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Energy Effectiveness of Duct Sealing and Insulation in Two Multifamily Buildings

Iain S. Walker, Mark P. Modera, Adrian Tuluca[*] and Ian Graham[*]
Lawrence Berkeley National Laboratory
Berkeley, California
* Steven Winter Associates
Norwalk, Connecticut

SYNOPSIS

This paper discusses field measurements from five apartments in New York that were monitored to determine the effect of duct retrofits on energy use.

ABSTRACT

Energy losses from forced air distribution systems have a significant impact on the energy efficiency of buildings. Little work has been done to quantify these losses in apartment buildings. In this paper we will discuss field measurements made on four forced air heating systems to evaluate the duct system energy losses to unconditioned basements. The apartments were heated by natural gas furnaces located in the basements. The systems had bare sheet metal ductwork exposed to the basement conditions. The pre-retrofit measurements were made on the systems after sealing large easily visible leaks. The post-retrofit measurements were made after wrapping the ducts in foil backed glass fiber insulation and additional leak sealing. Only the sections of duct exposed to the basement were retrofitted because only these sections were accessible. This study examines the potential energy savings for this type of limited retrofit.

The energy losses were separated into leakage and conduction terms. Leakage measurements were made using register flowhood techniques. Conduction losses were estimated by measuring temperatures in the plenums and at the registers. Analysis of the measurements has shown typical reduction in leakage flow due to duct sealing of about 40%. The reduction in leakage translated into a reduction in energy consumption of about 10%.

INTRODUCTION

Previous studies of energy losses from forced air distribution system ducts have concentrated on single family houses (e.g., Modera et. al. 1991, Jump and Modera 1994 and Palmiter and Francisco 1994). However, little work has been done in multifamily apartment buildings. To address this lack of knowledge in this area, this study examined the energy losses associated from gas furnace duct systems in the basements of multifamily apartment buildings. This type of heating system is common in many parts of the U.S. where houses have been converted into apartments.

The potential energy savings due to retrofitting the ducts by sealing leaks and adding insulation will be examined separately. The duct systems in this study were in extremely poor condition, and in several cases extensive repairs were made in addition to standard sealing techniques.

The apartments in this study had gas furnaces installed in their basements. The basements were the only place where the ducts were accessible because the rest of the duct systems were in the wall and floor spaces of the apartments. This arrangement limited the scope of any retrofit because only this exposed part of the duct system could be changed. The results of this study show that, despite the limited accessibility of the duct systems, the retrofits still allow significant increases in energy delivered to the conditioned space by the duct system. The objectives of this study were to estimate the potential energy savings due to the retrofit measures and to determine baseline conditions of energy losses for multifamily apartment duct systems in basements. The results concentrate on evaluating the delivery efficiency of the ducts, rather than the efficiency of the whole system, because other data required to determine the efficiency were not measured (e.g., air infiltration rates for the apartments and basements). In this study, time and budget constraints meant that the duct system was thoroughly investigated but only rough estimates could be made of any thermal regain of energy lost within the building structure and secondary duct system impacts on energy use (e.g., changing infiltration rates).

The duct systems were evaluated using diagnostic field measurements of air flows and temperatures. These temperatures and air flows were used to calculate energy flows for the duct system and to determine the magnitude of energy losses. The apartments in this study are all in upper New York State where the major energy use is for winter heating. To evaluate the systems under typical operating conditions, the tests were performed in winter. The results presented here are from four systems that were part of a larger study that examined seven additional duct systems. Some preliminary results from these other systems will also be discussed.

Some of the duct losses are regained by the building by conduction and air flow through the basement ceiling. Estimates of this regained energy are highly dependent on the infiltration rate for the basement. For the buildings in this study, the basements were very leaky, with many large cracks in the walls and doors open to outside. This condition implies that the infiltration rate would be quite high. Assuming an infiltration rate of 1 Air Change per Hour (ACH) (of which 0.1 ACH is through the ceiling) and typical thermal conductivity values for the basement walls and ceiling, about 12% of the energy lost by the ducts is regained by the building. For simplicity, other possible sources of energy regain (such as a plume of warm air from a duct rising to the basement ceiling and thus heating the apartment floors) were not investigated in this study. Note that this regain effect applies to both leakage and conduction losses and acts to reduce the potential energy savings of the duct sealing and insulating.

