Energy Saving Through HVAC System Improvement

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Introduction

An air-conditioning or HVAC&R (Heating, Ventilating, Air-Conditioning, and Refrigerating) system consists of components and equipment arranged in sequential order to condition the air, to transport it to the conditioned space, and to control the indoor environmental parameters of a specified within required limits. Most air-conditioning systems perform the following functions:

- Provide the cooling and heating energy required
- Condition the supply air, i.e. heat or cool, humidify or dehumidify, clean and purify, and attenuate any objectionable noise provided by the HVAC&R equipment
- Distribute the conditioned air, containing sufficient outdoor air, to the conditioned space
- Control and maintain the indoor environmental parameters – such as temperature, humidity, cleanliness, air movement, sound level, and pressure differential between the conditioned space and surroundings – within predefined limits.

In institutional, commercial, and residential buildings, air-conditioning systems are mainly for the occupants' health and comfort. They are often called *comfort air-conditioning system*s. In manufacturing buildings, air-conditioning systems are provided for product processing, or for the health and comfort of workers as well as processing, and are called *processing air-conditioning system*s. The following areas are examples of process air conditioning systems:

- Pharmaceutical, textile and many process industries
- Precision, electronic production facilities
- Storage and warehouses
- Some food item production facilities.

There are seven main processes [1] required to achieve full air conditioning and they are listed and explained below:

1. *Heating* -- the process of adding thermal energy (heat) to the conditioned space for the purposes of raising or maintaining the temperature of the space.
2. *Cooling* -- the process of removing thermal energy (heat) from the conditioned space for the purposes of lowering or maintaining the temperature of the space.

3. *Humidifying* -- the process of adding water vapor (moisture) to the air in the conditioned space for the purposes of raising or maintaining the moisture content of the air.
4. *Dehumidifying* -- the process of removing water vapor (moisture) from the air in the conditioned space for the purposes of lowering or maintaining the moisture content of the air.
5. *Cleaning* -- the process of removing particulates, (dust etc.,) and biological contaminants, (insects, pollen etc.,) from the air delivered to the conditioned space for the purposes of improving or maintaining the air quality.
6. *Ventilating* -- the process of exchanging air between the outdoors and the conditioned space for the purposes of diluting the gaseous contaminants in the air and improving or maintaining air quality, composition and freshness.
7. *Air Movement* -- the process of circulating and mixing air through conditioned spaces in the building for the purposes of achieving the proper ventilation and facilitating the thermal energy transfer.

The requirements and importance of the seven processes varies. In a climate that stays warm all year, heating may not be required at all. Conversely, in a cold climate the periods of heat in the summer may be so infrequent as to make cooling unnecessary. In a dry desert climate, dehumidification may be redundant, and in a hot, humid climate dehumidification may be the most important design aspect of the air-conditioning system.

Modern air conditioning is critical to almost every facet of advancing human activity. Although there have been great advances in HVAC, there are several areas where active research and debate continue.

- *Indoor air quality* is one that directly affects us. In many countries of the world there is a rapid rise in asthmatics and increasing dissatisfaction with indoor-air-quality in buildings and planes. The causes and effects are extremely complex. A significant scientific and engineering field has developed to investigate and address these issues.
- *Greenhouse gas emissions* and the destruction of the earth's protective *ozone layer* are concerns that are stimulating research. New legislation and guidelines are evolving that encourage: recycling; the use of new forms of energy; less energy usage; and low polluting materials, particularly refrigerants. All these issues have a significant impact on building design, including HVAC systems and the design codes.
- *Energy conservation* is an ongoing challenge to find novel ways to reduce consumption in new and existing buildings without compromising comfort and indoor air quality. Energy conservation requires significant cooperation between disciplines.

Energy Usage

The world's economy literally runs on energy. To support continued economic progress for the world's growing population, more energy will be needed. Even with significant improvements in energy efficiency, the world's total energy demand is expected to be approximately 40 percent higher by 2030 than it was in 2005.

Global economic output, as measured by Gross Domestic Product (GDP), rose on average nearly 3 percent per year from 1980 to 2005. Worldwide GDP is expected to increase by approximately the same rate to 2030, led by rapidly expanding economies of developing countries. While the global economy grew since 1980, the world also became more energy efficient. Global energy demand from all sources – expressed in million barrels per day of oil equivalent (MBDOE) – is expected to increase 1.3 percent per year on average from 2005 to 2030. This rate is considerably slower than the growth experienced from 1980-2005, reflecting strong improvements in energy efficiency. Still, global demand in 2030 is likely to reach nearly 325 MBDOE (Fig. 1).

