Investigation of Leak Sealing for Supply and Exhaust Ductwork

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Abstract

Although there has been a considerable amount of activity over the past ten years with respect to duct sealing in single family residences, the issue of duct sealing in other types of buildings has received relatively little attention. This paper attempts to touch upon the key issues with respect to duct leakage in these types of buildings, including the screening of such buildings for leakage problems, the tools for estimating the energy impacts of those leaks, and the results of recent sealing activities in these buildings. One technique for measuring leakage downstream of VAV boxes with the system fan in normal operation is described. The testing and sealing results presented for 10 buildings indicate an average leakage of 23% of fan flow, and that 87% of that leakage was sealed by means of aerosol sealant injection.

Introduction

Over the past 10 years there has been a considerable body of research performed on the subject of duct leakage in buildings other than single family residences (Cummings et al 1996, Delp et al 1996, Delp et al 1998, Delp et al. 1998b, Franconi et al 1998). The earlier research included a characterization of the stock of duct systems in large commercial buildings (Modera et al. 1999), characterization of duct leakage levels and efficiency-rating yardsticks for commercial building thermal distribution systems (Diamond et al. 2003), field testing of the impacts of supply duct sealing an office building (Diamond et al. 2003) and a light commercial building (Sherman et al. 2002), as well as the development and field testing of a version of the aerosol based sealing technology applicable to large commercial buildings (Diamond et al. 2003). In addition, considerable efforts have been devoted to the development and application of detailed simulation tools for commercial building thermal distribution systems (Wray 2003, Wray and Matson 2003). This paper describes recent experiences with sealing the leaks in these types of duct systems, with a particular focus on one subset of duct systems in "commercial" buildings that was not adequately investigated by the prior research, specifically exhaust duct systems.

Duct-system research at Lawrence Berkeley Laboratory (LBNL) also resulted in the development of a technology for sealing duct leaks from the inside (Carrie and Modera 1993, Modera et al. 1996). This technology seals leaks in ductwork from the inside by pressurizing the duct system with a fog of atomized sealant particles. By temporarily blocking all of the normal exits from the duct system (as well as any coils or fans) the fog is forced to the leaks. The acceleration of the air through the leaks causes the sealant particles to leave the air stream and deposit on the leak edges. By the right choice of particle size, duct flow rate and duct pressure, the particles remain suspended as they travel through the duct system, and thus only a very small fraction of the particles deposit on the walls.

The aerosol sealing technology allows leaks that had previously been inaccessible to be sealed. It has been commercially available for single-family residences since1999, however it only became commercially available for large buildings starting in 2003 with the introduction of a new atomization technology that significantly increases sealing rates, and allows sealant to be atomized inside the ductwork instead of externally.

This paper presents some issues and results related to duct sealing in large buildings that have come to light over the past three years of aerosol sealing ducts in these types of buildings. The issues touched upon include:1) duct leakage identification, 2) measured duct leakage levels, 3) duct sealing results, 4) energy savings estimation, and 5) particular considerations associated with 100% outside air (e.g. laboratory and exhaust) duct systems.

Duct Leakage Identification

Requests for duct sealing in existing buildings other than single family residences have generally come from several sources: 1) test and balance reports that indicate duct leakage and/or inadequate zone flows, 2) comfort and/or pressure control complaints, and sometimes 3) a desire to save energy. These sources are listed in order of frequency of occurrence, which happens to correspond to the order of certainty of leakage. Systems with test and balance reports that indicate leakage generally seem to leak, whereas low zone flows could be due to other problems, as can comfort or flow complaints, as well as energy use issues.

In general, knowing whether the ducts in a large building are leaking is considerably more difficult and expensive than uncovering duct leakage in single family residences. Test and balance reports provide a reasonably certain indication of leakage, however such measurements are generally too expensive to be performed solely to look for duct leakage. The fan pressurization techniques normally used in residences requires all normal openings to be temporarily sealed during pressurization, which is generally impractical in large buildings. Fan pressurization can however be used on sections of ductwork in large buildings, for example downstream of a VAV box.

A modified fan pressurization technique was used in several buildings to measure duct leakage downstream of VAV boxes without turning off the main system fan. This test is performed with the HVAC system in normal operation, and measures VAV damper leakage (or minimum setting), as well duct leakage downstream of the VAV box.

