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ABSTRACT

Residential air distribution systems, used both for heating and cooling and less commonly for ventilation, have important interactions with the building envelope. These systems can either be enclosed within the envelope or pass outside the envelope (in which case they represent an extension of the envelope). This paper addresses the three major types of interaction between air distribution systems that pass outside the envelope and single-family buildings: (1) duct leakage and duct conduction when the distribution fan is off, which act like a thermal bridge in the envelope; (2) duct leakage during system operation, which creates large changes in the quantity and location of air infiltration and exfiltration through the envelope; and (3) supply/return flow imbalances within individual zones during fan operation, which create elevated envelope pressure differentials, infiltration rates, and exfiltration rates. A simulation tool that was developed to take into account all of these interactions is presented and applied. The simulation tool, based upon the DOE-2 thermal simulation model, a multi-zone airflow network model (COMIS), and an equipment model for the ducts, is used to examine the magnitude of all three interactions. The interaction issues examined include air infiltration/exfiltration magnitude and location, overall thermal exchange when the system is off, and air exchange when the system is operating, with and without internal doors closed. The most surprising result of the analyses presented was that the thermal siphon effect for perfectly sealed ducts was shown to have an impact on the heat exchange between the house and unconditioned spaces that can be more than four times larger than that due to typical duct leakage when the fan is not in operation. This result suggests that this issue merits more careful examination than it has received in the past.

INTRODUCTION

Residential air distribution systems, used both for heating and cooling and less commonly for ventilation, have important interactions with the building envelope. These systems can either be enclosed within the envelope or pass outside the envelope (in which case they represent an extension of the envelope). Approximately 35% of U.S. single-family houses contain forced-air heating and cooling ducts that pass through unconditioned spaces (Andrews and Modera 1991). Recent research has shown that these duct systems have potentially large impacts on energy use and ventilation rates. Researchers at a national laboratory measured an average increase of 80% in the infiltration rate of 31 Tennessee houses whenever the distribution fan was operated (Gammage et al. 1986). In more detailed testing in five houses, researchers in Florida measured a tripling of the infiltration rate due to distribution system operation with internal doors open, and a further tripling of that rate when the doors between rooms were closed during system operation (Cummings and Tooley 1989). Both the infiltration rate increases in the Tennessee houses and the initial tripling of the air change rate of the Florida houses were attributed to leakage in ducts passing through unconditioned spaces, whereas the second tripling of the infiltration rate in the Florida houses was attributed to system imbalances due to inadequate return-air pathways. The importance of air distribution system problems recently has been further highlighted by various researchers (Cummings and Tooley 1989; Cummings et al. 1990; Lambert and Robison 1989; Modera 1989; Modera et al. 1991; Parker 1989; Robison and Lambert 1989). This paper focuses on the building envelope impacts of air distribution systems passing through unconditioned spaces, relying principally on a complex simulation tool that has received limited verification with field measurements.

SIMULATION TOOL

A simulation tool was developed to analyze the interactions of a residential air distribution system with the building envelope and HVAC equipment. This tool is based upon the DOE-2 thermal simulation code (Birdsall et al. 1990), the COMIS airflow network code (Feustel and Raynor-Hoosen 1990), and a new duct performance simulation model, which, in addition to determining the combined impacts of leakage and conduction on duct performance, serves as the interface between COMIS and DOE-2. The basic methodology is to use COMIS to compute airflows through the duct system and the building simultaneously, with and without the distribution fan and heating/cooling equipment in operation. These flows are then passed to DOE-2, within which they are used to calculate loads in conditioned zones and temperatures in unconditioned zones. The COMIS simulation results with the system on are first passed through DUCTSIM, which calculates the duct system efficiency and fractional on-time and incorporates these into the "COMIS-output" file that is passed to DOE-2. A flow chart for the simulation tool is presented in Figure 1, and each of the three simulation codes is described in more detail below.

The prototype building chosen for the analyses in this report is a one-story ranch house located in Sacramento, California. It consists of a floor area of 144 m^2 (1,540 ft^2), an attic with a gable height of 0.8 m (2.6 ft) and a roof angle of 12°, and a crawlspace of 0.8 m (2.6 ft) height. Figure 2 shows the floor plan of the house, including the attached garage. The central plant consists of a furnace/air-conditioning unit, 10 supply ducts, and one return duct. The furnace/air-conditioning unit, as well as the supply and return plenums, is located in the garage. The layout of the air distribution system, which includes both supply and return ducts in the attic, is shown in Figure 3. Both the return and supply ducts and plenums are assumed to be insulated to U-values of 1.42 $W/m^2 \cdot °C$ (R-4 English). The supply ducts have a diameter of 0.15 m and a combined length of 87 m, whereas the diameter of the return duct is 0.45 m with a total length of 9 m. The furnace/air conditioner has a heating output capacity of 80,000 Btu/h (23.4 kW) and a nominal heating efficiency of 80%. The cooling capacity is 40,000 Btu/h (11.7 kW) and the cooling coefficient of performance (COP) is 2.93, which translates into a seasonal energy efficiency ratio (SEER) of 10.

The insulation values for the building envelope were chosen to describe pre-Title 24 California construction. The exterior walls and the floor are assumed to be uninsulated, and the ceiling is assumed to have a U-value of 0.52 W/m^2 (R-11 English). All windows are single pane, and the total window area is 12% of the floor area, all with a shading coefficient of 1.

