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Characterizing the performance of residential air distribution systems

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Abstract

Approximately 35% of US single-family houses contain forced-air heating and cooling ducts that pass through unconditioned spaces. These duct systems have been shown to have a potentially large influence on energy use and ventilation rates. To investigate the parameters affecting the performance of these systems, a 31-house field study of distribution-system performance based on diagnostic measurements was performed in California, and an integrated airflow and thermal simulation tool was developed. The results of the field study, a brief description of the simulation tool, and the results of the first applications of the simulation tool are presented. The field-study measurements generally agreed with the findings in earlier studies, provided field experience with new diagnostic tools, and provided system/house characterization data for use in simulation codes and in the development of retrofit protocols. Some highlights of the field results include: (1) building envelopes appear to be approximately 30% tighter for California houses built after 1979; (2) duct system tightness showed no apparent improvement in the post-1979 houses; (3) distribution-fan operation added an average of 0.45 ACH to the average measured air change rate of 0.24 ACH, and (4) an average of 20% of the furnace heating effect was measured to be lost due to duct conduction losses alone. The simulation tool developed is based upon DOE-2 for the thermal simulations, MOVECOMP, an airflow network simulation model, for the duct/house leakage and flow interactions, and a combined heat and mass transfer model of the duct performance. The first complete set of simulations performed for a new ranch house in Sacramento CA indicated that steady-state duct-system efficiencies vary over a large range with outside temperature, ranging from 50 to 95% (decreasing with increasing outside temperature for cooling and decreasing outside temperature for heating). The simulations also indicated that the location of the return duct can have a large influence on duct-system efficiency during the cooling season.

Introduction

Approximately 50% of the households in the US have central warm air furnaces and air distribution ducts [1, 2], which translates into more than 1 million kilometers of residential ducts*. Given their widespread use, and the fact that they represent the vital link between houses and their space-conditioning plants, the energy and comfort-effectiveness of residential duct systems are regularly revisited as a topic of study. Interested parties have included the Gas Research Institute [3], researchers at the National Bureau of Standards and Princeton University [4], and Brookhaven National Laboratory [5], as well as a special project committee of the American Society of Heating, Refrigeration and Air-Conditioning Engineers [6–8], all of whom have reached the same conclusion, that air distribution systems can significantly influence residential heating and cooling.

Approximately 65% of US residential ducts (mostly in the southern and western regions) pass through unconditioned spaces, and therefore have the potential to incur significant energy losses, and, as will be seen below, can significantly change ventilation rates** [1]. A number of studies of unconditioned-space duct systems have measured large changes in building air infiltration rates due to air distribution system operation. Researchers at Oak Ridge National Laboratory measured an average increase of 80% in the infiltration rate of 31 Tennessee houses whenever the distribution fan was operated [9]. In more detailed testing in five houses, researchers in Florida measured an infiltration-rate

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*45 million households with an average length of ductwork of 30 m.

**Although most prevalent in the US, such installations can also be found in the UK.

tripling 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 [10]. 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 infiltration tripling in the Florida houses was attributed to system imbalances due to inadequate return-air pathways.

The importance of air distribution system problems has recently been further highlighted by various researchers [10–15]. Based upon measured leakage data from 200 houses and upon measurements of actual driving pressures, the energy required to cool the air that leaks to and from a typical duct system in a Sacramento house has been calculated to represent between 1 and 2 kW (depending upon the location of the ducts) of peak-hour demand and 20–40% of the peak cooling day consumption [13]. That same leakage was also calculated to create approximately 1 kW of peak heating demand and 2000–3500 kWh of annual electricity consumption for a heat-pump heated house in Sacramento [13].

This paper presents the results of a field study to better characterize these systems, a brief description of a simulation tool developed to analyze the implications of the field characterization results, and the results of a preliminary application of the simulation tool.

Field characterization of duct systems

Three potential inadequacies are usually identified with residential air distribution systems:

(1) leakage between the ducts and their surroundings (particularly ducts in unconditioned spaces);

(2) excess infiltration and temperature imbalances due to improper balancing of supply and return flows;

(3) heat conduction through the duct surfaces (particularly ducts in unconditioned spaces, and including transient effects).

To improve our understanding of these inadequacies, two major efforts were undertaken: (1) a field study to characterize air-distribution system performance and retrofit potential in California, and (2) development of a simulation-based tool for analyzing peak-load mitigation and energy conservation potentials.

Field-study measurements

Although preliminary studies have indicated large potential effects of distribution systems on heating, cooling and ventilation, a more directed field study to characterize air distribution systems in California residences was needed prior to embarking on large-scale air-distribution retrofit efforts, or incorporating new algorithms for distribution-system performance in the building energy code for the state. The field study performed consisted of comprehensive measurement and analysis of distribution-system performance in thirty-one houses, chosen to be consistent with of the stock identified in surveys of builders and HVAC-contractors within California*.