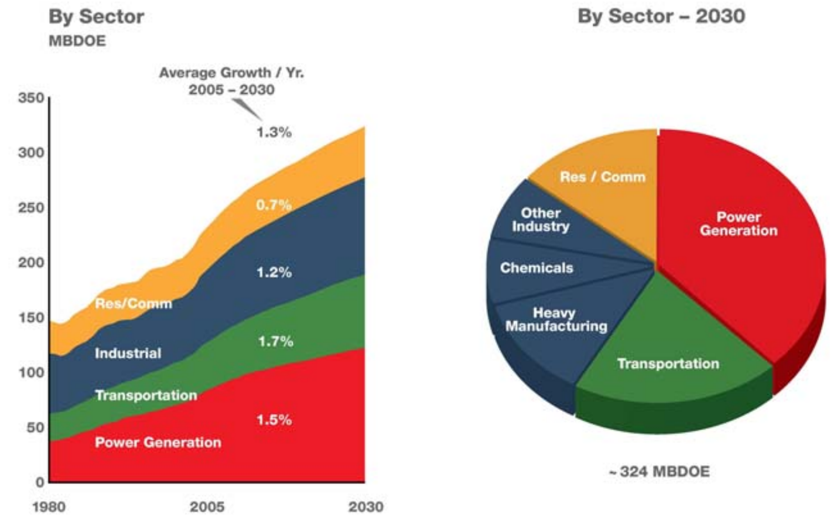

Fig. 1 World energy demand [2]

Shown in Fig. 2 is the breakdown of typical total building electrical energy consumption. As shown, the HVAC is by far the largest energy consumer and thus potentially an area where large energy savings may be realized. In Fig. 2, the “other” represents all diverse energy consuming equipment such as lifts, computers, etc.

In Fig. 3, HVAC energy consumption is broken down into the various components of the HVAC system. It is seen that, the design performance does not indicate how well the system will operate annually. The annual energy usage tells a different story. Although pumps are much smaller that the chiller, they end up using almost two-thirds the energy that the chiller uses. This happens because the chilled water and condenser pumps must operate at plant design flow rates any time there is a requirement for chilled water.

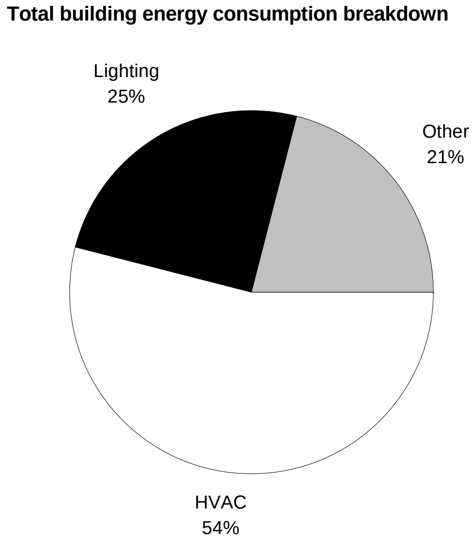

Fig. 2 Breakdown of the total building electrical energy consumption [3]

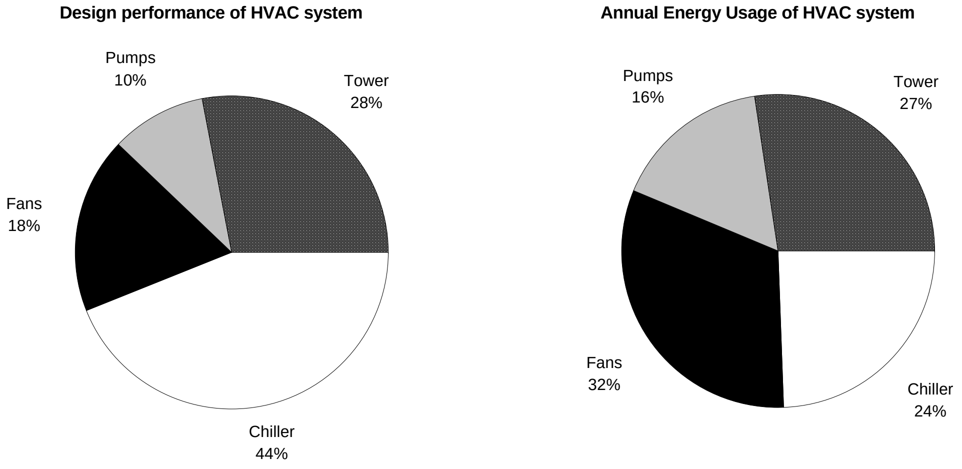

Fig. 3 HVAC energy consumption breakdown [4]

Basic Air-Conditioning System

An *air-conditioning cycle* comprises several air-conditioning processes that are connected in a sequential order. An air-conditioning cycle determines the operating performance of the air system in an air-conditioning system. The *working substance* to condition air may be chilled or hot water, refrigerant, desiccant, etc. Psychrometric analysis of an air-conditioning cycle is an important tool in determining its operating characteristics and the state of moist air at various system components, including the volume flow rate of supply air, the coil's load, and the humidifying and dehumidifying capacity.

Fig. 4 shows the schematic diagram of an air-conditioning plant. The majority of the air is drawn from the space, mixed with outside ventilation air and then conditioned before being blown back into the space.

