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Reducing the Permeability of Residential Duct Systems

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REDUCING THE PERMEABILITY OF RESIDENTIAL DUCT SYSTEMS

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SYNOPSIS

In this paper, we investigate the potential of an aerosol-based technique to significantly reduce the leakiness of residential air distribution systems (ADS). The first part is dedicated to a short review of theoretical analyses of particle transport and deposition in an ADS as well as particle removal in the leaks. The purpose of this review is to pre-determine the ranges of the flow rates, pressure differentials and miscellaneous characteristics of the particles that would allow plugging of the leaks in a relatively short time. The remainder of the paper deals with our experimental investigation and includes a description of experiments performed to assess the feasibility of the technique. We found that an aerosol alone made out of a liquid suspension of a vinyl polymer can plug 16 cm^2 of Effective Leakage Area in a branch in less than 30 minutes. Based on our theoretical and experimental results, we designed a field device and performed laboratory experiments on a small-scale duct system. We showed that with this portable unit, the Effective Leakage Area of a typical duct network in California can be reduced by about 80%.

LIST OF SYMBOLS

C_m	aerosol mass concentration [kg/m^3]
D	duct diameter [m]
$d()$	differential [-]
d_p	particle diameter [m]
e	duct wall thickness [m]
h	leak-width [m]
i	integer [-]
L	duct length [m]
P	penetration [-]
Q	flow rate [m^3/s]
Re	Reynolds number [-]
SE	sealing efficiency [-]
Stk	Stokes number [-]
t	time [s]
t_i	i-th characteristic sealing time [s]
t_{res}	residence time in the separation zone [s]
U_s	velocity upstream of the slot at $y=y_s$ [m/s]
u	velocity along x [m/s]
v	velocity along y [m/s]
v_s	bulk velocity through the slot [m/s]
w	thickness of the seal [m]
x	horizontal coordinate [m]
y	vertical coordinate [m]
y_s	height of the dividing suction streamline [m]

Greek symbols:

ΔP	pressure differential [Pa]
η	deposition efficiency [-]
ν	kinematic viscosity of the fluid of interest [m^2/s]
ρ	density [kg/m^3]
τ	particle relaxation time [s]

Subscripts and superscripts:

o	at t = 0
D	pertaining to duct
f	pertaining to the fluid of interest
p	pertaining to particle
ref	at the reference pressure differential
s	pertaining to slot
$seal$	pertaining to particle build up
$\overline{}$	average value

Abbreviations:

ADS	Air Distribution System
ELA	Effective Leakage Area [m^2]

1. INTRODUCTION

During the past five years, research has quantified the impacts of residential duct system leakage on HVAC energy consumption and peak electricity demand. A typical California house with ducts located in the attic or crawlspace wastes approximately 20% of heating and cooling energy through leaks and draws approximately 0.5 kW more electricity during peak cooling periods (Modera, 1993). Besides, given that 25% to 75% of the leaks are not accessible (Robison and Lambert, 1989), conventional technologies such as using duct tape or mastic are often not satisfactory. Existing remote sealing technologies have been examined (e.g. introducing a rolling mechanical cart, or unfolding a cylinder in the duct network). Although the application of these techniques might be of interest for some pipe networks (the cart was patented and used for gas pipes (Smith, 1983) and the unfolding cylinder is used to seal large underground pipes), the complexity of a residential duct system does not allow straightforward application of these technologies. Our attention is thus focused on the use of aerosol sealants, the versatility of this technique allowing us to deal with bends and bifurcations without significantly affecting its performance.