The diagnostic measurement protocol developed for the field measurements consisted of a two-day two-person procedure based upon computer-controlled prompting and data acquisition. To increase the precision of the results, and reduce the possibility for operator error, 90% of the data taken was recorded by a computer/data-acquisition-system programmed to step the operator through the entire measurement sequence. The system developed was based upon a single instrumentation rack filled with: (1) tracer-gas injection and sampling equipment, (2) multiplexed and fixed-purpose pressure measurement equipment, and (3) a data-acquisition/control system (see Fig. 1). This system was interfaced with a personal computer programmed to step the operator through the full series of diagnostic measurements. This system was programmed to make simultaneous time-averaged temperature, pressure, and flow measurements, as well as instantaneous concentration measurements and to record those measurements directly on the personal-computer hard disk. This type of operation reduces both instrumentation- and operator-induced uncertainties. To further minimize field-technician errors, the protocol includes step-by-step sensor installation and measurement instructions, including pictorial descriptions of sensor installations and building configurations (see example configuration in Fig. 2), photographic documentation lists, and building-documentation instructions. The measurements performed included:

- *leakage measurements*: including envelope leakage area, supply duct leakage area and return duct leakage area. The duct leakage was measured in

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*Houses were selected by asking for volunteers amongst the employees of three California electric and gas utility companies. Although a random selection of the houses was not performed, the sample of houses encompassed a large geographical region including four distinct climate zones, the full range of house and system vintage, and all of the duct types and locations identified in the surveys.

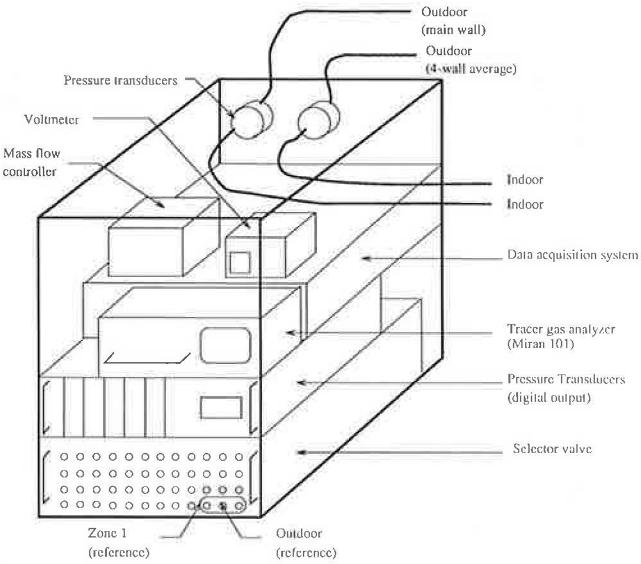


Fig. 1. Schematic representation of the instrumentation rack used for the field study of residential air distribution systems.

each house using two techniques, both of which are incorporated into a proposed ASTM standard on field measurement of duct leakage. The first technique (Proposed ASTM Method A) uses subtraction of fan-pressurization test results with and without supply and/or return registers sealed to determine duct leakage areas. The second technique (Proposed ASTM Method B) uses a flow-capture hood connected to a single unsealed supply or return register during fan pressurization testing to measure the flow through the duct leaks. The results presented in this paper are based on the second technique (Method B).

- *duct pressure measurements*: during normal fan operation, including pressure differential measurements across the supply plenum, the return plenum, just inside the supply registers nearest and furthest from the plenum, and just inside the return grille.
- *pressure imbalance measurements*: including pressure differential measurements across the envelope and between zones with and without the distribution fan in operation, and with and without interior doors closed.
- *ventilation-rate measurements*: with and without the distribution fan in operation. These measurements were made with a single tracer gas in all houses.
- *distribution-fan and register flow measurements*: The distribution-fan flows were measured with a tracer-gas technique, and the register flows were measured with a flow-capture hood.
- *temperature measurements*: including indoor, outdoor, attic and crawl-space measurements, with and without the distribution fan in operation, and duct temperature measurements during normal equipment cycling. The attic and crawl-space measurements are used to verify the assumptions used in analyses of duct-leakage and duct-conduction energy implications. The duct-system temperatures included the supply plenum, the return plenum, and just inside the supply registers nearest and furthest from the plenum. These temperatures are used to estimate conductive losses from the ducts.
- *site description*: including pictures of the house and its surroundings, the duct system (including plenums and registers), and the furnace/air-conditioner, as well as detailed maps of the crawl-space, house, attic and duct system.

