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Designing Forced-Air HVAC Systems

Heating and cooling design loads should be calculated for the home using the protocols set forth in the latest edition of the Air Conditioning Contractors of America's (ACCA) Manual J (currently the 8th edition), ASHRAE 2009 Handbook of Fundamentals, or an equivalent computation procedure. ACCA provides free speed-sheets for performing Manual J calculations on their website (http://www.acca.org/speedsheet/), though you will need their Manual J handbook to complete the forms. There are several software packages available that are designed to do Manual J load calculations, including (but not limited to):

- Wrightsoft's Right-Suite: http://www.wrightsoft.com
- Elite Software's RHVAC: http://www.elitesoft.com/web/hvacr/elite_rhvacw_info.html
- Nitek Software's Load Wizard: http://www.niteksoftware.com/web2008/product2008.html
- Adtek's AccuLoad: http://www.adteksoft.com/

Commercial load calculation tools are generally not appropriate for residential sizing. Major discrepancies between residential and commercial load calculations often occur in relation to:

- Ventilation Rates
- Infiltration Rates
- Occupancy Hours
- Lighting
- Other latent and sensible internal gains

Before hiring any HVAC contractor, you should require a minimum of Manual J and S calculations to be completed in your bid request. If a contractor is either unfamiliar or unwilling to do these calculations, you are better off looking elsewhere for a contractor, regardless of how low that contractor's bid may be. If a contractor is not willing to design your system based on the best available methods in the industry, what makes you believe that they are knowledgeable enough to provide you a quality installation? Excessive capacity, low airflow, high duct leakage, and improper refrigerant charge can easily lead to your system running at 70% efficiency or worse, so choosing a qualified contractor is very important.

It is also recommended to have your HVAC contractor agree to provide their services in compliance with ACCA's Quality Installation Specification (https://www.acca.org/Files/?id=116). This is an ANSI-approved standard that describes precisely the steps a contractor must take to ensure a quality HVAC installation.

Energy Efficiency vs Comfort?

There will always be those in the HVAC industry that believe right-sizing is actually under-sizing or that it is an energy efficiency measure that disregards comfort. Building America's goal has always been to minimize energy consumption while maintaining or improving comfort and durability. SWA has right-sized numerous projects in which we have followed up with short and long-term monitoring to ensure that comfort is maintained within the home. When incorporated into a whole-building systems approach to home construction, right-sizing is an effective method.

This is not to say that issues can not arise when right-sizing a home's HVAC equipment. To be clear, HVAC design is just that…"design" at the onset of the project. Right-sizing only works if quality control is maintained throughout the construction process. If the home is significantly leakier or building specifications change drastically from design, the HVAC design needs to be modified as well. In the majority of cases, it is not that your system was under-sized, it is that your home was poorly constructed.

Design Conditions

For programs such as EPA's ENERGY STAR Qualified Homes and USGBC's LEED for Homes, the outdoor cooling design temperature used for load calculations must be the 1.0% design temperatures as defined in the ASHRAE Handbook of Fundamentals for the nearest appropriate weather site. Indoor design temperature should be 75°F for cooling. The infiltration rate should be assumed to be "tight" or equivalent. These programs have no specific requirements for heating as there isn't the same concern about addressing both sensible and latent loads. It has been suggested that a 99% outdoor design temperature and 70°F indoor design temperature should be utilized for these programs. SWA typically uses the 0.4% (cooling) and 99.6% (heating) outdoor design conditions when designing projects outside of these national certification programs as a compromise between national programs and HVAC contractors (who typically utilize the mean extreme outdoor design conditions).

If your HVAC contractor actually does an approved load calculation method, they still likely utilize the mean extreme outdoor design condition. Many contractors also design for an indoor temperature of 70°F for cooling. This is not necessary, but contractors do it as they believe that providing a larger capacity system will reduce the number of callbacks. They would be better off actually sealing ductwork, so that the distribution system doesn't leak. Typical forced-air systems leak an average of 15-30% of the supplied forced air (as SWA has commonly tested in new construction).

