Laboratory and Field Testing of an Aerosol-Based Duct-Sealing Technology for Large Commercial Buildings

AUTHOR NOTE

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ABSTRACT

Laboratory and field experiments were performed to evaluate the feasibility of sealing leaks in commercial duct systems with an aerosol sealant. The method involves blowing an aerosol through the duct system to seal the leaks from the inside, the principle being that the aerosol particles deposit in the cracks as they try to escape under pressure. It was shown that the seals created with the current sealant material can withstand pressures far in excess of what is found in commercial-building duct systems. We also performed two field experiments in two large-commercial buildings. The ASHRAE leakage classes of the systems were reduced from 653 down to 103, and from 40 down to 3. Methods and devices specifically devised for this application proved to be very efficient at (a) increasing the sealing rate and (b) attaining state-of-the-art duct leakage classes. Additional research is needed to improve the aerosol injection and delivery processes.

Keywords: air distribution, air leakage, duct system, energy, seal

INTRODUCTION

Air distribution duct systems are frequently used in U.S. residences and commercial buildings to transport conditioned air to the occupied space and/or to provide fresh air. Air leaking in or out of these systems has been identified as a major source of energy loss in U.S. buildings. There exists a substantial body of research on residential air distribution system leakage that includes both detailed field characterizations and energy analyses (Cummings *et al.* 1990; Davis and Roberson 1993; Jump and Modera 1994; Modera 1993; Modera and Jump 1995; Parker *et al.* 1993; Proctor *et al.* 1992; Walker *et al.* 1998). Published material on these subjects indicate that duct system inefficiencies account for approximately 30% of space conditioning energy use in U.S. residences; these inefficiencies explain the considerable efforts that are being undertaken to retrofit these systems, or to better design and install them.

Despite their potentially large energy implications, very little information is available on the magnitude and impact of air leakage and heat conduction losses in large commercial buildings. In fact, in California, heating and cooling in commercial buildings typically accounts for 18% of their electricity consumption and 42% of their natural gas consumption. This represents roughly 15,600 GWh of the electricity and 24,000 GWh of the gas consumed statewide. It is estimated that an additional 3,200 GWh of electricity is used to operate the fans and pumps of commercial air central systems and large-office packaged systems (Modera *et al.* 1999b).

Limited field studies conducted at Lawrence Berkeley National Laboratory (LBNL) (Fisk *et al.* 2000) report ASHRAE leakage classes that range from 60 to 270 in e commercial buildings. These values are above the “unsealed” values o to 48 typically assumed (ASHRAE 1997). Based on simulations of a v ble air volume (VAV) system with a leakage class of 137, Franconi *et al.* (1998) predicted an energy-cost increase of 14% and an increase in annual fan energy use of 55% due to duct leakage. Thus, sealing duct leaks in large-commercial buildings appears to be an effective means for reducing energy consumption in this sector.

In this paper, we investigate the commercial-building potential of an aerosol-based duct sealing technology which has been developed at LBNL for residential applications (Modera and Carrié 1996; Carrié and Modera 1998). The technology involves blowing an aerosol through the duct system to seal the leaks from the inside, the principle being that the aerosol particles deposit in the holes and the cracks of the ductwork as they try to escape under pressure. Before the sealant is injected, the registers are blocked, and sensitive components (e.g., the heat exchangers) are isolated from the aerosol sealant. Although this technique has been successfully used in several hundred residences and is currently commercialized for residential buildings in the U.S., its application to large commercial duct systems poses new challenges. This paper reports on the development of new methods and concepts to overcome these challenges, and on their assessment via field trials in two large commercial buildings in California.

OBJECTIVES

The goal of this research is to explore the feasibility of reducing duct leakage in large commercial building duct systems with an aerosol sealant. This work entails the following objectives:

1. to quantify the losses of sealant material near the aerosol generator;
2. to evaluate the ability of the seals to withstand the high pressures encountered in large commercial duct systems;
3. to evaluate new concepts to speed up the sealing rates; and
4. to conduct field experiments to assess the ability to seal large and long ducts in a reasonable amount of time.

This work is part of a broader research program that aims to evaluate the energy implications of duct leakage and conduction gains in large-commercial duct systems, and develop new technologies to improve the thermal performance of those systems.

BACKGROUND

The proof-of-concept with the use of aerosol particles to remotely seal leaks in duct systems from the inside was demonstrated in 1994 by researchers at LBNL (Modera and Carrié 1996). The current protocol requires blocking of all the registers and isolation of sensitive equipment (e.g., heat exchangers). The aerosol is generated and blown into the system through a conveniently-located opening in the duct system, using a single device that incorporates a fan, a heater, and an atomizer. The device is connected to the duct inlet with thin-wall ("lay-flat") plastic tubing. It is designed to monitor the sealing process, and measures the airtightness of the system before, during, and after aerosol injection. The aerosol is highly concentrated (typically 0.1 to 1 g/m^3) and is made of sticky particles whose diameter typically lies between 5 and 30 μm. As the aerosol is forced through the leaks, some particles tend to leave the air stream and collide with the edges of the leak opening. As a result, they gradually form a bridge over the crack. This technique has proved to be very efficient at sealing duct leaks in residences (Modera *et al.* 1996).

The sealant is a water-based vinyl-acetate polymer liquid adhesive. There are 0.12 g of solid adhesive per mL of liquid sealant. The durability of the seals created in this process has been studied by Sherman and Walker (1998). The aerosol sealant was subjected to heated air and 20 minute cycle time at about 200 Pa of pressure. The seals showed no signs of failure over about 40,000 cycles.

There are two major advantages to this aerosol-sealing technique. First, it is an automated remote sealing process since the particles "automatically" find the leaks in the system. Second, in residences, the technique has proved to be geometry-independent as the particles can travel within the whole system and thus access any leak site.

In large commercial buildings, however, the systems are much larger and much more complex than those in residences. To seal the large and long ducts in commercial buildings, several challenges are faced, including:

1. higher aerosol-production rates are required;
2. aerosol deposition on the surfaces of long ducts may reduce the efficiency of the sealing process;
3. the aerosol seals must withstand the higher operating pressures of commercial ducts;
4. because large commercial buildings systems have a large surface area and operate at higher pressures than do residential systems or small commercial systems, the target

leakage classes must be considerably smaller than those in residences or even small commercial buildings to attain reasonable leakage-to-fan flow ratios; and

5. new technologies and protocols are required to block commercial registers and to isolate sensitive equipment from the aerosol flow.