The procedure consists of the following steps:

1) close the VAV box to its minimum setting (either by means of the control system or mechanically)
2) block all downstream diffusers except for one
3) connect a fan pressurization device to the remaining diffuser
4) measure the flow through the fan pressurization device and the pressure in the ductwork downstream of the VAV box at several duct pressures, starting with the fan pressurization fan in the off position, and ending with a duct pressure of at least 50 Pa
5) measure the normal operating duct pressure upstream and downstream of the VAV box with the VAV damper in its fully open position.
6) perform an iterative fit of the data, solving simultaneously for the leakage flow coefficient, the leakage flow exponent, and the flow through the VAV damper with the fan pressurization fan off.
7) calculate the percentage leakage based upon the measured upstream and downstream pressures, the nominal or measured flow through the VAV box, and the calculated duct leakage coefficient and exponent.

The key trick to this technique is the iterative fit and proper accounting for the flows through the damper and the calibrated fan. The technique is based upon the fact that when the calibrated fan is off, the flow through the VAV damper is split between flowing through the leaks downstream of the VAV box, and through the calibrated fan, but that this damper flow is leaving only through the leaks when the calibrated fan is turned on. The iteration is based upon adjusting the unmeasured flow through the leaks so as to produce the best fit to the data obtained when the calibrated fan is turned on to produce a range of pressures in the ductwork. The fit also accounts for the reduction in damper flows as the pressure downstream of the damper is increased by the calibrated fan.

The advantages of this technique are: a) that the main system fan can operate normally, b) it can generally be completed by one person within roughly 1 to 1.5 hours, c) it also determines the leakage or minimum position of the VAV damper, and d) it utilizes standard, relatively inexpensive measurement equipment.

Figure 1 shows the technique being employed in the cafeteria of a classroom building.

Figure 1: Measurement of leakage downstream of a VAV box in a classroom building. Note duct pressure measurement on left, and calibrated fan on right.

Duct System Leakage and Sealing Results

Over the past couple of years, roughly 30 duct systems in buildings other than single family residential or light commercial buildings have been sealed using the aerosol sealing technology. These buildings have had a number of different types of duct systems, each having their own unique attributes. A brief characterization of these buildings is presented in Table 1, and a summary of the leakage and sealing results for these buildings is presented in Table 2.

Table 1: Building/System Characterization

Bldg	Building Type	Size [ft^2]	System Type	Location
#1	Office	78,000	Constant Volume Supply	CA University
#2	Lab	63,550	Dual Duct Supply	CA University
	Lab	63,550	CV Exhaust	CA University
#3	Barracks (8 bldgs)	~124,000	CV Exhaust	NC Navy Base
#4	Navy BEQ (dorm)	64,800	Constant Volume Supply	WA Navy Base
#5	Office	54,341	VAV Supply	FL Navy Base
	Office	54,341	CV Exhaust	FL Navy Base
#6	Classroom/Office	20,500	VAV Induction Supply	RI Navy Base
#7	Classroom/Office	N/A	CV Supply/Exhaust	CA University
#8	Hospital	10,000	CV Exhaust	OH
#9	University Dorms	40,000	CV Exhaust	NY University
#10	Office	66,500	Constant Volume Supply	CA University
#11	Museum	N/A	Supply/Return Risers	OH

Table 2: System Leakage and Sealing Performed				
Building	**Fan Flow [cfm]**	**Initial Leakage [%]**	**Fraction Sealed**	**Notes**
#1	69,000	19%	87%	4 floors, 6 coils/floor
#2	93,000	36%	78%	2 floors, 3 loops (hot/cold/lab make-up) 1-2 injections/loop, 2 fans
	22,000	27%	85%	80 grilles on 2 floors, single point injection
#3	N/A	3000 cfm25	93%	shower/toilet exhaust
#4	14,000	19%	87%	dorm room supply, exhaust was chase with large penetrations
#5	46,200	19%	92%	downstream leakage only, slot diffusers, sealed w/fan on, 3 flrs
	10,000	10%	90%	no pre-qualification
#6	16,610	15%	92%	sealant flow thru terminal system-power induction boxes, pneumatic line connected to pitot inlet
#7	10995	1% - 23%	87%	no pre-qualification
#8	8,200	19%	85%	found undocumented take-offs, 11 stories, penthouse inject
#9	4,350	54-70%	75%	sealing stopped due to large inaccessible opening
#10	63,000	29%	89%	sealed from inside 6-story shaft, using bosun's chair
#11	18,000	17%	91%	risers not yet connected to equipment, sealed two at a time

The results in Table 1 indicate a range of different building and system types whose leakage has been measured and sealed, including supply systems and exhaust systems in laboratory buildings, office buildings, hospitals, museums, high-rise residential, and classroom buildings. The last column in Table 2 indicates further variety in the types of systems and the strategies that were employed to seal them. Figures 2 through 6 show some sealing strategies employed for different types of HVAC systems, including rooftop sealing of exhaust duct systems, sealing of supply ductwork downstream of VAV boxes, sealing of medium pressure supply ductwork, as well as internal and external sealant atomization techniques.

