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HVAC Design

Fundamentals of System Selection, Sizing, and Design

by

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Introduction

This course in the fundamentals of HVAC system selection, sizing, and design will benefit design professionals including engineers, architects, and designers, as well as those involved in facility management and maintenance. Upon completion of this course, you will have a better understanding of the basic principles involved in HVAC system selection, sizing, and design.

HVAC System Types

There are many different types of HVAC (Heating, Ventilating, and Air-Conditioning) systems including direct expansion (DX) packaged systems (straight cool and heat pumps); chilled water systems (air-cooled and water-cooled); constant volume and variable air volume systems; computer room units (CRU's); packaged terminal air conditioners (PTAC's); ground-source heat pumps; heating systems utilizing electricity, gas, hot water, and steam; evaporative cooling systems; and heating/ventilating-only systems. What follows is a description of these different types of HVAC systems along with the advantages and disadvantages inherent with each type of system.

Direct expansion (DX) packaged systems provide cooling using the basic refrigeration cycle. The major components of a DX system are the compressor, the condenser, the evaporator, and the evaporator fan. Refrigerant gas is compressed in the compressor, condensed to a liquid in the condenser, provides cooling as it expands back into a gas through the expansion valve at the evaporator, then returns to the compressor where the cycle begins again.

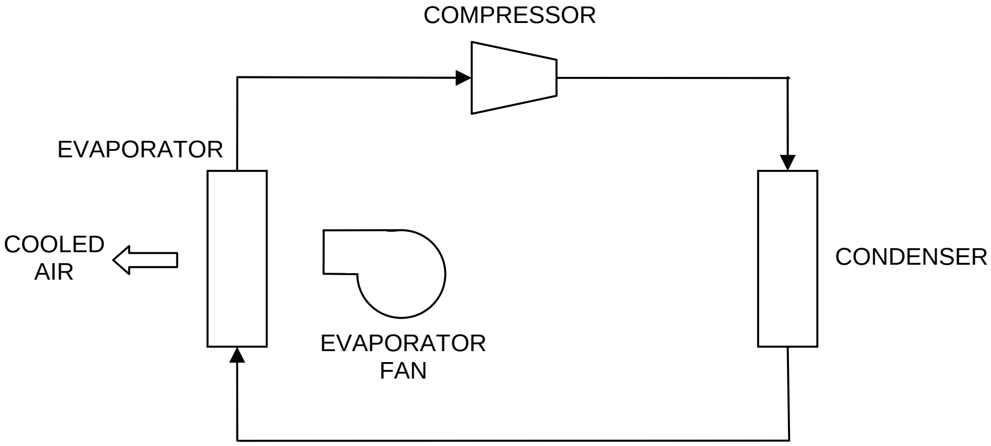

Diagram 1 – Basic Refrigeration Cycle

The evaporator fan serves to move the airstream across the evaporator coil and into the conditioned space. All of the DX system components can be contained in one unit or in two separate units. Typically the condenser for a DX system must be installed outdoors in order to reject heat as part of the refrigeration cycle. Therefore a DX system which is all in one unit must be installed outdoors. These units are typically located on the roof, hence the name Rooftop Unit (RTU). A DX system separated into two units is referred to as a split system. The Air-Handling Unit (AHU) contains the fan and evaporator and is typically installed indoors. The Condensing Unit (CU) contains the compressor and condenser, therefore it must be installed outdoors. A variation of the DX system is a heat pump, which has the ability to operate the refrigeration cycle in reverse to provide heating in the winter. The primary advantage of a DX system is reduced first cost. Two disadvantages are less energy efficiency (typically 1.5 KW/ton) and reduced service life (15 years). A heat pump is more costly than a straight cool unit in terms of first cost, but is more energy efficient.

Chilled water systems also use the basic refrigeration cycle but instead of cooling the air directly, chilled water systems cool water which in turn is used to cool the air. The condenser side of a chilled water system can be either air-cooled or water-cooled. Air-cooled chillers must be located outdoors in order for the condenser to reject heat to the outdoors. Water-cooled chillers are located indoors and their condensers reject heat via a separate water loop which circulates water through a cooling tower located outdoors. In a chilled water system, the chilled water is distributed by a pump through supply and return piping. Chilled water is piped to each AHU where the chilled water cools the air. The main components of an AHU consist of a cooling coil and a supply fan. Chilled water flows though the cooling coil and the supply fan provides the motive force to move the air across the coil and into the conditioned space. The primary advantages of a chilled water system are increased energy efficiency (0.5 KW/ton for a water-cooled chiller) and increased service life (20 – 23 years). The main disadvantages are higher first costs and increased maintenance costs. Air-cooled chilled water systems are less costly in terms of first costs than water-cooled systems, but they are less energy efficient (1.0 KW/ton).

A Variable Air Volume (VAV) system is a type of air distribution system which varies the volume of conditioned air delivered to the space. The volume of air delivered is based on the space conditions as sensed by a temperature sensor. Any system which is not a VAV system is known as a constant volume system. Constant volume systems provide a constant volume of conditioned air and match the heating/cooling system output to the load by varying the temperature of the supply air. VAV systems maintain a constant supply air temperature and match the heating/cooling system output to the load by varying the volume of the supply air.

VAV systems conserve energy due to the fact that as the volume of supply air is reduced, the energy required to operate the supply fan is reduced. Areas with similar thermal characteristics are grouped together into zones, each of which is served by a single VAV terminal. A typical VAV system has numerous VAV zones. Each VAV terminal varies the volume of air in response to its own temperature sensor located somewhere in the zone. A VAV system provides better occupant comfort because where a constant volume system only has one thermostat for the entire conditioned area, VAV systems have numerous temperature sensors located throughout the conditioned area. VAV systems offer the advantages of increased occupant comfort and increased energy efficiency. The disadvantage of a VAV system is increased first cost.