METHODOLOGY

Evaluating the application of this aerosol-based technology to large-commercial buildings involves overcoming many practical problems. Injected aerosol particles tend to deposit on the duct walls, mainly because of gravitational settling and turbulent diffusion, but also by impingement near the aerosol generator. Therefore, it is necessary to develop methods that can ensure sufficient particle transport into the entire system, and to quantify the particle losses near the injection location.

Our methodology consisted in undertaking hardware developments to improve the aerosol generation and aerosol delivery processes. Also, laboratory experiments were designed to (a) characterize the fraction of particles removed from the air stream near the injector; (b) assess the size distribution of the particles left for sealing a few meters downstream of the injection device; and (c) evaluate the bursting pressure of properly sealed leaks. Finally, we conducted field tests of the aerosol duct-sealing technology in two large commercial buildings.

HARDWARE DEVELOPMENTS

Multi-Point Injection

The standard aerosol sealing procedure involves only one main injector that delivers about 36 mL min^{-1}. The multi-point injection method developed and tested in this study adds extra sources of pre-heated aerosol spray at distances far from the main fan/heater/injector apparatus. This process is intended to accelerate the sealing process by increasing the aerosol mass flux delivered to leaks. For multi-point injection, we designed and had fabricated compact injector units that deliver about 20 mL min^{-1} of sealant material. The atomizer airflow rate is about 14 L s^{-1} and is added to the carrying airflow generated by the main injector.

Atomizers

The atomizer of each injector may be equipped with either a standard vortex nozzle or a modified vortex nozzle (Figure 1). The vortex nozzles use counter-rotating swirls of air generated by the fixed wheels to atomize a liquid stream. The modified nozzle has been equipped with an extra wheel-shaped fin, or “wheel”, in an attempt to produce smaller particles to decrease the fraction of injected sealant that deposits on the duct walls.

CHARACTERIZATION OF AEROSOL INJECTORS

Evaluating the application of this aerosol-based technology to large-commercial buildings requires an accurate understanding of particle deposition processes in duct systems. These are closely linked to the size distribution of the particulate matter injected into the system, which in turn depends on the injection device being used (e.g., type of atomizer) and the boundary-conditions (e.g., the airflow rate).

The sealing process employs two types of aerosol injectors described above. Four injector configurations were evaluated:

1. main injector with a standard vortex nozzle;
2. main injector with a modified vortex nozzle;
3. compact injector operated in low duct airflow; and
4. compact injector operated in high duct airflow.

In each case, the injector was used to spray an aerosol of sealant particles into a four-meter-long duct of pressurized, thin-walled plastic tubing for a period of one to two hours (Figure 2).

Aerosol Size Distribution Measurements

We used a cascade impactor with 10 stages to assess the particle size distribution 3 meters downstream of the injection location (Pilat 1970). Some of the stages were modified so that the resulting cut-off diameters enable us to better characterize the size distribution. The stages were weighed using a 0.1 mg resolution scale. Typically, the mass collected on each stage was in the range of 2 to 20 mg.

Particle Losses Near Injection Location

Deposition of sealant on the duct wall due to impingement, turbulence, and gravity was measured by cutting the thin-wall plastic tubing into 50-cm-long segment for the first three meters of the tubing after aerosol injection. We weighed each segment and calculated the net deposition by subtracting out the initial weight of the whole tubing. The deposition is expressed as a fraction of the total sealant mass injected into the duct, and the variation in cumulative deposition depends on distance from the injection point.

Main Injector Configurations

The main injector with a modified vortex nozzle yielded about 50% or more deposition on the first three meters of duct wall than did the main injector with a standard vortex nozzle (Table 1). Little deposition occurred more than two meters downstream of the injector in either configuration. The standard-nozzle main injector deposited 22 to 24% of the injected sealant on the first three meters of duct wall, mostly within one meter of the injection point. The modified-nozzle main injector deposited 34 to 44% of the injected sealant on the first three meters of the duct wall, also mostly within one meter of the injection point (Figure 3).

The modified-nozzle injector also yielded larger particles three meters downstream of the injection point than did the standard-nozzle injector. The downstream mass-median particle diameters of particles generated by the modified and standard vortex nozzles were 14.9 and 8.1 μm, respectively, with geometric standard deviations of 3.2 and 3.1 (Figure 4).

The particles lost in the plastic tubing connecting the aerosol injector to the building's duct system are not available for sealing the leaks. The wall-deposition results indicate that a main injector equipped with a standard nozzle will deliver approximately 75% of injected sealant to duct inlet, while a main injector with a modified nozzle will deliver only about 60% of the injected sealant to the duct system. This suggests that it is preferable to use the standard vortex nozzle rather than its modified version.

Compact Injector Configurations

All aerosol particles produced by the compact injector enter the duct system, but a portion deposit near the injection location, and therefore are not available for sealing the leaks. The results are provided in Table 1 and Figure 5. With the low duct airflow, 47 to 66% of the injected sealant deposited on first three meters of duct wall, mostly within 50 cm of the injection point. With the high duct airflow, 25 to 29% of the injected sealant deposited on the first three meters of the duct wall, mostly within one meter of the injection point. Little deposition occurred more than one meter downstream of the injector in either configuration.

The discrepancies in the results are probably due to slight variations in the alignment of the atomizer. This explanation is consistent with the significant variations in particle deposition by impingement observed within the first meter (Figure 3 and Figure 5). This suggests that the nozzle should be aligned very carefully for best results.

The size of the particles still airborne 3 m downstream of the compact injector varied with the airflow rate. With the lower airflow rate (38 L s^{-1}), the mass median diameter was 5.5 μm, with a geometric standard deviation of 2.4. With a flow rate of 142 L s^{-1}, the mass median diameter was 17.6 μm, with a geometric standard deviation of 3.4 (Figure 4).

OPERATING PRESSURE LIMITS OF SEALED LEAKS

The bursting pressure is the duct air pressure at which the force exerted by the air punctures the glue bridge sealing the leak. The bursting pressures of glue-sealed 3, 6, and 16-mm wide slots were measured in the laboratory.