Simulation tool

A simulation-based analysis tool was developed to complement the diagnostic measurements. The

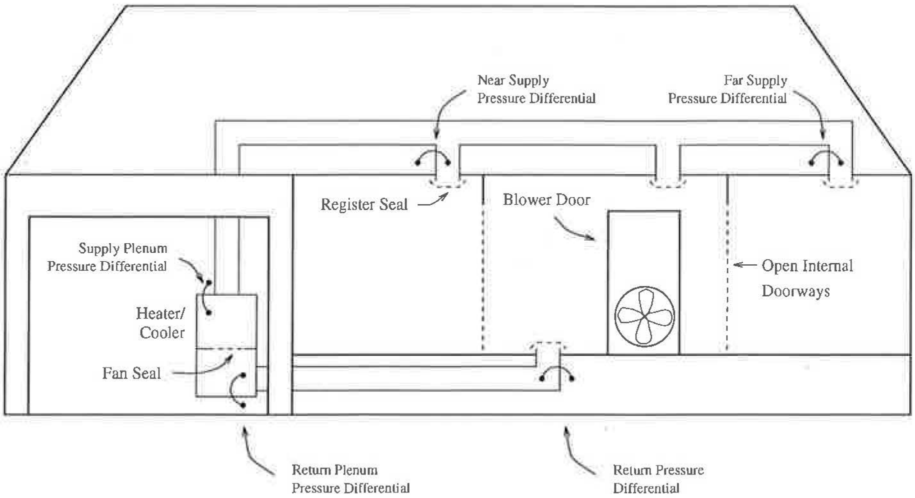


Fig. 2. Schematic of house/equipment configuration used in the field study to measure the leakage of the return ducts.

tool was designed for evaluating peak-load mitigation and overall energy conservation potential for improved distribution systems, including measure-by-measure analysis of duct-system retrofits or new-construction alternatives. To accomplish this, in addition to building envelope simulation with a thermal model, accurate modeling of the leakage-induced airflows, airflows created by system imbalances and conduction heat losses from the ducts is required. This modeling was accomplished by interfacing DOE-2 [16], an hour-by-hour thermal simulation model, with MOVECOMP [17], a multi-zone airflow network model, and with a combined heat and mass transfer model of a duct system. The entire simulation tool is illustrated schematically in Fig. 3.

To use the MOVECOMP airflow network model for our purposes we needed to specify all of the air-leakage characteristics of the distribution system, the building envelope, the attic, the crawl-space and the garage, as well as the internal airflow characteristics of the distribution system. The house with the chosen characteristics is implemented into the model by defining a set of uniform-pressure zones (i.e., pressure nodes) that are connected to each other by specified airflow resistances. To adequately describe the pressure field in the duct system we settled on using one node for every three meters (ten feet) of duct, which corresponds to approximately 30 pressure nodes for the entire duct system. In addition, six nodes were required to describe the interior zones of the house, one note was used for the attic, one for the crawl-space, and one for the garage.

The leakage data required to describe the interconnections between the pressure nodes were obtained from the LBL air-leakage database [18], as well as from more recent measurements made by LBL, the Florida Solar Energy Center (FSEC) and Lambert Engineering (Oregon) [10, 13, 15, 19]. To allow for easy modification, the input data was specifically constructed in a modular manner. Based upon the present input data, three prototype simulations were constructed and run, one modeling the airflows while the distribution fan is operating, one modeling airflows with the fan off, and one modeling airflows for the same house without an air distribution system.

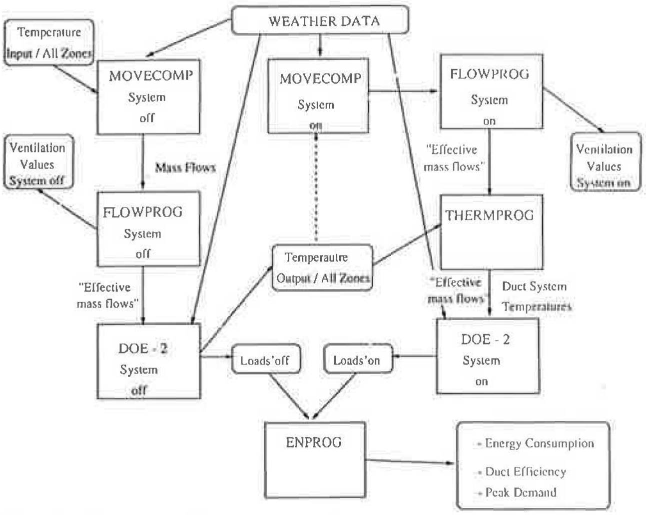


Fig. 3. Schematic flow charge of programs used for simulating the performance of residential air distribution systems.

To simulate the operation of the duct system, and its interaction with the house, energy transfer between the ducts and their surrounding zone (attic or crawl-space) is modeled by a separate combined heat and mass transfer simulation program (THERMPROG) specifically developed for the ducts. The attic and crawl-space temperatures are obtained from DOE-2 interactively, based on applying the energy transfer to/from the duct to the zone in which it is located. This process takes into account the partial recovery of duct heat and mass transfer, however the simulation presently does not take into account the effects of the thermal mass of the duct system, the influence of the duct system on air-conditioner or furnace efficiency, nor the energy implications of the distribution-system fan. THERMPROG also calculates the overall duct-system efficiency, including leakage and conduction, for each hour of the year, where the duct-system efficiency is defined as the energy delivered to the house divided by the energy delivered by the furnace or air conditioner.