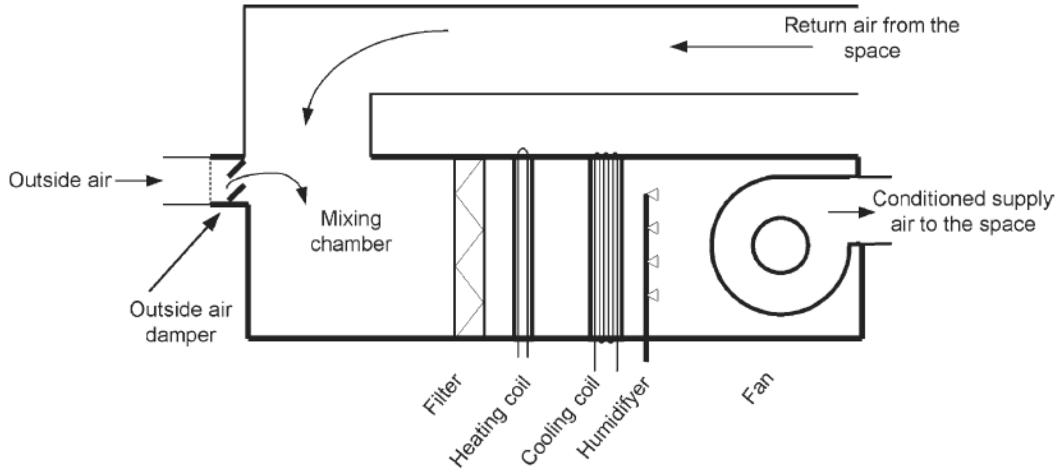

Fig. 4 Schematic of a typical HVAC system

The components, from left to right, are:

- *Outside Air Damper*, which closes off the outside air intake when the system is switched off. The damper can be on a spring return with a motor to drive it open; then it will automatically close on power failure. On many systems there will be a metal mesh screen located upstream of the filter, to prevent birds and small animals from entering, and to catch larger items such as leaves and pieces of paper.
- *Mixing chamber*, where return air from the space is mixed with the outside ventilation air.
- *Filter*, which cleans the air by removing solid airborne contaminants (dirt). The filter is positioned so that it cleans the return air and the ventilation air. The filter is also positioned upstream of any heating or cooling coils, to keep the coils clean. This is particularly important for the cooling coil, because the coil is wet with condensation when it is cooling.
- *Heating coil*, which raises the air temperature to the required supply temperature.
- *Cooling coil*, which provides cooling and dehumidification. A thermostat mounted in the space will normally control this coil.
- *Humidifier*, which adds moisture, and which is usually controlled by a humidistat in the space.
- *Fan*, to draw the air through the resistance of the system and blow it into the space.

The air-conditioning system considered so far provides a single source of air with uniform temperature to the entire space, controlled by one space thermostat and one space humidistat. However, in many buildings there is a variety of spaces with different users and varying thermal loads. These varying loads may be due to different inside uses of the spaces, or due to changes in cooling loads because the sun shines into some spaces and not others. Thus our simple system, which supplies a single source of heating or cooling, must be modified to provide independent, variable cooling or heating to each space.

This need for zoning leads us to the four broad categories of air-conditioning systems, and consideration of how each can provide zoned cooling and heating. The four systems are:

All-air systems

All-air systems provide air conditioning by using a tempered flow of air to the spaces. These all-air systems need substantial space for ducting the air to each zone. To change the heating or cooling capacity of the air supply to one zone, the system must either alter the supply temperature or alter the flow, to that zone.

The simplest, and least energy efficient system, is the constant volume reheat system. Let us assume that the main air system provides air that is cool enough to satisfy all possible cooling loads, and that there is a heater in the duct to each zone. A zone thermostat can then control the heater to maintain the desired zone set-point-temperature. The system, shown in Fig. 5, is called a *reheat system*, since the cool air is reheated as necessary to maintain zone temperature.