Figure 2: Testing and sealing of exhaust duct leakage at a classroom/laboratory building. Note that the sealant atomizer is installed in the ductwork pointing away from the exhaust fan on the downstream side.

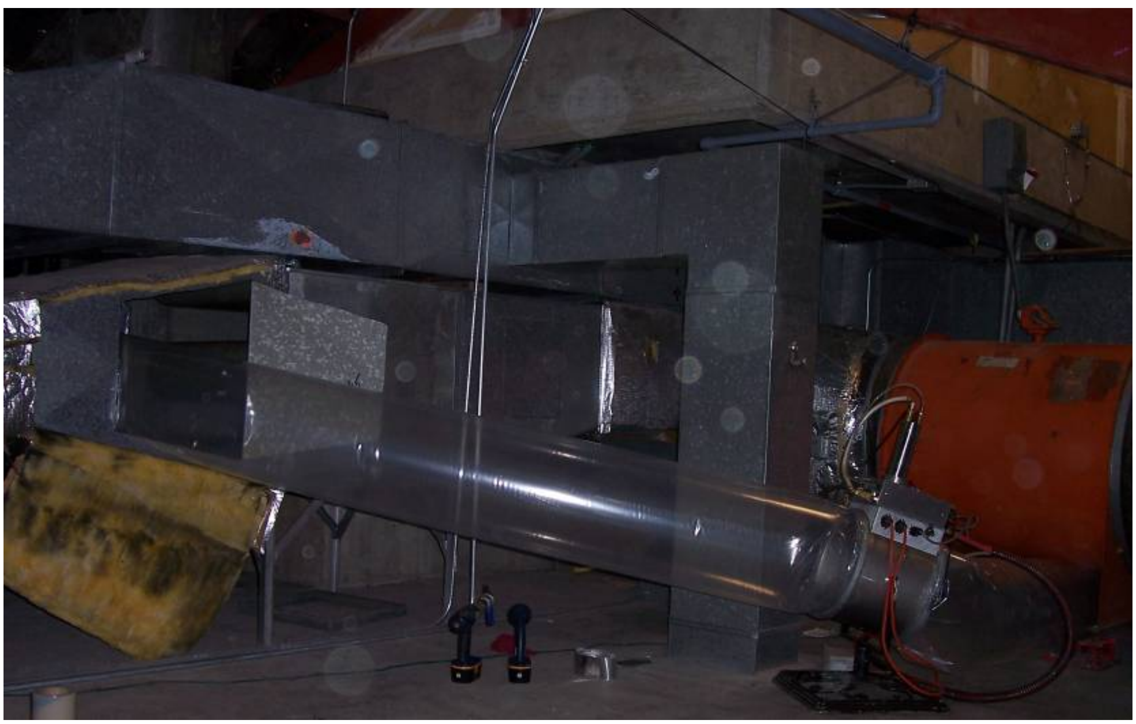

Figure 3: Bachelor's Enlisted Quarters building (i.e. dormitory) being sealed from the penthouse. Note that the sealant atomizer is located outside of the ductwork in the cylinder, and sprays the sealant inside the clear plastic tubing.

Figure 4: Sealing leaks in an office-building slot diffuser system downstream of VAV boxes. Photo to the right shows one of the injection points used to seal downstream of two VAV boxes simultaneously.

Figure 5: Temporary closure of grilles during aerosol injection. The grille on the left was stuffed with a closed-cell foam plug, whereas the grille on the right was covered with a magnetic sheet and taped at the edges.

Figure 6: Pressurization through the intake of a 69,000 cfm supply fan for an office building, followed by injection into one of the vertical shafts served by that fan.

Table 2 also shows that the level of leakage encountered in the systems tested and sealed was relatively high (average = 23%), and quite variable (ranging from 1% to 70%). This suggests that the potential for sealing can be significant, and also illustrates the importance of having a reliable means for estimating the leakage level prior to engaging in a sealing project.