What does a 1%/0.4%/mean extreme or 99%/99.6%/mean extreme outdoor design conditions mean? This is the dry-bulb temperature that corresponds to annual cumulative frequency of occurrence. This value represents the value that is exceeded on average by the indicated percentage of the total number of hours in a year (8760 hrs). For example, the 0.4% outdoor cooling design temperature for Sterling, VA is 93°F. This means that the outdoor conditions only exceed 93°F on average for 35 hours per year, or 0.4% of the year.

Just because a system is designed to this lower than mean extreme outdoor condition, it doesn't mean that the system simply won't be able to cool a home for 35 hours each year. A properly sized system may only be able to cool to 76°F or 77°F rather than 75°F for these hours. The benefits (better dehumidification and lower energy consumption) of a right-sized system out weigh any slight temperature increase and those 35 hours are not consecutive. They are spread out during the peak of summer days or winter nights. A room that is 77°F, but is controlling humidity levels will feel more comfortable than a room that is 75°F but not effectively controlling humidity.

EPA was working on the following draft disclaimer for requiring right-sizing for all Energy Star Homes. Though it never became official, it provides a good explanation for why to right-size:

"As part of your new home's ENERGY STAR certification, engineered sizing calculations have been performed to match the cooling system capacity with the load requirements of your home. This helps ensure that your cooling system runs more continuously rather than in a short-cycling mode with frequent on-off operation. EPA has added this requirement to ENERGY STAR Qualified Homes for several important reasons. First, your equipment can operate much more

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efficiently, much like a car getting higher fuel efficiency at highway speeds than stop-and-go traffic. This can also extend the lifetime of your equipment because on-off cycling imposes much more stress on critical components. Lastly, continuous operation also helps improve the comfort of your home because the cooling coils stay cold for a longer period of operation time, and therefore, can remove more moisture from the air.

Right-sizing of your air conditioning equipment was based on national standard procedures developed by the Air Conditioning Contractors of America (ACCA) or equivalent computation procedure. These calculations are based on recommended set-points for indoor comfort and predominant weather conditions assuming appropriate equipment selection and proper system installation. It should be noted that extreme weather conditions can always occur that may leave your air conditioning system with temporary limits on delivering full comfort performance. This is much like selecting siding, roofing and window materials to handle very harsh weather conditions, but not extreme weather such as hurricanes and tornadoes."

Common Design Assumption Errors

Often a HVAC designer will size based on a maximum entertaining occupancy load expected in the home. ACCA's occupancy load guideline (Manual J 8th Edition: Section 22-3) is to design for the total number of full time occupants. If unknown, this should be based on two people for the master bedroom and one for each additional bedroom. For heating dominate climates, leave in occupants in the bedrooms. For cooling dominate climates, these occupants should be distributed throughout the living space, as they will typically be in these areas during the maximum load period.

When a builder/homeowner requests a system that can accommodate a large number of guests, this temporary occupant load needs to be handled by a supplemental cooling system or by a system that can shift capacity from zone-to-zone (a variable volume/refrigerant system).

In addition, HVAC designers often include an internal lighting load. This is not a recommended practice unless there is minimal window area. The inclusion of lighting will minimize the design heating load and will inflate the design cooling load. Typically, homes will have few lights on during the peak summer hours, as daylighting will be utilized for the most part. For lighting, equipment, and appliance load assumptions, ACCA's Table 6 can be utilized.

Equipment Sizing

Heating and cooling equipment should be sized according to ACCA Manual S based on the loads calculated per Manual J protocols. Additional safety factors shouldn't be applied when sizing a system. When sizing cooling equipment, it is important to ensure that both the sensible and latent capacities meet the required building loads, and not just the total cooling capacity is met. If slightly short on either sensible or latent capacity, the designer should first account for fan speed adjustments to meet capacity requirements prior to upsizing.

Energy Star only allows a maximum oversizing limit for air conditioners and heat pumps of 15% (except in Climate zones 5-8, which are allowed a maximum of 25% oversizing for heat pumps). As manufacturer's equipment sizes typically come in half or one ton increments, it is acceptable to install the next available manufacturer's size though it may exceed EPA's oversizing limit. For example, if the design building load is 19,000 Btuh, a 2 ton air conditioner can be installed even though it is a ~21% oversizing. The designer/contractor should provide documentation of both the selected unit and the unit one size smaller for approval of this exception.