Fifty-millimeter-long slots of widths 3, 6, and 16 mm were cut in a 26-gauge sheet metal duct cap. The slots were sealed by attaching the cap to the end of a duct system into which aerosol particles were injected for several hours. The sealant color was changed over the course of the sealing process. When the color of sealant being injected did not appear in the glue bridge spanning the slot, the gap was considered sealed.

Bursting pressure was measured by increasing the air pressure difference across each sealed slot until the pressure difference suddenly dropped, indicating that the seal had been punctured. The following procedure was followed for each of the three sealed slots.

The positive-pressure-side surface of two of the three sealed slots was covered with petroleum jelly, wax paper, and metal tape to leave only one sealed slot exposed to puncture by air pressure. A pump and a mass flow controller were used to inject air at a known rate into the enclosed duct cap, and the difference in air pressure between the system interior and the room—i.e., the pressure across the seal—was measured with an electronic transducer. The flow rate and pressure were recorded by a data logger.

As the air-injection flow rate was rapidly increased from zero to about 1 L min^{-1}, the system pressure rose to a steady value at which the pressure-driven air losses through small leaks in the system (e.g., imperfections in the duct-cap construction) equaled the injection rate. The air-injection rate was increased in steps of about 1 L min^{-1}, raising the system-pressure, until a leak in the slot's seal was indicated by a sudden system pressure drop. The presence of a leak through the sealed slot was confirmed by manually sensing an air jet through the sealant.

The 3-mm-wide seal developed a small puncture at a pressure above 5,600 Pa, which was the highest pressure measurable with the pressure sensor used. The hole was not visible to the unaided eye, but a jet of air could be detected, and the pressure suddenly dropped to 4,100 Pa. The 6-mm-wide seal developed a similar hole at a pressure of 5,200 Pa, and the system pressure rapidly decreased to 2,200 Pa. This hole was also invisible to the unaided eye. The 16-mm-wide slot was never fully spanned by the aerosol-sealing process, even after 6 hours of injection. Hence, it was not possible to raise the system pressure above 660 Pa.

These results indicate that the bursting pressure of a properly-sealed slot leak exceeds 5,000 Pa, which is well above normal operating pressures in commercial building duct systems. (Operating pressures in commercial buildings rarely exceed 1,500

Pa. Operating pressures upstream and downstream of a VAV unit are typically in the range of 400 to 700 Pa, and 0 to 100 Pa, respectively.)

FIELD TESTING IN TWO LARGE COMMERCIAL BUILDINGS

Metrics

A common metric used to evaluate the effectiveness of a sealing technique is the Effective Leakage Area (ELA) measured before and after retrofitting. ELA is defined as the cross-sectional area of a perfect nozzle that would produce the same flow as that passing through the leaks at a reference pressure. The reference pressure is usually set to 25 Pa for U.S. duct system characterization. This reference pressure is questionable for large systems in large commercial buildings, where operating pressures are often considerably higher. Nevertheless, since it remains a common metric to measure and compare duct leakage in the U.S., the 25 Pa characterization is used in this paper. With the currently available apparatus, ELA is measured with the standard one-point pressurization technique at 25 Pa.

In addition to leakage area measurements, the field testing protocol for the two buildings reported in this paper, designated building L-2 and L-5, included the following measurements:

- measurement of the particle mass deposited on the thin-wall plastic tubing used to connect the main injector to the duct inlet;
- aerosol concentration measurements at different locations in the system, either by using impaction plates in system L-5 (as reported by Modera *et al.* (1999a)), or by using gravimetric disposable filters in system L-2;
- velocity measurements at different locations in the system, made using a hot-wire anemometer (for system L-2 only).

Aerosol Concentration Measurements

The measurement of aerosol concentration is complicated by the significant fraction of the particles that have high inertia; therefore, isokinetic sampling conditions should be achieved to obtain a representative sample. Sampling probe misalignment and velocity mismatch effects are negligible when the Stokes number (based on the air velocity in the duct) is less than 0.01 and when the ratio of the sampling velocity to the duct air velocity (U_0/U) satisfies $0.2 < U_0/U < 5$ (Hinds 1982). Because these conditions are not met for most particles in our sampling conditions, non-isokinetic sampling can lead to significant errors. However, aerosol concentration measurements yield valuable relative information about aerosol penetration at various locations in the system, and help explain the sealing rate behavior.

Characteristics of the duct systems

Tests were performed on isolated sections of two large-commercial buildings whose characteristics are summarized in Table 2. Schematic representations of the systems' layouts are provided in Figure 6 and Figure 7. The system investigated in building L-2 was a perimeter heating system located in a ceiling plenum with a single 30-cm (12-inch) diameter, 60-m (180-ft) long sheet-metal duct (system L-2). (This building also had a VAV cooling system serving about 2,200 m^2 (24,000 ft^2) of floor area on two floors that was not investigated.) The section of the HVAC system investigated in building L-5 was part of a dual duct system serving about 3,200 m^2 (34,000 ft^2) of floor area on two floors. Both systems tested were located in a ceiling plenum. They were originally sealed with either tape or mastic or both depending on the location. However, their initial leakage areas were high (Table 3), which concurs with the high leakage rates previously found by Fisk *et al.* (2000) in large commercial duct systems.

Sealing Strategies

The injection and sample locations are shown in Figure 6 and Figure 7. The tests were performed in two phases. In building L-5, we started with the "standard" injection procedure (i.e., a main injector delivering the aerosol to the duct system at a single location via a 6-m length of plastic tubing), then continued by adding one compact injector to the main injector. In building L-2, we started with the standard injection procedure, and then created a downstream leak (airflow outlet) in the duct to help maintain airflow sufficient to transport the particles to the leaks while keeping the pressure in the system below the threshold limit value. With the currently available apparatus, this pressure is set to 500 Pa based on the field experience on the residential systems. Although most large-commercial ductwork systems should be able to withstand larger pressures, we kept the same value as that adopted for the residential systems, because the fan in the current equipment cannot supply adequate flows at higher pressures.