Finally, Table 2 also indicates that the aerosol sealing technology is capable of regularly sealing the vast majority of the leakage encountered. The average fraction of the leakage sealed was 87%, with the minimum fraction sealed being 75%. This suggests that although the techniques required for sealing are quite variable, the sealing results are very consistent. Figure 7 shows the sealant spray and an example of a sealed leak (from inside the ductwork), while Figure 8 is an example graph of the sealing process, showing duct leakage as a function of time. All sealing processes are run by a laptop computer that displays graphs similar to that in Figure 8 and uploads all of the sealing data to an Aeroseal server that has been used to archive every sealing job ever performed.

Figure 7: Sealed leak as seen from inside the ductwork, and sealant spray leaving the nozzle. Note that the sealant does not coat the inside of the ductwork, but rather is concentrated at the leaks.

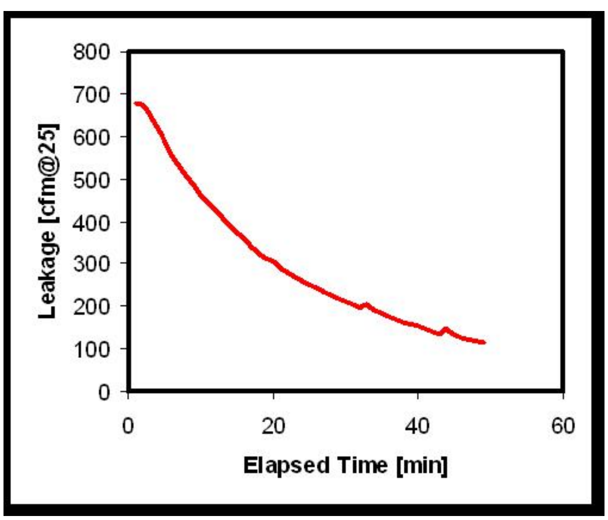

Figure 8: Example of sealing graph displayed during sealing process and uploaded to server for archiving.

Energy Savings and Performance Improvement

In order to estimate the energy savings associated with sealing duct leaks in buildings other than single family residences, several simplified tools have been utilized. The techniques utilized depend upon the type of duct system being analyzed. Table 3 summarizes the basic calculation tools used for the common types of duct systems found in buildings other than single family residences.

Table 3 does not include the common inputs required for all duct leakage energy analyses, namely Heating and Cooling Degree Days, the system/section air flow, the percentage leakage, the operating pressure, and the floor area being served, as well mechanical plans denoting the duct layout, and the location of all grilles, any VAV boxes, any fire dampers, etc.

Table 3: Energy Savings Calculation Procedures

System Type	Input Data Required	Calculation Principles	Resources
Light Commercial	Ceiling Insulation Configuration, City and State, full-load heating and cooling hours	Thermal losses to unconditioned spaces	ASHRAE Standard 152, ARI full-load hours data
Large Office Supply	Return Configuration, % Outside Air, type of VAV boxes	Fan power scales with flow raised to power 2.5, thermal loads from outside air flow and fan power	Franconi et al. 1998
Laboratory Supply Systems (100% out air)	Type of flow control (e.g., zone pressures)	Fan power scales with flow raised to power 2.5, thermal load from air flow and fan power	Franconi et al. 1998
Exhaust Systems	Heat Recovery Wheel?	Fan power scales with flow cubed, thermal load from air flow	

The degree to which the analysis tools in Table 3 adequately represent actual energy savings varies between the different system types. Light Commercial and Large Office Supply systems have received the most attention to date, including some limited field validations of the predicted savings. The use of ASHRAE Standard 152 for light commercial buildings has been compared with field test results in one building (Sherman et al. 2002), as have the savings algorithms for a particular type of large office building supply system (Diamond et al. 2003). Although the savings from reducing fan flow in 100% Outside-Air

Laboratory Supply systems should be straightforward to calculate, the author is not aware of any field studies that have carefully measured the savings.

It should also be straightforward to calculate savings from reducing exhaust flows in certain types of buildings/applications, however once again there have not been any careful field studies to measure this savings. On the other hand, there are certain applications where sealing exhaust ductwork leaks, and then reducing exhaust flows out of the building, results in non-linear interactions with existing air intake flows, making an exact calculation of savings uncertain. In brief, if the supply system is controlled to maintain a constant pressure in the building, then any reductions in exhaust flow should result in one-for-one reductions in outdoor air intake. On the other hand, if the exhaust-flow reduction changes the pressure in the conditioned zone(s), then the impact on outside air intake becomes much more complex, and generally the change in outside air intake is less that the change in exhaust air flow.