COMIS Airflow Model

To model the airflows through a building and its air distribution system, a public domain simulation code that solves nonlinear airflow networks (COMIS) is used (Feustel and Raynor-Hoosen 1990). The implementation of this model revolved principally around the specification of the air distribution system. Although the model of the building itself only consists of six nodes for the conditioned spaces and one each for the attic, the crawlspace, and the garage, the model of the duct system includes 35 pressure nodes (or zones).

These various zones are connected via 45 different, nonlinear flow resistances, some of which are described in detail below. For the shell of the building, the resistances are based upon field measurements of whole-building leakage, which was assumed to be uniformly distributed according to surface area. The total envelope leakage chosen produces 8.2 air changes per hour (ach) at a pressure difference of 50 Pa, which corresponds to 860 cm^2 of leakage area, and is based upon field measurement results (Modera et al. 1991; Modera 1986). To take the stack effect into account, the leakage in the walls is divided into three equally sized horizontal leaks for each room in the house, placed at one quarter, one half, and three quarters of the wall height. The leaks through the garage walls to the outside are defined in the same manner. The leaks between the conditioned and unconditioned zones are defined as one vertical leak from each room through the ceiling to the attic, and one from each room through the floor to the crawlspace. The flow exponent, n, used for the leaks through the house envelope is 0.666. The only leaks considered between the rooms are the internal doorways. When the interior doors are open, the leakage assigned to the open doorways corresponds to an effective leakage area of 9,900 cm^2. Closed doors were assumed to have an undercut of 1 cm, based on a field study in 31 California houses, along with a discharge coefficient of 0.6 (Modera et al. 1991).

The leakage values for the crawlspace and attic were calculated based on a 1-m^2 opening per 150 m^2 and a 1-m^2 opening per 413 m^2, respectively. The attic leakage value is based upon the average ratio observed in field measurements of 31 California houses (Modera et al. 1991). Laboratory measurements on vent screens showed a 20% reduction of the airflow due to the presence of screens on these openings. This reduction has been taken into account when calculating the outside airflows for the attic and the crawlspace. It is assumed that the walls of the crawlspace have one horizontal leak each placed at the mid-height of the wall. The leakage of the attic is represented by three leaks: one along the gable and two leaks placed at the attic floor level (soffits) along the north and south walls. Assuming orifice flow through the vents in the attic, the vents in the crawlspace walls and garage and in the internal doorways indicate that $n = 0.5$ for these flow resistances.

The duct system is divided into 3-m (10-ft) duct sections to account for the frictional pressure drop through the ducts, thereby allowing for analyses of selective leak sealing. For the analyses in this paper, the duct leaks on the supply side are assumed to be uniformly distributed and those on the return side are evenly split between the duct and the plenum. The nonuniform return-side split stems from field observations of high leakage rates in the return plenum and the low-pressure side of the air-handling unit. The leakage values for the duct system are calculated by assuming that the specific effective leakage area (ELA) for the duct system, duct leakage per unit floor area, follows that measured by Modera et al. (1991) for pre-1980 houses. For the supply side this corresponds to 0.48 cm^2/m^2, and for the return side 0.54 cm^2/m^2. This gives 39 cm^2 for the return duct, 39 cm^2 for the return plenum, and 69 cm^2 for the supply side, divided into 59 cm^2 for the ducts and 10 cm^2 for the supply plenum, all with a flow exponent of 0.65. In addition, the fan curve for a typical centrifugal fan with a nominal 125-Pa pressure differential at 1,700 m^3/h (corresponds to 2,040 kg/h for an air density of 1.2 kg/m^3) is used to drive the system, and the return filter is assumed to be located between the return duct and the plenum.

Wall-averaged pressure coefficients (C_p-values) for relating the wind-induced pressures at the outer surfaces of the building to the dynamic pressure of the undisturbed wind at roof height were obtained from the *ASHRAE Handbook of Fundamentals*, chapter 14 (ASHRAE 1989). The shielding effect due to the impact of surrounding buildings, trees, etc., on the wind is taken into account by modifying the pressure coefficients to correspond to a shielding class of three (*ASHRAE Handbook of Fundamentals*, chapter 23, 1989), which roughly divides the open-plain pressure coefficients by two.

Duct Simulation Model

The thermal performance simulation program, DOE-2 (Birdsall et al. 1990), which was chosen for the thermal simulation for the prototype building, does not have the option to simulate the thermal loss mechanisms in the duct system. To be able to simulate the impact of the air distribution system on the energy consumption in the building, it was therefore necessary to develop a separate thermal model for the duct system. This model, known as DUCTSIM, calculates the temperature distribution in the ducts when the system is on, the energy delivered to the house by this system, the fractional on-time of the heating/cooling system, and the overall duct system efficiency. DUCTSIM goes through a three-step process to determine the duct system efficiency: (1) it determines the temperature (and humidity) of the air entering the furnace (air conditioner) from the return duct based upon combined conduction and leakage effects, (2) it determines the temperature (and humidity) of the air leaving the furnace (air conditioner), and (3) it determines the flow rate and temperature of the air reaching each of the supply registers.

