Achieving and Certifying Building Envelope Air Tightness with an Aerosol-Based Automated Sealing Process

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ABSTRACT

This paper describes a process developed at UC Davis that uses aerosolized sealant particles to seal leaks in building envelopes. The process is similar to that used for sealing leaks in ducts; however it does not depend on a carrier flow to transport the sealant to the leaks, and therefore has to address the likelihood of particles settling to the ground, as well as the possibility of particles depositing on vertical surfaces. One unique aspect of this process is that it utilizes a blower door to both facilitate and track the sealing process, providing immediate certification of the sealing performed. Testing of the process in the laboratory and in several homes is described. The laboratory tests investigated the impacts of pressure and particle size on the sealing process. The field tests showed how well the process performed in new-construction applications (sheetrock installed, but not yet painted), and an empty existing home application (horizontal surfaces covered with paper and plastic). The results presented include a sub-set of the laboratory tests, as well as selected field test results. These tests suggest that the process should be able achieve better levels of air tightness as compared to manual sealing methods, at lower cost, and with automated air-tightness verification.

KEYWORDS

Envelope, air-tightness, sealing, aerosol

1. INTRODUCTION

Residential building shells are often leaky, causing unintended flows between conditioned and unconditioned spaces that result in additional loads for the heating and air conditioning equipment to address. Sherman indicates that houses built in the 1990's can have as much as 180 in^2 of leakage area for a 1500 ft^2 home [Sherman and Dickerhoff 1994]. A significant effort has been made to reduce the leaks in building shells through current construction practices, but the problem remains one of excess labor costs, constant vigilance and quality control issues. The objective of this research is to develop and demonstrate a remote sealing process that uses aerosolized sealant particles to simultaneously measure, find, and seal leaks in a building envelope shell in a cost effective manner. The tested process involved pressurizing a space with a fog of sealant particles that travel to, and as they escape, seal the leaks.

A similar process, developed by Lawrence Berkeley National Laboratory (LBNL) and commercialized under the name Aeroseal, has been used to seal leaks in ducts with great success. The process injects a solution of Poly Vinyl Acetate (PVA) sealant and water into a high-pressure air stream to produce tiny droplets. A calibrated fan and heater produce the carrier flow that transports the sealant through the duct system and evaporates the water surrounding the sealant particle. Tests at LBNL of the particle size produced by a compressed-air nozzle similar to the one used in the commercial Aeroseal machine (used for our testing) generated particles with a mean diameter around 7 µm. With all catastrophic leaks repaired, such as disconnected ducts, the aerosol sealants have been shown to typically seal approximately 80% of the leaks encountered in residential homes [Modera et al 1996]. In general, the sealing rate in duct applications was shown to vary with the width (or smallest dimension) of the leak squared [Carrie and Modera 1998, 2002]. Thus, although there is no well-established maximum leak size, this efficiency creates practical limitations on the size leak that can be sealed. For example, a 1/8th inch (3 mm) gap should seal sixty-four times faster than a 1 inch (25 mm) gap, although 1 inch (25 mm) gaps have been sealed. For reference purposes, the company that sells the equipment for aerosol duct sealing quotes maximum practical leak sizes between 3/8 inch and 5/8 inch (10 mm to 16 mm) across. The work presented in this paper looks at a similar process applied instead in a nominally quiescent environment without the use of a carrier flow to deliver the aerosol sealant to the location of the leaks.

2. LABORATORY TESTING

2.1 Test Apparatus

The Western Cooling Efficiency Center (WCEC) constructed an 8 ft x 8 ft x 4 ft (2.4m by 2.4m by 1.2 m) enclosure with leak panels distributed at various locations around the shell of the enclosure (Figure 1). Figure 2 presents an illustration of the location of the leak panels installed. The approximate size of each leak is 0.1 to 0.12 inch X 10 inch X 0.125 inch (2.5 to 3 mm by 25 cm by 3 mm) (H X W X D) and there are six leaks on each leak panel. The height of each leak was meant to be representative of a typical leak in a building shell, but the depth is much shorter than what is expected to be found in buildings. The total measured leakage was approximately 41 square inches (260 cm^2) of open leakage area. A 14-inch (36 cm) diameter hole was used as the injection site to introduce the sealant fog near the top of the enclosure (see Figure 1).

