Technical Fundamentals for Design and Construction of HVAC Systems

Key Points

- Knowledge and application of the fundamentals presented in this Executive Insight regarding design and construction of heating, ventilation, and air conditioning (HVAC) systems enhances performance.
- Technical fundamentals for HVAC systems include heating and cooling loads related to the facility needs and configuration, major components, and operating scheme.
- Balancing and commissioning involves a multi-step process and is necessary to ensure HVAC system efficiency.

Purpose and Scope of HVAC Systems

The primary purpose of HVAC systems is to heat and cool working fluids (typically air or water) that in turn heat, cool, and/or ventilate spaces in buildings and plants. This process is designed to satisfy specific criteria for indoor air quality, safety, and comfort. It provides flow to devices in selected areas of buildings (termed zones) that allow separate temperature control.

Four types of energy exchange processes create heating and cooling loads for HVAC systems:

1) Heating or cooling compensation for heat transmission through all surfaces exposed to unconditioned spaces
2) Heating or cooling compensation for infiltration air (calculated by crack or infiltration methods)
3) Heating or cooling ventilation air
4) Miscellaneous loads such as humidification

Heat load calculations are the most straightforward. They involve summing all losses, often using heat load forms for tabulation.

Cooling load is determined by: insulation, fenestration, lighting, appliances, human occupancy, infiltration, heat gain through glass areas, and heat gain through walls and roof. These calculations are complex because of diverse internal gains (lights, people, and equipment), large variation in hourly load, and the influence of the building's thermal mass.

HVAC systems typically include large equipment to condition and circulate air for the spaces served, custom fabricated piping and ductwork to connect the equipment and provide a flow path for the working fluids, and specialized capability such as emergency operating modes in case of fire.

Laws Regarding Energy Balance

Three laws govern all types of processes involving energy:

1. The law of *conservation of energy* states that energy is neither created nor destroyed.
2. The *first law of thermodynamics* states that heat and mechanical energy can be converted into each other.
3. The *second law of thermodynamics* states that it is impossible for a self-acting machine (without external energy input) to convert heat from a body at a lower temperature to one at a higher temperature. This law limits the transformation of heat (available energy) into work and requires that thermal cycles include both low and high temperature heat sinks.

Requirements for HVAC Systems

HVAC systems for technical and other facilities satisfy heating and cooling loads and provide simultaneous control of room dry bulb temperature, humidity, air quality, air cleanliness, and air motion to meet standards of comfort. HVAC systems also perform life safety functions such as smoke control. They must satisfy standards of economic and energetic efficiency, low initial and operating costs, and energy consumption, along with other desires of the owner. Also, they must fit in the overall architectural program.

Heating and ventilating loads include heat transmission through all surfaces exposed to unconditioned spaces, heating or cooling to compensate for unconditioned infiltration air (calculated by crack or infiltration methods), heating and cooling to compensate for unconditioned ventilation air, and miscellaneous loads such as humidification.

Cooling loads are determined by: insulation; fenestration; lighting, appliances, and human occupancy; infiltration; heat gain through glass areas; and heat gain through walls and roof. Office building loads typically vary in perimeter and interior zone spaces. Perimeter cooling load changes with sun position in summer. Lighting loads can vary from 2 to 10 watts/square foot.

Dry Side of HVAC Systems

Pressure and Flow in Air Systems

Total pressure in duct equals static pressure plus velocity pressure. It determines how much energy must be supplied to the system to maintain the flow. Total pressure always decreases in the direction of flow. Total pressure is measured by differential across the fan using inches of water (27.7 inches of water = 1 psi).

Static pressure is the "blow-up pressure" (like a balloon) that is the basis for duct design. Fan static pressure equals total pressure less velocity pressure or outlet static pressure minus inlet total pressure.

Velocity pressure is the force from or kinetic energy of flowing air, such as the wind blowing on the face. It is typically measured with a Pitot tube. The velocity of air in duct (fpm) equals 4005 x square root of velocity pressure in inches water gage at standard air conditions.

Fans and Air Handling Units

Fans in HVAC systems circulate the air by converting mechanical energy to gas energy. They create the pressure difference that causes flow in ductwork and open spaces. *Centrifugal* fans are the most used type because they offer a range of pressures and flow rates with quiet and efficient operation. *Axial flow* fans are used in higher volume applications where higher noise levels are not a major concern, such as industrial air conditioning and ventilation.

