied using hand-held sensor. Perform all testing in non-economizer mode.

References/Additional Information

American Society of Heating, Refrigerating and Air Conditioning Engineers. *ASHRAE Journal*, April 1997. Interpretation of ventilation standard IC-62-1989-27.

American Society of Heating, Refrigerating and Air Conditioning Engineers. *ASHRAE Standard 62-99*.

GUIDELINE MV27: CO SENSORS FOR GARAGE EXHAUST FANS

Recommendation

Use carbon monoxide (CO) sensors to prevent parking garage exhaust fans operating when they are not needed.

Description

Parking garage ventilation is often provided by an exhaust fan operated during normal occupancy hours. However, the high ventilation rate required when traffic is present need not be maintained most of the time, when no vehicles are operating. Substantial energy savings may be realized by limiting fan operation to only those periods during normal occupancy when CO concentration in the garage rises above acceptable levels. CO concentration-sensor technology has advanced substantially in recent years, reducing cost and improving reliability.

Applicability

School buildings with enclosed parking garages requiring mechanical ventilation.

Cost Effectiveness

$0.20/ft^2 to $0.40/ft^2 of garage. $1,000 to $2,000 per sensor installation.

Benefits

Benefits include energy savings, wear reduction, and noise reduction.

Design Tools

None.

Design Details

Control strategies, like CO sensors, help reduce energy loads by preventing equipment from operating when not necessary. NREL/PIX 11332

Applicable Climates

Applicable Spaces

- Classrooms
- Library
- Multi-Purpose
- Gym
- Corridors
- Administration
- Toilets
- Other

When to Consider

- Programming
- Schematic
- Design Dev.
- Contract Docs.
- Construction
- Commission
- Operation

Costs: L, M, H

Benefits: L, M, H

- Diesel exhaust does not contain high levels of CO. Consider nitrogen dioxide (NO_2) sensors if substantial traffic or idling of diesel vehicles is anticipated.
- Include time-of-day control in addition to CO concentration control.
- Sensor coverage area is limited, so multiple sensors may be required.
- Specify calibration tools provided to operation and maintenance personnel at time of training.

Operation and Maintenance Issues

- Annual calibration of sensors is required.

Commissioning

- Verify threshold adjustment and function. Also verify training of operation and maintenance personnel, including calibration.

References/Additional Information

None.

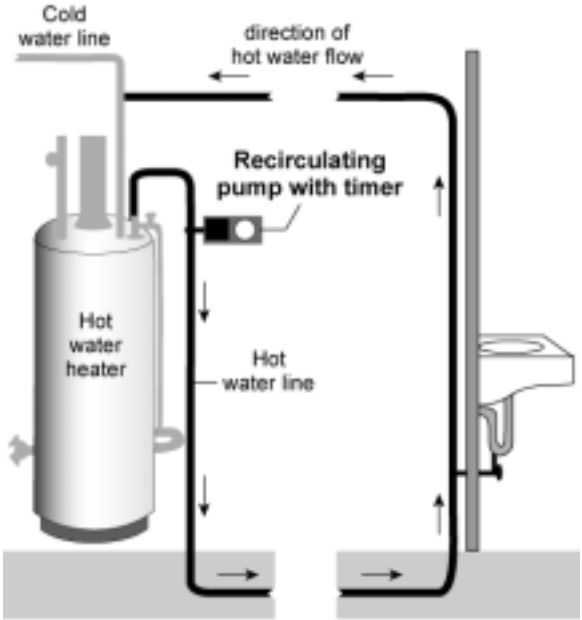
GUIDELINE MV28: TIMERS FOR RECIRCULATING HOT WATER SYSTEMS

Recommendation

Use recirculation timers to control circulation of hot water based on demand. Use separate hot water systems for areas with significantly different demand patterns.

Description

Recirculating hot water systems connect to the hot water pipe and constantly circulate hot water through the pipes, from the heater to the furthest fixture and then back to the heater, making warm water immediately available upon turning the tap. Large facilities use recirculating hot water systems, which result in heat losses through the distribution piping. Installing timers ensures that hot water circulates only during times of need, which greatly reduces the heat loss through the distribution piping as well as the daily pumping load.



Applicability

Timers are applicable for large facilities where hot water is recirculated. Timers will work effectively only when the hot water demand for a facility can be predicted accurately, as in the case of classrooms and school administrative areas.

Applicable Climates

Cost Effectiveness

Timers are very cost effective and have a two- to five-year payback period.

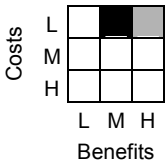
Prices for recirculating system timers range between $40 and $50.

Applicable Spaces

- Classrooms
- Library
- Multi-Purpose
- Gym
- Corridors
- Administration
- Toilets
- Other

When to Consider

- Programming
- Schematic
- Design Dev.
- Contract Docs.
- Construction
- Commissioning
- Operation



Benefits

Timers greatly reduce heat losses through distribution piping. Daily pumping loads are also reduced considerably.

Design Tools

None.

Design Details

Most schools are ideal candidates for using timers because of the predictability of classroom schedules. Set the system to operate only between classes, just before and after the school day, and during lunch periods.

Administrative areas, locker rooms, and other areas may have a demand schedule different from that of the classroom facility. Separate hot water systems or gas-powered, instantaneous water heaters can be used to accommodate these areas. Avoid using timers for areas with random and intermittent schedules.

Consider using thermostats connected in series with the timers. The thermostat turns off the pump when the water in the pipes reaches a certain temperature. Once the water in the pipe is hot, the pump turns off. If the timer and thermostatic controls are installed together in series, the circulator operates only at the preset clock times and only when the temperature conditions of the thermostat are met. That is, if either the timer control or the thermostatic control switch is open (off), the circulator will not operate, which results in additional savings.

Operation and Maintenance Issues

- Adjust the initial timer schedule based on observed or monitored demand data. Schedules may vary from school to school, and it is important to fine-tune the timer settings based on specific demand patterns.
- Check the hot water supply every six months to ensure that the timer is functioning as expected.
- Always set the timer switch to the actual time by turning the programming ring in the direction of the arrow until the timing arrow points to the actual time on the ring.
- In a power outage, the timer will not keep time. After power has been restored, the correct time of day must be reset by rotating the programming ring in the direction of the arrow until the timing arrow points to the actual time on the ring.

Commissioning

If installing a thermostat along with the timer, ensure that the two devices are installed in series.

After wiring is completed and checked, install the timer control unit onto the terminal box bracket of the pump and reinsert the terminal box screw. Be careful not to bind or leave any terminal box wires exposed.

References/Additional Information

http://www.eren.doe.gov/buildings/consumer_information/water/waterques.html#13.