Results

Figure 8 shows particle concentration measurements in building L-5. The concentration was considerably increased downstream of the compact injector (location 3) when the injector was turned on. (Note that compact injectors do not necessarily increase particle penetration in the system (penetration is usually defined as the ratio of the particle flux at some location to the total particle flux injected). However, they increase the particle flux downstream of their location.)

Significant deposition was observed in the lay-flat tubing. In building L-2, 35% of the mass injected was collected in this tubing over the course of the test. In building L-5, a temporary failure of the equipment to properly atomize the liquid sealant yielded significant liquid deposition in the lay-flat tubing, preventing a quantitative analysis of those losses.

Table 3, Figure 9, and Figure 10 summarize the changes in the duct leakage area. The ELA at 25 Pa over the course of the experiment was calculated assuming a flow exponent of 0.6 [(1)]. The sealing rate increased considerably when the compact injector was turned on. However, the sealing rate did not decrease when the compact injector was turned off between 6.4 hours and 6.8 hours of elapsed time, probably because the leakage downstream of its location was small compared to that of the rest of the system.

[1] In system L-5, the pressure was found to be significantly lower in mixing boxes 3 and 4. While the presence of a flow restriction in mixing box 4 can explain the lower pressure in the downstream trunk, it is unclear why a lower pressure was observed downstream of mixing box 3. There may have been an unobserved restriction in that section. In any case, the ELAs have been corrected to the observed pressure differences by assuming that the ratios between the leakage coefficients of each branch remain constant over the course of the test. This crude assumption can explain the discrepancies between the initial ELA displayed in Figure 9 and the initial ELA reported in Table 3.

Figure 10 illustrates how the ELA changes with time in building L-2. The section started with a relatively low initial ELA_{25} of 45 cm^2 and was reduced to about 4 cm^2. As expected, adding an opening in the downstream section of the duct at 0.4 hours allowed us to continue the sealing process after the threshold limit value for the pressure (500 Pa, with the present apparatus) was reached.

SUMMARY OF KEY RESULTS

1. Our atomizers produce aerosols of large particles with a wide size distribution.
2. With the standard-nozzle main injector, about one quarter of the injected sealant deposits within the first meter of the injection point. With the compact injector, one-quarter to two-thirds of the injected sealant deposits near the injection point (mostly within 0.5 m of the injector).
3. The bursting pressure of properly-sealed leaks exceeds 5,000 Pa.
4. In building L-5, adding a single compact injector to our existing sealing apparatus increased the sealing rate by a factor of 4.
5. The leakage area of system L-5 was reduced by more than 80%. The sealing rates were found to be very low in this system (on average, 60 $cm^2\ hr^{-1}$). On the other hand, leakage levels as low as ASHRAE leakage class 3 could be attained with an airflow outlet in a 30-cm (12-inch) diameter, 60-m (180-ft) long duct (system L-2).

DISCUSSION

Overall, the results presented in this paper suggest that the new concepts tested and developed herein are promising. First, the failure of properly-sealed leaks is very unlikely under the operating pressures encountered in large commercial HVAC systems. Second, the leakage area of large-commercial systems can be significantly reduced with this aerosol-sealing technique. (Note that the leakage class attained in system L-2 corresponds to the Eurovent leakage class C that is usually required and fulfilled for circular systems larger than 50 m^2 in Sweden (VVS AMA 98 1998). Recent field studies (Carrié *et al.* 1999) indicate that Belgian and French systems are typically about 30 times leakier.)

Successful sealing of large-commercial-building duct systems would allow reduction of the fan airflow rates without adversely affecting the indoor climate in those buildings, thereby significantly decreasing fan energy use. The work of Franconi *et al.* (1998) suggests that 30 to 50% of the fan energy can be saved by sealing duct leaks. Extrapolating this result, duct sealing retrofits for 50% of commercial air central systems and large-office packaged air systems in California would yield an energy savings potential of 480 GWh per year. Other benefits to airtight duct systems in such buildings include better control of airflows at the registers (flow balancing) and potentially-better indoor air quality and thermal comfort.

Cost analyses of the sealing process were performed on a hypothetical large office building that has a floor area of 4,600 m^2 (50,000 ft^2) with a C_L=200 duct system of about 1,840 m^2 (19,800 ft^2)—i.e., a duct surface to floor area ratio of 40%, see Fisk *et al.* (2000)—assuming an average sealing rate similar to that experienced in building L-5 (60 $cm^2\,hr^{-1}$) and a sealant injection rate of 56 mL min^{-1}. Typically, the fan energy use for this kind of building is about 30 kWh m^{-2} per year (3 kWh ft^{-2}) in California (Modera *et al.* 1999b). About 103 hours of injection would be necessary to seal the system down to a leakage class of 12, and the cost of the sealant material would be of US$900 to US$1800. Based on the market experience of aerosol-sealing in residences [2], this yields a total cost for the process (including labor) of US$4,500 to US$9,000. If we assume that 30% savings can be achieved on the fan energy use (Franconi *et al.* 1998), the approximate simple pay-back period of aerosol duct sealing in this particular building would be of one year to two years.

Assuming that the average sealing rate remains constant, the necessary time to seal one fraction of a ductwork system is directly proportional to the duct surface area of that section. This suggests that the time spent by on site by a crew during a sealing job can be significantly reduced by injecting the aerosol-sealant in multiple isolated sections of the duct system at the same time. Therefore, the injection time of 103 hours obtained in the previous hypothetical example should be compared with the time involved in the

[2] In residences, the entire process cost (including labor cost) is about 5-10 times that of the material cost.

retrofitting of a similar duct system using conventional techniques such as manual sealing; however, we did not find reliable information on that subject.

CONCLUSIONS AND FUTURE WORK

Laboratory and field experiments were performed to evaluate the feasibility of sealing leaks in commercial duct systems with an aerosol sealant. We have obtained promising results with respect to the following points.

1. The laboratory tests performed to evaluate the operating-pressure limits of the sealant showed that the failure of properly-sealed leaks is very unlikely under the operating pressures encountered in large commercial HVAC systems. Therefore, there is no need to improve the strength of the seals for this application, although longevity issues should be addressed.
2. We have tested our multi-point aerosol injection technique in the sealing test of one section of a large-commercial building system. Adding a single compact injector to our existing sealing apparatus increased the sealing rate by a factor of 4.
3. The ASHRAE leakage classes of two real systems were reduced from C_L=653 down to C_L=103, and from C_L=40 down to C_L=3, corresponding to reductions of more than 80 and 90%, respectively.