Starting with the return duct, the temperature distribution is found by performing an energy balance for an infinitesimal section of the return duct, with all leakage assumed to be into the duct at the surrounding air temperature. The resulting differential equation is

$$\frac{d\tau(x)}{\tau(x)} + \frac{a+b}{\dot{m}(x)}\,dx = 0\,. \tag{1}$$

Assuming that the leakage is uniform along the length of the duct, the solution to Equation 1 is

$$\tau(x) = (\dot{m}_{inlet}+ax)^{-(\frac{b+a}{a})}\,(T_{inlet}-T_{\infty})\,\dot{m}_{inlet}^{\;\frac{b+a}{a}} \tag{2}$$

where

$\tau(x)$ $= \Delta T(x) = T(x) - T_{\infty}$, K,

T_{∞} = temperature in the surrounding zone, K,

x = distance from the duct inlet, m,

$\dot{m}$ = duct flow, m^3/s,

a $= K'\overline{(\Delta p)}^{n}$ = leakage flow per unit length, m^2/s,

b $= \frac{U\pi d}{\rho C_p}$, m^2/s,

d = diameter of duct, m,

ρ = density of air, kg/m^2,

C_p = specific heat of the air, J/kg·K, and

U = conductance of the duct wall, $W/m^2 \cdot K$.

The total return is divided into two sections when using Equation 2 - duct and plenum - because it passes through two zones (attic and garage) with different temperatures, so that the temperature at the entrance to the garage section (plenum) and the temperature at the entrance to the furnace/air conditioner are determined. The humidity ratio of the air entering the air conditioner is simply determined from a flow-weighted average of the humidity ratios of the air entering from the house, the attic, and the garage. The heat exchange between the return duct, the attic, and the garage are computed by calculating the average temperature and overall conductance for each section. The average temperature obtained by integrating Equation 2 is

$$\bar{T} = \frac{1}{L}\,\frac{(T_{inlet}-T_{\infty})}{-b}\,(\dot{m}_{inlet}^{\frac{b+a}{a}}\,(\dot{m}_{inlet}+aL)^{\frac{-b}{a}} - \dot{m}_{inlet}) + T_{\infty} \tag{3}$$

where

L = length of duct section, m.

In DUCTSIM, the furnace is assumed to provide a constant output under full load; the full load output of the air conditioner is corrected based on the actual outside dry-bulb and entering wet-bulb temperatures whenever the temperatures differ from the ARI (Air-Conditioning and Refrigeration Institute) test conditions. The temperature rise across the heat exchanger is defined simply from an energy balance on the traversing air. To determine the efficiency of the duct system during air conditioner operation, the temperature and humidity of the air leaving the cooling coil must be calculated. In DUCTSIM, the latent capacity is presently assumed to be limited only by the overall full-load capacity of the air conditioner. Thus, the temperature of the air leaving the cooling coil is determined iteratively based upon the full-load cooling capacity and by assuming that the air leaving the coil is saturated, except for the assumed 10% bypass air.

Moving to the supply ducts, the temperature distribution is found by performing an energy balance for an infinitesimal section of each duct, a procedure similar to that for the return duct. The difference between the two is that all leakage in the supplies is assumed to be out of the duct. The resulting differential equation is

$$\frac{d\tau(x)}{\tau(x)} + \frac{b}{\dot{m}(x)}\,dx = 0\,. \tag{4}$$

Assuming that the leakage is uniform along the length of the duct, the solution to Equation 4 is

$$\tau(x) = (\dot{m}_{inlet} - ax)^{\frac{b}{a}} \, (T_{inlet} - T_{\infty}) \, \dot{m}_{inlet}^{\frac{-b}{a}} \,. \tag{5}$$

Once again, the supply duct is divided into two sections when using Equation 5 because it passes through both the attic and garage, so that the temperature at the exit of the garage section (plenum) and the temperature at the entrance to the house are determined. The heat exchange between the supply duct, the attic, and the garage are computed by calculating the average temperature and overall conductance for each section. The average temperature obtained by integrating Equation 5 is

$$\bar{T} = \frac{1}{L} \, \frac{(T_{inlet} - T_{\infty})}{a+b} \, (\dot{m}_{inlet} - \dot{m}_{inlet}^{\frac{-b}{a}} \, (\dot{m}_{inlet} - aL)^{\frac{b}{a}+1}) + T_{\infty} \,. \tag{6}$$

For simplicity, all 10 supply ducts can be represented by a single temperature, $\bar{T}_{av}$,

$$\bar{T}_{av} = \frac{\sum_{1}^{10}\left[\left(C_p \dot{m} + UA\right)_i \bar{T}_i\right]}{\sum_{1}^{10}\left(C_p \dot{m} + UA\right)_i} \,. \tag{7}$$

The duct efficiency is defined as the enthalpy delivered to/removed from the house by the duct system divided by the enthalpy delivered to/removed from the return plenum air by the furnace/air conditioner. These efficiencies do not include the effects of increased/decreased envelope infiltration caused by the operation of the air distribution system.

The above model for both the return and supply ducts is steady state for each hourly time step. However, a simplified correction for thermal storage in the distribution system as a function of cycles per hour is incorporated in DUCTSIM. Using the above algorithm is reasonable for most duct systems, particularly for plastic flex-ducts (on which this analysis is based), which have very little thermal mass.

DOE-2 Thermal Simulation Model

As mentioned above, DOE-2 does not have the ability to simulate the thermal loss mechanism of a duct system. Thus, the simulation tool is set up such that DOE-2 "sees" a house consisting of a single conditioned zone, an attic, a crawlspace, and a garage. For the conditioned zone, a thermostat maintains the temperature according to a preset schedule; the attic, crawlspace, and garage are unconditioned. Information about infiltration flows into each zone is passed to DOE-2 along with the average distribution system temperatures. To take into account conduction losses as well as leakage, duct conduction losses are translated into equivalent leakage rates before being passed to DOE-2 from DUCTSIM. The modified infiltration flows, herein called "effective flows," combine the infiltration to the zone from the duct components and the conduction losses of the duct components. The effective flows can be obtained from the energy balance for each duct section:

$$\dot{m}_{effective} = \dot{m}_{leak} + \frac{UA_{duct}}{C_p} \tag{8}$$

where

$\dot{m}_{leak}$ = leakage flow, kg/s,
U = conductance of the duct wall, W/m^2·K,
A_{duct} = duct surface area, m^2, and
C_p = specific heat of the air, J/kg·K.