Computer Room Units (CRU's) are systems specifically designed to handle the high sensible cooling load associated with a computer room. Cooling loads can be broken down into two components; sensible and latent. The sensible component is the load associated with lowering the drybulb temperature; i.e., heat that can be measured with a thermometer. The latent component is the load associated with reducing the moisture content of the air; e.g., moisture entrained in humid outdoor air or moisture given off by people. Typical air-conditioning equipment is designed to handle cooling loads which are approximately 70% sensible. Computer room units are designed to handle cooling loads which are up to 100% sensible. CRU's are also typically provided with the controls and equipment required to maintain both the upper and lower relative humidity conditions within prescribed limits. CRU's offer the advantage of better control for computer room environments; the disadvantage is increased first cost.

Packaged Terminal Air Conditioners (PTAC's) are unitary DX cooling and electric heating units which are designed for through-wall installation. PTAC's are commonly used in hotel guest rooms. The advantage of PTAC's is reduced first cost, the disadvantage is decreased energy efficiency.

Ground-source heat pumps (also known as geo-thermal systems) are similar to DX heat pumps with one exception: instead of using an air-cooled condenser to exchange heat with the outdoors, ground-source heat pumps utilize water circulated through underground pipes to exchange heat with the outdoors. Six feet underground, the temperature varies between 45˚F - 75˚F depending on the locale and the season. Buried pipes at this level allow the mechanical equipment to exchange heat with the earth. During the summer, a ground-source heat pump rejects heat to the earth through the underground pipes. During the winter, the refrigeration cycle is reversed and heat is collected from the underground pipes. The primary advantage of ground-source heat pumps is increased energy efficiency; the main disadvantage is higher first cost.

In much the same way as a cooling source for a system can be located within a unit like with a DX system, or remotely-located like with a chilled water system, heating systems can either be located within a unit or remotely-located. Electric and gas heaters are two examples of systems where heat is located in the unit. Steam and hot water systems are two examples of remotely-located heating. Electric heaters produce heat by passing a current through an electric resistance element. Gas heaters burn either natural gas or liquefied petroleum gas in a burner enclosure vented to an outdoor flue. A hot water system consists of a central boiler with heating water pumped to mechanical units through supply and return piping. A steam system consists of a central steam boiler with steam supplied to mechanical units through pressurized steam headers. Condensate (condensed steam) is returned back to the boiler though condensate piping via condensate return pumps which can be steam-powered or electric. Boilers burn natural gas or fuel oil and can be supplied as dual fuel units which have the ability to burn either type of fuel in the same unit for increased operational flexibility. In VAV systems, electric heat or hot water heat is often provided to the VAV terminals for increased temperature control. The advantage of electric heat is lower first cost; the disadvantage is higher energy costs. The advantage of gas heat is lower energy costs; one disadvantage can be increased first costs. The advantage of a central boiler heating system is lower energy costs; the disadvantages are higher first costs and increased maintenance costs.

Evaporative coolers provide cooling by evaporating water into the supply airstream. The evaporating water has a cooling effect on the supply airstream, but it also increases the humidity of the supply airstream. The major components of an evaporative cooler consist of wetted media, a water recirculation pump, and a supply fan. A variation on evaporative cooling is indirect evaporative cooling where the supply airstream is one step removed from the evaporative cooling process thereby preventing the supply airstream from increasing in humidity. In an indirect evaporative cooler, the supply airstream passes over a heat exchanger which was cooled on the other side by the evaporative cooling process. Part of the comfort cooling process is the removal of moisture from the supply airstream. The supply airstream must be cooled below its dewpoint temperature in order for moisture to condense out of the airstream at the cooling coil which serves to dehumidify the supply air. The removal of moisture in the supply airstream dehumidifies the occupied space and helps to make the occupants feel more comfortable. Since direct evaporative cooling adds moisture to the airstream rather than removing it, direct evaporative cooling is not typically used for air-conditioning applications. Indirect evaporative cooling is not capable of suppressing the supply airstream below its dewpoint temperature, so likewise indirect evaporative cooling is not typically used for air-conditioning applications. Evaporative cooling is commonly used in non-critical applications where some amount of cooling is desired, but conventional air-conditioning is deemed unwarranted. The advantage of evaporative cooling is lower first costs and lower energy costs. The disadvantage is the lack of complete comfort air-conditioning.

Heating/ventilating-only systems can include fans, louvers, gravity ventilators, unit heaters, air rotation units, and make-up air units. Fans supply outdoor air or they can be used to exhaust building air. Fans can be mounted on rooftops or located in exterior walls. The major components of a fan include the fan blades or wheel, the motor, and the fan housing. Louvers are installed in exterior walls and can be used to allow outdoor air to enter the building or relieve building air to the outdoors. Louvers allow the passage of air while preventing the entry of rain, birds, insects, or other undesirable elements. Louvers consist of angled blades with screens mounted in a wall frame. Gravity ventilators allow the passage of air into or out of a building much like wall louvers do, except gravity ventilators are installed on the roof. Ventilation is typically designed to meet a prescribed air-change per hour rate (ACH). ACH is defined as the number of times per hour that the volume of air in a space is changed (replaced) with fresh air. Unit heaters and air rotation units are mounted inside a building and can be electric, gas, hot water, or steam. Unit heaters are typically provided in smaller sizes and are wall-mounted or hung from the building steel. Air rotation units are larger than unit heaters and are typically floor-mounted. The major components of a unit heater or air rotation units include a heating coil, fan, and housing. Make-up air units provide outdoor air which is heated in the unit and can be electric, gas, hot water, or steam. Make-up air units can be mounted on the roof or can be located inside the building with an outside air intake hood installed through an exterior wall. The advantage of heating/ventilating-only systems is lower first costs and lower energy costs. The disadvantages include increased noise and the lack of complete comfort air-conditioning.

HVAC System Selection

There are a myriad of available HVAC systems which can be applied to any given project. In a perfect world unencumbered by budgets or schedules, every project would begin with an exhaustive study of each type of HVAC system. Teams of research scientists would be consulted in order to evaluate every possible system type in terms of equipment first cost, energy costs, environmental impact, equipment service life, constructability, maintenance costs, occupant comfort, acoustics, and aesthetics. The system would be selected based on the best overall fit for the specific set of project circumstances. In the real world, very few projects have the time or money for that kind of study. The HVAC system is usually selected rather quickly in order to move forward with the design to meet the always too-brief project design schedule. HVAC system selection is typically a product of the perceived expectations of the client together with general design guidelines and good engineering judgment.

