Optimal Forced-Air Distribution in New Housing

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Introduction

Studies of forced-air thermal distribution systems in small buildings show that significant energy losses are common in ductwork. These losses stem from several mechanisms, including duct leakage, thermal conduction through duct walls, and selective pressurization and depressurization of different zones of the house when the air-distribution fan is operating. One way to reduce or eliminate duct losses is to place the ductwork within the conditioned space, rather than the more usual attic, crawlspace, or basement locations. This approach is encouraged by new standards such as ASHRAE 90.2.

A major impediment to this solution is the size and unsightliness of the ductwork. If ducts could be made smaller in cross section, builders might be motivated to place them within the conditioned space. The required cross section of the ductwork is related to the air-flow requirement, which for a house of conventional design is driven by the peak cooling load, even in northern climates. Typically, an air conditioner of ~3 tons [10.6 kW] is installed. At 400 cfm/ton [0.05 m^3/kJ] this translates to an air-flow requirement of ~1200 cfm [0.57 m^3/s]. The heating load, by contrast, could be met with much lower air-flow rates, even in conventional houses in northern climates.

From these considerations, three approaches to reducing the required air flow in ductwork present themselves. One is to meet part or all of the cooling load through means other than a forced-air system. Although this approach should be considered, it is beyond the scope of this presentation. The other two approaches are, first, to reduce the peak cooling load, and second, to reduce the air flow required to produce a given amount of cooling. Integrating these two approaches is the key to the design optimization that is advocated here.

Cooling-Load Characteristics of the Optimized House

A calculation of the peak cooling load in New York State was performed for both a conventional house and the optimized design that would replace it (Andrews et al. 1989). The conventional house was a single-story 1500 ft^2 [140 m^2] structure with R-11 insulation in the walls, R-20 in the ceiling, unshaded window area 15% of the south wall and 10% of the other walls, and an average summertime air infiltration rate of 0.7 air changes per hour (ACH). Calculated heat gains from various sources are shown in the first column of Table 1. Duct losses equal to 30% of the cooling input are assumed here, within the range of recent results (Cummings and Tooley 1989, Modera et al. 1991).

In the advanced house, the following steps are taken to reduce the peak cooling load. First, the windows are specified such that solar gains are decisively dealt with by some combination of glazing treatment, shading, and controllable reflectivity. Second, the insulation in the walls and ceiling is approximately doubled. Third, the envelope is tightened and forced ventilation is used (see below). Finally, the ductwork is reduced in size as part of the design optimization, permitting it to be brought inside the conditioned space. Further, the distribution system is carefully designed to avoid fan-induced infiltration. Duct losses are therefore eliminated. The resulting cooling loads are shown in the second column of Table 1.

The Forced Ventilation System

The optimized house is conceived as having a tight envelope, with a natural air infiltration rate no greater than 0.1 ACH. An additional 0.4 ACH is accomplished via the forced-air distribution system, in which a heat-recovery heat pump is installed that can, in the summer months,

Table 1. Components of the Peak Cooling Load (Btu/h [kW])

	Conventional House	Advanced House Gross	Advanced House Net
Sensible Cooling (Except Duct Losses)			
Heat Gains Through Opaque Surfaces	5350 [1.6]	2760 [0.8]	2760 [0.8]
Solar Gains Through Windows	8250 [2.4]	4100 [1.2]	4100 [1.2]
Air Infiltration--Sensible Part	3020 [0.9]	2160 [0.6]	-1730 [-.5]
Internal Gains--Sensible Part	2000 [0.6]	2000 [0.6]	2000 [0.6]
Latent Cooling (Except Duct Losses)			
Air Infiltration--Latent Part	2670 [0.8]	1910 [0.6]	- 760 [-.2]
Internal Gains--Latent Part	1000 [0.3]	1000 [0.3]	1000 [0.3]
Total Cooling (Except Duct Losses)	22290 [6.5]	13930 [4.1]	7370 [2.2]
Duct Losses	9550 [2.8]	0	0
Total Cooling	31840 [9.3]	13930 [4.1]	7370 [2.2]

precool and dehumidify the forced ventilation air. Because the outside air is hotter and more humid than the house air, this precooled ventilation air can carry, under peak-load conditions, almost three times as much cooling as an equivalent volume of recirculated house air (see below).