The building chosen for the simulations was a slightly enlarged version of the single-story California ranch house traditionally used for residential energy policy calculations. This prototype house has 143 m^2 of floor area, supply ducts with a U-value of 1.42 W/m^2K located in the attic, and a single return duct with the same U-value located either in the crawl-space or in the attic. An exterior elevation and plan for the prototype house are depicted in Fig. 4, and the duct layout is depicted in Fig. 5. The air-leakage input data, along with the thermal specifications of the prototype house, are summarized in Table 1.

Results

Field study

The two-day diagnostic measurement procedure was performed in a total of 31 houses in the San Diego, Sacramento, and San Francisco Bay regions

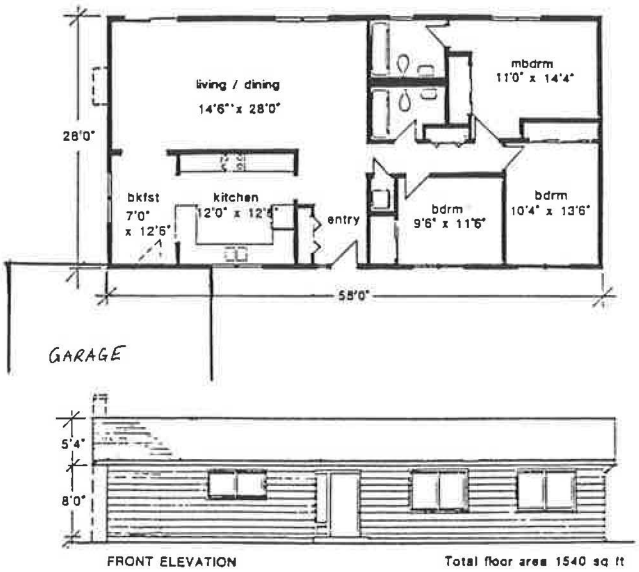
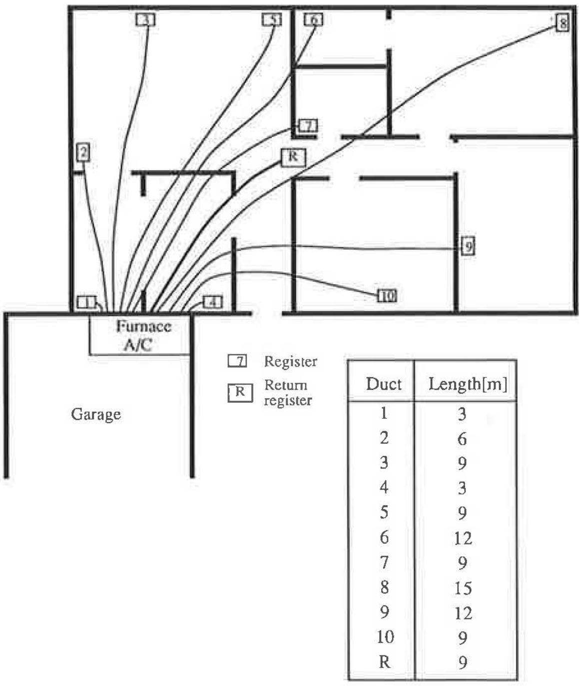


Fig. 4. Floor plan of the prototype building used for simulating the performance of residential air distribution systems.



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

Fig. 5. Layout of the duct system in the prototype building used for simulating the performance of residential air distribution systems.

of California. Of these houses, 19 were constructed prior to 1980, the remainder constructed in 1980 or later. The Sections below summarize the data for the significant parameters associated with each of the duct-system loss mechanisms: (1) duct leakage, (2) duct conduction, and (3) supply/return flow imbalances, for both the pre-1980 and post-1979 houses.

Duct leakage

Duct leakage results are reported for one of the techniques applied in each house. The set of measurements reported (Proposed ASTM Method B) uses a direct measurement of the flow through the duct leaks together with auxiliary duct-pressure measurements to obtain the duct leakage. Although Method B suffers from higher uncertainties in the determination of the pressure difference across the duct leaks, it seems to provide the most reliable results overall. The envelope leakage measurements and duct leakage measurements obtained by Method B are summarized in Table 2 for both pre-1980 and post-1979 construction.

Several observations can be made from the results presented in Table 2. First, it seems that the specific leakage area of the building envelope dropped by approximately 35% in the post-1980 construction, a result which suggests that California houses, like those in the remainder of the US are getting tighter. On the other hand, it seems that duct tightness has not improved with time, the data suggesting that, if anything, both supply and return duct leakage have increased. Finally, as observed in earlier studies, the coefficient of variation of the measured duct leakage is high (40–80%), suggesting that retrofit programs would benefit from pre-retrofit measurements of duct leakage. The supply/return leakage fractions in Table 2 are also consistent with earlier field results [13]. More specifically, despite their substantially smaller surface area, return ducts typically have more leakage area than supply ducts. This is generally attributed to the impression among duct installers that return leakage is not as important as supply duct leakage. The significance of excess return leakage area is amplified by the fact that the pressure differentials across return-duct leaks are apparently twice those across supply-duct leaks (see Table 3). Moreover, the cooling energy implications of airflow into return leaks in attics can be even larger than those of supply leaks, due to the potentially larger enthalpy differential between attic air and house air compared to that between supply air and outside air.