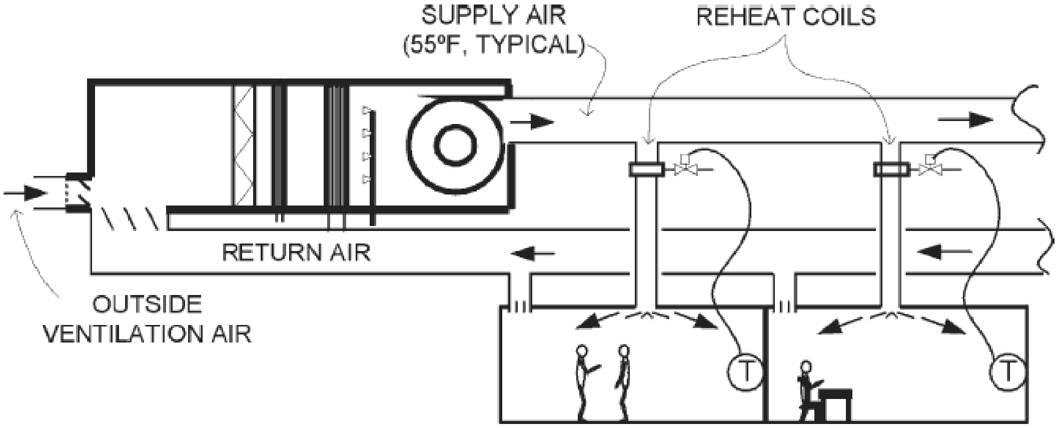

Fig. 5 Reheat System

Variable Air Volume (VAV) System: Fig. 6 illustrates another zoned system, called a Variable Air Volume system, VAV system, because it varies the volume of air supplied to each zone. Variable Air Volume systems are more energy efficient than the reheat systems. Again, assume that the basic system provides air that is cool enough to satisfy all possible cooling loads. In zones that require only cooling, the duct to each zone can be fitted with a control damper that the airflow to maintain the desired temperature.

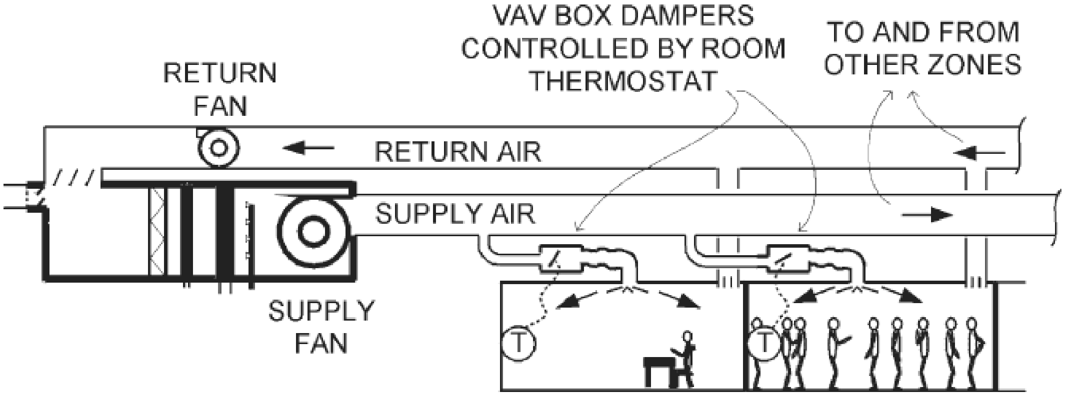

Fig. 6 Variable Air Volume (VAV) System

Air-and-water systems

Another group of systems, air-and-water systems, provide all the primary ventilation air from a central system, but local units provide additional conditioning. The primary ventilation system also provides most, or all, of the humidity control by conditioning the ventilation air. The local units are usually supplied with hot or chilled water. These systems are particularly effective in perimeter spaces, where high heating and cooling loads occur.

All-water systems

When the ventilation is provided through natural ventilation, by opening windows, or other means, there is no need to duct ventilation air to the zones from a central plant. This allows all processes other than ventilation to be provided by local equipment supplied with hot and chilled water from a central plant.

Unitary, refrigerant-based systems

The final type of system uses local refrigeration equipment and heaters to provide air conditioning. The window air-conditioner is the simplest example of this type of system (Fig. 7). In these systems, ventilation air may be brought in by the unit, by opening windows, or from a central ventilation air system. The unitary system has local refrigerant-based cooling. In comparison, the other types of systems use a central refrigeration unit to either cool the air-conditioning airflow or to chill water for circulation to local cooling units.

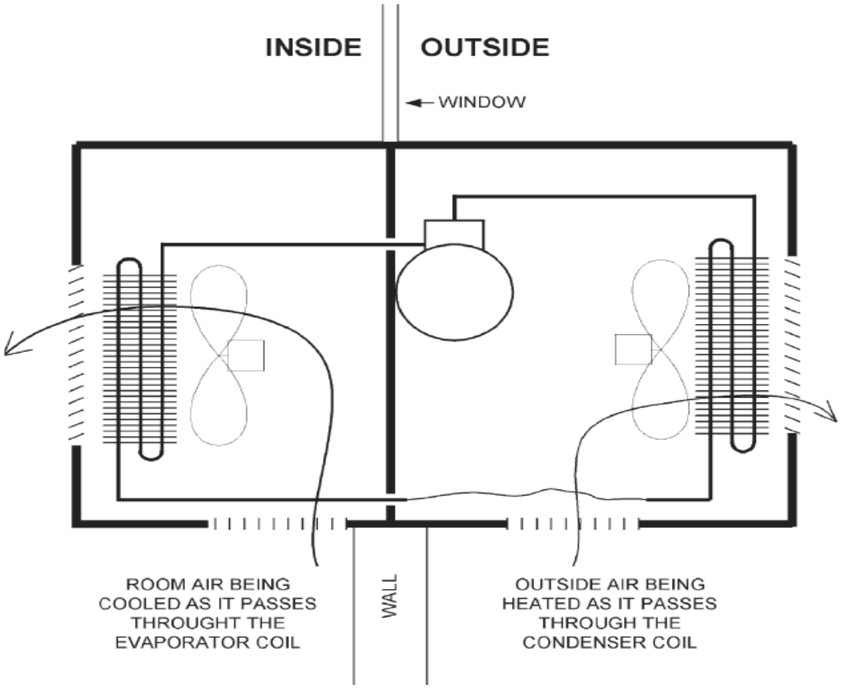

Fig. 7 Window Air Conditioner

Thermal Comfort and Indoor Design Criteria

“Provide a comfortable environment for the occupants” sounds like a simple objective, until you start to consider the variety of factors that influence the comfort of an individual. Fig. 8 is a simplified diagram of the three main groups of factors that affect comfort. *Indoor design criteria*, such as space temperature, humidity, and air cleanliness, specify the requirements for the indoor environment as well as the quality of an air-conditioning or HVAC&R project.