The type of client is an important factor in choosing the appropriate HVAC system. Every client is unique and there are as many different variations in client expectations as there are clients. That being said, there are at least two major types of clients that are prevalent and worthy of discussion. The first type is a developer. The typical developer oversees a project from start to finish then sells the developed property for a profit. He or she buys a tract of land, secures the necessary funding and public approvals to construct a building on it, hires a team of consultants to design the building, hires a contractor to built it, then turns around and sells it. Developers typically borrow a significant amount of money for their developments, so they want to get the building completed as inexpensively as possible. As a result, the most important thing to a developer is first cost. The second type of client is an owner. Large manufacturing corporations or university systems are two good examples of an owner type of client. An owner builds a facility and then lives with it for as long as it remains standing. Consequently, owners want HVAC systems which are both energy efficient and long-lived.

The size of a project is another key characteristic in determining the right HVAC system. Smaller projects are almost always designed using DX systems. The lower first cost and ease of maintenance inherent with DX systems lend themselves to smaller projects. As the project size increases above 100 tons in terms of cooling capacity, the energy saving benefits of a chilled water system begins to outweigh the first cost and maintenance savings of a DX system. In the 100 – 250 ton range, air-cooled chillers are commonly used. Projects over 250 tons in cooling capacity can justify the added cost of a water-cooled system due to the inherent energy savings. Water-cooled chilled water systems require more sophisticated maintenance for such elements as the electric water chillers, pumps, refrigerant management, cooling towers, and water treatment. Consequently, some projects are not good candidates for water-cooled chillers regardless of the project size due to the maintenance issues or the need to locate the cooling tower outdoors.

The type of project also has a significant bearing on the HVAC system selection. The HVAC system for an office building will often be different than that for a retail store, which in turn will be different than that for a warehouse. Office buildings require a high degree of individual occupant comfort and as a result are almost always designed with VAV systems. Conversely, in a big box retail store, constant volume systems are a good application because the large, open stores have essentially the same thermal loading throughout. Constant volume systems are required on some applications due to the need for constant airflow. Manufacturing plants are good applications for evaporative cooling systems because the while a manufacturing plant needs some degree of cooling, the cost to fully air-condition such facilities may not be justified. Warehouses are almost always heated and ventilated unless the product requires air-conditioning or refrigeration. Some applications require a great deal of individual space flexibility or the ability to bill each space separately. These types of applications are well-suited for DX systems in each space which can easily be turned off when the space is not in use. Such applications would include K-12 school classrooms, retail strip malls, and hotel guest rooms. The selection of the type of heating system tends to follow the type of cooling system selected. For example, heating systems for DX units are typically localized in-unit electric or gas for constant volume systems, and electric heat in the VAV terminals for VAV systems. On projects with centralized cooling such as water- or air-cooled chillers, heating is often centralized. The centralized heating system married to a chilled water system will often be a hot water system which utilizes a hot water boiler. The use of steam heating systems is generally limited to projects which use steam elsewhere, such as a manufacturing plant.

The following table provides a comprehensive guide to HVAC system selection based on the principles outlined above. *Table 1* provides system selection guidelines for typical developer projects, and *Table 2* provides system selection guidelines for typical owner projects.

PROJECT TYPE	UNDER 100 TONS	100 - 250 TONS	OVER 250 TONS
TABLE 1: HVAC SYSTEM SELECTION GUIDE - DEVELOPER PROJECTS			
Medical Office Building	DX Rooftop VAV	DX Rooftop VAV	DX Rooftop VAV
Office Building	DX Rooftop VAV	Air-Cooled Chiller, VAV	Air-Cooled Chiller, VAV
Residential	DX Split System CV	N/A	N/A
Retail Strip Mall	DX Split System CV	N/A	N/A
TABLE 2: HVAC SYSTEM SELECTION GUIDE - OWNER PROJECTS			
Airport Terminal	DX Rooftop VAV	Air-Cooled Chiller, VAV	Water-Cooled Chiller, VAV
Apartment Units	DX Split System CV	N/A	N/A
Bank	DX Rooftop VAV	N/A	N/A
Church	DX Split System CV	Air-Cooled Chiller, VAV	Air-Cooled Chiller, VAV
Computer Room	Computer Room Unit	Computer Room Unit	Computer Room Unit
Courthouse Building	DX Rooftop VAV	Air-Cooled Chiller, VAV	Water-Cooled Chiller, VAV
Hospital	Air-Cooled Chiller, CV	Air-Cooled Chiller, CV	Water-Cooled Chiller, CV
Hotel Guest Rooms	PTAC	N/A	N/A
Jail	DX Rooftop CV	Air-Cooled Chiller, CV	Water-Cooled Chiller, CV
K-12 Classroom	DX CV	N/A	N/A
Laboratory Building	Air-Cooled Chiller, VAV	Air-Cooled Chiller, VAV	Water-Cooled Chiller, VAV
Library	DX Rooftop VAV	Air-Cooled Chiller, VAV	Water-Cooled Chiller, VAV
Manufacturing Plant	Evaporative Cooling	Evaporative Cooling	Evaporative Cooling
Police Station	DX Rooftop VAV	Air-Cooled Chiller, VAV	Water-Cooled Chiller, VAV
Restaurant	DX Rooftop VAV	Air-Cooled Chiller, VAV	Air-Cooled Chiller, VAV
Retail Big Box Store	DX Rooftop CV	DX Rooftop CV	DX Rooftop CV
Supermarket	DX Rooftop CV	DX Rooftop CV	DX Rooftop CV
Theater	DX Rooftop VAV	Air-Cooled Chiller, VAV	Air-Cooled Chiller, VAV
University Building	DX Rooftop VAV	Air-Cooled Chiller, VAV	Water-Cooled Chiller, VAV
Warehouse	Ventilation at 3 ACH	N/A	N/A

Abbreviations:

ACH – Air Changes per Hour
CV – Constant Volume
DX – Direct Expansion
VAV – Variable Air Volume

HVAC System Sizing

Proper HVAC system sizing is perhaps the most critically important aspect of HVAC design. If a cooling system is oversized it may not energize long enough to properly dehumidify the space which could result in serious humidity-related issues including mold and mildew. If a heating or cooling system is undersized, the system may not be able to maintain the required space conditions for much of the cooling or heating season. In either case, remedial action may be required and there may be liability on the part of the mechanical engineer. Remedies can run the gamut from the addition of supplemental HVAC equipment to complete system replacement. In cases of sick building syndrome, an owner may choose to pursue legal action against the engineer. Obviously it is better to avoid such costly problems by properly sizing the HVAC system to begin with using proven design techniques.