The proposed concept involves blowing an aerosol through a duct system to seal the leaks from the inside, the principle being that the aerosol particles would deposit in the cracks of the ductwork as they try to escape because of the pressure differential. The reader may find similarities between this internal-access sealing and the after-market automotive sealants for tires although proper use of those sealants is rather restrictive (e.g. it requires the spinning of the tire after foam injection). One company was marketing a vinyl polymer suspension to immobilize dust in residential air-distribution systems. The company used a nozzle-produced jet to entrain air and generate an aerosol, and to blow the aerosol through the ducts. Filter paper was used in all the registers to block the fog from directly entering the house. The sealing effectiveness of this aerosol was tested at Lawrence Berkeley Laboratory for naturally occurring and for artificially created leaks in a duct system. Although the pressure-driven flow of aerosol was a good vehicle for transporting the sealant through the system, the particles' size and type as well as the degree of control of pressure and flow rate were apparently inappropriate for sealing the typical leaks encountered. Thus, it appeared key to better understand aerosol transport in an ADS as well as particle deposition in the leaks.

This papers begins with a theoretical approach to the problem which includes: a) aerosol transport in an ADS and b) particle deposition in leaks. The second part of this paper is dedicated to our experimental investigation and describes the different series of experiments we did in order to obtain proof-of-concept and assess the applicability of this technique *in situ*. The third part deals with the design of a prototype field device and its testing on a small-scale ADS and in a house.

2. OVERVIEW OF THEORETICAL INVESTIGATIONS

To develop a successful technology for remotely sealing leaks with an aerosol, we need to solve two fundamental problems: how to transport aerosol particles from the injection to the vicinity of the leaks, and how to have them deposit in the cracks to be sealed. As for the first problem, literature was reviewed and we subsequently developed a simplified model that can predict particle deposition in a duct system as a function of the total air flow rate and the miscellaneous characteristics of the aerosol (Carrié, 1994).This model is based on Agarwal's (Agarwal, 1975) work on turbulent deposition of particles in a straight tube. A similar approach to that of Balásházy (Balásházy *et al.*, 1990) is used to quantify aerosol penetration in bends, tees and wyes. To solve the second problem, which is key to a) assessing the feasibility of the technique and b) optimizing the sealing effectiveness, we started with an identification of the different types of leaks. We were able to divide the leaks in two major categories, which are: a) simple holes in the duct wall (Type-I, Figure 1), and b) annular channels that are characteristic of leaks at duct joints (Type-II, Figure 1).

Because of the complexity of the assessment of particle behaviour in such configurations, we limited our detailed investigation to two-dimensional Type-I leaks (Figure 2). Even though restricted, this research presented the advantage of being "experimentally verifiable" while providing us with some understanding of aerosol collection in leaks. In our approximate analysis, we found that the deposition efficiency, defined as the ratio of the mass flux of particles that deposit in the crack due to impaction versus that of particles that are originally on streamlines that exit through the orifice ($y_p \leq y_s$), may be expressed as follows (Carrié and Modera, 1994) :

$$\eta = \frac{\tau v_s^2}{y_s} \frac{e}{v_s h} = Stk \frac{e}{h} \tag{1}$$

The theoretical limits of the model are the following:

1. $\mathrm{Re}_p \sim Stk \frac{v_s d_p}{\nu} << 1$
2. $Stk \sim \frac{\tau}{t_{res}} << 1$
3. $\frac{\tau v_s}{e} >> 1$

We further assumed that the only geometrical parameter that varies as impaction occurs is the slot-width. Thus, if the aerosol is monodisperse (or in general, if the mean deposition efficiency ($\overline{\eta}$) can be evaluated over the particle size range) and if the sticking probability of the aerosol is 1 (ideal case), the rate at which the leak-width decreases is:

$$-\frac{dh}{dt} = \overline{\eta} \times \frac{h}{\rho_{seal}\, w} \times v_s \times C_m \tag{2}$$

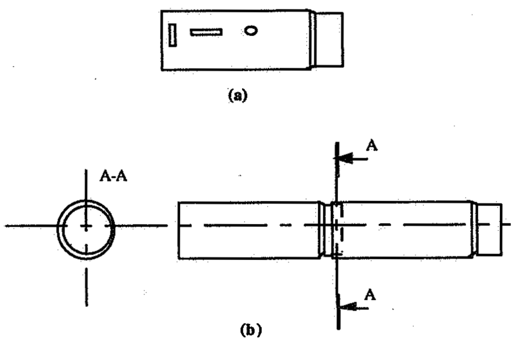

Figure 1: Identification of the different types of leaks; (a) Type-I leaks; (b) Type-II leak.