Another key issue with respect to duct sealing in large buildings is that duct leakage often results in more than energy waste, as it impacts the air flow performance in these buildings. For example, in a hospital, laboratory or manufacturing facility, it is often necessary to maintain pressures in specific rooms or zones, and duct leakage can make this difficult or sometimes impossible to achieve. Similarly, duct leaks can make it that code requirements for toilet and/or kitchen exhaust flow rates cannot be met. In the case of high-rise buildings, these flows can sometimes even change direction. One reason for highlighting the performance issue is that the available energy savings from sealing duct leaks can sometimes be reduced by the desire or need to improve the performance of these systems, taking back some of the potential savings in the form of improved or required performance.

100% Outside-Air Duct Systems

The recent duct sealing experiences described in this report also highlighted two groups of duct systems whose potential for sealing had not been previously reported, namely 100% outside air systems, including supply systems for laboratories and exhaust systems in general. In the case of 100% outside-air supply systems, any increases in system flow to meet zone flow requirements translate directly into increased heating and cooling loads associated with the extra air drawn into the building. As noted above, in the case of exhaust systems, the supply-air system design and control strategy impacts the thermal implications of exhaust duct flows, although it appears that in many situations the thermal load associated exhaust systems is directly proportional to the flow being exhausted from the building.

Recent duct sealing experiences have also brought to light several additional reasons for focusing on sealing leaks in exhaust systems, including: 1) the fan power for exhaust systems scales with the cube of the airflow rate (as compared to supply systems, which often scale with flow raised to a power closer to 2.5), 2) exhaust systems are present in almost all large buildings, as they are needed for toilets and showers, even in buildings without central heating and cooling systems (e.g. hotels, dormitories, barracks), 3) any increases in exhaust flows to compensate for exhaust duct leakage represent additional thermal energy losses to outdoors, as long as those leaks into the exhaust come from the conditioned spaces, and 4) exhaust systems in existing buildings are simpler to seal with aerosol technologies, both because of the lack of coils and VAV boxes, and because most of the ductwork is often vertical, which means that gravity helps transport the particles to the leaks.

Unlike supply duct systems, exhaust systems generally do not contain coils or filters, which means that all of the pressure drop that the fan needs to overcome is either turbulent friction in the ducts, or inertial losses through intakes and exhausts, both of which scale with the square of the flow rate. Thus, as the fan power is the product of the pressure drop and the flow, it scales with the flow cubed, thereby making small (e.g. 25%) increases in required fan flow cause large increases in fan power. Moreover, as these fans generally operate at constant speed for 24 hours per day, these increases in power are seen at peak demand periods. This means that sealing, which impacts fan power uniformly throughout the day, will have the same impact on peak fan power demand as it does on energy use. This stands in contrast to efficiency technologies that reduce fan flow during non-peak hours, which although they save energy, will not impact peak power demand. Finally, the thermal impacts of excess exhaust flow scale with the severity of the outdoor air conditions, which means that the absolute magnitude of their impact on cooling load is highest at peak weather conditions.

Their simplicity of construction is one of the factors that make aerosol duct sealing more cost effective for exhaust systems. The lack of coils means that the entire exhaust system can be generally be injected from single point. In addition, because most of the ductwork is vertical, as long as the injection is performed from the top of the system, lower flows can be used for injection, as the sealant particles generally drift down towards the leaks, rather than having to be held aloft by mild turbulence in horizontal ducts (which requires higher flows and sometimes creates the need for additional equipment). Finally, as many buildings have multiple exhaust shafts terminating at the same location (e.g. roof or penthouse), the set-up time is also reduced when sealing multiple exhaust systems.

Conclusions and Recommendations

Based upon the data and observations presented in this paper, several conclusions and recommendations can be made. First, it is clear that there are ducts in buildings other than single family residences that leak significant fractions of the air flowing through them, 23% of fan flow on average for the 10 buildings with complete testing and sealing data. Second, the data presented also indicate that the vast majority of the leaks in these ducts systems can be sealed by means of aerosol sealant particle injection, 87% on average.

This paper also highlights some needs with respect to duct leakage in large and/or non-residential buildings, in particular the need for simple, accurate means for determining which buildings merit duct sealing, and the need for more field data on the actual savings produced by sealing leaks in these types of buildings. Concerning the screening of buildings for significant duct leakage, test and balance reports currently seem to be the best source of data, however such reports are generally too expensive to be used solely as a screening tool. Concerning field measurements of actual savings produced, the lack of measured thermal savings data from sealing exhaust systems stands out as the largest need, however field measurements of savings for the other types of buildings/systems is also merited.

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