The human body requires energy for physical and mental activity. This energy comes from the oxidation of food. The rate of heat release from the oxidation process is called the *metabolic rat*e, expressed in met (1 met = 58.24 W/m^2). The metabolic rate depends mainly on the intensity of the physical activity of the human body (Table 1). Heat is released from the human body by two means: *sensible heat exchange* and *evaporative heat los*s. Experience and experiments all show that there is thermal comfort only under these conditions:

- Heat transfer from the human body to the surrounding environment causes a steady state of thermal equilibrium; that is, there is no heat storage in the body core and skin surface.
- Evaporative loss or regulatory sweating is maintained at a low level.

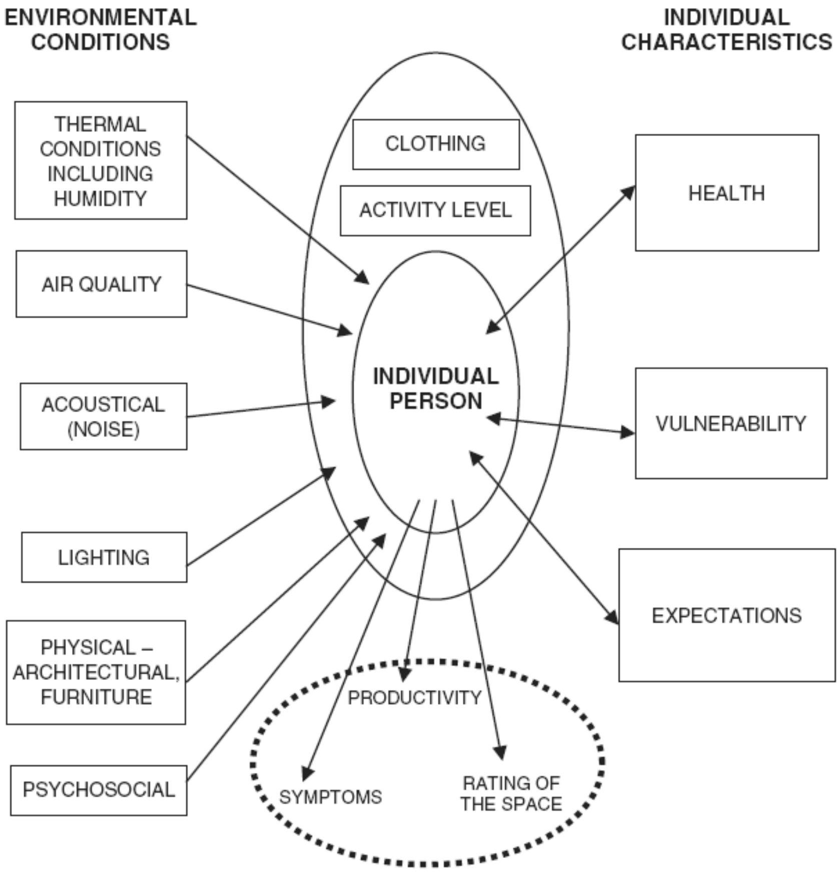

Fig. 8 Factors affecting thermal comfort

Table 1 Metabolic rates of various activities (based on ASHRAE [5-7]

Activity	**M, met**
Sleeping	0.7
Seated, quiet	1.0
Standing, relaxed	1.2
Light activity, standing (shopping, lab, light industry)	1.6
Medium activity, standing (shop assistant, domestic work, machine work)	2.0
Heavy activity (heavy machine work, garage work)	3.0

The physiological and environmental factors that affect the thermal comfort of the occupants in an air-conditioned space are mainly:

1. *Metabolic rate M* determines the amount of heat that must be released from the human body.
2. *Indoor air temperature* and *mean radiant temperature.*
3. *Relative humidity* of the indoor air, in %, which is the primary factor that influences evaporative heat loss.
4. *Air velocity* of the indoor air, which affects the heat transfer coefficients and therefore the sensible heat exchange and evaporative loss.

5. *Clothing insulation*, in clo (1 clo = 0.16 m^2 $^oC/W$), affects the sensible heat loss. Clothing insulation for occupants is typically 0.6 clo in summer and 0.8 to 1.2 clo in winter.