To estimate the influence of duct leakage on distribution system performance, the leakage characteristics of the ducts, the pressures driving the flow through those leaks, and the enthalpy of the air leaking into or out of the ducts, are needed. The measured leakage characteristics were measured as described above, and the driving pressures were measured at five locations in every duct system

TABLE 1. Characteristics of prototype house

Construction	Single-story ranch
Foundation	Crawlspace
Floor area	143 m^2
Ceiling *U*-value	0.189 W/m^2K
Floor and wall *U*-value	0.30 W/m^2K
Windows	Standard double-pane
Envelope leakage area*	6.8 cm^2/m^2 980 cm^2
Return-duct leakage area*	0.6 cm^2/m^2
Supply-duct leakage area*	0.4 cm^2/m^2
Duct *U*-value	1.4 W/m^2K
Operation	Night set-back and set-up Window openings based on outdoor enthalpy Interior doors always open

*All leakage areas are effective leakage areas at 4 Pa, defined as in ASTM Standard E779, and normalized by conditioned floor area of the house.

TABLE 2. Envelope and duct leakage data by year of construction

Characteristic	Pre-1980		Post-1979	
	Mean	Std. dev.	Mean	Std. dev.
Number of houses	19		12	
Floor area (m^2)	162	49	185	36
Specific envelope leakage area (cm^2/m^2)*	6.0	2.6	3.9	0.5
Supply-duct leakage area (cm^2/m^2)↓ (Pressurization)	0.48	0.20	0.52	0.33
Supply-duct leakage area (cm^2/m^2)↓ (Depressurization)	0.47	0.20	0.55	0.39
Return duct leakage area (cm^2/m^2)↓ (Pressurization)	0.56	0.36	0.49	0.39
Return-duct leakage area (cm^2/m^2)↓ (Depressurization)	0.52	0.43	0.51	0.34

*Leakage of the envelope only (excluding duct leakage) divided by conditioned floor area.
↓ Duct leakage divided by conditioned floor area.

during normal fan operation (supply plenum, nearest supply register, furthest supply register, return plenum, return register), and are summarized in Table 3. The enthalpy of leaking air is computed in our simulation model.

The results in Table 3 agree with earlier estimates of duct-leakage pressure differentials [13], confirming the fact that the infiltration, ventilation and energy effects of duct leaks should be far more substantial than those of building envelope leaks. These results also suggest that characterizing duct leaks at a reference pressure of 25 Pa is actually more appropriate than the more-uncertain 4-Pa characterization. The 4-Pa characterization is employed in this paper to provide consistency with other papers and previously reported data.

TABLE 3. Pressure differences between ducts and their surroundings during normal system operation

Location	Mean value (Pa)	Standard deviation (Pa)	Min. (Pa)	Max. (Pa)
Supply plenum	46	28	9	138
Supply duct average*	29	17	7	83
Return plenum	−88	43	−14	−181
Return duct average↓	−57	31	−5	−126

*(2×Plenum+(Near Register)+(Far Register))/4.
↓ (Plenum+Register)/2.

The influence of duct leakage on ventilation was also quantified in the field study by directly measuring the whole-house air exchange rate with and without the system fan in operation. This was done in each of the houses by analyzing tracer-gas concentration decays with and without the distribution-system fan in operation. The results of these measurements are summarized in Table 4.

The results in Table 4 confirm and even exceed earlier estimates of the importance of duct leakage in residential house infiltration and ventilation. These results also suggest that natural infiltration rates during shoulder periods are often lower than most standards would allow.

Duct conduction

The magnitude of supply-duct conduction losses were estimated for each house based on measurements of air temperatures at the supply plenum, the register of the shortest supply duct, and the register of the longest supply duct. The results of these analyses are summarized in Table 5, for which the fractional energy losses by conduction are computed by dividing the average temperature drop through the longest and shortest ducts by the temperature rise across the furnace. Because the temperature at the end of a supply duct is not significantly affected by leakage from that duct (except in the relatively minor influence of reduced flow rates on residence time and on convective heat transfer coefficients), this technique isolates the conduction losses of the supply ducts (the combined heat and mass transfer problem was solved for the simulation code).

The results in Table 5 suggest that conductive heat losses from existing ducts are substantial. The average duct-insulation (fiberglass) thickness observed in the field was 2.1 cm, which was calculated to correspond to an average U-value of 2.2 W/m^{2}K based upon standard thermal resistances for fiberglass wall insulation. These results suggest that there may be considerable energy-savings potential in increasing the insulation value of residential ducts.