DUCT SYSTEM DESCRIPTION

The four systems analyzed in this paper were from two apartment buildings. The systems were referred to as SJ1, SE3, SE4 and SE5. System SJ1 had two apartments sharing the same duct system. Systems SE3, SE4 an SE5 had an individual duct system for each apartment within a single building. This building also contained two other apartments and duct systems and a commercial space. All of the systems were located in the basements of the buildings under study, with ducts exposed to the basement conditions. Other parts of the duct system were hidden within the structure of the buildings (walls and floors). Given visible duct locations and register locations, it was possible to estimate approximate duct runs, but actual duct size and location within the structure was unknown. In addition, even where it was obvious that ducts were in a particular wall cavity, there was no way of knowing about the heat transfer to either the apartments or to outside. This resulted in a lot of uncertainty in estimates of thermal regain effects.

All the systems had natural gas furnaces with sheet metal plenums and all the supply ducts were bare sheet metal except for one flex duct in system SJ1. The return ducts were also similar for each system. The return ducts were a combination of sheet metal ducts and joist spaces made into ducts by covering the bottom of the joists with sheet metal "panning".

The duct systems had multiple supply ducts and few returns (this was also found to be typical in the additional seven systems) which implied that there would be greater imbalance air flows within the apartments and through their exterior envelopes than if each room had a return. The following list summarizes these characteristics of the duct systems:

- System SJ1, apartment 1 had four supplies and one return, and apartment 2 had two supplies and two returns.
- System SE3 had six supplies and two returns.
- System SE4 had four supplies and four returns.
- System SE5 had eight supplies and two returns.
- Two returns from SE3 were connected to the furnace for SE4.
- SE3 shared a return with two unmeasured apartments and a commercial space.
- Two returns for SE4 were disconnected and opened to the basement.

The return flows for system SE4 from SE3 were not counted as leakage for system SE4 because they came from conditioned space. These cross connections could have a significant impact on building energy use because of increased or decreased infiltration loads induced by the flow imbalances. The cross connected and disconnected ducts were fixed during the retrofit.

The retrofit procedure consisted of sealing leaks with mastic and tape and wrapping the ducts in foil backed glass fiber insulation (approximately 50 mm (two inches) thick). Some leaks were determined by simple visual inspection (e.g., large holes and joints between duct sections and ducts and plenums) and others by using smoke sticks to visualize the air leakage. The sealing of large holes, fixing disconnected ducts and rerouting ducts to the correct furnaces was considered to be duct repair and not duct sealing. The large holes were sealed before any flow measurements were made, however the cross connected ducts were rerouted after the pre-retrofit flow measurements. Thus, the results presented here are representative of repaired and retrofitted systems rather than systems that have only had the leaks sealed.

MEASUREMENTS

In addition to the air flow and temperature measurements, the following duct system and building information was recorded. This information was used to classify the buildings and duct systems, or in generalizing duct system performance based on general building and system characteristics:

- Sketches of apartment and building floor plans.
- Records of register and duct locations (including large visible holes in the ducts).
- Records of duct lengths and diameter.

All of the following measurements were made before and after the ducts were sealed and insulated (pre- and post-retrofit).

System Fan Air Flows

The pressure in the supply plenum was measured during normal system operation. The return was then blocked off from the system fan at the return plenum. A flow capture hood connected to a fan assisted flowmeter was attached at the air handler and the system fan turned on. The fan assisted flowmeter unit was then adjusted to achieve the same pressure difference between the supply plenum and the conditioned space as under system operating conditions. The flow through the flow capture hood and fan assisted flowmeter apparatus was the system fan flow under operating conditions (Q_e). For energy calculations, this was converted to a mass flow (M_e) using the measured air temperature in the return plenum.

