HVAC Design – Fundamentals
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 such as 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 systems, and knowing which type of system to apply to a particular project is a key part of being successful in this field. System types include:

- 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 (CRUs)
- Packaged terminal air conditioners (PTACs)
- Ground-source heat pumps
- Heating-only systems utilizing electricity, gas, hot water, or steam
- Evaporative cooling units
- Heating & Ventilating Systems

What follows is a description of these different types of systems along with the advantages and disadvantages of each:

Direct Expansion

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 into a liquid in the condenser, expanded back into a gas at the evaporator, and returned to the compressor where the cycle begins again.
Diagram 1 – Basic Refrigeration Cycle

All of the DX system components can be contained in one unit or separated into two units. Typically, the condenser for a DX system must be installed outdoors so that it may reject heat which is part of the refrigeration cycle. Accordingly, a DX system consists of one single unit must be installed outdoors. Such 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) houses 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 the heat pump, which has the ability to operate the refrigeration cycle in reverse. Operating a refrigeration cycle in reverse serves to provide heating in the winter.

The primary advantage of a DX system is reduced first cost. Two disadvantages are less energy efficiency (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

Chilled water systems also use the basic refrigeration cycle but instead of cooling the air directly, chilled water systems cool water which in turn cools 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. Water-cooled chillers are typically located indoors and their condensers reject heat via a separate water loop. The separate water loop goes through a cooling tower which must be located outdoors in order to reject heat.
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 through 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).

Variable Air Volume

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. VAV systems maintain a constant supply air temperature and modulate the system capacity by varying the volume of the supply air.

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. Constant volume systems modulate the system capacity by varying the temperature of the supply air.

Areas with similar thermal characteristics are grouped together into zones, each of which is served by a single VAV terminal (sometimes referred to as a VAV box). 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.

VAV systems conserve energy due to the fact that as the volume of supply air is reduced, the energy required by the supply fan is reduced. VAV systems provide better occupant comfort compared to a constant volume system 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 Unit

A Computer Room Unit (CRU) is specifically designed to handle the high sensible cooling load (dry heat) 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 related to 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 100% sensible. CRUs are typically provided with the controls and equipment required to maintain both the upper and lower relative humidity conditions within prescribed limits.

CRUs offer the advantage of better control for computer room environments; the disadvantage is increased first cost.

Packaged Terminal Air Conditioner

A Packaged Terminal Air Conditioner (PTAC) is a small unitary DX system designed for through-wall installation. PTACs are commonly used in hotel guest rooms.

The advantage of a PTAC is reduced first cost, the disadvantage is decreased energy efficiency.

Ground-Source Heat Pump

A ground-source heat pump (also known as a geo-thermal system) is similar to a DX heat pump with one exception: instead of using an air-cooled condenser to exchange heat with the outdoors, a ground-source heat pump uses 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 season. Buried pipes 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.

Heating-Only Systems

In much the same way that a system’s cooling source can be located within a unit like with a DX system, or it can be 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 the heat is located in the unit. Steam and hot water systems are two examples of systems with remotely-located heating.
Electric heaters produce heat by passing a current through an electric resistance element. Gas heaters burn either natural gas or propane in a burner which is vented to the outdoors. 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 via pressurized steam piping. Condensate (condensed steam) is returned back to the boiler though condensate piping via condensate return pumps. Boilers typically burn natural gas or fuel oil and can be supplied as dual fuel units which have the ability to burn either.

In VAV systems, electric or hot water heat is often provided to the VAV terminals for increased zone 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 Cooling

Evaporative coolers provide cooling by evaporating water into the airstream. The evaporating water has a cooling effect on the airstream, but it also increases its humidity. The major components of an evaporative cooler consist of a wetted media, a water pump, and a supply fan.

A variation on evaporative cooling is an indirect evaporative cooling unit. In an indirect evaporative cooling unit, the supply airstream is one step removed from the evaporative cooling process. This prevents the supply air from increasing in humidity and it also serves to eliminate any potential airstream contamination issues. In an indirect evaporative cooler, the supply airstream passes over a heat exchanger which is itself cooled by the evaporative cooling process.

Part of the comfort-cooling process is most HVAC systems 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. This occurs at the cooling coil and it serves to dehumidify the supply air. The removal of moisture in the supply airstream dehumidifies the occupied space and helps 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 the expense of conventional air-conditioning is deemed unwarranted. Such applications might include factories, warehouses, or repair shops.
The advantages of evaporative cooling are lower first costs and lower energy costs. The disadvantage is the lack of complete comfort air-conditioning.

**Heating & Ventilating Systems**

Heating & ventilating systems can include fans, louvers, gravity ventilators, and make-up air units. Ventilation is typically designed to meet a prescribed air-change rate commonly quantified as Air-Changes per Hour (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.