Using the above protocol, DOE-2 doesn't have to know anything about the duct system. The only important issue is that it receives actual or effective infiltration flows for each zone, including those from the duct system, so as to perform the correct energy balance for each zone. The calculation of the infiltration flows is achieved partially by the COMIS post-processor (see Figure 1) and by DUCTSIM, which modifies the post-processor results for fan-off and fan-on operation based upon the fractional on-time.

The second important modification that was made to DOE-2 was to incorporate the duct efficiency into its systems simulation. The effect of a duct efficiency smaller than one is that the house experiences less heat supplied/removed. Hence, the unit has to operate longer to cover the loads, which, in addition to increasing energy consumption, increases the part-load efficiency of the heating/cooling equipment. This effect was incorporated by directly accessing the DOE-2 code, modifying the variables in the program flow, and/or recomputing intermediate variables within the code.

Table 1: Characteristics of the House	
Construction	Single-Story Ranch
Foundation	Crawlspace
Floor Area	144 m^2 (1,540 ft^2)
Insulation	California pre-Title 24
Ceiling U-value	0.52 $W/m^2\cdot°C$ (0.092 $Btu/h\cdot ft^2\cdot°F$)
Floor and Wall U-value	Uninsulated
Windows	Standard Single-Pane
Envelope Leakage Area	860 cm^2
Return Leakage Area	0.5 cm^2/m^2 78 cm^2
Supply Leakage Area	0.5 cm^2/m^2 69 cm^2
Duct U-value	1.42 $W/m^2\cdot°C$ (0.25 $Btu/h\cdot ft^2\cdot°F$)
Operation	Heating Setpoint 20 °C (68 °F), Night Setback 16 °C (60 °F) Cooling Setpoint 26 °C (78 °F) Window Openings Based on Outdoor Enthalpy

DUCT COMPONENT OF BUILDING ENVELOPES

In the case of a distribution system passing outside the building envelope, it acts as an extension of the building surface. This implies that such a duct system is involved in heat and mass transfer with the surrounding zones. The heat transfer is given by the level of duct insulation and surface area, along with the temperature difference across the surface. The mass transfer is a function of the leakage area of the duct system and is driven by the differential pressures across the leaks. This section focuses solely on the impact of the distribution system on the performance of the house without the influence of the fan.

For the purpose of comparison, the base-case was assumed to be a house without any duct system. Its loads are covered by internal heating/cooling sources not requiring any ducts. It is understood that the thermostat operation is identical for both the base-case house and any house to which it is compared.

The average infiltration/exfiltration over one year of the base-case house described above is 150 kg per hour or 0.43 air changes per hour (ach) excluding window opening. The largest infiltration components are the crawlspace flows (81 kg/h or 54%) and the outside flows (66 kg/h or 44%). An outside flow is considered to be the flow coming directly through the facade and not via the crawlspace, attic, or garage. This house experiences a heating load of 9,900 kWh (33.8 MBtu) and a cooling load of 4,200 kWh (14.2 MBtu) over a period of one year, resulting in a total site energy impact of 14,100 kWh/yr (48.0 MBtu/yr). The loads are determined by zone infiltration, heat transfer between the zones and to the outside, and the prescribed indoor air temperature range (see Table 1). The corresponding natural gas consumption for heating is 15,200 kWh/yr (52.0 MBtu/yr), and the electric consumption for cooling is 1,768 kWh/yr.

Adding a distribution system without a fan, which is described in the "Simulation Tool" section, to the base-case house not only changes the total infiltration/exfiltration of the house, but also skews the ratio of infiltration to exfiltration for different envelope components. It also results in a 1% increase in gas consumption, but the impact on the cooling consumption is negligible. Again, the heating/cooling is provided by internal sources not utilizing the distribution system. The average infiltration/exfiltration of the house increases by 13% to 169 kg/h (0.49 ach) owing to the distribution system. Based simply on the increase in leakage area due to the addition of the duct system, the total house leakage flow would be expected to increase by 17%. This is not a contradiction, since the leakage area isn't added uniformly to the house leakage area, but is concentrated at a certain height. Finally, as the infiltration from the crawlspace increases by 15%, whereas that from outside only increases by 7%, higher indoor radon concentrations would occur in some regions as a result of the duct system.

An examination of the air leakage flows for the inoperative distribution system reveals that exfiltration is dominating by a factor of 40. The total exfiltration of the duct system averages 41 kg/h versus a 1-kg/h average of total duct infiltration flows. This is due to the fact that all the ducts are located in the attic, and that the house is rarely under inverse stack conditions. The exfiltration of an inoperative distribution system thus accounts for 24% of the total house exfiltration and is equal in magnitude to 27% of the base-case house exfiltration.

Considering the house envelope only, the attached distribution system decreases the envelope exfiltration by 15% (128 kg/h). Contrary to the change in exfiltration, the envelope infiltration expands to 168 kg/h, an increase of 12%.