Register Air Flows

The air flows were measured at each register using a flow capture hood combined with a fan assisted flowmeter. The register flows were used to determine duct leakage separately for supply and return. The supply duct leakage (Q_s) was the difference between the sum of the flows from the supply registers and the system fan flow. The return duct leakage (Q_r) was the difference between the sum of the return register flows and the system fan flow. As with the system fan flow, the leaks are converted to mass flows (M_s and M_r) for energy calculations using the measured air flow temperatures.

Temperatures

Air temperatures were measured at the following locations:

- Apartment air temperature, T_{in}, measured at each return register and weighted by the flow at each register.
- Duct ambient (basement air), T_{amb}
- Return Plenum, T_{rp}
- Supply plenum, T_{sp}
- Each supply register. These are weighted by each register flow to give an average supply register temperature, T_{sd}

Temperatures were measured with hand held transducers (thermistors). Therefore, the temperatures were not measured simultaneously at all locations. This introduced an uncertainty into the energy calculations because the temperatures change during a furnace cycle as the ducts, heat exchanger and the apartment air (air into the returns) warm up during the beginning of a cycle and then decrease when the furnace turns off. In addition, it was found that the basement air temperature increased by typically 2° C (3° F) during a furnace cycle. Because of these cyclic effects, the temperatures used in the energy calculations were taken after the system had been forced to stay on for at least half an hour, when the system was at or near steady state operation. This reduced the effect of temperature changes during the time required to move the transducers from one location to another.

RESULTS

Air Leakage

All of the systems had large leakage sites in the duct system. In system SJ1, two supply ducts had been cut off near the supply plenum and had been "sealed" by stuffing glass fiber insulation into the exposed stub end of the duct. In system SE3 there was a hole in the end of one of the ducts that was about 30 cm x 20 cm (approx. 12"x7"). In system SE4 there was a disconnected supply duct and two openings in the return ducts that were 40 cm x 20 cm (approx. 17"x7") and 25 cm x 13 cm (approx. 10"x5"). In system SE5 there was a single large hole in the return. All of the above large openings were in the basement of the buildings. The presence of these easily observable large holes meant that there was a large potential for easy leakage reduction. These large holes were sealed before any duct flow measurements were made. Table 1 summarizes the results of the air leakage tests.

The pre-sealing supply leakage is substantial for every system tested. The average total (to outside, the basement and interstitial spaces of the building) supply leakage before retrofitting is 291 m^3/hour (171 cfm) which is 29% of the system fan flow. i.e., about one third of the energy from the furnace is lost from the duct system by supply leakage. The return leaks are typically much larger than the supply leaks. The average total return leakage pre-retrofit was 768 m^3/hour (452 cfm) or 77% of the system flow. In other words, only one fifth of the air entering the return side of the furnace came from the return registers in the apartments. The fan flows were reduced by sealing leaks in the duct system. The fan flows for SE3, SE4 and SE5 were reduced by an average of 162 m^3/hour (95 cfm) or about 16% of their pre-sealing flow.

Substantial reductions in leakage were obtained during the system retrofitting. Due to the lack of post-retrofit leakage measurements for SJ1, the following results are for the SE3, 4 and 5 apartments only,:

- The average reduction in supply leakage is 151 m^3/hour (89 cfm). The reduction is equivalent to 44% of the pre-sealing leakage flow. If the leakage is expressed as a fraction of the fan flow (rather than as a flow rate), the leakage reduction is less than this result indicates because the fan flow rates have also been reduced by sealing the leaks. The leakage as fractions of fan flow are 34% and 22% pre- and post-retrofit respectively.
- A similar reduction in return leakage was also achieved. For the returns, the reduction in leakage flows was from 835 m^3/hour (491 cfm) to 486 m^3/hour (286 cfm), corresponding to

fractional leakage of 82% and 57% of the system fan flows. The average reduction was 42% of the pre-sealing leakage flows.

The remaining post-retrofit leakage was not accessible from the basement, and was from leaks into the walls and floors of the apartments. This interstitial leakage may be to the apartments or to outside through openings in the building structure.