Every building is unique in terms of its size, building materials, and physical orientation. Sophisticated design software is required to analyze the building and properly size the HVAC equipment. Heating and cooling load calculations should be performed using computer programs such as *Trane Trace* or *Carrier HAP*. These load programs analyze each room in the building on an hour-by-hour basis in order to determine the heating and cooling peaks at the exact hour of the year in which they occur. For each room, the input requirements include information such as the floor area, roof area, wall area and orientation (north, south, east, or west), window area and orientation, number of people, lighting wattage, miscellaneous power, as well as the construction materials and characteristics of the roof, walls, and windows.

For VAV applications, the HVAC system designer must establish the zones. A zone, in HVAC vernacular, is an area identified by the HVAC designer which has similar space usage and similar thermal loading. Each zone is provided with a VAV terminal controlled by its own thermostat. In instances where a zone requires more supply air than can be provided by a single

VAV terminal, two or more VAV terminals are provided which are controlled by the same thermostat.

The load programs do an excellent job of performing the calculations that they were designed to do, but like all computer programs, garbage in equals garbage out. What follows are a few tips aimed at optimizing the program results for HVAC equipment sizing.

The load programs come with a means to allow the user to select the city in which the project is located. The city selection corresponds to hourly weather data built into the program. HVAC equipment must be sized for weather extremes, i.e., the equipment should have enough capacity to adequately cool on the hottest day and heat on the coldest night. In HVAC vernacular, these extremes are referred to as 'design days.' Once the city is selected, the programs allow the user to override the default value for both the heating and cooling design days. It is advisable to do so. If there is ever a question concerning the design, it is better to have based the design on recognized standards than to have based it on a default value in a computer program. The recognized standard for design day temperatures is the *Design Conditions for Selected Locations* table found in the *ASHRAE Fundamentals Handbook* (ASHRAE: American Society of Heating, Refrigerating, and Air Conditioning Engineers). Temperatures are listed in DB (drybulb) and WB (wetbulb). The drybulb temperature is the sensible temperature of the air and the wetbulb temperature is related to the amount of moisture in the air. The higher the wetbulb temperature (assuming constant drybulb temperature), the greater the amount of moisture in the air. The heating design day should be based on the 99% Heating DB and the cooling design day should be based on the 1% Cooling DB/WB. The percents refer to the number of hours that are expected to exceed the listed values. For example, the 99% Heating DB value means that according to ASHRAE, 99% of the hours of the year will be warmer than the listed value. Therefore, it follows that 87 hours of the year will be colder than the listed value:

365 days per year x 24 hours per day x 1% = 87 hours

The International Energy Conservation Code (IECC) requires that the HVAC load calculation indoor design temperatures can be no more than 72˚F for heating and no less than 75˚F for cooling (IECC ¶302.1). However, the code does not prescribe the outdoor design temperatures to be used in the calculations, therefore the designer has some degree of flexibility in that regard. Furthermore, ASHRAE cautions the designer in the use of the ASHRAE outdoor design conditions in its discussion on this subject by saying "*use judgment to ensure that results are consistent with expectations.*" (*2009 ASHRAE Fundamentals Handbook*, pg 18.3). Those 87 hours where the outdoor conditions are expected to exceed the listed design day values can be a cause for concern for the HVAC designer. It would not be unreasonable to add 3% to the 1% outdoor sensible cooling design DB and subtract 10˚F from the 99% outdoor heating design DB. For example, if the heating design day is listed at 32˚F and the cooling design day sensible temperature is listed at 94˚F, the program overrides for heating and cooling respectively would be 22˚F and 97˚F. Another consideration with regard to outdoor design temperatures which affects only the cooling load is the location of the ventilation outside air intake. RTU's draw their outside air from the rooftop which is measurably hotter in the summer than the ambient temperature due to the heat reflecting off the surface of the roof. It would not unreasonable to add 5˚F to the 1% outdoor sensible cooling design DB on projects with RTU's. In the example outline above, that would result in a program override for the outdoor sensible cooling design DB of 99˚F.

The design heating and cooling supply air temperatures in the load program are another area where it is advisable to override the default values. The design supply air temperature is the temperature at which air is supplied to the conditioned space from the mechanical system. The heating supply air temperature default of "*To Be Calculated*" should be changed to a value of at least 85˚F. Some designers use as much as 95˚F for the heating supply air temperature. If left to the program to calculate, the resulting heating supply air temperature might be 80˚F or lower. Given enough time, 80˚F supply air will eventually heat a space, but the occupants who feel cold to begin with will not appreciate 80˚F air blowing on their 98.6˚F skin. They want the air coming out of the supply diffusers to feel hot or at least warm. In order to avoid complaints, it is advisable to design the heating system to supply air at least 85˚F. Allowing the load program to use anything less will result in the program sizing the heating equipment with inadequate capacity to achieve this goal. The cooling supply air temperature default "*To Be Calculated*" should also be changed but for a different reason. If left to the program to calculate, it is not unusual to see cooling supply air temperatures as high 62˚F. In order to properly dehumidify the air, the cooling system must be capable of suppressing the supply air temperature below its dewpoint temperature. Therefore it is advisable to set the cooling supply air temperature in the load program to 55˚F in order to have the program properly size the cooling system.