On the other hand, the laboratory characterization of the aerosol injectors in use show that particle losses near the injection point are quite high under some operating conditions. In addition, the sealing rates observed during the field tests were low. These results suggest that further optimization of the sealing hardware is needed to increase the efficiency of the technology. We also believe that the optimum pressure and flow conditions for sealing typical leaks should be experimentally investigated, as previous work in this area cannot be applied directly to the current sealing protocols.

Several potential shortcomings to this aerosol-sealing technique should be investigated in the future. One major difference between residential and large-commercial systems is that the latter are more likely to have components that may be harmed by sticky aerosol deposition. These include hot-wire anemometers, smoke or Indoor Air Quality (IAQ) sensors, and heating or cooling coils at terminal units. The two systems of the present study did not have such components; however, we believe that these issues should be carefully addressed should this technique prove to be viable for long, large, and complex systems. In two previous trials (Modera *et al.* 1999a), aerosol sealing did not modify the calibration of the airflow rate sensors in a pressure-signal VAV unit. However, further experiments with other units are needed. The time required to block all of the registers in large systems is another practical issue that needs to be addressed.

In summary, the laboratory and field study reported in this paper suggests that aerosol duct sealing in large commercial buildings is promising, but that additional research efforts to increase the efficiency of the technology should be pursued before its widespread use can be envisioned.

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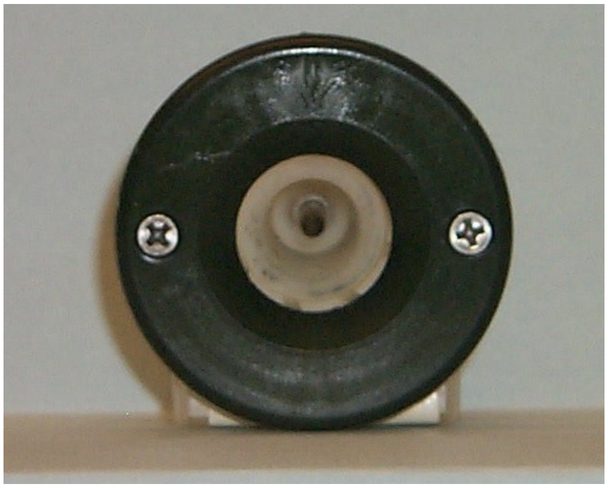

(a) (b)

Figure 1. Front and side view of standard vortex nozzle (one inlet wheel at the bottom of nozzle). Counter-rotating swirling flows generated by the upper and lower wheels atomize a liquid stream delivered by the central tube. The modified vortex nozzle has two inlet wheels (bottom of nozzle).

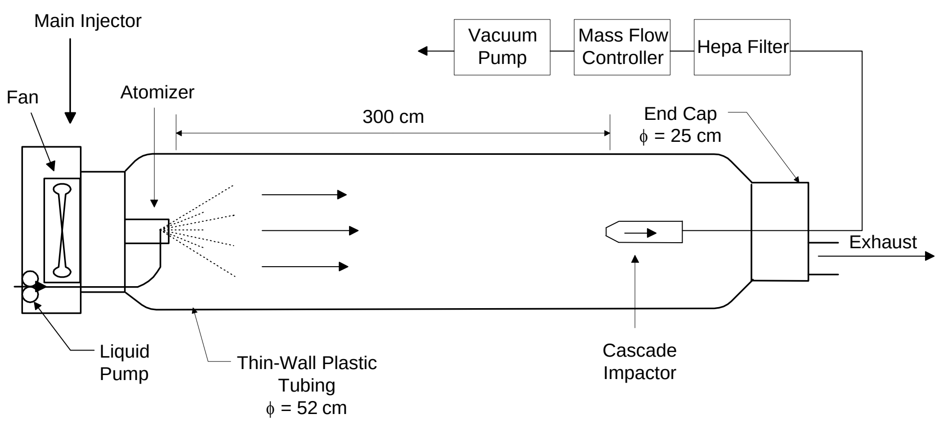

Figure 2. Main injector configuration: aerosol sprayed into 4-m long, 52-cm diameter thin-walled plastic tube, with particle size distribution sampled 3 m from the injection point.

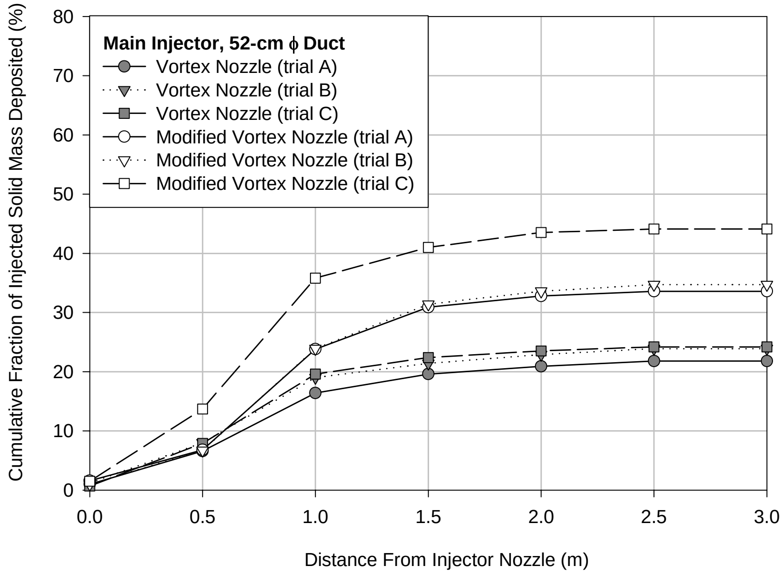

Figure 3. Deposition of solid sealant on duct wall due to impingement, turbulence, and gravity, shown for two configurations of the main injector (see Figure 2). Discrepancies in the results of multiple trials possibly due to atomizer misalignment.