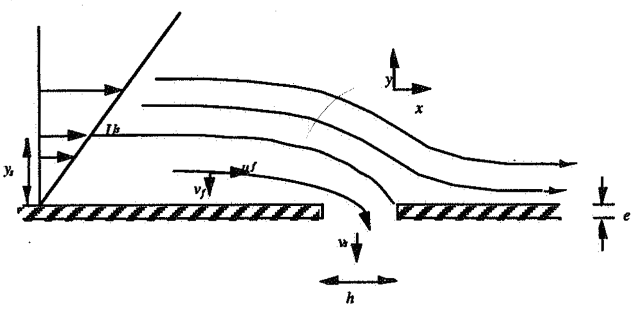

Figure 2: Uniform shear flow approaching a two-dimensional slot (see (Thomas and Cornelius, 1982)).

Videotaping the sealing process to monitor leak-width as a function of time under varying conditions, we found good agreement between theoretical and observed leak behaviours for low pressure differentials ($\Delta P \leq 60$ Pascals). Assuming that the deposition efficiency is well assessed by this model in a typical duct system, we developed simplified calculations to approximate key parameters that will affect the sealing time. Given a two-dimensional slot at a distance L from where the concentration C_m is measured, the leak-width decrease rate is given by Equation (2), where the left hand side is multiplied by the aerosol penetration P over the distance L. On this basis, we define the sealing efficiency[1]:

$$SE = \overline{\eta} \times P \tag{3}$$

[1] Calculations of P are detailed in (Anand and McFarland, 1989)

Also, the time required to obtain a slot width decrease of $\frac{1}{i} h_o$ (i-th characteristic time, t_i) appeared to be an interesting indicator of the sealing effectiveness. Assuming that the sealing efficiency computed by Equation (3) remains constant within that time frame we obtain:

$$t_i = \frac{\rho_p e}{SE \times v_s \times C_m} \times \ln\left(\frac{i}{i-1}\right) \tag{4}$$

where v_s and y_s (that are needed to compute SE) can be approximated with the following equations:

$$v_s = 0.6\sqrt{\frac{2\Delta P}{\rho_f}} \tag{5}$$

$$y_s = D\sqrt{50.63\frac{\mathrm{Re}_s}{\mathrm{Re}_D^{7/4}}} \tag{6}$$

and the variation of SE over t_i is:

$$\frac{\Delta SE}{SE} = \left(\frac{i}{i-1}\right)^{3/2} - 1 \tag{7}$$

Obviously this i-th characteristic time is all the more realistic as i is sufficiently large so as to ensure that SE is constant over t_i (for i = 2, $\frac{\Delta SE}{SE} = 0.41$; for i = 20, $\frac{\Delta SE}{SE} = 0.08$).

Calculations to assess the sealing efficiency and the i-th characteristic time can be performed with the help of a spread-sheet program (see Table 1).

Table 1: Sample calculations of the penetration, the sealing efficiency, and the i-th characteristic sealing time (D=0.15 m; L=10 m; h=3 mm ; e=0.6 mm; ΔP=40 Pa; C_m=5.0 mg/l; d_p=10 µm).