Another important part of the load calculation design phase is to determine the required quantity of outside air. Outside air is required for ventilation and for make-up air. The outside air must be filtered and conditioned in the system before being introduced into the space as ventilation air. Outside air brought into the building through the HVAC systems represents a significant heating and cooling load on the mechanical equipment. The HVAC system designer must evaluate both the ventilation requirements and the make-up air requirements and use the greater of the two in order to satisfy both requirements.

Outside air for ventilation is required to be provided in code-prescribed quantities based on the space type and room area. The International Mechanical Code (IMC) is the applicable code in most (but not all) of the United States and is used elsewhere throughout the world. The approved method for calculating the amount of ventilation air for each space is given in IMC Section 403. IMC Equation 4-1 is used to determine the amount of outside air required for a system which serves various spaces with different ventilation rate requirements:

$$Y = X / (1 + X - Z) \qquad \text{(IMC Equation 4-1)}$$

where
$Y = V_{ot} / V_{st}$ = Corrected fraction of outdoor air in system supply.
$X = V_{on} / V_{st}$ = Uncorrected fraction of outdoor air in system supply.
$Z = V_{oc} / V_{sc}$ = Fraction of outdoor air in critical space. The critical space is that space with the greatest required fraction of outdoor air in the supply to this space.
V_{ot} = Corrected total outdoor airflow rate.
V_{st} = Total supply flow rate, i.e., the sum of all supply for all branches of the system.
V_{on} = Sum of outdoor airflow rates for all branches on system.
V_{oc} = Outdoor airflow rate required in critical spaces.
V_{sc} = Supply flow rate in critical space.

HVAC designers commonly use spreadsheets to perform and document the outside air calculations. Because IMC Equation 4-1 requires the supply air flow rate for each space to be entered as an input, the load calculations must be performed prior to performing the ventilation calculation.

The make-up air quantity must be determined in order to ensure that adequate make-up air is provided. All of the air that is exhausted from a building must be “made-up.” The make-up air must be filtered and conditioned in the heating and cooling system before being introduced into the space as make-up air. A good way to evaluate the required make-up air is to draw a simplified diagram of the air coming in and going out of the building. The diagram can be included as an airflow schematic on the construction drawings to help document the design intent. This is not rocket science, but it can get confusing when there are multiple units and sources of air entering and leaving the building. The following example illustrates a simple airflow diagram:

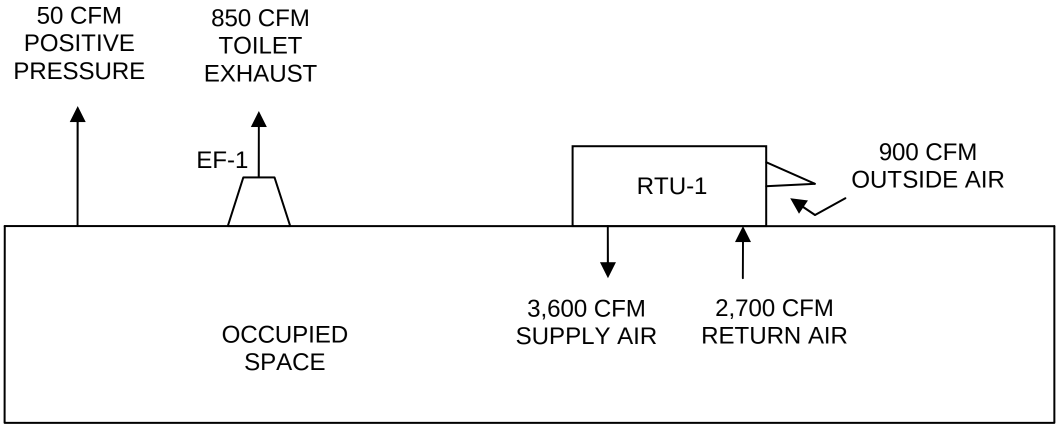

Diagram 2 – Simple Airflow Diagram

The procedure for determining the required make-up air is to start with the exhaust requirement and work backwards to arrive at the required make-up air quantity. In Diagram 2, the exhaust fan EF-1 is shown exhausting 850 CFM (Cubic Feet per Minute). Toilet exhaust rates are prescribed by code such as the IMC and are based on the quantity and type of plumbing fixtures. In order to prevent infiltration, the example shown is positively pressurized. Infiltration is the undesirable migration of air into a building which occurs in neutral or negatively pressurized buildings. Infiltration air enters the building through cracks and crevices in the building exterior. Positively pressurizing a building prevents infiltration and ensures that all of the outside air entering the building is properly filtered and conditioned in the HVAC systems. The 5% positive pressurization in Diagram 2 is calculated as follows: 1.05 x 850 CFM = 892.5 CFM, rounded to 900 CFM. 900 CFM – 850 CFM = 50 CFM positive pressure. In this example, the exhaust rate and positive pressurization value is all that is needed to calculate the required make-up air. EF-1 exhausts 850 CFM, 50 CFM is assigned to positive pressurization, therefore 900 CFM is the required amount of make-up air for rooftop unit RTU-1.

After the outside air for ventilation is calculated and the required make-up air quantity has been determined, the greater of the two values is used in the load calculations and scheduled on the drawings for outside air intake. The outside air is a unit load, not a room load, so while the outside air has a significant impact on unit capacity requirements, it has no effect on the room supply air rate calculated by the load program. Consequently, all of the outside air can be entered into one room in the program provided that the outside air CFM does not exceed the calculated room supply air CFM. If needed, the outside air quantity can be divided up over several rooms in the program if the outside air quantity exceeds the calculated room supply air. This shortcut puts the outside air load on the unit and saves time compared to entering a small portion of the outside air into each room.

The following summarizes the steps required to perform the HVAC load calculations with regard to the outside air quantity:

1. Perform the load calculations with no outside air.
2. Determine the code-required amount of outside air for ventilation.
3. Determine the required amount of outside air for make-up.
4. Compare the outside air for ventilation to the required make-up air and use the greater of the two values as the required outside air quantity.
5. Re-run the load calculations including the required outside air quantity.