Indoor Design Temperatures for Comfort Conditioning

According to ANSI/ASHRAE Standard 55-1992 [5], and ASHRAE/IES 90.1-1999 [6], the following indoor design temperature and air speed apply for comfort air conditioning when the activity level is 1.2 met, there is a relative humidity of 50% in the summer, mean air speed is less than 0.15 m/s:

	Typical clothing insulation, clo	**Optimum operative temperature**	**Indoor design temperature range**
Winter	0.9	22^{o}C	20-23.5^{o}C
Summer	0.5	24.5^{o}C	23.5-26^{o}C

Indoor Design Humidity for Comfort Conditioning

For comfort air conditioning, the recommended indoor relative humidity levels are as follows:

	Relative humidity, %
Summer	**30-65**
Winter	
Commercial and public buildings	20-60
Health care buildings	30-60

Outdoor Air Requirement for Occupants

For both comfort and process air conditioning systems, outdoor air is required to do the following:

- To meet metabolic requirements of the occupants
- To dilute the indoor air contaminants, odors, and pollutants to maintain an acceptable indoor air quality
- To support any combustion process or replace the amount of exhaust air required in laboratories, manufacturing processes, or restrooms
- To provide makeup for the amount of exfiltrated air required when a positive pressure is to be maintained in a conditioned space.

Some of the outdoor air requirements for ventilation, often called the ventilation rate, specified in ASHRAE Standard 62-1999 are indicated in Table 2.

Table 2 Outdoor air requirements recommended by ASHRAE

Application	**Liter/s per person**
Hotels, conference rooms, offices	9.4
Classroom, theaters, auditoriums	7.0
Hospital patient rooms	11.8

Refrigeration Equipment

A *refrigeration system* is a combination of components, equipment, and piping, connected in a sequential order to produce the refrigeration effect. Refrigeration systems that provide cooling for air-conditioning are classified mainly into the following categories:

1. *Vapor compression systems.* In these systems, a compressor(s) compresses the refrigerant to a higher pressure and temperature from an evaporated vapor at low pressure and temperature. The compressed refrigerant is condensed into liquid form by releasing the latent heat of condensation to the condenser water. Liquid refrigerant is then throttled to a low-pressure, low-temperature vapor, producing the refrigeration effect during evaporation. Vapor compression is often called *mechanical refrigeratio*n, that is, refrigeration by mechanical compression.
2. *Absorption system*s. In an absorption system, the refrigeration effect is produced by means of thermal energy input. After liquid refrigerant produces refrigeration during evaporation at very low pressure, the vapor is absorbed by an aqueous absorbent. The solution is heated by a direct-fired gas furnace or waste heat, and the refrigerant is again vaporized and then condensed into liquid form. The liquid refrigerant is throttled to a very low pressure and is ready to produce the refrigeration effect again.

The domestic refrigerator and most other refrigeration systems use the same basic process of vapor compression and expansion. The vapor compression refrigeration system comprises four components: compressor, condenser, expansion valve, and evaporator. Fig. 9 shows the arrangement.

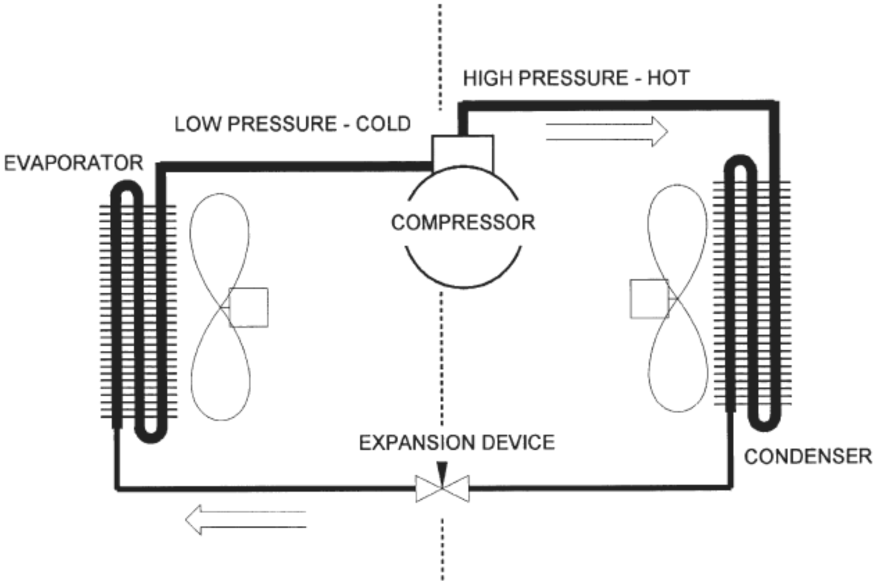

Fig. 9 Basic Vapor Compression Refrigeration Cycle

1. <u>*Compressor*</u> which compresses refrigerant vapor to a high pressure, making it hot in the process.
2. <u>*Condenser*</u> in which air or water cooling reduces the temperature of the refrigerant sufficiently to cause it to condense into liquid refrigerant and give up its latent heat of evaporation. Latent heat of evaporation is the heat required to convert a liquid to a vapor at a particular temperature and pressure and is the heat released when a vapor condenses at a particular temperature and pressure.