Conduction losses from duct systems are normally computed from the level of insulation and the surface area. However, for an inoperative system these losses are determined by the airflow to the duct walls, as the predominant thermal resistance is embodied in the airflow resistance of the duct system. This airflow is only established if there is a thermal siphon effect, i.e., air circulating through the house and the duct system driven mainly by temperature differences. Such a flow is largest if vertical sections of the duct system pass through zones with temperatures different from the house. Therefore, a distribution system with the return in the crawlspace and the supply in the attic (or vice versa) will experience the largest flows. The simulated natural flow for a crawlspace return/attic supply setup is 95 kg/h on average with a peak at 202 kg/h, reversing in direction depending on the temperatures in the crawlspace, garage, and attic. During the summer, when the garage is hotter than the house, air flows into the return, warms up in the garage, and enters the house through the supply registers. This pattern reverses whenever the garage temperature sinks below the house temperature, which is by far the more common situation for this Sacramento house. The conduction loss flow corresponds to a UA-value 70% smaller than the actual UA-value of the distribution system, which is 88.6 W/°C. It must be kept in mind that this number was achieved under the geometric configuration most favorable to the siphon effect, and is therefore close to the upper limit of what can reasonably be expected in a single-story house.

IMPACT OF FAN OPERATION ON AIR INFILTRATION

To obtain results on the impact of the fan operation on the house, it was necessary to simulate continuous fan operation for a period of one year. Thus, the results described below will be observed only during fan operation and not on average for normal cycling of the heating/air-conditioning system, since such a system generally does not operate continuously in an actual house.* For the house/appliance configuration described above, it is sufficient that the system operates for a total of 1,222 hours per year in order to cover the loads and thus maintain the desired space temperature. The furnace is operational during 3,496 hours with an average on-

* It should be noted that some manufacturers recommend continuous fan operation.

time of 17%. The air conditioner is working during 1,217 hours with an average on-time of 51%. The resulting rather limited distribution fan operation, however, influences the quantity and location of the leakage flows significantly. The reason for this is the large pressure differences imposed by the fan on the duct leaks. They significantly exceed the differential pressures caused by the wind or stack effects (duct pressures are as high as 80 Pa across the return plenum).

During fan operation, the average house air exchange becomes 434 kg/h (1.24 ach), which is almost three times that of the base-case house. Both crawlspace and outside infiltration to the house decrease to a negligible 29 and 48 kg/h, respectively. This, however, is a welcome side effect, since the infiltration of potentially radon-laden air from the crawlspace shrinks by 69%. Overall 7% of the infiltration comes from the crawlspace with the system on versus 54% of the infiltration coming from the crawlspace when the system is off or for the base-case, suggesting a much lower radon concentration. On the other hand, it is important to keep in mind that a reduction in entry from the crawlspace and in concentration inside the house will not always occur. This particular case has more return than supply leakage (see the "Simulation Tool" section); others may have excess supply leakage, in which case the indoor radon concentration would increase when the system turns on. Thus, leaky ducts should not be considered a radon mitigation technique.

During times when the distribution fan is operating, the main component of house infiltration, 357 kg/h (82%), is the infiltration through the distribution system, which occurs solely on the return side. The duct infiltration by itself is 138% larger than the total house infiltration for the base-case. The supply side has an exfiltration of 177 kg/h, the result being that the house envelope infiltration shrinks by 49% whereas the house envelope exfiltration expands by 71% compared to the base-case. Additional analysis should be performed to determine whether these changes are uniformly distributed over the year or tend to vary seasonally. Such a seasonal analysis would determine the impact of these results on moisture problems.

The average duct infiltration of 357 kg/h described above does not represent the total leakage mass flow into the distribution system. The system sucks in 400 kg/h of attic and garage air through the return. However, a fraction of this air gets expelled on the supply side with the exfiltration flow. Thus, only 357 kg/h of outside air reaches the house through the supply registers, which, when combined with the 77 kg/h of air infiltration through the envelope, yields a total of 434 kg/h of infiltration to the conditioned space.

PRESSURE-INDUCED IMBALANCES DUE TO INTERNAL DOOR CLOSURES

All three cases described above - the base-case, the distribution system with the fan off, and the distribution system with the fan on - were simulated with the internal doors open. As can be seen on the layout (Figure 3), there is only one return for all six conditioned rooms. Therefore, five rooms have supplies but no returns. Approximately 600 kg/h of air is flowing from these rooms through the door openings to the one return when the distribution fan is operating. Closing these doors severely restricts the internal airflows between conditioned spaces and thus creates pressure differentials not only across these doors but also across the envelope. The imposed pressure differences have a large impact not only on the total house air exchange but also on the sources of the associated infiltration.

An inoperative system with closed internal doors has a rather minor impact on the total house air exchange, increasing it negligibly relative to a house with open doors. However, the air change rate of 0.5 is 16% higher than that for the base-case. On the other hand, when the system fan is turned on the leakage flows change dramatically.

When the fan is turned on, the total house air exchange rate grows to 2.05 ach (714 kg/h), which is 65% greater than that with open doors, or 376% greater than the base-case. Both envelope infiltration and exfiltration swell, the former by 353% and the latter by 105%, due to closing the doors compared with open doors. The massive changes in flows through the envelope coincide with relatively minor increases in duct infiltration/exfiltration flows, by 2% to 365 kg/h and by 6% to 187 kg/h, respectively. The reason for this is that closing internal doors influences the duct pressures relatively little since the distribution system experiences high pressures even with the doors open. In contrast to the distribution system, closing doors has a large impact on differential pressures across the envelope and thus results in significantly increased air exchange. Additionally, the crawlspace infiltration to the house increases approximately fivefold from 29 kg/h to 143 kg/h by closing the internal doors.