HVAC System Design

After the HVAC systems have been sized and selected, the last (and most time-consuming) part of the overall process is the actual design of the HVAC systems. This stage involves code research, energy code calculations, locating the equipment, coordination with other design professionals, sizing and layout of all ductwork and piping, specifying all of the equipment and materials, defining the HVAC controls, and – the final product of the HVAC design – preparing the drawings and specifications.

At the outset of this process, some perspective is in order with regard to the final product. The drawings and specifications are the culmination of the design effort, and they generally serve at least five purposes. First, the drawings provide the client with a means to review and agree to the proposed design before it is built. Secondly, the drawings serve to document that all applicable building codes have been followed. The drawings are signed and sealed by the professional engineer in responsible charge of the design who is registered in the state in which the construction will take place. The drawings are submitted for approval to the Building Department where the construction will take place. Once approved, a building permit will be issued to authorize the start of construction. The third purpose that the drawings serve is to provide for competitive bidding. Contractors use the drawings to bid on the project and typically the lowest bidder is awarded the project. The fourth and main purpose of the drawings is to be used by the contractor to build the project. Finally, after the construction has been completed, the drawings serve as a record of what was built which can be used at a later date if the building is to be remodeled or expanded.

As a part of the design process, all applicable building codes must be reviewed in order to ensure that the proposed design will meet code. A call to the Building Department or a visit to the city's website will help determine which codes are enforced. Most of the requirements pertaining to HVAC are found in the Mechanical Code. However, additional HVAC-related requirements are found in the other codes such as the Energy Code, the Plumbing Code, the Architectural Building Code, the Gas Code, and the Electrical Code.

The HVAC design must comply with the Energy Code in force and many building departments require submittal of signed and sealed energy code calculations. A few states such as California and Florida have their own energy codes for which software may be purchased to demonstrate compliance. Most other states use the Department of Energy software program *Comcheck* which is available for free download at www.energycodes.gov/comcheck. Again, a call to the Building Department or a visit to their website will help determine the energy code submittal requirements.

The HVAC equipment selection is based on the chosen system type and the load calculations. The capacity of the equipment selected is generally the first available size greater than the capacity calculated by the load program. With regard to heating, the capacity selected is always greater than the calculated load because there is no such thing as too much heat. For example, if the calculated heating load were 18.1 KW (Kilowatts), a 20 KW heater would be selected. With regard to the cooling equipment, some degree of judgment is needed because too much cooling capacity is undesirable and can lead to humidity-related problems. While there are no specific rules, it is generally acceptable to select the next smaller unit size when the calculated cooling load is just slightly higher than a standard unit size. Conversely, when the calculated cooling load is appreciably higher than a standard unit size, the next greater standard unit size should be selected. For example, if the cooling load were calculated to be 10.2 tons, a 10 ton unit might be selected. If the cooling load were calculated to be 10.6 tons, then a 12.5 ton unit might be selected.

On projects large enough to justify chilled water and boiler systems, the chiller and boiler room equipment must be sized and selected. Chillers and boilers are sized to meet the sum total of the heating and cooling loads for the entire facility. Most load programs provide the flexibility to define the type of system and generate coincident peak capacity requirements for both the heating and cooling. In other words, chillers and boilers need not be sized for the total of every system peak, they only need to be sized to handle the maximum simultaneous peak. Sizing central systems in this way is commonly referred to as applying diversity. An easy way to think of diversity is to imagine the solar cooling load for a building which has both an eastern and western exposure. The sun rises in the east so the systems serving the eastern exposure may reach their peak at 10:00 am when the sun is shining directly into the east-facing windows. At that same point in time, the systems serving the western exposure may essentially be idling because they have little or no direct solar load. Similarly, at 4:00 pm when the sun is shining in the west-facing glass, the systems serving the western exposure may be peaking while the systems serving the eastern exposure have receded from their peak. The load programs analyze the building and determine the exact point at which the maximum simultaneous peak occurs so that central heating and cooling equipment can be properly sized.

Chiller/boiler plants are often designed with some degree of redundancy, meaning that if something fails the overall facility will still be functional. This matter should be discussed with the owner upfront since it has a significant impact on both project cost as well as functionality. On projects where the owner is not knowledgeable in such matters, good engineering judgment should be used. At one end of the spectrum, N+1 redundancy is applied for facilities which cannot tolerate any degradation or interruption of service. N+1 simply means that the number of chillers (and similarly the number of boilers) is chosen such that if one of them fails, 100% of the required capacity is still provided. For example, if the cooling load is determined to be 1,000 tons, N+1 redundancy would be achieved if (3) 500 ton chillers were provided. At the other end of the spectrum, no redundancy is provided. If something fails, the building shuts down until the failed component is repaired. In between those two extremes is the two-thirds approach. With the two-thirds approach, the capacity of each chiller (and similarly the capacity of each boiler) is chosen such that if one of them fails, 2/3 of the required capacity would still be provided. Using the same 1,000 ton example, 2/3 of the required capacity would still be provided if two 670 ton chillers were installed and one of them failed. With the two-thirds approach, the hope is that if one of the units fails, it will either a) not occur on a design day so that the load might possibly be fully met, or b) if it does occur on a design day, the occupants can suffer through on 2/3 capacity until the failed component is repaired.

Other ancillary HVAC equipment to be sized during the design phase include VAV terminals, fans, cooling towers, pumps, unit heaters, and make-up air units. VAV terminals are sized based on noise criteria and maximum cooling CFM. VAV terminals are typically oversized to avoid acoustical problems. Fans are sized based on the required CFM for the application and required static pressure. Fan static pressure requirements are determined by analyzing the connected ductwork. For projects with chilled water and boiler systems, cooling towers are selected to match the chiller requirements and circulation pumps are sized based on the required flow in Gallons Per Minute (GPM) and head. Pump head is analogous to fan static pressure in that it is the pressure output required to overcome the configuration and length of the piping system. Pump head is determined by analyzing the connected piping system. Projects with chiller rooms and boiler rooms require special heating and ventilation for those rooms in connection with the mechanical equipment. Chiller rooms require ventilation and refrigerant detection systems tied to emergency ventilation as prescribed by code. Boiler rooms require combustion air as prescribed by code. In colder climates, all chiller/boiler room ventilation air must be provided with adequate heat to prevent freezing conditions from occurring during the winter. One might think that the heat radiating from a boiler would be more than adequate to prevent freezing conditions inside the boiler room. However, the degree of insulation provided in modern boilers results in very little heat loss radiating into the room. The amount of combustion air can be significant, so sprinkler pipes can freeze in a boiler room if the combustion air is not heated or else directly ducted to the boilers. NFPA 13 (National Fire Protection Association) requires that all spaces with sprinkler piping must be maintained above 40˚F.