In addition, indoor and outdoor coils should be matched in accordance with AHRI standards. SWA recommends obtaining the AHRI certification documents for each system installed from your HVAC contractor (http://www.ahridirectory.org/ahriDirectory/pages/home.aspx) and to verify that model numbers on the condenser, evaporator coil, and air handler/furnace match the documentation provided.

For dual-capacity cooling equipment, when matching cooling capacity to cooling load, the total/full capacity of the unit should be referenced (not part load capacities). Only in cases when there is a combined heating and cooling system and when the cooling load is substantially smaller than the heating load should an absolute sizing limit not be strictly enforced. This exception is provided to ensure that adequate heating is maintained within the home. It is the responsibility of the designer to ensure that the system will still provide adequate humidity control (enhanced controls, whole-house dehumidifier, etc.).

If there is a need to accommodate a significant number of temporary occupants (guests) on a regular or sporadic basis, a supplemental cooling system (i.e., mini-split unit) or a variable volume zoning system should be utilized.

Supplemental & Auxiliary Heat Sizing (Electric Resistance Coils)

For heat pump heating system, you will need some amount of supplemental heat provided by the resistance coils (or other back-up heating source) when the outdoor temperature is below the balance point of the heat pump, it is recommended that the resistant coils are staged. The capacity of the supplemental heating coils will need to be equal to the difference between the Manual J heating load and the high-speed output of the heat pump when the outdoor temperature is equal to the winter design temperature.

Request a balance-point diagram from the manufacturer on the unit selected to determine the capacity of the system at the desired outdoor design temperature. The maximum amount of electric resistance heat that is controlled by the second stage of the room thermostat should as closely sized to the supplemental heat requirement that is associated with the balance point diagram.

An example of sizing the supplemental heat requirement:

Assume the outdoor design condition is 17°F, cooling load of 19,105 Btuh, and a heating load of 21,947 Btuh. The selected two ton heat pump provides 22,600 Btuh of heating capacity at 47°F and 14,000 Btuh capacity at 17°F (from AHRI rating), the equivalent resistance coil to meet the supplemental load of the heat pump is 2.52 kW:

$$(22{,}600 \text{ Btuh} - 14{,}000 \text{ Btuh}) / 3{,}412 \text{ Btuh/kW} = 2.52 \text{ kW}$$

This example uses a 17°F outdoor design condition, because it is available in the AHRI rating…but this example would need to be revised based on the balance-point diagram for the selected unit and the desired outdoor design condition.

In terms of emergency heat (assuming the compressor fails), the total resistance coil sizing for the example two ton unit would be 6.62 kW (= 22,600 / 3,412).

Electric resistance coils typically come in sizes of 5, 8, 10, 15, and 20 kW. Two 5 kW coils that are staged would cover this unit. If smaller electric coil sizes were available, they should be utilized.

HVAC Distribution

ACCA Manual D establishes protocols for sizing duct systems based upon loads calculated per Manual J. Manual D is based on typical flow, pressure, and friction calculations for duct systems. The table below has been reproduced from ACCA's Manual D Table A1-1.

Recommended Velocity [fpm]								
	Supply Side				Return Side			
	Recommended		Maximum		Recommended		Maximum	
	Rigid	Flex	Rigid	Flex	Rigid	Flex	Rigid	Flex
Trunk Ducts	700	600	900	700	600	600	700	700
Branch Ducts	600	600	900	700	400	400	700	700
Supply Outlet Face Velocity	Size for Throw		700		-		-	
Return Grille Face Velocity	-		-		-		500	
Filter Grille Face Velocity	-		-		-		300	

According to Hart&Cooley, a register and grille manufacturer, stamped, louver-faced residential returns should be limited to no more then 600 feet per minute (fpm). Filter returns should be limited to a face velocity of 400 fpm to minimize noise and to allow the filter to properly remove particulates from the air stream.

Central Returns

Locating central returns should be in a central area that is outside the influence of supply register throws. For bedrooms and other rooms with doors, a suitable return air pathway other than a door undercut should be provided, such as “transfer grilles” or “jump ducts”. In terms of vertical placement on walls, when heating is the primary requirement, the return should be located close to the floor and when cooling is the priority, the return should be located near or in the ceiling.