Supply/return flow imbalances

The field study collected data on three parameters that can be used to characterize the effects of closed internal doors on duct-system performance. These parameters were:

(1) the indoor-outdoor pressure differentials in each zone that are created by the operation of the distribution-system fan;

(2) the changes in supply-duct and return-duct pressures created by closing the internal doors;

(3) the height of all undercuts of internal doorways.

The indoor-outdoor pressure differences created by closing the doors during distribution-fan operation were measured for each of the 144 zones

TABLE 4. Whole-house air exchange rates with and without distribution fan in operation

Parameter	Mean value (ACH)	Standard deviation (ACH)	Minimum (ACH)	Maximum (ACH)
Whole-house air exchange (System off)	0.24	0.15	0.01	0.57
Pre-1980	0.30	0.16		
Post-1979	0.16	0.10		
Whole-house air exchange (System on)	0.69	0.29	0.18	1.69
Pre-1980	0.69	0.33		
Post-1979	0.69	0.25		
Air exchange differential (On–off)	0.45	0.31	0.02	1.50
Pre-1980	0.39			
Post-1979	0.53			

TABLE 5. Measured conduction losses in supply ducts (26 houses)

Parameter	Mean Value	Standard deviation	Minimum	Maximum
Temperature rise across furnace (K)	37	9	26	62
Temperature drop through ducts* (K)	9	8	1	34
Fractional energy loss by conduction (%)	23	14	4	55

*Average drop from supply plenum to shortest duct register and to longest duct register.

TABLE 6. Indoor-outdoor pressure differences for various zones resulting from closing all interior doors

Location	Mean value (Pa)	Minumum (Pa)	Maximum (Pa)
Supply-only zones	6.0	−5.3	23.7
Return/supply zones	−2.7	−17.4	0.2

encountered in the field study, the results of which are summarized in Table 6.

The results in Table 6 indicate that, on average, closing internal doors should significantly change the infiltration rate of a house when the fan is in operation, as typical driving pressures for natural infiltration are 1–4 Pa. The large scatter in these results is not surprising, considering the large observed variability in door undercuts, and the additional variability introduced by the variations in supply flows to individual zones, as well as variations in envelope leakage*. Moreover, in four houses, zones that did not have return grilles were actually depressurized when the doors were closed. Although this result seems counter-intuitive, it is real. The house with the largest depressurization of supply-only zones had a unique internal configuration in which the return was in a hallway that was separated from all the supply registers when the doors were closed. This created an extreme depressurization of the return zone (−17 Pa), and subsequent depressurization of the supply zones that had the best connections to the return zone (i.e., large door undercuts). The other depressurized supply-only zones were found in houses with large supply-duct leaks relative to return-duct leaks. In those cases, the entire house tends to be depressurized when the fan turns on, even if the internal doors are open.

A comparison of supply-duct and return-duct pressures with and without the internal doorways closed indicated that the pressure differentials across the ducts typically increased when the internal doors were closed. The average pressure differential across supply leaks increased by approximately 10%, whereas the average pressure differential across return leaks increased by approximately 6%. These results, combined with our knowledge of the flow exponent of duct leakage sites, suggest that closing internal doors will increase the leakage flows through ducts by 4–7%.

The heights of door undercuts for the 144 doors measured in the field study were found to vary between 0 and 3.5 cm, with a mean value of 1.3 cm and standard deviation of 0.76 cm.

Simulation model

The first application of the multi-zone airflow and thermal simulation tool developed for a residential air distribution system was to the new-construction California ranch house described above. The results of the simulations performed for a crawl-space-return/attic-supply configuration of this house located in Sacramento (a moderate heating and cooling climate) are summarized in Table 7.

The results in Table 7 suggest that the energy implications of a residential air distribution system are large. Namely, approximately one third of the heating bill in a Sacramento ranch seems to be due to the inefficiencies of the air distribution system, whereas between 23 and 40% of the electricity

TABLE 7. Annual space-conditioning energy use in a new (well-insulated) Sacramento ranch

System	Cooling* (kWh)	Heating↓ (Joules (10^9))
No ducts	980	9.2
Typical ducts	1270	13.7
Potential savings	290 (23%)	4.5 (33%)
Potential savings with attic ducts	640 (40%)	

*Assuming a COP of 2.93.

↓ Assuming an AFUE of 85% for the furnace or wall heater.

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*In one house, two similarly sized zones with approximately equal supply-air flow rates and door undercuts were measured to have pressure differentials of 2.7 and 17.5 Pa. This large discrepancy stemmed from the fact that one zone had new airtight windows, whereas the other had the original leaky windows, pointing out that the pressure differential is only serving as a surrogate for the desired airflow effects.

consumption for cooling is due to distribution inefficiencies. Perhaps the most interesting result is the large cooling penalty associated with locating the return duct in the attic rather than the crawl-space. This examination of return-duct location indicated that at least for this relatively well-insulated house, the cooling energy consumption increased by 28% when the return duct was located in the attic rather in the crawl-space. Attic installation of return ducts occurs in many slab-on-grade houses, suggesting that the cooling energy and peak-demand effects of duct leakage and conduction might be larger in that type of construction. On the other hand, the influence of return-duct location on heating performance is expected to be small, due to the small differences between attic and crawl-space temperatures in the winter (assuming both are similarly ventilated and similarly insulated from the house).