3. *Expansion valve* which allows a controlled amount of the liquid refrigerant to flow through into the low-pressure section of the circuit.
4. *Evaporator* in which air or water heats the liquid refrigerant so that it evaporates (boils) back into a vapor as it absorbs its latent heat of evaporation.

Typical energy consumption of various components of a vapor compression type screw chiller and a vapor absorption chiller is presented in Table 3. According to ARI Standards 550 [8] and 560 [9], respectively for vapor compression and vapor absorption chillers, chillers are rated under slightly different conditions and these are presented in Table 4.

Table 3 Typical energy consumption of components of 100RT chillers

Description	**Screw Chiller (kW)**	**Absorption Chiller (kW)**
Chiller (100RT)	60	4.5
Chilled water pump	13.5	13.5
Condenser water pump	17.5	26.5
Cooling tower	10.5	13.5
AHU/FCU/Control unit	25.5	25.5
Total energy demand	127	83.5
Total gas demand	Nil	30 Nm^3/hr

Table 4 Standard rating conditions for chillers

	Vapor Compression System	**Vapor Absorption System**
Leaving chilled water temperature	6.7^oC	6.7^oC
Chilled water flow rate	2.4 gpm/ton (0.043L/s.kW)	2.4 gpm/ton (0.043L/s.kW)
Entering cooling water temperature	29.4^oC	29.4^oC
Cooling water flow rate	3.0 gpm/ton (0.054L/s.kW)	4.4 gpm/ton (0.079L/s.kW)
Fouling factor	0.000044 m^2.C/W	0.000044 m^2.C/W

Energy Use Indices

According to ASHRAE/IESNA Standard 90.1-1999 [6], the following are the current energy use indices for refrigeration compressors, packaged units, heat pumps, and chillers:

1. *Coefficient of Performance (COP)* is the ratio of cooling capacity in kW to the total power input in kW, at any given set of rating conditions.

$$COP = \frac{kW\ refrigeration\ effect}{kW\ input}$$

2. *Energy Efficiency Ratio (EER)* is defined as the ratio of net cooling capacity of a refrigeration compressor, a packaged unit, or other device, in BTU/h, to the electric power input to that device, in W, under designated operating conditions.

$$EER = \frac{BTU/h\ refrigeration\ effect}{W\ input}$$

3. <u>*KW/ton*</u> indicates the electric power consumption of a refrigerating compressor per ton of refrigeration effect.

$$kW/ton = \frac{kW\ input}{ton\ refigeration\ effect}$$

The following are the EERs indicating the energy use of a hermetic refrigeration compressor and motor, and the equivalent COP and kW/ton values:

EER	**COP**	**KW/ton**
6	1.76	2.0
8	2.34	1.5
10	2.93	1.2
12	3.56	1.0
15	4.39	0.8
20	5.86	0.6
30	8.89	0.4

<u>*Integrated Part Load Value (IPLV)*</u> is a single index of merit that is based on part-load EER or COP. It expresses part-load efficiency for refrigeration compressors, packaged units, and heat pumps based on the weighted operation at various load capacities.

$$IPLV = 0.01A + 0.42B + 0.45C + 0.12D$$

where,

A = EER or COP at 100% capacity
B = EER or COP at 75% capacity
C = EER or COP at 50% capacity
D = EER or COP at 25% capacity

ASHRAE Standard 90.1-1999 mandates the minimum efficiency requirements for chillers and these values are reported in Tables 5 and 6, for vapor compression and vapor absorption systems, respectively.

Table 5 Minimum efficiency requirements of vapor compression systems

Type	**Size Category**	**Minimum Efficiency**	
		COP	**IPLV**
Air cooled, with condenser	< 150 tons	2.7	2.8
	≥ 150 tons	2.5	2.5
Air cooled, without condenser	All capacities	3.1	3.2
Water cooled, positive displacement (reciprocating)	All capacities	3.8	3.9

Water cooled, positive displacement (screw and scrolls)	< 150 tons	3.8	3.9
	≥ 150 tons and < 300 tons	4.2	4.5
	≥ 300 tons	5.2	5.3
Water cooled, centrifugal	< 150 tons	3.8	3.9
	≥ 150 tons and < 300 tons	4.2	4.5
	≥ 300 tons	5.2	5.3

Table 6 Minimum efficiency requirements of vapor absorption systems

Type	**Minimum Efficiency**	
	COP	**IPLV**
Air cooled, single effect	0.48	-
Water cooled, single effect	0.6	-
Double effect, indirect fired	0.95	1.0
Double effect, direct fired	0.95	1.0

Chiller capacity and efficiency are profoundly affected by the evaporator and condensing temperatures. Shown in Figs. 10 and 11 are the refrigeration effect and COP of a basic vapor compression refrigeration system. Both of these values are found to be affected by the variation of evaporator temperature and condensing temperature, and necessitates the optimum use of these two temperatures.