Table 1. Summary of Duct Leakage Testing

PRE-RETROFIT

System	Duct Sealing	System Fan Flow, m^3/hour (cfm)	Supply Leakage m^3/hour (cfm) [% of fan flow]	Return Leakage m^3/hour (cfm) [% of fan flow]
SJ1	PRE	1003 (590)	138 (81) [14]	564 (332) [56]
SE3	PRE	1006 (592)	306 (180) [30]	930 (547) [93]
SE4	PRE	955 (562)	520 (306) [55]	672 (395) [70]
SE5	PRE	1093 (643)	199 (117) [18]	904 (532) [83]
mean SE3,4&5		1018 (599)	342 (201) [34]	835 (491) [82]

POST-RETROFIT

System	Duct Sealing	System Fan Flow, m^3/hour (cfm)	Supply Leakage m^3/hour (cfm) [% of fan flow]	Return Leakage m^3/hour (cfm) [% of fan flow]
SE3	POST	908 (534)	201 (118) [22]	641 (377) [71]
SE4	POST	763 (449)	315 (185) [41]	360 (212) [47]
SE5	POST	898 (528)	58 (34) [6]	457 (269) [51]
mean SE3,4&5		856 (504)	191 (113) [22]	486 (286) [57]

The other seven systems in this study showed reductions in leakage of about 10% for supplies and 20% for returns. Therefore, the systems studied in this paper have more leak sealing than was typical for the whole study. The better leak sealing is because these duct systems were so poor before the retrofits were performed, with many poor duct connections and some disconnected ducts that were easily repaired. Other studies have examined duct leakage in single family residences. Downey and Proctor (1994) surveyed 11 houses and found the supply leaks were 8% of fan flow and the return leaks were 10% of fan flow. The 24 houses studied by Jump, Walker and Modera (1996) had an average supply leakage of 17% and return leakage of 16% of fan flow pre-retrofit. This leakage was reduced to 8% for supply and 10% for return after a duct sealing and insulating retrofit. These results from other studies indicate that the duct systems examined in the current study have greater leakage than for the systems in the single family residences of the above studies.

Supply Leakage Energy Losses

The energy impact of the duct leakage on the duct system was determined by using the measured system operating temperatures and flowrates as follows:
The **power delivered to the duct system (E_{del})** was given by

$$E_{del} = M_e Cp\left(T_{sp} - T_{rp}\right) \quad \textbf{(1)}$$

where Cp is the specific heat of air and M_e is the mass flow of air through the furnace.
The **power lost from the ducts due to supply leakage (E_{ls})** was given by

$$E_{ls} = M_s Cp\left(T_{sp} - T_{rp}\right) \quad \textbf{(2)}$$

where M_s is the supply duct leakage. Equation 2 assumed that the ratio of supply leakage flow to fan flow gives the fraction of power put into the duct system that is lost due to leakage. This assumption implies that the leaks are at plenum temperature, and will tend to overestimate the power lost due to leakage because leaks at the registers will be at a lower temperature than T_{sp}. However, given the uncertainties in temperature measurement created by not measuring the temperatures all at the same time, this is a reasonable estimate.
The **fractional leakage loss (η_{ls}) for the supply ducts** was given by:

$$\eta_{ls} = \frac{E_{ls}}{E_{del}} \quad \textbf{(3)}$$

Table 2 summarizes the fraction of power put into the duct system by the furnace that is lost due to supply duct leakage. For systems SE3, SE4 and SE5, for the pre-retrofit case, about 34% of the power put into the ducts by the furnace is lost from the ducts due to supply duct leakage. The retrofitting reduced this power loss to about 23%. This result implies that 11% less of the furnace energy is lost from the ducts. Because only basement leaks were sealed, this is energy that would otherwise have gone into the basement.

Supply Conduction Energy Losses

Because all of these systems were in basements, the majority of their conduction losses were to the basement space. The following tables illustrate the conduction performance of the duct systems. The exposed duct areas in the basement are summarized in Table 3. Operating system temperatures are summarized in Tables 4 and 5. The power changes and fractional conduction loss are summarized in Table 6.