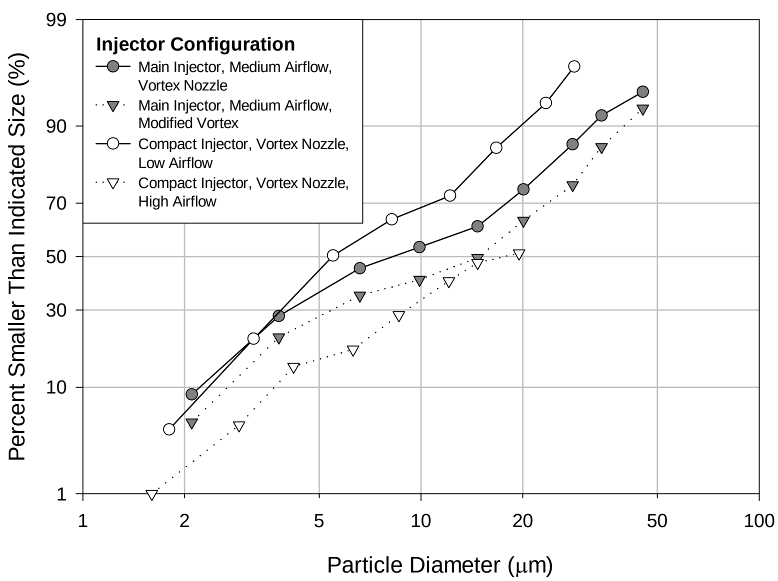

Figure 4. Particle-size distributions of aerosols generated by two main-injector and two compact-injector configurations, measured three meters downstream of the injection point (see Figure 2).

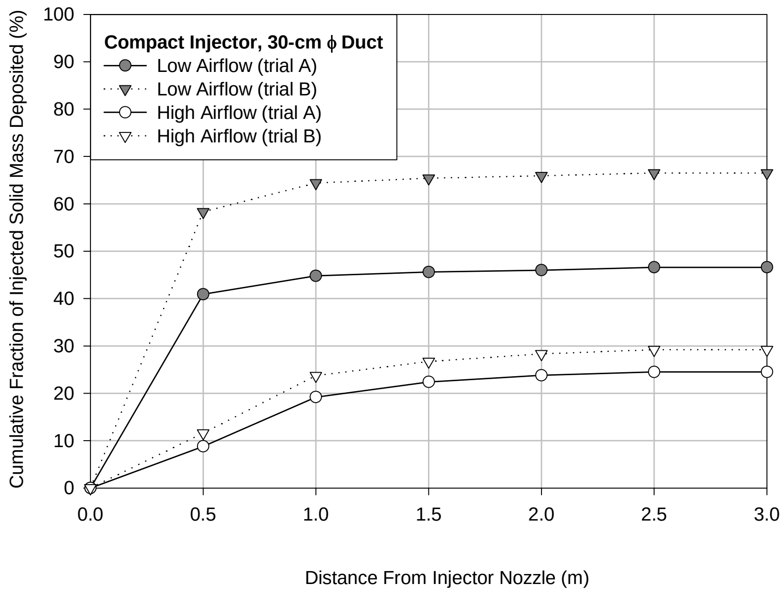

Figure 5. Deposition of solid sealant on duct wall due to impingement, turbulence, and gravity, shown for two configurations of the compact injector. Discrepancies in the results of multiple trials possibly due to atomizer misalignment.

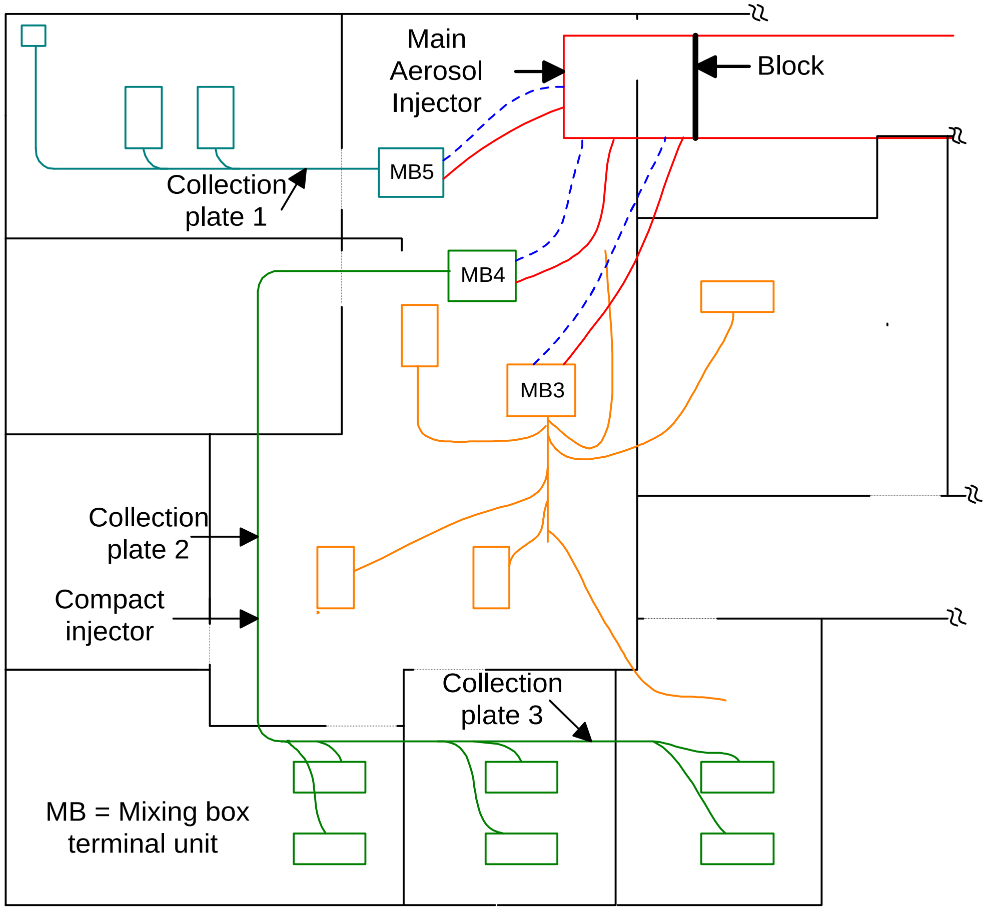

Figure 6. Duct layout, main and compact injector installation, and aerosol sampling locations in building L-5.