The simulation results were also used to examine the variability of the duct-system efficiency. The effect of weather conditions on duct efficiency is illustrated in Figs. 6 and 7, which are scatter plots of the duct efficiency against outdoor temperature, for heating and cooling respectively. Both of these Figures show a strong dependence of duct efficiency with outdoor temperature, making it clear that a single efficiency number may not be appropriate in many instances. It should also be noted that the duct efficiency should scale more closely with the temperature (or enthalpy during the cooling season) of the zone in which it is located, however outdoor temperature (or enthalpy) is a reasonable surrogate, and is generally more widely available.

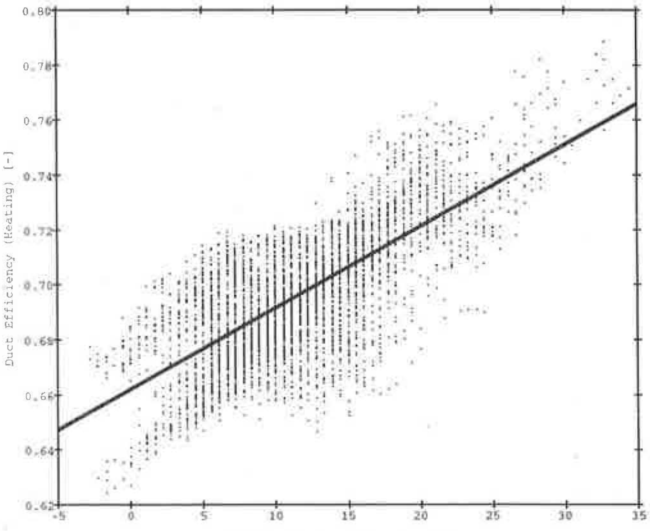

Fig. 6. Duct efficiency during heating mode as a function of outside temperature. Calculated from hourly simulation of Sacramento ranch house with crawl-space return and attic supply ducts. Heating duct efficiency (crawl-space return) $\doteq$ 0.662 + 0.00296*X.

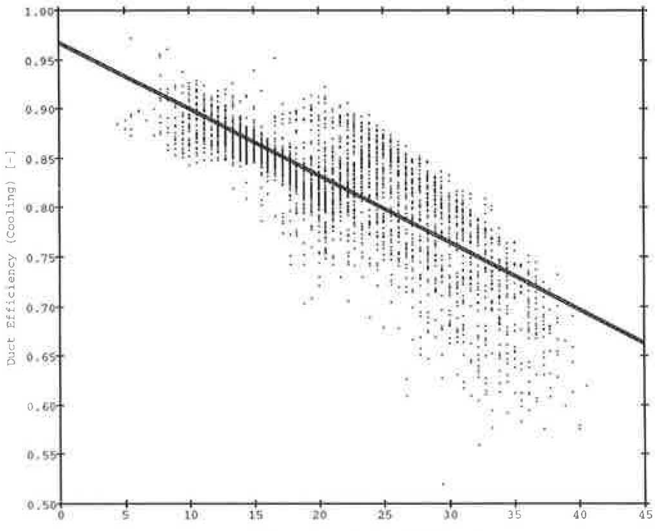

Fig. 7. Duct efficiency during cooling mode as a function of outside temperature. Calculated from hourly simulation of Sacramento ranch house with crawl-space return and attic supply ducts. Cooling duct efficiency (crawl-space return) $\doteq$ 0.968 − 0.00677*X.

Given the trend of duct efficiency with outdoor temperature demonstrated in Figs. 6 and 7, these systems should be expected to have a disproportionately large effect on peak energy demand, both in winter and summer. The peak-demand effects of residential air distribution systems for the prototype house on the peak Sacramento summer day are illustrated in Fig. 8. This Figure indicates the peak electricity demand due solely to leakage and conduction from the attic-supply/crawl-space-return duct system to be 0.8 kW, corresponding to a 40% increase in the peak electricity demand. Figure 8 also indicates an additional 0.5 kW of demand would occur at the peak if the return duct were located in the attic, which implies that the peak demand for a house with a typical attic supply/return system is 75% higher than for a house with room air-conditioners. These peak savings estimates should be treated somewhat cautiously as, depending on the degree of oversizing of the cooling equipment, many houses could be undercooled during peak-demand hours. If this is the case, some of the effects of duct improvements could appear as improved thermal comfort, rather than reduced demand. This issue is presently under investigation.