Table 2. Estimates of Power Impact of Supply Duct Leakage

PRE-RETROFIT				
System	Duct Sealing	Power Delivered to Ducts, E_{del}, kW (kBtu/hour)	Power Lost Due to Leakage E_{ls}, kW (kBtu/hour)	Fractional Leakage Loss, η_{ls}
SJ1	PRE	11.7 (39.8)	2.3 (5.5)	0.14
SE3	PRE	14.0 (47.6)	4.3 (14.7)	0.30
SE4	PRE	10.6 (36.0)	5.8 (19.7)	0.54
SE5	PRE	15.5 (52.8)	2.8 (9.5)	0.18
mean SE3,4&5		13.4 (45)	4.3 (14.6)	0.34

POST-RETROFIT				
System	Duct Sealing	Power Delivered to Ducts, E_{del}, kW (kBtu/hour)	Power Lost Due to Leakage E_{ls}, kW (kBtu/hour)	Fractional Leakage Loss, η_{ls}
SE3	POST	13.1 (44.7)	2.9 (9.9)	0.22
SE4	POST	13.6 (46.2)	5.6 (19.0)	0.41
SE5	POST	16.2 (55.3)	1.1 (3.7)	0.06
mean SE3,4&5		14.3 (49)	3.2 (10.9)	0.23

Table 3. Duct Exposed Surface Area

	Exposed Duct Area, m^2 (ft^2)		Apartment Floor Area m^2 (ft^2)	Exposed Duct Area/ Floor Area	
System	Supply	Return		Supply	Return
SJ1	15.5 [167]	20.8 [224]	108.4 [1167]	0.14	0.19
SE3	11.2 [121]	13.7 [147]	73.1 [787]	0.15	0.19
SE4	5.6 [60]	7.1 [76]	44.4 [478]	0.13	0.16
SE5	19.1 [206]	9.9 [106]	123.7 [1332]	0.15	0.08
mean	12.9 [198]	12.9 [198]	87 [941]	0.14	0.16

The exposed surface area of ducts scaled with the apartment size (floor area). The ratio of exposed supply duct area to apartment floor area was similar for each of the four systems at about 14% (this was also true for the other seven systems in this study). The reason for this was the similarity between the installation of each system (similar size furnace/air handler, same furnace location, similar duct layout geometries, etc.). For comparison, the return exposed areas were about 2% of floor area larger, however, the return for SE5 was half the size of the other return, which biased this result downwards.

Table 4. Operating System Temperatures at Plenums

	Supply Plenum Temp, T_{sp}, °C (°F)		Return Plenum Temp, T_{rp}, °C (°F)		Duct Ambient Temperature, T_{amb}, °C (°F)	
System	PRE	POST	PRE	POST	PRE	POST
SJ1	76 (136)	88 (190)	16 (61)	20 (68)	8 (46)	10 (50)
SE3	66 (151)	70 (158)	16 (61)	18 (64)	12 (54)	14 (57)
SE4	61 (142)	82 (180)	21 (70)	18 (64)	10 (50)	10 (50)
SE5	65 (149)	82 (180)	14 (57)	17 (63)	8 (46)	10 (50)
mean	67 (153)	81 (177)	17 (62)	18 (64)	10 (50)	11 (52)

Table 5. Flow Weighted Average Register Temperatures

	Supply Register Temperature, T_{sd}, °C (°F)		Return/Room Temperature, T_{in}, °C (°F)	
System	PRE	POST	PRE	POST
SJ1	50 (122)	61 (142)	24 (75)	25 (77)
SE3	37 (99)	44 (111)	26 (79)	28 (82)
SE4	35 (95)	45 (113)	26 (79)	27 (81)
SE5	43 (109)	58 (136)	20 (68)	25 (77)
Mean	41 (106)	52 (126)	24 (75)	26 (79)

Table 4 shows the operating system temperatures. The increase in supply plenum temperatures post retrofit (by an average of 14° C (24° F)) is due to reduced flow through the system and higher return plenum and duct ambient temperatures. The increase in return plenum temperature is mostly due to increased return register temperatures as shown in Table 5. The post retrofit supply plenum temperatures were higher than normal, indicating that there was too little air flow through these systems (this reduced air flow will also reduce furnace efficiency). The increased temperatures were due to the flow restriction of the duct systems indicating poor system design. The system temperatures are higher than normal because the systems were forced to be on for at least 30 minutes so that measurements of temperatures could be made at a quasi-steady-state. The increased return register temperatures post retrofit are due to the systems being operated slightly longer before measurements were made. Table 5 also shows that the increase in supply plenum temperature, shown in Table 4, resulted in increased register temperatures (by an average of 10° C (18° F)).