Thermal Impact of Preconditioning Ventilation Air

The next step is to determine the cooling load that remains after precooling and dehumidifying 80 cfm [0.04 m^3/s] of ventilation air from an entering (outside ambient) condition of 95°F [35°C] dry bulb and 75°F [24°C] wet bulb to a leaving (supply to house) condition of 50°F [10°C] dry bulb and nearly saturated (90% relative humidity). The sensible heat removed is 3890 Btu/h [1.1 kW] while the latent heat removal is 2670 Btu/h [0.8 kW]. This works out to less than 150 cfm/ton [0.02 m^3/kJ]. A net cooling load, after these amounts of heat have been removed by the heat-recovery heat pump, can then be calculated by subtracting these amounts from the infiltration loads (Table 1, Column 3). This results in negative loads because the air leaving the cooling coil is cooler and dryer than the house air.

The air flow required to meet this cooling load is the sum of the ventilation air plus the amount of air needed to deliver the remaining 7370 Btu/h [2.2 kW] at 400 cfm/ton [0.05 m^3/kJ], or 250 cfm [0.12 m^3/s]. So the total air-flow requirement is 330 cfm [0.16 m^3/s]. Some oversizing might be desirable, but the calculation shows that an air flow of ~400 cfm [0.19 m^3/s] can meet the cooling load in new housing designed with this as an object.

The Heating Mode

The 1200 cfm [0.57 m^3/s] flow rate needed to cool the conventional house is sufficient to support a 90,000 Btu/h [26 kW] heating furnace, assuming a 70°F [39°C] air-temperature rise. Such a unit would be oversized by 150% - 200%. The energy conservation measures listed in Table 1, whose object was to reduce the peak cooling load and thereby the required duct size, will also reduce the peak heating load to the point where only ~150 cfm [0.07 m^3/s] of air flow would be needed to satisfy it. Thus, a furnace sized to match the 330-400 cfm {0.16-0.19 m^3/s] flow rate needed for cooling could still be oversized by ~150%. That is, heating remains a slack variable in the optimization, even in northern U.S. climates.

The Danish House

In 1985 a Danish factory-built house was given to a U.S. national laboratory by the Danish Housing Ministry as part of a cooperative research project. The house was erected on the national laboratory site and monitored over part of a heating season. The approach to system integration advocated in this paper is based on experience gained with this house.

The house is an L-shaped, one-story 1500 ft^2 [140 m^2] structure with an unfinished attic that could serve as expanded living space at a later date. The envelope characteristics are similar to those specified for the advanced house, above. The natural air infiltration rate was measured as 0.1 ACH; this is supplemented by a heat-pump heat recovery system operating continuously at an air-flow rate between 60 and 90 cfm [0.03-0.04 m^3/s]. The ventilation air is delivered to the living space via ductwork located in the conditioned space, adjacent to the wall just below the ceiling. Exhaust air is drawn, through parallel ducts, from locations where odors and moisture are expected, i.e. the bathrooms and the kitchen range hood. The heat reclaimed by the heat pump, together with the heat equivalent of the electric power used, is rejected either to the domestic hot water or to the intake air stream. The normalized heat-loss rate of the house, after accounting for internal gains, (Loss et al. 1986) was 2.1 Btu/ft^2-degree-F-day [43 kJ/m^2-degree-C-day].

The house was not equipped with air conditioning, since cooling is not normally used in Danish residences. In a later project (Andrews et al. 1989), the cooling-mode performance of the house was predicted under the assumption that the heat pump was made to operate in the reverse mode, with appropriate controls. The conclusion was that a house constructed with the characteristics of the Danish House would be close to an ideal embodiment of the system integration approach discussed here. For various reasons, it has not yet been possible to test the theory in this house, but efforts to develop such a project continue.

Costs

A detailed cost comparison of the proposed system with the conventional approach would require that the whole house be included in the economic analysis. Qualitatively, one can identify potential cost savings in the downsized ductwork, balanced by a possible cost penalty associated with making the in-space ducts aesthetically pleasing. Since the heat-recovery heat pump performs base-load cooling for the house, its cost can be included in the overall cooling-equipment inventory. Direct energy cost savings for the heat-recovery heat pump will depend on the fuel used in the conventional system and, if that fuel is gas or oil, the fuel-to-electricity price ratio. A benchmark range based on reasonable assumptions would be $50 to $500 annually. To this must be added a reasonable portion of the additional savings accruing from the envelope and duct system optimization facilitated by the precooling ventilation system.

Conclusion

A system approach to reducing duct losses in new residential construction leads to an integrated system for heating, cooling, and ventilation--enclosed in a tight, efficient building envelope--with precooling and dehumidification of forced ventilation air, and with greatly downsized ductwork located in the conditioned space.

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