Another important part of the HVAC design process is the coordination of the mechanical design with the other design professionals. The project architect will need to agree on the proposed location for the HVAC equipment, as it can affect both the floor plan and building's overall appearance. Sight lines will be a source of concern for the architect when the HVAC designer wants to put mechanical equipment on the roof. The further the equipment is placed from the edge of the roof, the less likely it is that it will be seen from the ground. Space for mechanical rooms to house building-interior HVAC equipment must be negotiated with the architect early on in the project before the floor plans are fully developed. Chases for vertical ductwork and piping in multistory buildings must also be negotiated with the architect. The structural engineer will need to know the location, dimensions, and weight of all HVAC equipment in order to properly design the building structure. The electrical engineer needs to know the location and power requirements of all HVAC equipment. The plumbing designer will need to know condensate drain locations as well as the size and location of any domestic water requirements. Early in the mechanical design, the ductwork and piping are not yet designed. Therefore, estimates are made for fan static pressure and pump head in order to give horsepower (HP) estimates to the electrical engineer. Those values are refined later by calculations as the mechanical design progresses. Because so many other design disciplines provide support for the mechanical equipment, the HVAC design must be completed before the overall project deadline in order to give the other design disciplines adequate time to complete their work. Typically, preliminary equipment schedules and mechanical plans are issued at about the 30% design stage for initial discipline coordination. Coordination is an ongoing process up though 100% construction issue.

After the equipment has been sized and located on the drawings and that information has been shared with the rest of the design team, the HVAC design continues with equally important tasks that have less impact on the other design disciplines. The layout of the diffusers and ductwork might occur at this stage, as well as any piping design on those projects with heating and chilled water applications. Using the output from the load calculations, a design CFM is assigned to each space and shown on the drawings for each diffuser. One should note that there are certain conventions used in HVAC design and one of them is that design CFM values are rounded. This stems from the fact that all airflow rates shown on the drawings must be measured and documented by a Test & Balance contractor after the project is built. Typically, airflow rates measured to be within ±10% of the design values are acceptable. It follows then that depicting airflow rates accurate to within one CFM would appear out of place (and even amateurish). The degree to which the design CFM’s are rounded depends on the airflow rate, but as a general guideline, airflow rates of 300 CFM or less should be rounded to the nearest 5, and those greater than 300 CFM should be rounded to the nearest 10. For example, if the load program lists 253 CFM for a space, it would be rounded on the drawings to 255 CFM. If the load program lists 564 CFM for a space, it would be rounded to 560 CFM.

Once a design CFM has been established for each space, the diffusers can be sized and placed on the mechanical plan drawings. If a CAD (Computer-Aided Design) ceiling plan is available, it is advisable to snap the ceiling diffusers to the ceiling grid. If not, then the diffusers can be adjusted later once the ceiling grid becomes available. However, by that time the ductwork may be on the plans and adjusting the diffuser locations after the ductwork has been drawn leads to tedious text and ductwork manipulations. The diffusers must be aligned with the ceiling grid in CAD in order to provide the architect with a CAD block of the ceiling diffusers for the architectural reflected ceiling plan.

Care must be taken when sizing the diffusers in order to avoid noise issues. The ASHRAE Applications Handbook provides Noise Criteria (NC) guidance for various types of spaces. The NC rating corresponds to airflow values tabulated by diffuser manufacturers in their published literature. Air throw is another consideration when sizing diffusers. Diffuser manufacturers tabulate the distance the supply air will travel at various supply rates. When an issue arises between achieving an NC rating and achieving an air throw distance, it is advisable to favor the NC rating. A noisy diffuser will almost certainly raise owner issues, whereas falling short a few feet on the air throw is generally undetectable.

Ductwork sizing is based on the quantity of air flowing through the duct, the selected friction loss criteria, and the maximum airflow velocity criteria. A slide wheel chart such as Trane's *Ductulator* is commonly used to size ductwork. *Table 3* provides ductwork friction loss and maximum airflow velocity sizing criteria, tabulated by ductwork function. Medium pressure ductwork is typically used upstream of VAV terminals, all other ductwork in the table is low pressure.

FUNCTION	PRESSURE CLASS	FRICTION LOSS Inches w.g./100 Ft.	MAXIMUM VELOCITY FPM
TABLE 3: DUCTWORK SIZING CRITERIA			
Supply	Low Pressure	0.08”	1,800
Supply	Medium Pressure	0.25”	2,500
Return	Low Pressure	0.05”	1,800
Exhaust	Low Pressure	0.08”	1,800
Transfer	Low Pressure	0.03”	1,000

Note: Typical commercial office values shown; consult ASHRAE for other applications.

In a typical office building – as with many other applications – the ductwork is located between the structure and the ceiling. This space is commonly referred to as the “ceiling plenum.” Prior to sizing any ductwork, it is critically important for the HVAC designer to determine the distance between the bottom of the structure and the ceiling. An allowance must be made for the lights, sprinkler piping, and ductwork insulation as shown in *Diagram 3*.