Controls

When heat pumps are utilized with programmable thermostats, the thermostat should have “adaptive recovery” technology to limit the amount of auxiliary electric resistance heating. Typically, homeowners set back the heating temperature setpoint when sleeping. The morning ramp up of heat pumps often requires the system to switch to the auxiliary heat source. “Adaptive recovery” allows the system to start up ahead of the programmed time and completes the recovery at the programmed time, taking into account changes in outdoor temperature. This gradual ramp up of heating can allow the heat pump to operate fully or partially without the auxiliary heat source.

Whenever a single HVAC system is being utilized to condition a home that is 2+ stories, zoning controls should be incorporated into the design of the system. Also, if a home has high solar gain (through windows) on one or more exposures, some type of zoning should be considered for these areas.

Materials

Moving on to materials, flex ductwork doesn't mean that it can be put anywhere and can go around anything. Flex duct needs to be pulled taut to minimize pressure drop along the length of the duct run. According to the North American Insulation Manufacturers Association (NAIMA):

“Flexible duct shall be supported at manufacturers’ recommended intervals but at no greater distance than 5 feet on centers. Maximum permissible sag is ½” per foot of spacing between supports. Long horizontal duct runs with sharp bends shall have additional supports before and after the bend approximately one duct diameter from the centerline of the bend.”

One of the reasons that flex ducts are often installed poorly is due to how it is supplied. Flex duct typically comes in 25 ft lengths and some contractors won’t cut the flex duct to length unless it is significantly shorter than the 25 ft or if it can be split in half for two runs.

Thermaflex makes a plastic flex elbow support to assist with this Flexible Duct Performance & Installation Standard if needed.

Proper Installation

Typical Installation

Framing members are not considered to ductwork material. Panned returns and boxed-out wall cavities should not be utilized as part of the distribution system. All distribution should be “hard-ducted”.

Duct Sealing

Regardless of the type of ductwork material (sheet metal, ductboard, or flex duct), all ductwork should be sealed with mastic (water-based is preferable) during assembly (as joints may be inaccessible once installed). For gaps larger than $^1/_8$ of an inch, fiberglass mesh tape reinforcement should be embedded in the mastic.

Some basic recommendations for duct sealing:

- at any joint where 2 ducts connect
- where ducts connect to boots or air handler
- the boot to the subfloor or drywall
- at the air handler cabinet

For further details, refer to DOE’s Air Distribution Installation and Sealing Guide (http://www.toolbase.org/PDF/DesignGuides/doe_airdistributionsysteminstallation.pdf).

Comfort

“Proper system installation” is the key to a HVAC system operating correctly. Duct leakage is the primary reason for comfort issues in homes. The next major installation criterion that needs

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to be verified is proper refrigerant charging of your air conditioning or heat pump system. SWA highly recommends that you obtain written test values of refrigerant charge from your HVAC contractor. A good contractor will use one of three methods (super-heat, sub-cooling, or weigh), recommended by equipment manufacturers, to verify the correct refrigerant level. Ask your contractor how they verify that the refrigerant level is correct.

Also, a homeowner must realize that a single speed air handler with no zoning or balancing dampers will not provide perfectly even temperature control throughout a home. It simply isn't possible. ACCA's Manaul RS provides the following minimum performance standards for comfort for residential single-zone systems. Based on SWA's experience in field testing, these comfort levels are not met by the majority of today's standard HVAC system installations.

Comfort Item	**Heating Season**	**Cooling Season**
Thermostat setpoint	70°F	75°F
Maximum relative humidity	Humidification is optional do not exceed 30% RH	Maximum of 55% RH at Manual J design conditions
Minimum relative humidity	Humidification is optional 25-30% RH is desirable	25-55% RH at Manual J design conditions (humidification optional in very dry climates
Dry-bulb temperature at thermostat	Thermostat setpoint temperature plus or minus 2°F	Thermostat setpoint temperature plus or minus 3°F
Dry-bulb temperature in any conditioned room	Setpoint temperature at thermostat plus or minus 2°F	Setpoint temperature at thermostat plus or minus 3°F
Room-to-room temperature difference	Maximum – 4°F Average – 2°F	Maximum – 6°F Average – 3°F
Floor-to-floor temperature difference	Maximum – 4°F Average – 2°F	Maximum – 6°F Average – 3°F
Temperature variation from 4 inches above the floor to 72 inches above the floor	1°F for each 15 degrees of indoor-outdoor temperature difference	3°F for each 10 degrees of indoor-outdoor temperature difference
Floor temperature (slab floors or floor over cold space)	With thermostat set at 70°F, the temperature at 4 inches above the floor surface should not be less than 65°F (except near the outside walls)	