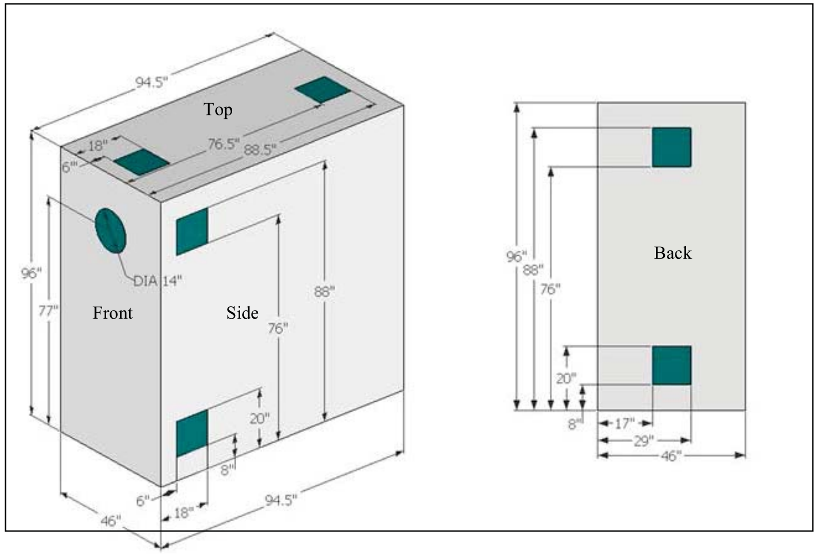

Figure 1: Dimensioned views of the enclosure showing the various leak locations. Each leak panel, illustrated by the green squares, contained six slot leaks, and the sealant was introduced through the injection hole illustrated by the green circle on the front.

2.2 Analysis Method

The performance of the remote sealing technology was evaluated using three primary metrics: 1) the time needed to seal the enclosure, 2) particle deposition inside the enclosure, and 3) the uniformity of sealant deposition at the leaks. These performance metrics were used to evaluate several independent parameters to understand their effects. The parameters evaluated included the pressure inside the enclosure, the flow rate of sealant injected, and the size of the particles injected.

The commercial Aeroseal machine, although probably not appropriate for building applications, was used for our initial tests of sealing building shells. It includes instrumentation for measuring differential pressure between the enclosure and ambient, as well as for measuring the air flow, thereby facilitating continuous monitoring of leakage area during the sealing process. The leakage area was computed using Equation 1 [4] and Equation 2 [5].

$$Q = ELA_{ref} \cdot \sqrt{\frac{2 \cdot \Delta P_{ref}}{\rho}} \cdot \left(\frac{\Delta P}{\Delta P_{ref}}\right)^{n}$$ Equation 1

$$LA = \frac{ELA}{0.6}$$ Equation 2

Where Q is the measured airflow rate, ELA_{ref} is the effective leakage area, ΔP is the pressure measured across the leak, ΔP_{ref} is a reference pressure (chosen to be 25 Pascals), ρ is the air density, n is the flow exponent (typically 0.5 for an orifice), and LA is the leakage area. The ELA_{ref} of a leak is the area of a sharp-edged orifice that at some reference pressure that will produce the same flow as the leak at that pressure. It has been shown experimentally and theoretically that the ELA is related to the actual area of an orifice by a factor of 0.6 [Batchelor 1967].

A mass balance was used to determine where the sealant was ultimately deposited. Using a scale with a 0.001 gram resolution, the weight of various components before and after sealing allowed us to track the fraction of sealant that was lost due to settling or turbulent deposition onto surfaces. These components included: a sheet of plastic placed on the bottom of the test enclosure, the plastic tubing used to transport the sealant from the generation point to the enclosure, and plastic sheets placed on the walls and ceiling. In addition, the sealant deposited in each panel leak was determined by removing the sealant in and around the leak and then weighing the removed sealant. The results for different panels were to get a feel for the particle distribution inside the enclosure. Errors may have been introduced by the following: not completely removing all sealant from the panels, the sample sections of plastic used for measuring wall and ceiling deposition not being representative of the entire surface, and the fact that we used the manufacturer calibration for the sealant flow rates. Assuming the pump calibration is reasonably accurate, the overall error in the measurements was expected to be with ±5%.