DISCUSSION

The annual average infiltration and exfiltration effects resulting from different physical mechanisms associated with duct systems passing outside conditioned spaces are summarized in Table 2.

Table 2: House Air Exchange and Duct Infiltration/Exfiltration [kg/h]		
Base Case:	House	150 (0.43 ach)
	Duct Infiltration	-
	Duct Exfiltration	-
	Envelope Infiltration	150
	Envelope Exfiltration	150
	Infiltration from Outside	66
	Infiltration from Crawlspace	81
System Off:	House	169 (0.49 ach)
	Duct Infiltration	1
	Duct Exfiltration	41
	Envelope Infiltration	168
	Envelope Exfiltration	128
	Infiltration from Outside	71
	Infiltration from Crawlspace	93
System On:	House	434 (1.24 ach)
	Duct Infiltration	357
	Duct Exfiltration	177
	Envelope Infiltration	77
	Envelope Exfiltration	257
	Infiltration from Outside	48
	Infiltration from Crawlspace	29
Doors Closed, System Off:	House	174 (0.5 ach)
	Duct Infiltration	1
	Duct Exfiltration	40
	Envelope Infiltration	173
	Envelope Exfiltration	134
	Infiltration from Outside	70
	Infiltration from Crawlspace	93
Doors Closed, System On:	House	714 (2.05 ach)
	Duct Infiltration	365
	Duct Exfiltration	187
	Envelope Infiltration	349
	Envelope Exfiltration	527
	Infiltration from Outside	87
	Infiltration from Crawlspace	143

Examining first the impact of the duct system on exfiltration through the building envelope, it seems that the addition of the duct system, although it increases the overall air change rate of the building, actually decreases envelope exfiltration while the fan is not in operation. This can be seen by subtracting the duct exfiltration from the house air change and realizing that the remaining exfiltration must be through the envelope. This is not surprising, as the entire duct system is located in the attic, and therefore represents a significant exfiltration. When the fan is turned on, however, the exfiltration rate through the building shell increases dramatically. This can be explained by the fact that the return leakage rate is significantly larger than the supply leakage rate when the fan turns on, which results in pressurization of the house. This effect is magnified even further when the internal doors are closed. As door closures have a much larger relative effect on the house pressures than on duct pressures, the exfiltration rate through the envelope increases dramatically. All of these results suggest that moisture transport through the walls can be significantly affected by the addition of an air distribution system. It is also clear that the data should be split by season to evaluate the importance of this effect.

One other effect that can be extracted from the results in Table 2 relates to the relative importance of off-cycle duct leakage and conductance. Namely, the addition of a passive air distribution system increases the air exchange rate of the house by 19 kg/h on average. Comparing this with the average flow through a perfectly sealed duct system due to the siphon effect when the fan is not operational, it becomes clear that the latter effect can be significant. More specifically, if it is assumed that the air siphoning through the sealed duct system comes to equilibrium with the space through which the duct passes, it seems that the heat exchange between the living space and the unconditioned spaces is more than four times larger for the siphon effect compared to the whole-house infiltration impacts of duct leakage when the fan is not operating. It should be noted, however, that the effect of duct leakage would be somewhat greater if the return duct were in the crawlspace, as was assumed for the siphon simulation. On the other hand, the impact of return duct location on off-cycle air exchange is expected to be relatively minor. It should also be noted that the complete heat transfer assumption for the duct during siphoning needs to be checked and a more rigorous model derived to deal with the impacts of higher levels of duct insulation.

CONCLUSIONS

The simulation-based analyses presented in this paper lead us to conclude that duct systems passing through unconditioned spaces have a significant impact on the performance of a house, independent of the operating status of the distribution fan. They increase the house air exchange rate, the conduction losses, and the overall energy consumption. Earlier studies have focused on the effects when the distribution fan is operating; however, our analyses also show significant impacts even when the system is off. Most surprisingly, the siphon effect for perfectly sealed ducts was shown to have a thermal impact on the heat exchange between the house and unconditioned spaces that can be more than four times larger than that due to typical duct leakage when the fan is not in operation. These results suggest that this issue merits more careful examination than it has received in the past, including examination of the internal flow resistance of the ducts, examination of duct geometry and location impacts, and examination of the point at which the R-value of the duct insulation becomes the dominant resistance to heat transfer.

The second conclusion to be drawn from the results presented is that the simulation tool developed, in addition to its utility in analyzing distribution system efficiencies, can also provide valuable information about the interactions between the distribution system and the house envelope. Issues that remain to be explored based upon the data generated for this paper include the moisture and radon concentration impacts of distribution systems with and without the distribution fan in operation.