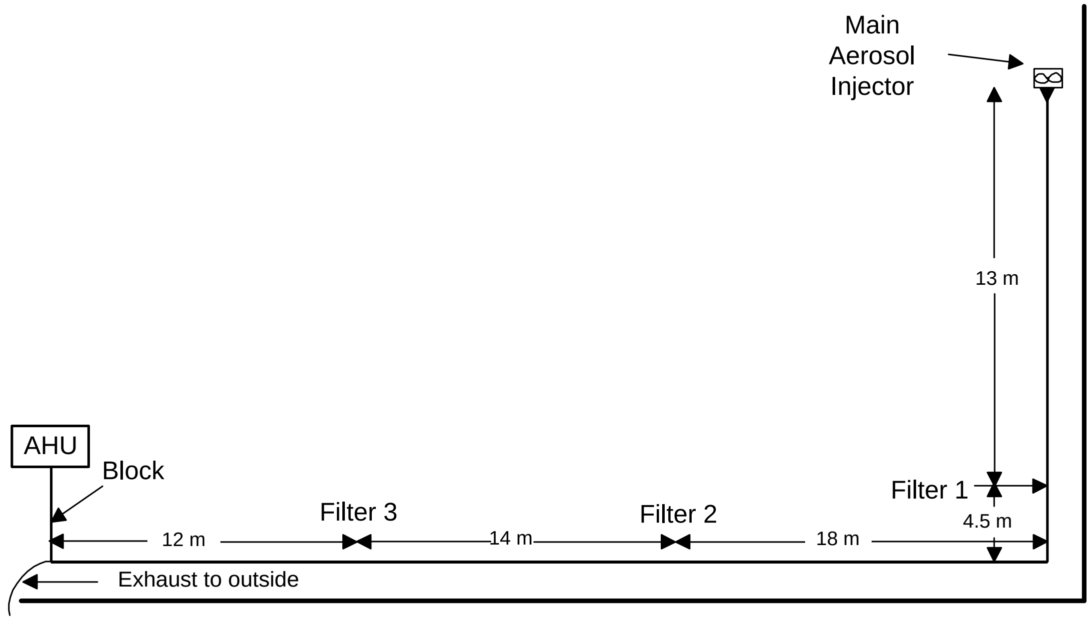

Figure 7. Duct layout, main injector installation, and aerosol sampling locations in building L-2.

Sample number	Start time, h	End time, h
1	-0.2	0.5
2	0.5	1.9
3	1.9	3.3
4	3.3	4.8
5	4.8	6.4
6	6.4	6.8
7	6.9	7.4
8	7.4	8.3

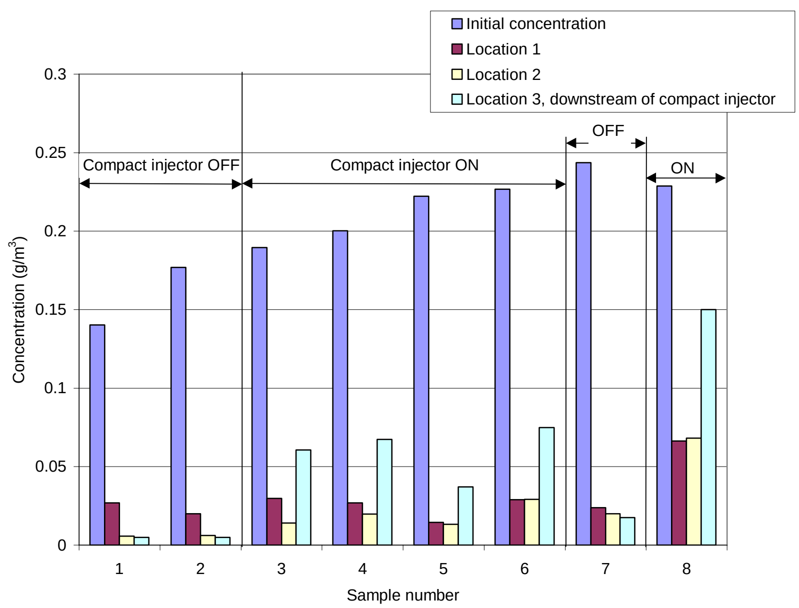

Figure 8. Aerosol concentrations measured at several locations in building L-5 using the impaction plate method. Initial concentration is calculated based on the fan flow rate and the liquid injection flow rate. The relatively high concentrations measured in sample 8 are likely due to re-positionning the lay-flat tubing.