The approach for the first stage of development employed the existing Aeroseal equipment to seal the test enclosure. Initially, it was expected that the particle size produced by the existing Aeroseal equipment would be too large to allow for sufficient particle suspension. This was not the case, as the leaks were more than sufficiently sealed in the initial tests. Observations in the small-scale tests led to further research on the impact of reducing particle size. In addition to reducing particle size, oscillating fans could be used to assist in keeping the particles suspended and to make the indoor-air particle distribution more uniform in an actual application.

The performance of each test was evaluated using leakage versus time profiles, as well as analyses of sealant use efficiency quantified by the mass balance of sealant materials (i.e. fraction on floor, in leaks, on walls, and lost through leaks).

The independent variables investigated included:

- Average particle size (controlled by sealant dilution)
- Enclosure pressure control
- Sealant injection rate

The dependent variables that were used to quantify performance included:

- Sealing rate
- Sealing uniformity (comparison of the amount of sealant deposited on panels in different locations)
- Sealant use efficiency (fraction that settles on the floor and other surfaces, versus deposited in leaks)

2.3 Results

Several tests of the envelope sealing process were performed, all of which showed promising results, sealing the enclosure in as little as six minutes. Tests were performed to study the impacts of the independent variables on the sealing parameters (Table 1).

Table 1: Test protocol for each of the nine tests

Test number	Box Pressure (Pa)	Sealant Injection Rate (ccm)	Sealant Dilution
1	No pressure/flow control	100	No Dilution
2	100	25	No Dilution
3	No pressure/flow control	25	No Dilution
4	50	25	No Dilution
5	100	25	No Dilution
6	50	25	No Dilution
7	100	25	No Dilution
8	50	25	No Dilution
9	100	25	1 part sealant/1 part water

Figure 2 shows the leakage profiles for each of the nine tests in the enclosure. All tests successfully sealed the enclosure to nearly zero leakage in less than 30 minutes. Note that, at the beginning of each test, the sealant lines were first purged of water before sealant reached the injection nozzle, causing a slight delay at the beginning of each test, which for 25 ccm tests was about 5 minutes and for 100 ccm test was about 2 minutes.

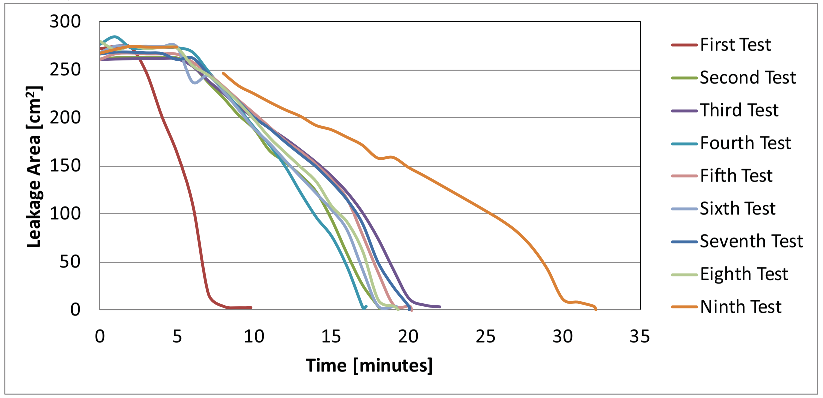

Figure 2: Leakage profiles for each of the nine tests

The leakage profiles show that the sealant injection rate has a significant impact on sealing time, whereas controlling the pressure inside the enclosure had a less significant impact. Tests performed at a 25 ccm injection rate at various pressures all sealed the enclosure in 13-15 minutes, whereas injecting sealant at 100 ccm sealed the enclosure in six minutes. Reducing sealant particle size by diluting the sealant with water also significantly extended the sealing time. This is due to the reduced solid sealant injection rate associated with diluting without adjusting the pump rate. In the test with diluted sealant, the enclosure sealed in approximately 28 minutes (Figure 2).