Fans can be used to supply outdoor air and they can be used to exhaust building air. Ventilation fans are commonly 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 which are 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.

Make-up air units provide outdoor air which is heated in the unit by electric heat, gas, hot water, or steam. Make-up air units can be mounted on the roof, inside the building, or on grade. Make-up air units are typically provided with an intake hood designed to prevent rainwater from entering the make-up airstream.

The advantages of heating & ventilating systems are 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 brought in to evaluate every possible system in terms of equipment costs, energy costs, environmental impact, equipment service life, constructability, maintenance costs, occupant comfort, acoustics, and aesthetics. The system selected would be 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 get on with the design as needed to meet the design schedule. In short, HVAC system selection is typically a product of the stated or perceived expectations of the client and good engineering judgment.
The type of client is an important factor to consider when choosing an 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 two major types of clients worth noting: developers and owners.

The typical developer oversees a project from start to finish and then sells or leases 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 there, employs a design team, and hires a contractor to build it. Developers typically borrow significant amounts of money for their developments, so they want to get the building completed as quickly and as cheaply as possible. As a result, typically the most important thing to a developer is first cost (equipment cost).

Large manufacturing companies and university systems are two examples of the owner type of client. An owner builds a facility and has to live with it for as long as it remains standing. Consequently, owners are concerned with total cost; i.e., energy efficiency, ease of maintenance, longevity, as well as first cost.

The size of a project is another key component to consider when choosing an HVAC system. Smaller projects lend themselves to DX systems due to the lower first costs and ease of maintenance. As the project size increases in cooling capacity over 100 tons, the energy-saving benefits of a chilled water system begins to outweigh the first cost and maintenance savings associated with DX systems. In the 100 – 250 ton range, air-cooled chillers are commonly used. Energy savings in projects over 250 tons typically justify the added cost of a water-cooled system. Water-cooled systems require more sophisticated maintenance for the associated pumps, cooling towers, water treatment and refrigerant management.

Some projects are not good candidates for water-cooled chillers, regardless of the project size. One example might be a project where there is no good place to locate the cooling tower. Cooling towers are noisy and they emit mist (drift). Not every project can accommodate that. Another example might a very isolated location. Such a facility might not have access to a maintenance company willing to travel that far, and hiring permanent maintenance employees would result in a great deal of idle time. Situations like these are where good engineering judgment comes into play.

The type of project also has a significant bearing on the selection of the HVAC system. The HVAC system for an office building will often be different than the HVAC system for a retail store, which will be different than the HVAC system 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. Manufacturing plants are good applications for evaporative cooling systems because the while a
manufacturing plant needs some degree of cooling, fully air-conditioning such facilities may not be cost-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 small 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 often limited to projects which use steam elsewhere, such as manufacturing plants.

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.
### TABLE 1: HVAC SYSTEM SELECTION GUIDE - DEVELOPER PROJECTS

<table>
<thead>
<tr>
<th>PROJECT TYPE</th>
<th>UNDER 100 TONS</th>
<th>100 - 250 TONS</th>
<th>OVER 250 TONS</th>
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<tr>
<td>Medical Office Building</td>
<td>DX Rooftop VAV</td>
<td>DX Rooftop VAV</td>
<td>DX Rooftop VAV</td>
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<td>Air-Cooled Chiller, VAV</td>
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<td>Residential</td>
<td>DX Split System CV</td>
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<td>N/A</td>
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<td>Retail Strip Mall</td>
<td>DX Split System CV</td>
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### TABLE 2: HVAC SYSTEM SELECTION GUIDE - OWNER PROJECTS

<table>
<thead>
<tr>
<th>PROJECT TYPE</th>
<th>UNDER 100 TONS</th>
<th>100 - 250 TONS</th>
<th>OVER 250 TONS</th>
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<td>Church</td>
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<td>Computer Room Unit</td>
<td>Computer Room Unit</td>
<td>Computer Room Unit</td>
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<td>Courthouse Building</td>
<td>DX Rooftop VAV</td>
<td>Air-Cooled Chiller, VAV</td>
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<td>Hospital</td>
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<td>Hotel Guest Rooms</td>
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<td>Evaporative Cooling</td>
<td>Evaporative Cooling</td>
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<td>University Building</td>
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<td>Warehouse</td>
<td>Ventilation at 3 ACH</td>
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**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 critical aspect of HVAC design. If a cooling system is oversized, it may not stay energized long enough to properly dehumidify the space. This could result in serious humidity-related issues such as mold, mildew, and sick building syndrome. If a heating or cooling system is undersized, the system may not be able to maintain the required space conditions for part of the cooling or heating season. In either case, remedial action may be required and there could 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 design professional. Obviously, it is far better to avoid such potentially costly issues by properly sizing the HVAC system to begin with.