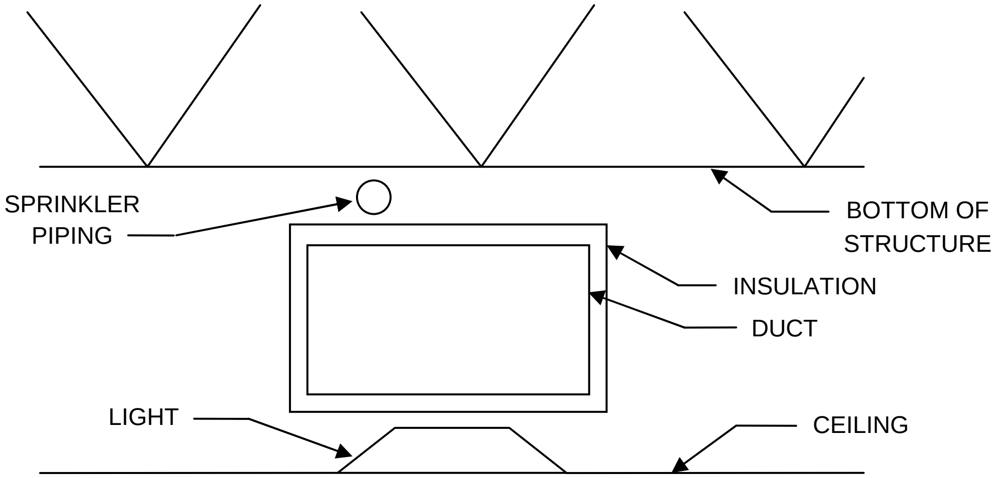

Diagram 3 – Ceiling Plenum Diagram

Evaluating the ceiling plenum space as depicted in *Diagram 3* establishes the maximum allowable duct height. Other potential conflicts not shown in the diagram such as plumbing, roof drains, or HVAC-related piping can be addressed on a case-by-case basis as the design progresses. Often such conflicts can be resolved by routing the ductwork to avoid large HVAC-related piping or plumbing. The aspect ratio – the ratio of the duct width to the duct height – should be no more than 4:1 (except in extreme cases). Additionally, the size of any piece of ductwork is constrained by the size of the ducts which tap off from it. Ducts must be at least 2" taller than the size of the tap in order to allow for a proper connection. Ductwork ultimately terminates at a diffuser, so the size of the largest connected diffuser neck plus 2" for the tap establishes the minimum duct height.

When showing ductwork sizes on mechanical drawings, the convention is to first indicate the size of the side that is depicted on the drawing, and then indicate the size of the side that is not depicted. For example, a duct which is 20" tall and 36" wide would be indicated as 36x20 on a plan drawing, and 20x36 on a section drawing. This convention applies to rectangular and flat oval ductwork, but is a nonissue on round ductwork.

The following summarizes the steps required to size ductwork:

a. Size the diffusers; minimum duct heights are based on diffuser neck sizes.

b. Determine the space available in the ceiling plenum for ductwork; this establishes the maximum duct heights.
c. Determine the friction loss and maximum airflow velocity sizing criteria based on duct function.
d. Use a Ductulator to size the ductwork based on the duct CFM and friction loss sizing criteria, but: 1) do not exceed the maximum velocity, 2) do not exceed a 4:1 aspect ratio, 3) do not exceed the maximum duct height, and 4) do not go below the minimum duct height.

On those projects with chilled water and heating water, the distribution piping for the chilled water and heating water systems must be designed and sized. Typically the chilled water and heating water piping are run side-by-side in order to economize on pipe supports and because they generally serve the same HVAC equipment. The supply and return mains emanate from the chiller/boiler rooms and should be centrally located to serve all of the HVAC equipment which utilizes chilled water and heating water. Branches are run from the mains to serve groups of HVAC equipment and individual units. After the supply and return piping for both the chilled water and heating water systems have been laid out, the piping can be sized. First, the plans are marked with the chilled water and heating water GPM for each piece of HVAC equipment. Next, working backwards from the most distant piece of HVAC equipment, the usage in terms of GPM is calculated for each section of piping. The size for each section of piping is determined by the maximum allowed fluid velocity and the corresponding GPM. Pipe sizing is typically performed using a chart which shows the maximum GPM by pipe size based on the fluid velocity. Maximum allowed fluid velocity for chilled water and heating water systems is primarily a function of the noise generated by the water inside the piping. Pipe sizing can be based on a velocity limit of 10 feet per second (FPS) for unoccupied spaces (such as mechanical rooms) and 6 FPS for occupied spaces (such as in a ceiling plenum above an office space). The *ASHRAE Fundamentals Handbook* recommends a velocity limit of 4 FPS for pipe sizes 2” or less.

The mechanical drawing set includes plan drawings which show all of the HVAC equipment, ductwork, and HVAC-related piping. In addition to the plans, there are other drawings such as the legend and notes sheet typically located in the front of the set. This sheet provides a key to the symbols used on the drawings and includes general notes aimed at the contractor who will build the project. The schedule drawing sheets depict tables that define each piece of HVAC equipment. The schedules include such information as required capacity, electrical data, weight, various options to be included, as well as manufacturer and model numbers for the basis of design. Section sheets show sections cut through the plan drawings at various locations as needed for clarity. The detail sheets depict equipment, ductwork, and piping details which apply to the project. Flow diagram sheets may depict airflow schematics, and chilled water/heating water piping schematics as applicable. The controls sheets include a written sequence of operation for each system, as well as control schematics for the various pieces of equipment. Controls sheets may include a points list which defines for the controls contractor each point of HVAC system monitoring or control.

Specifications can be in 8.5”x11” format (often referred to as a “book spec”) or may be placed on the drawings. This decision is typically made by the architect. The mechanical specifications define all of the characteristics of the mechanical systems which are not defined elsewhere on the drawings. Such characteristics would include standards, materials, construction procedures, and testing requirements. The specifications serve to define the quality standards for the project.

Conclusion

After starting with nothing more than a floor plan, in the end the mechanical engineer has created a complete set of documents which define in every conceivable way the mechanical systems. Creating a mechanical design is an awesome challenge, but it is also an awesome responsibility. Thousands of decisions are made along the way, but it only takes one mistake to derail an entire project. Every calculation, every decision, every selection must be carefully reviewed to ensure that the mechanical systems will perform properly as desired. In the end, the best HVAC systems are invisible. The best HVAC systems maintain comfortable indoor environments year round without being seen, heard, or felt.