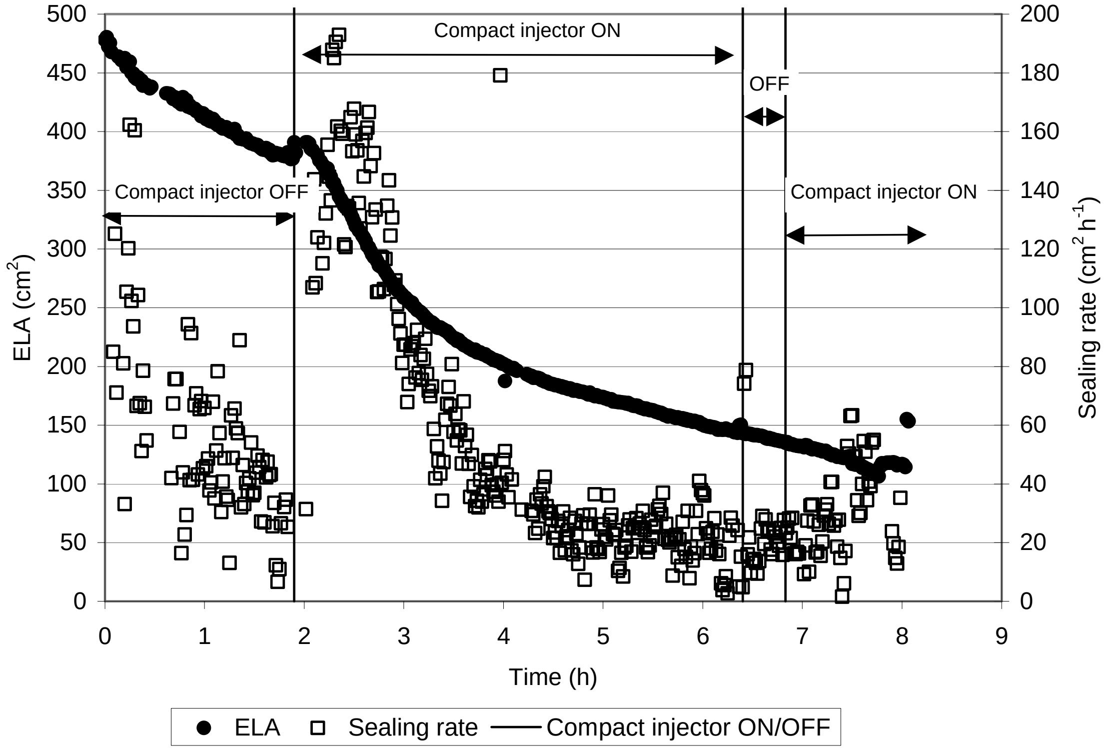

Figure 9. Effective leakage area (ELA) and sealing rate during sealing process in building L-5. The solid vertical line shows when the compact injector was turned on. The beginning of the experiment (about 20 minutes) has been removed for clarity.

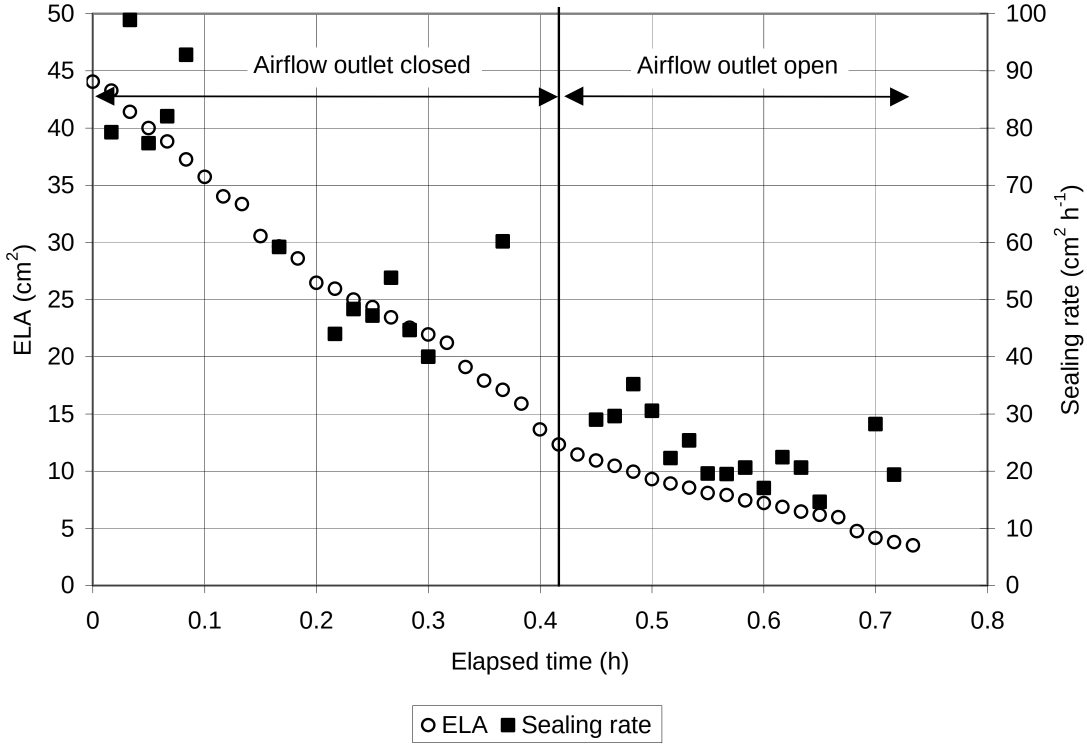

Figure 10. Effective leakage area (ELA) and sealing rate in building L-2 during the sealing process. The solid vertical line shows when the pressure-relief outlet was opened. The leakage area measurement of the system during the second phase of the test was corrected for the air flowing through the outlet. For clarity, periods where injection was turned off are removed.

Table 1. Operating conditions, particle-size distributions, and wall-depositions of four aerosol-injector configurations (see Figure 2). Additional data of duct wall deposition measurements only are shown in brackets. Discrepancies in the results seem to be due to atomizer misalignment.

Configuration	Main injector, vortex nozzle	Main injector, modified vortex nozzle	Compact injector, low airflow	Compact injector, high airflow
Injector **Nozzle**	main vortex	main modified vortex	compact vortex	compact vortex
Liquid sealant flow rate (mL min^{-1})	36	36	20	20
Duct diameter (cm)	52	52	30	30
Total duct airflow rate (L s^{-1})	84	84	38	142
Air temperature immediately upstream of injector nozzle (°C) [multiple trials]	78 [77] [77]	74 [79] [77]	74 [60]	68 [71]
Mass fraction deposited on duct wall (-) [multiple trials]	22% [24%] [24%]	44% [34%] [35%]	47% [66%]	25% [29%]
Cascade impactor sampling airflow rate (L min^{-1})	3.0	3.0	4.4	16.3
Mass median particle diameter (μm)	8.1	14.9	5.5	17.6
Mass geometric standard deviation	3.1	3.2	2.4	3.4

Table 2. Large-commercial duct system characteristics.

System	Age of building, years	Total building floor area, m^2 (ft^2)	Floor area served by sealed section, m^2 (ft^2)	Duct surface area of sealed section, m^2 (ft^2)	Number of diffusers in sealed section
L-5	9	3,200 (34,000)	140 (1,500)	47 (506)	13
L-2	20	2,200 (24,000)	420 (4,500)	64 (689)	21

Table 3. Leakage area before and after field trials of aerosol-sealing.

Building	Pre-sealing ELA at 25 Pa, cm^2	Pre-sealing leakage class, cfm/100 ft^2	Post-sealing ELA at 25 Pa, cm^2	Post-sealing leakage class, cfm/100 ft^2	Percentage of reduction, %	Duration of aerosol injection, hours
L-5	544	657	95	103	83	8.5
L-2	45	40	4	3	92	0.7