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 building construction materials.

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 a thermostat located somewhere in the zone. In instances where a zone requires more supply air than can be provided by a single VAV terminal, two or more VAV terminals are used 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 most programs, garbage in means 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 must 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 the default values 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 (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 directly correlated with the amount of moisture in the air. The higher the wetbulb temperature (keeping the drybulb temperature constant), 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 percentages 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 in the year will be warmer than the listed value. Therefore, it follows that for 1% of the time, specifically 87 hours, it will be colder than the listed value:

\[
365 \text{ days per year} \times 24 \text{ hours per day} \times 1\% = 87 \text{ hours}
\]

The International Energy Conservation Code (IECC) requires that the indoor design temperatures for HVAC load calculations 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 use of the ASHRAE outdoor design conditions in its discussion on the subject. It says “…use judgment to ensure that results are consistent with expectations” (ASHRAE Fundamentals Handbook, chapter entitled Non-Residential Cooling and Heating Load Calculations).

Those 87 hours of the year where the outdoor conditions are expected to exceed the listed design day values can be a cause for concern. It would not be unreasonable to add 3% to the outdoor sensible cooling design DB and subtract 10°F from the outdoor heating design DB. For example, if the cooling design day is listed at 94°F, the program override would be set to 97°F. Similarly, if the heating design day is listed at 32°F, the override would be set to 22°F.

Another consideration with regard to outdoor design temperatures which affects only the cooling load, is the location of the ventilation outside air intake. RTUs draw their outside air from the rooftop. If you have even been on the roof of a building on a hot summer day, you know that it is measurably hotter up there than the ambient temperature measured on the ground. This is due primarily to reflected heat coming off the surface of the roof. It would not unreasonable to add another 5°F to the outdoor sensible cooling design DB on projects with RTUs. In the example outline above, that would result in a program override for the outdoor sensible cooling design DB of 102°F.

The design heating and cooling supply air temperatures in the load program are another place 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 can be as low as 80°F. Given enough time, 80°F supply air will eventually heat a space, but the occupants who are cold to begin with may not appreciate 80°F air blowing on their skin. They want the air coming out of the supply diffusers to feel hot. 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 can result in the load program sizing the heating equipment without enough capacity to achieve this goal.

Similarly, the cooling supply air temperature default “To Be Calculated” should 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 57°F in order to have the program properly size the cooling system.

Another important part of the calculations is to determine the required quantity of outside air. Outside air is required for ventilation and make-up. The outside air must be filtered and conditioned in the system before being introduced into the space. 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 number of occupants, space type, and room area. The International Mechanical Code (IMC) is the applicable code for most (but not all) projects in the United States and in many parts of the world. The method for calculating ventilation air quantity is given in IMC Section 403. The tables and equations contained in that section are used to determine the amount of outside to be brought in through the mechanical equipment.

Outside air for make-up must be determined in order to ensure that adequate make-up air is provided for all exhaust sources; i.e., 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. A good way to evaluate the required make-up air is to draw a simple diagram of the building which depicts the air coming in and going out. The diagram can be included as an airflow schematic on the construction drawings to document the design process. 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 diagram illustrates a simple example:
Diagram 2 – Simple Airflow Diagram

The procedure for determining the required make-up air is to start with the exhaust requirements and work backwards. 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 can occur in neutral or negatively pressurized buildings. Infiltration enters 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 mechanical 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 as positive pressurize, therefore the required amount of make-up air for rooftop unit RTU-1 is 900 CFM.

After the ventilation and make-up air quantities have been determined, the greater of the two values should be 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, 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 where the outside air quantity exceeds the calculated room supply air. This puts the outside air load on the unit and saves time as 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 with the required outside air quantity included.

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 locating the equipment, coordination with other design professionals, sizing and layout of the 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:

1. The drawings provide the client with a means to review and agree to the proposed design before it is built.
2. The drawings serve to document that all of the applicable building codes have been followed. The drawings are signed and sealed by the professional engineer in responsible charge of the design. He or she must be registered in the state where the construction will take place. The drawings are then submitted for approval to the Building Department where the project is located. Once approved, a building permit will be issued to authorize the start of construction.
3. Contractors use the drawings to bid on the project and typically the lowest bidder is selected to construct the project.
4. The main purpose of the drawings is for their use by the contractor to build the project.
5. After construction is 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 is code-compliant. 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 can be found in other sections including the Energy Code, the Plumbing Code, the Architectural Building Code, the Fuel Gas Code, and the Electrical Code.
The HVAC design must comply with the Energy Code and some building departments require 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 code compliance. Most other states use the Department of Energy software program *Comcheck* which is available as a free download at www.energycodes.gov/comcheck.