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LIST OF FIGURES

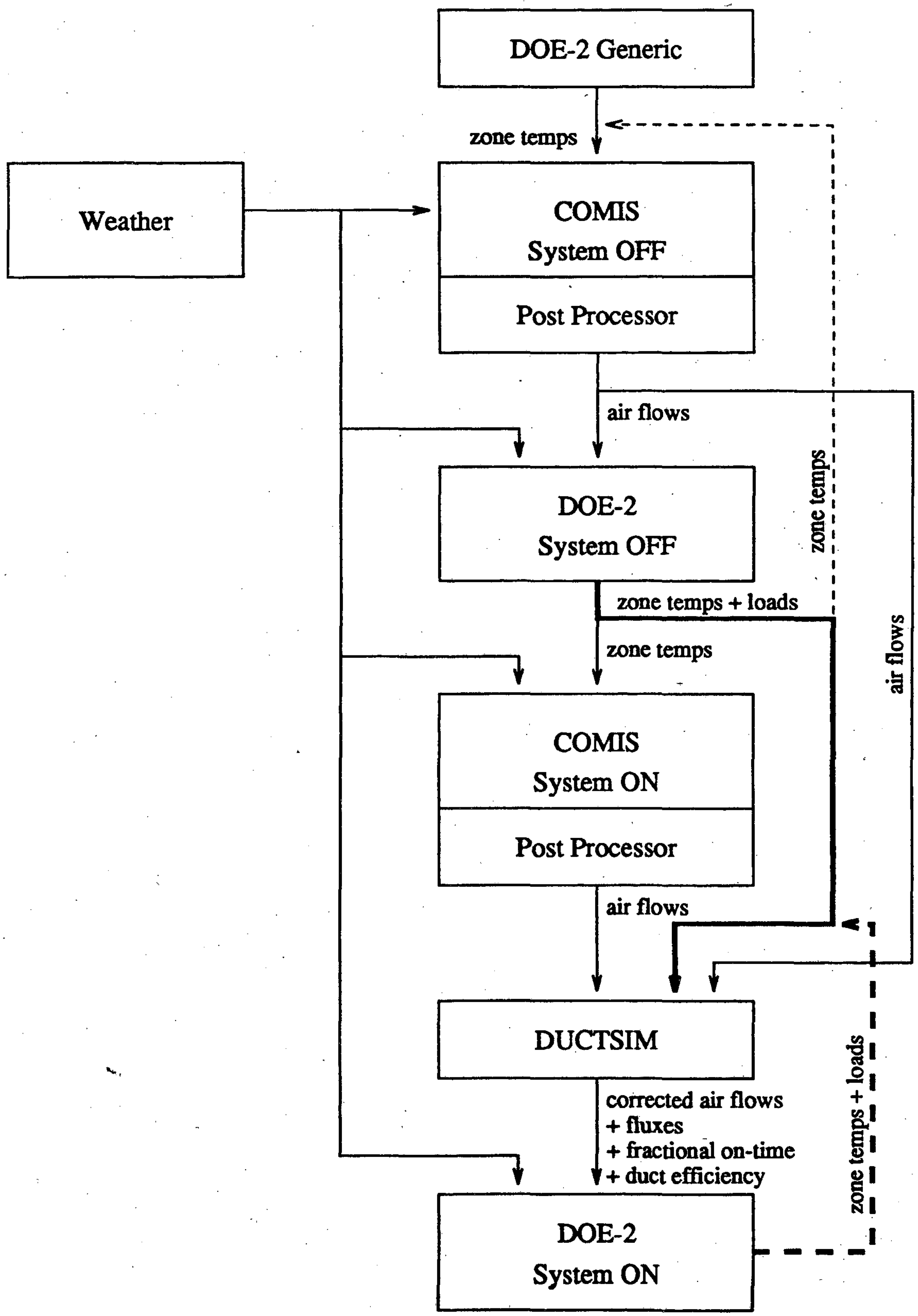


Figure 1. Schematic flow chart of programs used for simulating the performance of residential air distribution systems.