Comfort problems are seldom a result of undersized equipment. Most are caused by deficiencies that have nothing to do with the capacity of the HVAC equipment. Examples include:

- Excessive building leakage in humid climates can result in large latent loads and poor humidity control. Over-sizing equipment is will not fix this and is likely to make this issue even worse, as short-cycling cooling equipment minimizes latent removal. Cooling systems are sized based on sensible heat ratio (SHR) and if the latent capacity isn't met, an additional dehumidification system is needed. According to AprilAire, a manufacturer of indoor air quality products, "Any region with a summer dew point average above 55°F needs dehumidification separate from cooling."
- Many people expect the cooling system to provide perfect humidity control, but in swing months when there isn't a call for sensible cooling (temperature), the system is unlikely to run and therefore can not address any of the latent load (humidity). There are some thermostats that provide a humidity control setting, but this basically drops the temperature setpoint down a couple degrees to allow the cooling system to run.

- The ductwork has not been tested and balanced. Manual dampers are still needed for each supply even if the Manual D design is followed perfectly.
- Duct leakage due to poor installation results in loss of heating and cooling to unconditioned spaces rather than being supplied to the desired rooms.
- Improper location of the thermostat. SWA has commonly seen thermostat placed directly below or above supply registers which result in the system short-cycling. Also it is common to see thermostats located in direct path of sunlight.
- Air conditioner or heat pump is not properly charged resulting in reduced capacity.
- Dirty filters and/or coils increase external static pressure of the system resulting in reduced airflow.

Maintenance

For a HVAC system to perform properly over its lifespan, homeowners need to clean or change the air filter in their heating and cooling system according to the filter's instructions, or at least once per heating and cooling season (twice a year). Regardless, it is recommended that a homeowner schedules an annual maintenance check-up with a licensed contractor to ensure that the HVAC system is operating efficiently. Just like a car needs a tune-up, so does your home.

Observations from the field

Builder - "I got a complaint with regard to the temperature difference between the master bedroom to the master bath. [The homeowner] reports the master bath is at a measured 67°F when the master bedroom is at 74°F [during the heating season], a setting that they seem to be comfortable at. These two rooms are adjoining. He also made mention the master closet in front of the master bath was at 67°F as well. I know [the HVAC contractor] missed the supply to that front closet initially and added it in the field thinking there would be no adverse CFM effect. Would you help me pinpoint the problem?"

With the HVAC contractor not properly sizing the system based on Manual D calculations, the post retrofit stole cfm from the bathroom to supply the closet. Unfortunately, as installed, the system is only providing 47 cfm to the master bath when the Manual J design called for roughly 93 cfm for heating and 61 for cooling.

Builder – "We are noticing mold on our basement drywall during the construction process."

Construction was occurring during late spring/early summer. Contractors were leaving the doors open all day long allowing hot, moist air into the home. At the end of the day, they would close up the home. The basement air would cool enough to result in condensation at roughly 8 inches above the slab floor. This left a band of moist drywall that began breeding mold. The HVAC system hadn't been connected at this point, so there was no humidity removal mechanism available in the home.

Using the psychometric charts, we see that if the basement air (essentially the same as ambient due to doors and windows being open) is at 90°F and 50% relative humidity and cools down to 69°F, the relative humidity of the air will now be 100% or fully saturated. The same amount of water vapor is in the air, but the capacity of that air has changed due to the temperature. Condensation can occur when the water vapor is cooled to its dew point. This will likely be near to the floor as the air will stratify.

Builders should be cognizant of this and place a standalone dehumidifier in the basement until the HVAC system is up and running. It was also found during this inspection that there would have been an additional source of the latent load due to a decoupling of the dryer exhaust line under the first floor in a joist bay.

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