Deposition at high pressure and 100 ccm injection rate

Deposition at high pressure and 25 ccm injection rate

Deposition at 50 Pa and 25 ccm injection rate

Figure 3: Sealant deposit pattern on back low panel for tests 1, 3 and 4

The sealant deposition pattern could be a quick indication of the sealant deposition efficiency. Figure 3 shows the sealant deposition pattern observed during three different tests, a) a high-pressure test with 100 ccm sealant injection rate, b) a high-pressure test with 25 ccm sealant injection rate, and c) a test at 25 ccm sealant injection rate, but with the pressure differential controlled to maintain 50 Pa. The largest spread of sealant around the leak is for the high-pressure test at 100 ccm, and this spread is decreased when the sealant injection rate is reduced, and when the pressure differential is maintained at 50 Pa. These results suggest that excess deposition is reduced, producing cleaner seals, when the sealant flow rate is reduced, and when the building pressure is reduced. We believe the former may be due to the size particles created by the nozzle used for these experiments, and that the latter is due to the lower velocities around the leaks at lower pressures. In terms of spatial uniformity in the lab tests, there was only a 1-2% variation in the mass of sealant deposited between any of the leak panels distributed around the enclosure at any given sealant flow, suggesting very good particle distribution and sealing uniformity for all the lab tests performed.

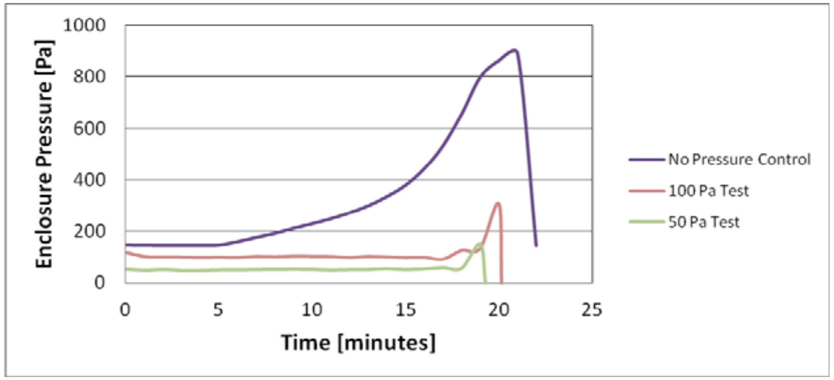

Figure 4: Typical Pressure profiles inside the enclosure during tests with no pressure control, and tests controlled at 100 Pa and 50 Pa

The pressure was regulated by a calibrated fan that controlled the airflow delivered to the test enclosure. Three operating pressures were studied in the small-scale tests: 1) no pressure control (which effectively allows the fan curve to control the injection flow), 2) manual flow control to maintain 100 Pascal pressure differential, and 3) manual flow control to maintain 50 Pascal pressure differential. Due to the very low absolute leakage level achieved by injecting aerosol sealant, the pressure inside the enclosure became difficult to control as the flow approached the minimum achievable by the equipment (Figure 4). This could mean that better control of the pressure inside building shells for the duration of the installation of aerosol sealant will be needed to prevent over-pressurizing the space, although there is no need to bring building leakage levels to the values obtained in the laboratory.

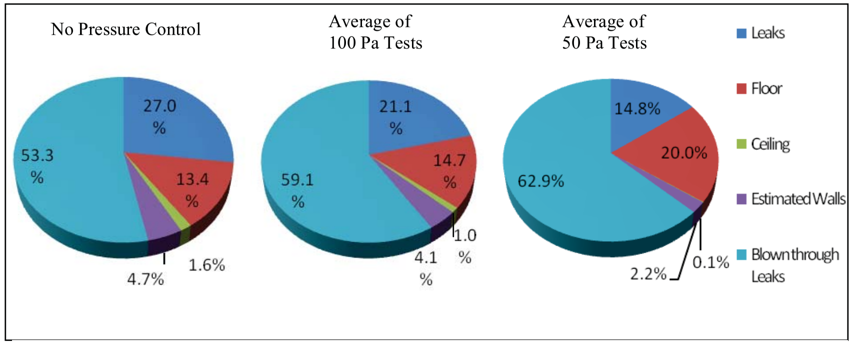

Figure 5: Average sealant distribution for tests at various pressures and 25 ccm sealant injection rates

The mass balance analysis allows for accurate tracking of where the sealant is ultimately deposited. The sealant distributions in Figure 5 show how pressure control affected the sealing process. There is a clear trend showing that lower enclosure pressure leads to less sealant deposited in and around the leaks, more sealant depositing on the floor, less sealant depositing on the walls and ceiling, and more sealant getting blown through the leaks. Although the majority of sealant injected was blown through the leaks, it is expected that the geometry of leaks in typical buildings will be different than the test enclosure. The longer flow path of typical leaks in buildings is expected to reduce the amount of sealant blown through and, therefore, improve the efficiency of sealant use. We expect that the typical building leaks sealed during this process would be at the joints and seams between building materials that are much deeper then the leaks tested in the lab enclosure.