Flow Rate [m³/h]	Penetration [-] (in %)	Sealing Efficiency [-] (in %)	t_2 [s]	t_{20} [s]
14.6	32.7	0.3	6558	485
29.3	57.2	0.8	2046	151
43.9	68.9	1.4	1191	88
58.5	75.6	2.0	844	62
73.2	80.0	2.6	656	49
87.8	83.0	3.1	539	40
102.4	85.2	3.7	459	34
117.1	86.9	4.2	401	30
131.7	88.2	4.8	356	26
146.3	89.2	5.3	321	24

3. LABORATORY EXPERIMENTS

Because we previously assumed that all of the deposited particles contribute to a decrease of the opening size, an important aspect of the issue of particle deposition in the leaks that remains is to understand how the particles are going to stick to the duct wall and eventually "build a bridge" between the boundaries. Vinyl plastics seem appropriate to achieve this goal since they are widely used to smooth and waterproof surfaces. However, it is key to understand that particles need to hold their shape in order to "build a bridge". If the particles are too deformable, they will tend to spread over the duct wall preventing any particle build up.

A preliminary approach to the problem (see (Carrié *et al.*, 1994)) enabled us to show that by drying our aerosol we obtain solid particles that can stick to the duct wall and to one another and thus allow the decrease of the leak size. Enlightened by this preliminary research, the apparatus described in Figure 3 was designed. It includes: 1) a desiccant drying section, 2) a vane-anemometer flow measurement device, 3) an assortment of commercially available sprayers, 4) a peristaltic pump to control and measure the liquid flow rate to the spray nozzle,

5) a sampling unit to measure aerosol concentration, 6) a mass-flow controller network to ensure isokinetic sampling and 7) precisely constructed Type-I and Type-II leaks. The data from all of the measurement devices described in Figure 3 is sent to an IBM-PC and stored electronically.

With this apparatus, we found that round Type-I leaks as large as 3 mm in diameter could be sealed in 10-20 minutes. 3 mm Type-II leaks were found to be partly sealed during the same experiments. These results were all the more promising as they were repeatable and could be obtained with a two-branch duct network as well (see (Carrié *et al.*, 1994)).

In order to quantify the sealing effectiveness, it was further decided to measure the permeability of the network before and after injection of the aerosol. To this end, the Effective Leakage Area (ELA) (see (Modera, 1993)) commonly employed to measure the leakiness of a building envelope or an ADS was used. The equation linking the leakage flow rate to the pressure differential is given by:

$$Q = ELA\sqrt{\frac{2\Delta P_{ref}}{\rho_f}}\left(\frac{\Delta P}{\Delta P_{ref}}\right)^n \tag{8}$$

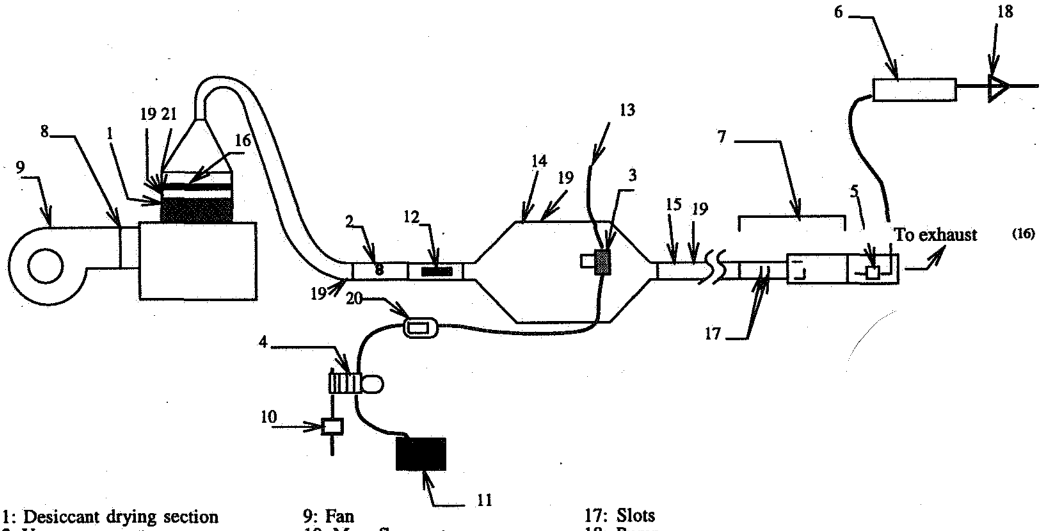

Figure 3: Schematic diagram of the experimental apparatus in use to quantify aerosol sealing effectiveness.