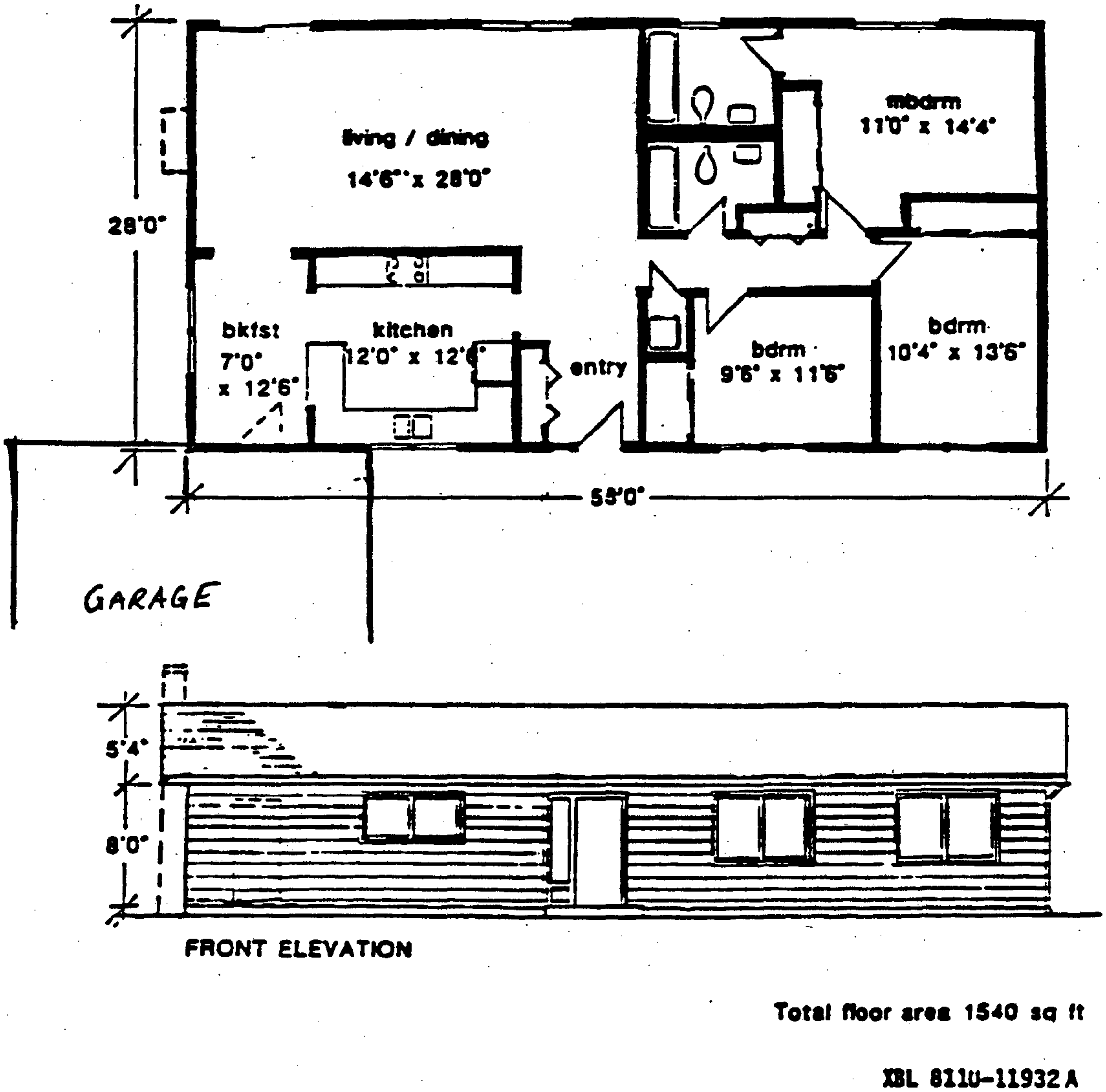
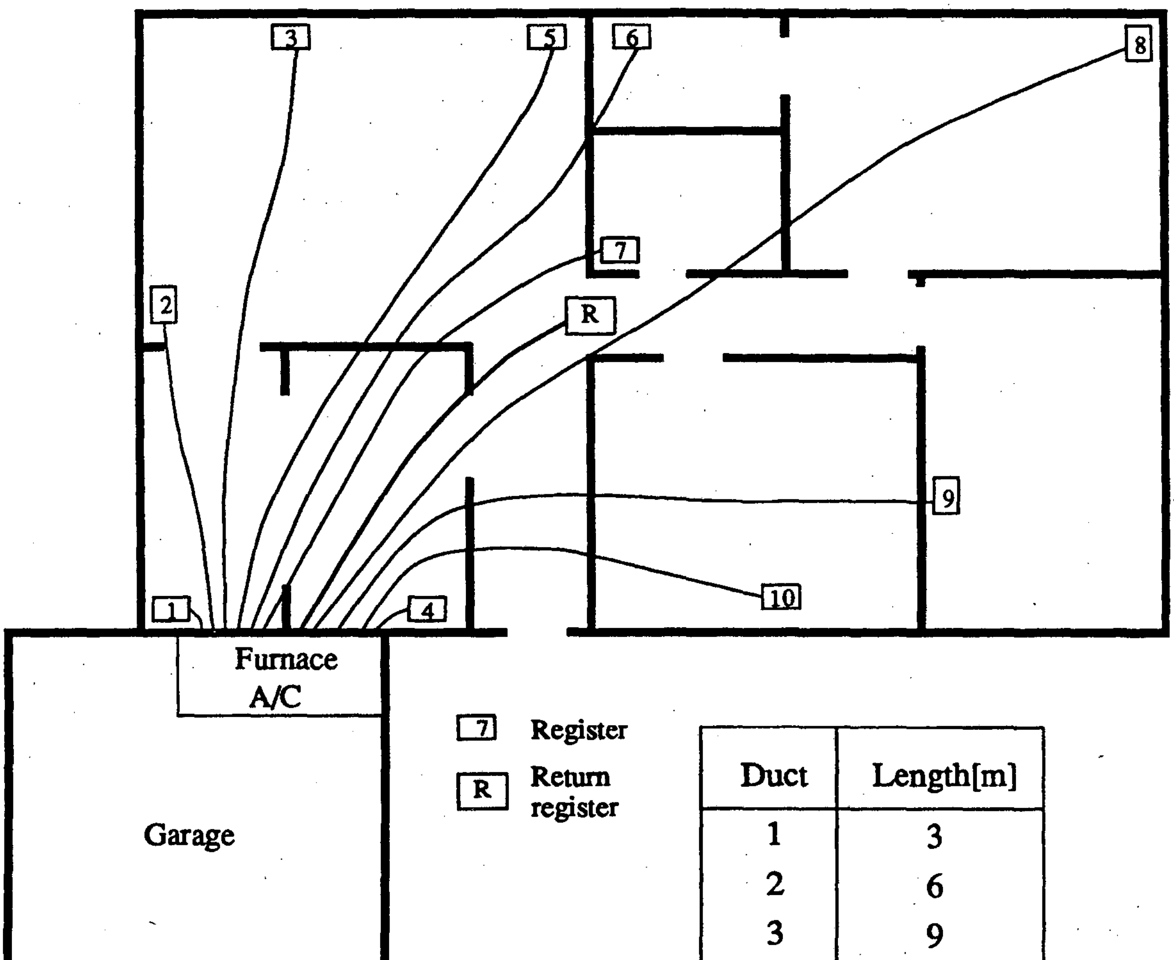


Figure 2. Floor plan of the building used for simulating the performance of residential air distribution systems.



Duct	Length[m]
1	3
2	6
3	9
4	3
5	9
6	12
7	9
8	15
9	12
10	9
R	9

Figure 3. **Layout of the duct system in the building used for simulating the performance of residential air distribution systems.**

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