The HVAC equipment selection is based on the system type chosen 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 can be undesirable as outlined earlier. 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 greater than a standard unit size. Conversely, when the calculated cooling load is appreciably higher than a standard unit size, the next larger standard unit size should be selected. As an example, standard unit sizes jump from 10 tons to 12.5 tons. If the cooling load were calculated to be 10.2 tons, the 10 ton unit should be selected. If the cooling load were calculated to be 10.8 tons, then the 12.5 ton unit should 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 about it is to imagine the 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 and has no opinion, it is up to the design professional to exercise good judgment.
At one end of the spectrum, N+1 redundancy is provided for facilities which cannot tolerate any degradation or interruption in 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 peak capacity will still be provided. For example, if the cooling load is determined to be 1,000 tons, N+1 redundancy would be achieved if three (3) 500 ton chillers were used.

At the other end of the spectrum, no redundancy is provided. If something fails, the building has no HVAC until the failed component is repaired or replaced. 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 peak capacity would still be provided. Using the same 1,000 ton example, the 2/3 approach would result in two (2) 670 ton chillers. 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 and the load might possibly still be met, or b) if it does occur on or near a design day, the occupants can suffer through on 2/3 capacity until the failed component is fixed.

Other HVAC equipment (as applicable) to be sized during the design phase include the 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 issues. Fans are sized based on the required CFM and static pressure for the application. Fan static pressure requirements are determined by analyzing the connected ductwork. For projects with chilled water and/or heating water, 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 an emergency ventilation system as prescribed by code. Boiler rooms require combustion air which is also prescribed by code. In colder climates, all chiller/boiler room ventilation air must be provided with adequate heat to prevent freezing. One might think that the heat radiating from a boiler would be adequate to prevent freezing inside the boiler room, but in fact modern boilers are so well-insulated that very little heat is lost to the room.

Another important part of the HVAC design process is coordination 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 to 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.

The tendency for engineers is to wait until everything has been 100% designed to release any information. However, in HVAC design that can be a big mistake. But, you might say, early on in the design process nothing has been sized; not the equipment or the ductwork. That’s where rule-of-thumb numbers and estimates come in handy. A first pass at the aforementioned coordination – particularly with the architect – should be undertaken earlier on in the project to ensure adequate space is provided for the HVAC equipment and ductwork. The information can be refined and updated as the calculations and mechanical design progresses.

Because so many other design disciplines support for the mechanical discipline, the HVAC design must be completed prior to the overall project deadline. Otherwise the other disciplines will not have adequate time to complete their work. Typically, preliminary equipment schedules and mechanical plans are issued at the 30% design stage. Coordination is an ongoing process up to 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 should continue with equally important tasks that have less impact on the other design disciplines. In other words, the HVAC design should be prioritized to address coordination issues first, then other tasks can follow. 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 calculates 253 CFM for a space, it would be rounded on the drawings to 255 CFM. If the load program calculates 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 or Revit 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 already 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 or Revit for coordination with 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 not perceivable.

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.

<table>
<thead>
<tr>
<th>FUNCTION</th>
<th>PRESSURE CLASS</th>
<th>FRICTION LOSS</th>
<th>MAXIMUM VELOCITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Low Pressure</td>
<td>0.08”</td>
<td>1,800</td>
<td></td>
</tr>
<tr>
<td>Supply Medium Pressure</td>
<td>0.25”</td>
<td>2,500</td>
<td></td>
</tr>
<tr>
<td>Return Low Pressure</td>
<td>0.05”</td>
<td>1,800</td>
<td></td>
</tr>
<tr>
<td>Exhaust Low Pressure</td>
<td>0.08”</td>
<td>1,800</td>
<td></td>
</tr>
<tr>
<td>Transfer Low Pressure</td>
<td>0.03”</td>
<td>1,000</td>
<td></td>
</tr>
</tbody>
</table>

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 the ductwork insulation as illustrated in Diagram 3.
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 with round ductwork.

The following summarizes the steps required to size ductwork:

a. Size the diffusers which dictates the minimum duct heights.
b. Determine the space available in the ceiling plenum for ductwork which 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 plus allowance for fittings.

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 generally they are coming from and going to the same places. The supply and return mains emanate from the chiller/boiler rooms and should be centrally located to serve all of the HVAC equipment. 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” and smaller.

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 monitoring or control for the HVAC system.
Specifications can be in 8.5”x11” format (often referred to as “book specs”) or they 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 help define the quality standards for the project.

CONCLUSION

After starting with nothing more than the architect’s floor plan, in the end the mechanical engineer has created a complete set of documents which define the mechanical systems in every conceivable way. Creating a mechanical design is a big challenge, but it is also a big 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 required. In the end, the best HVAC system is one that is virtually unperceivable. The best HVAC system maintains a comfortable indoor environment year round without being seen, felt, or heard.

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