3. FIELD TESTING

Several full-scale tests of the aerosol-based sealing technology have been completed in the dry-wall phase of construction, plus one test on an empty existing home. The initial tests were performed using the existing aerosol duct sealing technology that was tested in the laboratory experiments while the latest application tested a new aerosol injection technology developed by UC Davis. The first full-scale tests demonstrated a lack of sealant transport to adjoining rooms which required that the atomization nozzle be moved from room to room. The new aerosol injection system is capable of multiple injection points allowing nozzles to be distributed throughout the building both expediting the sealing process and eliminating the need to enter the building while applying the aerosol (Figure 6 and Figure 7).

Figure 6: Photo of sealant atomization

Figure 7: System developed by UC Davis, capable of multiple aerosol injection points

Figure 8 shows a snapshot view of the time history of the sealing process, illustrating the slope of the sealing profile for two field tests, one using the new injection system with five injection points and the other the existing injection system with one injection point.

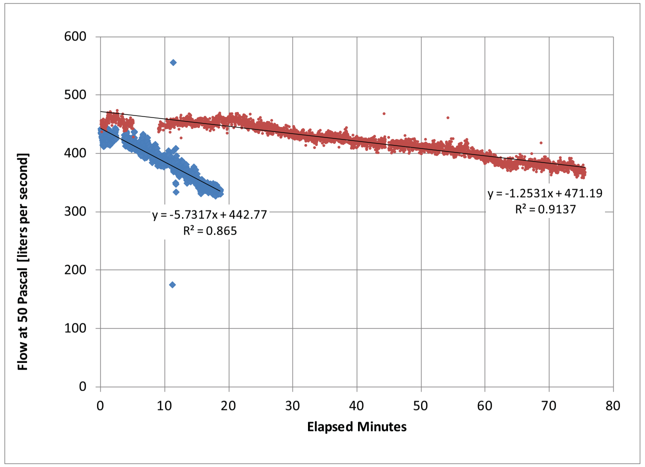

Figure 8: Snapshot of sealing profile for new injection system vs. existing duct sealing system

The slope of the sealing profiles indicates a more than four-fold increase in the sealing rate for the multi-point injection system. However, when the results were normalized by the solid sealant injection rate, the sealing performance was slightly lower for the newer injection system. The slight decrease in performance is likely due to the over-saturation of air during the sealing process, preventing the sealant particles from drying out sufficiently for effective deposition. Future testing will slow the sealant injection rate to test this hypothesis.

The field tests of the sealing process showed that it could seal at least 50% of the initial leakage observed prior to injection, as well as that the floors did not need to be prepped in new-construction applications. The tests also showed that particular care needs to be taken in existing homes, even if they are empty of contents at the time of sealing (e.g. protecting carpeted stairways from more than just particle settling). Figure 9 shows examples of leaks sealed during the field testing, including leaks at sill plates and electrical boxes.

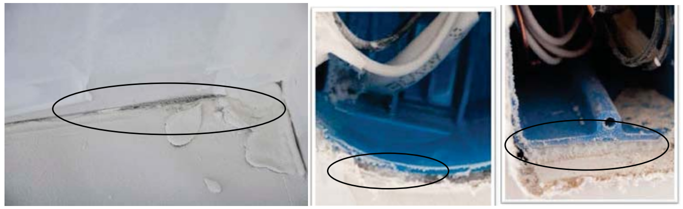

Figure 9: Envelope leaks sealed during the field tests (sill plate and electrical boxes).

4. CONCLUSIONS

Based upon the laboratory and field test results presented in this paper, it appears that aerosol particles can be employed to seal leaks in building envelopes. In the lab, our tests suggest that lower sealant injection rates result in cleaner seals, we believe due to smaller particles created by the lab-test nozzle at lower sealant injection rates. Our lab tests also suggest that a smaller pressure differential across the leaks creates an even cleaner seal, most likely due to lower approach velocities to the leaks. This needs further investigation.

In the field, in both the new construction and existing home applications, the process was able to seal at least 50% of the observed leakage within a reasonable amount of time. For field applications, what remains to be done is to understand and optimize the preparation process required for sealing, to get more experience in field applications of the sealant injection and preparation process, and to turn the multi-point injection system into a viable commercial product.

5. ACKNOWLEDGEMENTS

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