Designers frequently use air handling units to consolidate equipment at the point of intersection between wet and dry parts of HVAC systems. These units include coils for heating in winter and cooling in summer and fans to circulate the air. They also use filters and sprays to clean and humidify the air.

Types of Duct Systems

Low velocity ductwork is used in most installations. Velocities range from 400 to 2,500 feet per minute, generally less than 2,000. Some leakage is allowed. Low velocity systems have lower initial and operating costs, but require larger space for installation.

High velocity includes systems operating from 2,500 to 7,000 feet per minute, generally less than 6,000. They are typically used only when alternatives are not feasible. These systems require acoustic chambers at fans and attenuators for noise reduction at the end of duct runs. They use heavier and leak-proof construction. Pressure classifications of duct systems include low (from -2 to +2 inches of water), medium (from -3 to +3 inches of water), and high (from +3 to +10 inches of water) static pressure.

Configuration of Ductwork

Round ductwork is the most efficient and economical. It uses less material and creates less friction because of its lower surface area for a given flow cross-section. The spiral configuration allows light material that can withstand greater pressure (positive and negative) and physical abuse. Round ducts use simple and inexpensive joints that crimp one section to slide into the adjacent section.

Rectangular ductwork is the standard configuration where space is restricted. It is fabricated with stiffeners for large sizes. Metallic ductwork is the most common, using galvanized sheet steel, gauge 26 down to 20. Aluminum, copper, and stainless steel also are used. Stiffeners are normally standard structural shapes.

Major Components and Differences in Operations

HVAC systems typically include large fans and pumps to circulate air and water, coils for heating and cooling, filters or other devices to maintain air quality, ductwork and piping to connect the equipment, and control systems.

Centrifugal fans deliver high flow against lower static pressure. *Vane-axial* fans deliver lower flow against higher static pressure. Both types of fans are driven by electric motors and controlled by the control system described below.

Coils typically transfer hot or cold between air and water flow streams. Filters in ductwork clean the airflow to maintain air quality. Louvers open and close to throttle or shutoff airflow in ductwork. Design features to increase the energy efficiency for HVAC systems include energy transfer between the exhaust and fresh air parts of the systems.

Selected Construction Resources and Operations

Once the design and detailing for a HVAC system is completed, fabrication of ductwork for HVAC systems is the next major activity. This critical step may employ automated equipment for cutting, bending, joining, and welding.

Sized to consider access limitations, the ductwork is then transported to the project site, placed on the correct floors for installation, often using special baskets and cranes. Several pieces may be connected to form a subassembly for more efficient erection. The duct pieces are then erected and connected to previously placed hangers.

Wet Side of HVAC Systems

Equipment and coils

Heating and cooling coils are used for forced-convection heating or cooling of air in air-handling units or at distributed locations in duct systems. They allow for differing types of HVAC systems and provide options for type and size of distribution trees. Coils also dehumidify air by cooling below dew point temperature and recover waste energy in exhaust streams.

Cooling coils typically operate with air conditions of dry bulb temperatures ranging from 65º to 100ºF and a wet bulb range from 60º to 85ºF. Heating coils operate with air temperatures ranging from - 20º to 100ºF for steam coils and 0º to 100ºF for hot water coils.

Refrigeration Processes, Cycles, and Metrics

The purpose of refrigeration is to remove heat from a region of lower temperature and deliver it to a region of higher temperature. Refrigeration machines work in a thermal cycle and require mechanical input. For cooling of buildings, these cycles include compression and absorption refrigeration.

Compression refrigeration cycles includes *evaporation* of the refrigerant to absorb heat from the conditioned space; *compression* of the refrigerant by mechanical work; *condensation* to cool the high-pressure gas and reject heat from the cycle; and *expansion* of the high-pressure liquid through an expansion valve to reduce pressure and cause a portion of the liquid to "flash" to gas and absorb heat.

Refrigeration units are typically rated in tons of refrigeration. One ton equals a heat removal rate of 12,000 BTU/hour or the rate of heat absorption in melting a ton of ice.

HVAC Startup, Balancing, and Testing

Equipment Startup and Performance Testing

Initial operation of equipment requires rotation checks and interlock checks. For rotation checks the pump is uncoupled and the three-phase motors are “bumped” to verify correct connection and rotation. Checks of operation and interlock protection test various startup sequences and shutdown conditions to verify the proper operation of controls and interlocks.