Thus, by artificially creating a pressure differential in the test section and by measuring the leakage flow rate, one can calculate the ELA. The physical meaning of the Effective Leakage Area is that, at the reference pressure differential, the flow rate passing through the leaks would be the same as that leaking through a sharp-edged orifice of this same area under the same pressure differential. The reference pressure differential is usually set to 4 Pascals in building science applications in the USA, which is typical of wind pressure and stack effect in that country (Sherman *et al.*, 1984). However, because the pressure differential across duct leaks is significantly higher than 4 Pa when the system is in operation, characterizing duct leaks at a reference pressure of 25 Pa is more appropriate (Modera, 1993). Therefore, the 25-Pa characterization is utilized in this paper. Precision errors are calculated with the following equation:

$$\frac{\delta ELA}{ELA} = \delta\left(\ln\left(Q_{ref}\right)\right) \tag{9}$$

where $\delta(\ln(Q_{ref}))$ is estimated with the standard deviation of the extrapolation of $\ln(Q)$ at the reference pressure differential.

Sealing tests showed that with our unit (Figure 3) we could seal up to 88% of the Effective Leakage Area of our system in 45 minutes (see (Carrié *et al.*, 1994)). A preliminary approach to the design of a field device showed that an effective way of preventing aerosol entry into the dwelling without adversely affecting the sealing process is to block the ends of the ducts (rather than filtering particles from the flow exiting the registers). This way, filtration is complete and it avoids the additional requirement of having to place filters (that would eventually clog) at the registers. Tests were performed with the apparatus described in Figure 3 under the conditions quoted above (i.e. the ends of the ductwork were sealed). We found that the ELA of the ADS could be reduced by more than 90% in 20 to 45 minutes . In addition, the initial air flow rate could be lowered down to 40 m^3/h per branch and still provide us with sufficient aerosol penetration and significant ELA reduction. Plugging an equivalent of 16 cm^2 is possible in less than 30 minutes according to our experiments (see (Carrié *et al.*, 1994)). However, larger initial ELAs require more time. Furthermore, we noticed that an in-line heater was sufficient to lower the water content of the aerosol particles, eliminating the need of a desiccant drying section.

4. IN SITU SEALING APPARATUS

The portable unit that we have developed includes: a) a blower (Centrimax CXH 33A2B), b) an in-line resistance heater and c) a commercially available spray nozzle (SUE15B manufactured by Spraying Systems Co.). For both safety and control purposes, a thermostat and a pressure switch are also included in the apparatus. Injection is realized by pressurizing a liquid container to a specified value, and connecting the container to the spray nozzle[2]. Compressed-air is supplied with a separate portable unit.

Because the ends of the ducts are blocked when aerosol injection is performed, the fan curve is of paramount importance for designing the field device. Indeed, as the cracks are being plugged, the pressure in the system increases. When the pressure exceeds a pre-set value (mainly determined by the maximum pressure ratings of the ducts), the pressure switch disables the unit. Thus, once the stop-pressure is set, the final ELA[3] may be determined as a function of the flow exponent for a given fan curve. We found that our blower should give satisfactory results[4] when operated successively at full-speed (speed 1) and at reduced-speed (speed 2) with a stop-pressure set at 300 Pascals. At full-speed, the fan ensures proper aerosol transport throughout the system and will significantly reduce the ELA. Further reduction of the ELA has to be obtained by reducing the air flow rate (and thus the pressure) through the ADS. This way, particle transport may not be as effective; however, the sealing process however can be continued without exceeding the stop-pressure.