The increased register temperatures also produced increases in energy delivered to the conditioned space as shown in Table 6. The average energy delivered to the conditioned space pre-retrofit was 2.97 kW (10.2 kBtu/hour) and was increased to 4.33 kW (14.7 kBtu/hour) (a 46% increase in delivered energy). The average power delivered to the ducts (from Table 2) also increased from 13.5 kW (46 kBtu/hour) to 14.3 kW (49 kBtu/hour) after the retrofit. The corresponding fractions of input power delivered to the ducts are 22% and 30%.

Table 6. Summary of Supply Conduction Losses, Return Power Losses and Power Delivered to Conditioned Space

PRE-RETROFIT					
System	Power Delivered to Conditioned Space, E_{os}, kW (kBtu/hour)	Supply Conduction Loss E_{lc} kW (kBtu/hour)	Return Loss E_{ret}, kW (kBtu/hour)	Fractional Supply Conduction Loss η_{lc}	Fractional Return Loss η_{ret}
SJ1	6.3 (21.3)	6.3 (21.4)	1.9 (6.6)	0.37	0.11
SE3	2.1 (7.2)	5.6 (19.2)	1.9 (6.6)	0.40	0.14
SE4	1.1 (3.7)	3.1 (10.5)	0.6 (2.0)	0.30	0.06
SE5	5.7 (19.4)	5.5 (18.6)	1.5 (5.1)	0.35	0.10
mean SE3,4 &5	3 (10)	4.7 (16)	1.3 (4.5)	0.35	0.10

POST-RETROFIT					
System	Power Delivered to Conditioned Space, E_{os}, kW (kBtu/hour)	Supply Conduction Loss E_{lc} kW (kBtu/hour)	Return Loss E_{ret}, kW (kBtu/hour)	Fractional Supply Conduction Loss η_{lc}	Fractional Return Loss η_{ret}
SE3	3.1 (10.7)	5.1 (17.4)	2.0 (6.7)	0.39	0.15
SE4	2.2 (7.5)	4.6 (15.6)	1.1 (3.7)	0.34	0.08
SE5	7.7 (26.3)	5.6 (19.1)	1.9 (6.4)	0.35	0.12
mean SE3,4 &5	4.3 (15)	5.1 (17)	1.7 (5.7)	0.36	0.12

The power lost due to conduction was estimated using the following equations. The results of the calculations are shown in Table 6.

The **power delivered by the ducts to the apartment (E_{os})** was calculated using:

$$E_{os} = (M_e - M_s)Cp(T_{sd} - T_{in}) \tag{4}$$

The **power lost from the ducts by conduction (E_{lc})** was calculated by performing an energy balance on the air in the supply ducts. After the supply air has leaked out, M_e-M_s air is left in the ducts and this air cools from the plenum temperature to the register temperature, such that:

$$E_{lc} = (M_e - M_s)Cp(T_{sp} - T_{sd}) \tag{5}$$

The **fractional conduction loss (η_{lc})** was then defined as the ratio of conduction loss to power supplied to the duct system:

$$\eta_{lc} = \frac{E_{lc}}{E_{del}} \tag{6}$$

The losses from supply conduction are summarized in Table 6. The results in Table 6 clearly show the large conduction losses for supply ducts because of the large temperature differences for supply ducts. Approximately 36% of the furnace power is lost due to supply side conduction losses (on average for these systems). Some simple duct wall conduction (UAΔT) calculations show that about 2/3 of these loses are to the basement. If the ducts were not at equilibrium, some of the temperature drop in the air between the plenum and the registers could be due to heating of the ducts. To avoid this, the temperature measurements were made after the system had been forced to stay on for at least 30 minutes. Typically, this meant that the duct system temperatures were rising at less than 0.1° C (0.2° F) per minute (e.g., for the supply plenum in SJ1). For SE3, SE4 and SE5 there is almost no difference between the fraction of power lost due to conduction pre- (35%) and post- (36%) retrofit. The similarity of conduction losses was due to increased duct operating temperatures post retrofit (as shown in Tables 4 and 5) and increased duct surface area balanced the effect of the additional insulation. Without the added insulation, the increased temperature of the air in the ducts post-retrofit would lead to increased conduction losses. As a fraction of energy delivered through the duct system, the conduction losses would decrease because more energy is delivered to the conditioned space after the retrofits.

Return Energy Losses

The leakage tests pre- and post-retrofit show that less than one half of the return duct leaks are in the basement, therefore the remainder is from interstitial spaces of the building. Thus, the air entering the return leaks is some unknown combination of air from the basement, the apartments or from outside. For the return ducts, it was not possible to separate the leakage and conduction losses because the temperature of air entering the return leaks was unknown. Therefore, the **return losses were given by a single factor, E_{ret}.** This factor was determined by performing a power balance on the whole duct system, where the power from supply leakage (E_{ls}) and conduction (E_{lc}) losses and the energy delivered to the apartments (E_{os}) were deducted from the power input to the duct system (E_{del}).

$$E_{ret} = E_{del} - E_{os} - E_{lc} - E_{ls} \tag{7}$$

As with the other loss factors, E_{ret} was expressed as a fraction of the power into the duct system, i.e., the **fractional return loss (η_{ret}):**

$$\eta_{ret} = \frac{E_{ret}}{E_{del}} \tag{8}$$

The return losses, given in Table 6, are much less than the supply losses despite the large return leaks. The results for SE3, SE4 and SE5 show that there is a small increase in the return losses from pre (10%) to post (12%) retrofit. This change is too small to be considered significant given the uncertainty in measured temperatures and flows. These results imply that the much of the air entering the return leaks is not from the ambient air in the basement or outside, and that return conduction losses are small. The return conduction losses are expected to be small due to the small temperature difference between air in the return ducts and the basement (ambient) air, as shown in Table 4.

SUMMARY AND CONCLUSIONS

The duct leakage as a fraction of fan system flow was reduced from 34% to 22% for supply and from 82% to 57% for return. This reduction indicates that a significant fraction of duct leaks (about 40%) were accessible in the basement. The remaining leaks were elsewhere in the structure of the building.

The retrofits made a significant increase in energy delivered to the conditioned space through the duct system. The increase in the energy delivered by the ducts is a 46% increase over the pre-retrofit case (from 21% to 30% of power put into the ducts). Note that some of the supply losses are within the structure of the building and reach the apartments (but not through the duct system) so these calculations overestimate the true energy losses. Some simple calculations show that about 10% of the energy lost to the basement may be regained through the basement ceiling. This is in addition to thermal regain from losses in the walls and floor of the building to the apartments for which we do not have any quantitative estimates.

The results show that the combination of leak sealing and adding insulation for the supply ducts was responsible for the improvement in energy delivery:

- Of the 79% lost pre-retrofit, most (69%) is from the supply ducts, and is split 35% to 34% between conduction and leakage. The remainder (10%) is lost from the return ducts.
- Of the 71% lost post-retrofit, most (59%) is from the supply ducts, and is split 36% to 23% between conduction and leakage. The remainder (12%) from the return ducts is unchanged by the retrofit.

The power losses due to conduction were largely unchanged because the temperatures in the supply ducts were increased by leak sealing. The conduction losses would have increased post-retrofit if the ducts were not insulated. The small changes in return energy losses, despite the large reduction in leakage, indicate that conduction losses are small for the returns (due to their lower temperatures) and much of the return leakage (almost all of it post-retrofit) is from interstitial spaces within the building rather than the basement or outside.

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