In addition to investigating the energy-use effects of air distribution systems, the simulations were also used to analyze the ventilation effects of air distribution systems. The ventilation results for the well-insulated house are summarized in Table 8.

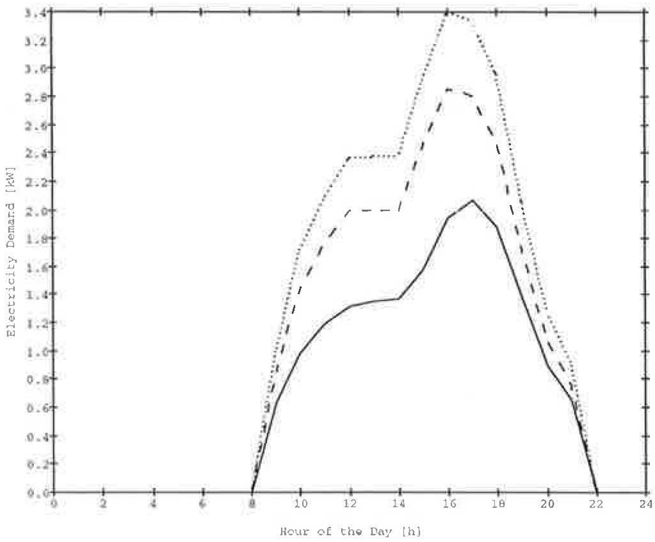

Fig. 8. Simulated air-conditioner electricity demand for peak cooling day in Sacramento. The three curves correspond to a house with: (1) room air conditioners with a COP of 2.93, (2) a central air conditioner with a COP of 2.93 and typical attic supply ducts and crawl-space return ducts (1.4 W/m^{2}K and 1 cm^2/m^2), and (3) a central air conditioner with a COP of 2.93, typical attic supply and return ducts (1.4 W/m^{2}K and 1 cm^2/m^2).

TABLE 8. Simulated annual average ventilation impacts of a typical duct system in a Sacramento ranch house* with doors open

House condition	Mean air change rate (ACH)
No ducts	0.35
Distribution-fan off	0.39
Distribution-fan on	1.06
Typical year**	0.48

*Ignoring the effect of opening windows for thermal venting.
**The total time the system is on is 1113 h, corresponding to an annual average fractional on-time of 0.127.

The results in Table 8 are consistent with earlier estimates of the influence of leaky ducts, yet the infiltration rates are all somewhat higher than the results of the field study. Some of this differential can be explained by the fact that the simulated house is approximately 13% looser than the older houses and approximately 74% looser than newer houses measured in the field study. Even with the higher leakage levels used for the simulations, it should be noted that despite the relatively short system on-time, a house with a typical air distribution system is suggested to have 37% more infiltration than a house without an air distribution system, and that the latter just meets the nominal ASHRAE Standard 62 ventilation level of 0.35 ACH. This observation could have important implications for ventilation in houses with tight duct systems, particularly when those duct systems are in 43% tighter houses.

Conclusions

Several conclusions can be drawn based upon the work presented. First, it seems clear from both the field data and simulation work that typical air distribution systems installed outside the conditioned space have dramatic effects on energy use and ventilation. Simulations indicate that a typical duct system passing through unconditioned spaces in a moderate California climate (1579 heating degree-days base 18.3 °C and 643 cooling degree-days base 18.3 °C) is 60–70% efficient, based only on losses due to leakage and conduction, and including any recovery of duct losses into unconditioned spaces. This implies that 30–40% of the thermal effect provided by the heating or cooling equipment is completely wasted. Moreover, the field measurements of leakage and conduction losses confirm and even exceed the simulated magnitude of these losses. The simulations also indicate dramatic cooling-efficiency reductions associated with locating return ductwork in attics rather than crawl-spaces, the overall duct efficiency being 17 percentage points lower for an attic return compared to a crawl-space return. This result highlights the importance of return leaks, and stems from the fact that the temperature differential between the attic air and the house is larger than the temperature differential between the supply ducts and the house.

Another conclusion that can be drawn from the simulations is that the efficiency of duct systems is by no means a constant. The results graphically demonstrated that duct efficiencies are a strong function of temperature, the lowest efficiencies being at the most extreme temperature conditions. Two obvious implications of this fact are:

(1) that inefficient distribution systems can have large peak electricity demand implications;

(2) that the concept of duct efficiency must somehow include the conditions of the building spaces in which the ducts are located.

On the ventilation side, both the field tests and simulations indicate dramatic effects of leaky ducts on residential ventilation rates. They both indicate that the ventilation rate with the distribution-fan running is approximately three times higher than that with the fan off. The simulations show that even if the distribution fan is running only 13% of the time, it accounts for 37% of the average annual ventilation rate of the house. Moreover, both sets of results suggest that without opening windows, many California houses will not meet nominal ventilation-rate standards. The fact that leaky duct systems are serving as terribly inefficient ventilation systems is an issue that this research has brought to light and which merits further examination.

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