Fan performance testing verifies the quantitative performance of the equipment from shutoff to free delivery conditions by obtaining sufficient points to define the curve. Static pressure checks involve measurement at various points in the system to determine loss in ducts, fittings, and accessories.

Air and Water System Balancing

The purpose of air balancing is to make the systems perform as intended and verify ability to perform under the most economical conditions. The process involves proportioning flows within a distribution system according to specified design quantities, typically within 10 percent of the specified values. Specialty firms typically use the Sheet Metal and Air Conditioning Contractors' National Association (SMACNA) procedures for balancing and document the results on report forms.

For manual measurements, technicians read pressures from permanent instrumentation if installed in the system, or use a Pitot tube, a double concentric tube that measures total pressure and static pressure, for the determination of air velocity. Flow hoods measure discharge at outlet devices.

Preparation for air balancing requires assembling many types of technical data: information from plans, contract documents, approved shop drawings, equipment submittals; schematic drawings showing flow distribution; fan and pump performance data; fan and pump motor and drive data; performance data for heat exchange equipment; and technical description of air distribution devices. Other preparations include inspecting the system, verifying integrity by leak testing, setting control dampers to fully open position, and setting splitter dampers to mid-position.

Balancing begins with starting all fans, operating the water systems serving the units, and operating all controls serving the system to verify each performs its required function. Technicians measure motor voltage and current and adjust fan RPM to design conditions. They then measure and record the static pressure at the entering and leaving side of all filters, fans, and coils, and determine the total cubic feet per minute (CFM) delivered by the fan by traversing the main duct(s).

Balancing operations continue to determine the CFM delivery of the main branches, working from higher to lower flow branches and adjusting dampers until each branch is at design conditions, + or – 10 percent. Test reports document the results. Final steps include recheck motor voltage, current, static pressures, CFM delivery; repeat process under wet coil conditions; repeat the procedures for return and exhaust systems; complete special steps for dual duct and variable air volume (VAV) systems; and prepare a complete air balance report.

Several considerations influence water system balancing. Technicians must coordinate this with air side work. Heat transfer capability for the heating mode is relatively insensitive to changing water flow rates because air side coefficient governs the heat transfer rate. The cooling mode has greater sensitivity to water flow rate because the air-to-water temperature difference is much less.

Other requirements for testing include temperature control verification, testing for sound and vibration, and air cleaner tests. Temperature testing verifies the capability of the automatic control system to match system capacity to varying load conditions; it is performed by verifying the operation of each control element. Testing for sound and vibration ensures the equipment operates properly and does not transmit objectionable noise or vibration to the building structure or occupied spaces. Air cleaner tests use prepared test dust or oil to verify cleaning capability.

Importance of HVAC Systems

HVAC systems are increasingly complex and costly, making them critical to maintaining project control regarding cost, time, and quality. Facility owners also rely on HVAC systems to meet important goals, such as:

- Meeting specifications for the interior space environment of many types of institutional, commercial, or residential facilities.
- Meeting demanding specifications for closely controlled research and manufacturing spaces, including parameters like temperature, humidity, particle count, and others.
- Increased efficiency of energy use to support decarbonization goals.

By understanding the fundamentals outlined in this Executive Insight, construction stakeholders can design, construct, and operate HVAC systems that will meet these important goals.

About the Authors

Bob Tatum was elected to NAC membership in 2002 and moved to emeritus status in 2022. He served in the U.S. Army Corps of Engineers on infrastructure projects in Vietnam (1968-69). His career progressed as mechanical engineer, construction engineer, resident engineer, and area superintendent on power plant projects (1970-81). He joined the Stanford University construction faculty in 1983 after receiving his PhD, and had a long and productive career there, including serving as department chair, conducting research, and offering courses on construction engineering until retirement as the Obayashi Professor Emeritus in 2015.

Charles (Chuck) Jahren was elected to the National Academy of Construction in 2018. He retired from Iowa State University after more than 30 years in education and research and six years of industry experience. Known nationally for his innovative approaches in construction engineering education, he holds a bachelor’s degree in civil engineering and an MBA from the University of Minnesota and a PhD in civil engineering with a specialization in construction engineering and management from Purdue University.