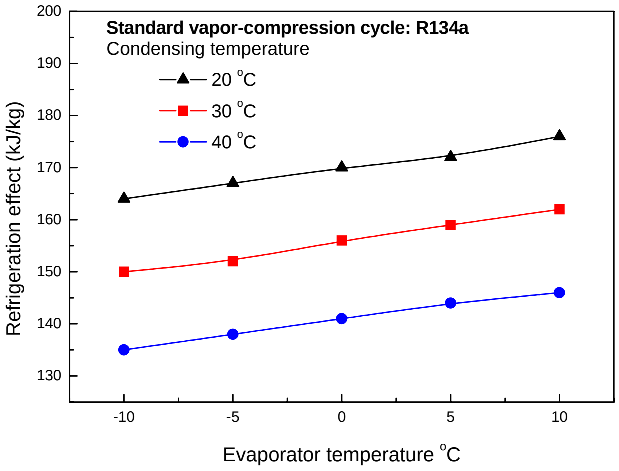

Fig. 10 Refrigeration effect of a vapor compression system

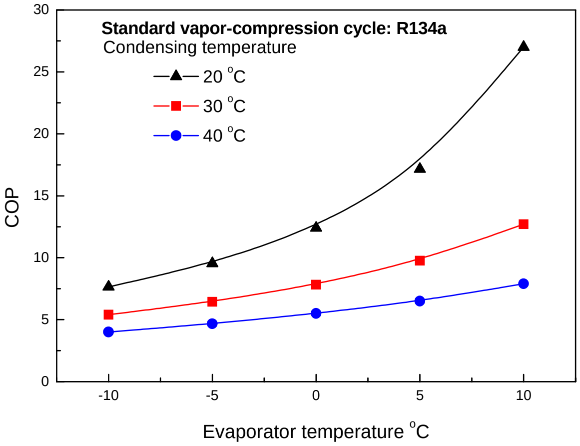

Fig. 11 COP of a vapor compression system

Air-Conditioning Project Development and System Design

The goal of an air-conditioning/HVAC&R system is to provide a healthy and comfortable indoor environment with acceptable indoor air quality, while being energy efficient and cost effective. ASHRAE Standard 62-2001 defines *acceptable indoor air quality* as “air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction.”

The basic steps in the development and use of an air-conditioning project are design, installation, commissioning, operation, and maintenance. There are two types of air-conditioning projects: *design-bid* and *design*-build. A design-bid project separates the design (engineering consultant) and installation (contractors) responsibilities. In a design-build project, the design is also done by the installation contractor. A design-build project is usually a small project or a project having insufficient time to go through normal bidding procedures.

Mechanical Engineer’s Responsibilities

The normal procedure in a design-bid construction project and the mechanical engineer’s responsibilities are

1. Initiation of a project by owner or developer
2. Organizing a design team
3. Determining the design criteria and indoor environmental parameters
4. Calculation of cooling and heating loads
5. Selection of systems, subsystems, and their components
6. Preparation of schematic layouts; sizing of piping and ductwork
7. Preparation of contract documents: drawings and specifications
8. Competitive bidings by various contractors; evaluation of bids; negotiations and modifications
9. Advice on awarding of contract
10. Monitoring, supervision, and inspection of installation; reviewing shop drawings
11. Supervision of commissioning

12. Modification of drawings to the as-built condition; preparation of the operation and maintenance manual
13. Handing over to the property management for operation

Codes and Standards

Codes are federal, state, or city laws that require the designer to perform the design without violating people's (including occupants and the public) safety and welfare. Federal and local codes must be followed. The designer should be thoroughly familiar with relevant codes. HVAC&R design codes are definitive concerning structural and electrical safety, fire prevention and protection (particularly for gas-or oil-fired systems), environmental concerns, indoor air quality, and energy conservation.

Conformance with *ASHRAE Standards* is voluntary. However, for design criteria or performance that has not been covered in the codes, whether the ASHRAE Standard is followed or violated is the vital criterion, as was the case in a recent indoor air quality lawsuit against a designer and contractor. For the purpose of performing an effective, energy-efficient, safe, and cost-effective air-conditioning system design, the following ASHRAE and ARI Standards should be referred to from time to time:

- ASHRAE/IES Standard 90.1-1999, Energy Standard for Buildings Except Low-Rise Residential Buildings
- ANSI/ASHRAE Standard 62-2001, Ventilation for Acceptable Indoor Air Quality
- ANSI/ASHRAE Standard 55-1992, Thermal Environmental Conditions for Human Occupancy
- ASHRAE Standard 15-1992, Safety Code for Mechanical Refrigeration
- ARI Standard 550/590, Water Chilling Packages Using the Vapor Compression Cycle.
- ARI Standard 560, Absorption Water Chilling and Water Heating Packages.
- ARI Standard 440, Room Fan-Coils
- ANSI/ARI Standard 430, Central Station Air-Handling Units.

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[7] ANSI/ASHRAE Standard 55 (1992), Thermal Environmental Conditions for Human Occupancy
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