We built the small-scale ADS to perform preliminary laboratory experiments. Although our unit was tested several times, only one complete test has been performed to date. The results of this experiment (in terms of ELA) are listed in Table 2. As expected, the pressure increased as soon as the aerosol injection began, and reached the stop-pressure (300 Pascals) in about 5 minutes. Then, we switched the unit to reduced flow and pressurized the liquid container to its new specified value. As the leaks were being sealed at reduced flow, the pressure differential in the duct system increased from 40 Pascals to 300 Pascals in about 15 minutes.

As for the types of leaks we had in the system, most of the joints between the different ducts were not taped at all; we also voluntarily made cracks at the registers boots; finally, some simple holes or slots were included in the ADS. The plugging of relatively large-size cracks

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[2] Note that this pressurization sets the liquid flow rate through the nozzle.

[3] Assuming that the stop-pressure is reached.

[4] "Satisfactory results" assume a final ELA on the order of 20-25 cm^2. Given that the ELA (at 25 Pa) of a residential ADS is typically on the order of 180 cm^2, that would constitute an 85% decay.

(~ 1-3 mm) was observed. Although significant aerosol collection was observed in the largest holes (~ 5-10 mm), these were found to be difficult to seal.
Our results may be summarized as follows:

1. The dimensions of the injection chamber of the original apparatus (see Figure 3) can be reduced without significantly affecting the sealing process.
2. The use of a variable-flow fan seems necessary.
3. Any type of leak can be sealed provided that they are sufficiently small (~ 1-3 mm).
4. This technique appears efficient for straight sheet metal ducts, sheet metal ducts with bends, and the plastic flexible ducts often encountered *in situ*.

Table 2: Measured and predicted ELA† before and after aerosol injection with field device in the laboratory‡.

	ELA [cm^2]	Precision Errors (in %) [-]	Exponent [-]
Before aerosol injection (measured)	124	6.7	0.55
After aerosol injection (measured)	26	5.6	0.51
After aerosol injection (predicted)	25	-	-

† ELA at 25 Pascals. ‡ Initial pressure: 170 Pa; Stop-pressure: 300 Pa.

The first field test was performed in a single-family house in Berkeley, CA in 1994. The device was found to seal approximately 60% of the leakage in the duct system within 15 minutes using about $6 worth of sealing material. However, the set-up time far exceeded the sealing time. In addition to attaching the device to the HVAC system and simple leakage measurements, these field tests included measurements of particle and volatile organic compound (VOC) concentrations before and after sealing. After the sealing process, total suspended particles were found to decrease and there was no detectable change in VOC concentrations. These results appear extremely promising. We may however propose a few improvements to the present apparatus. First, we noticed that the aerosol jet tended to directly impinge on the walls of the injection chamber. Slightly modifying the nozzle angle may help avoid this problem. Second, with minor changes, our device could measure leakage of the duct system before and after injection, eliminating the use of additional hardware.

5. CONCLUSIONS AND FUTURE EFFORTS

The practical objective of this research was to develop an aerosol-based technique to remotely seal leaks in residential air-distribution systems. Our theoretical investigations lead to the design of a laboratory apparatus capable of sealing 1 to 3 mm cracks in 10 to 20 minutes. Based upon a number of laboratory tests with this relatively large injection unit under controlled conditions we can conclude that this technique is capable of remotely sealing leaks.
Based on our theoretical investigations and our expertise, we constructed and tested a prototype field device. The results of laboratory experiments on a small-scale duct system to assess the performance of our unit under realistic conditions combined with a field test in a single-family house in Berkeley, CA allow us to conclude that *in situ* sealing of residential duct systems is achievable with this unit.
In the future, we will explore the longevity of the seals by tracking the air tightness of the Berkeley house duct system. We also plan to focus in the future on accelerated laboratory testing of the seals produced by the aerosol, designing reusable, quick-installation seals for the registers and HVAC heat exchangers, followed by larger-scale field testing, construction of a second prototype sealing apparatus, and related activities required for the technique's commercialization.

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