Final Scientific Report

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Project Title: Novel Infiltration Diagnostics based on Laser-line Scanning and Infrared Temperature Field Imaging

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Executive Summary

This project targets the building energy efficiency problems induced by building infiltration/leaks. The current infiltration inspection techniques often require extensive visual inspection and/or whole building pressure test. These current techniques cannot meet more than three of the below five criteria of ideal infiltration diagnostics:

1. location and extent diagnostics,
2. building-level application,
3. least surface preparation,
4. weather-proof, and
5. non-disruption to building occupants.

These techniques are either too expensive or time consuming, and often lack accuracy and repeatability. They are hardly applicable to facades/facades section.

The goal of the project was to develop a novel infiltration diagnostics technology based on laser line-scanning and simultaneous infrared temperature imaging. A laboratory scale experimental setup was designed to mimic a model house of well-defined pressure difference below or above the outside pressure. Algorithms and Matlab-based programs had been developed for recognition of the hole location in infrared images. Our experiment based on laser wavelengths of 450 and 1550 nm and laser beam diameters of 4-25 mm showed that the location of the holes could be identified using laser heating; the diagnostic approach however could not readily distinguish between infiltration and non-infiltration points. To significantly improve the scanning throughput and recognition accuracy, a second approach was explored, developed, and extensively tested. It incorporates a liquid spray on the surface to induce extra phase change cooling effect. In this spray method, we termed it as PECIT (Phase-change Enhanced Cooling Infrared Thermography), phase-change enhanced cooling was used, which significantly amplifies the effect of air flow (infiltration and exfiltration). This heat transfer method worked extremely well to identify infiltration and exfiltration locations with high accuracy and increased throughput. The PECIT technique was systematically developed and tested for through holes with diameters 1 mm to 2 mm, and diagonal lines of 0.5 mm width at different camera-wall distances of 46 cm to 200 cm, under different pressure differences from 5 Pa to 20 Pa, and under different wind conditions. The PECIT technique had either met or exceeded the goals proposed in the project. For exfiltration, we achieved 100% accuracy under a much lower pressure difference of 10 Pa (proposed one: 50 Pa with stretch goal of 15 Pa). For infiltration, we achieved >90% accuracy under a much lower pressure difference of 10 Pa (proposed one: 50 Pa with stretch goal of 15Pa). For exfiltration, we achieved 100% accuracy under a much lower pressure difference of 10 Pa. For infiltration, we achieved 100% accuracy under a much lower pressure difference of 10 Pa. The PECIT technique can reach a throughput of 120 m^2/h, which is 4 times the proposed goal for the laser line-scanning and simultaneous infrared temperature imaging approach. For commercialization and market penetration, we had meetings with two companies for feedback collection and further improvement for practical use. Also, we have interacted with Office of Intellectual Property and Technology Transfer of Iowa State University for idea disclosure and patent application.

i. Laboratory Setup

In this project, to mimic a house of well-defined pressure difference between the inside and outside, a laboratory scale experimental setup was designed that maintains a set pressure difference inside of a box. One side of the box is a mock wall made of ¼" thick plywood with a total of 44 through holes and half depth holes of 0.5-2 mm diameter. This mock wall is exchangeable with wall of other desired materials. Infrared images of this mock wall were recorded using laser heating of the surface and several laser, imaging, and pressure parameters. Specifically, pressure differences of 15 and 50 Pa, camera distances of 3-30 cm, laser wavelengths of 450 and 1550 nm and laser beam diameters of 4-25 mm were used in various tests with Laser-line Scanning and Infrared Temperature Field Imaging (LIT). A one-dimensional scanning system had been designed and was fully functional using a high precision optical linear stage. We had established the capability of linear scanning the laser only or both the laser and camera if necessary. For the Phase-change Enhanced Cooling Infrared Thermography (PECIT), the camera-wall distance could be varied up to 2 m. Algorithms had been developed for recognition of the location of a hole in the images based on the cooling induced by the air flow through the holes in the wall. LabView-based software had been developed to control the whole system, including pressure selection, imaging taking, video-taking, and image analysis. Figure 1 shows the model house with pressure control, water spraying system, and infrared thermal imaging system.

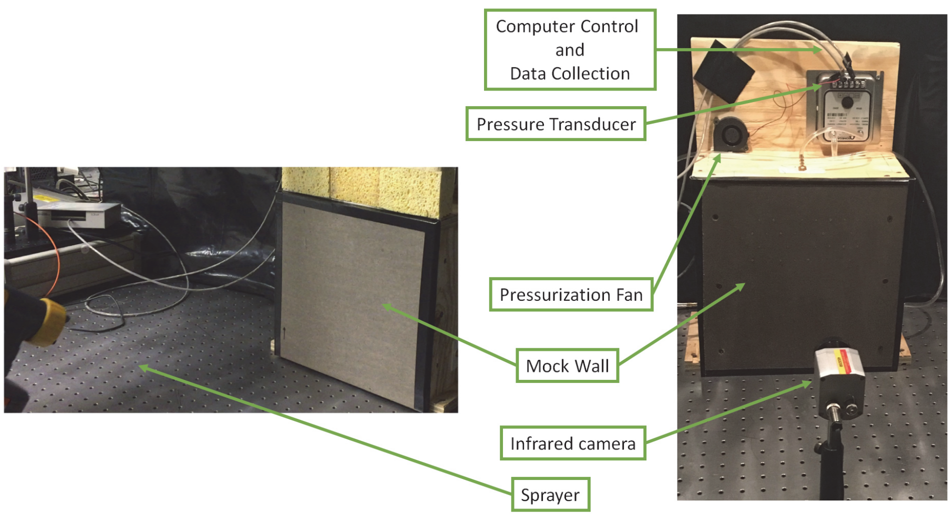

Figure 1: The lab-scale setup developed in the project with exchangeable front wall of desired materials and holes, pressure maintaining system, water spraying system, and image/video taking system.

ii. Infiltration Determination–Method 1

For the laser line heating experiment, infrared images of the mock wall were recorded under laser heating of the surface and varied parameters including the laser beam, camera-wall distance, and hole sizes. Specifically, pressure differences of 15 and 50 Pa, camera distances of 3-30 cm, laser wavelengths of 450 and 1550 nm and laser beam diameters of 4-25 mm were used in various testing. Several pattern recognition methods had been developed and tested using the recorded images in order to distinguish different patterns of temperature field between a through hole and a half depth hole. Figure 2 shows a sample of the collected image. For a through hole, its center temperature will be close to the room temperature when a sufficiently high imaging resolution is used, which requires that either the infrared camera is very close to the wall, or the infrared camera has a very high resolution.

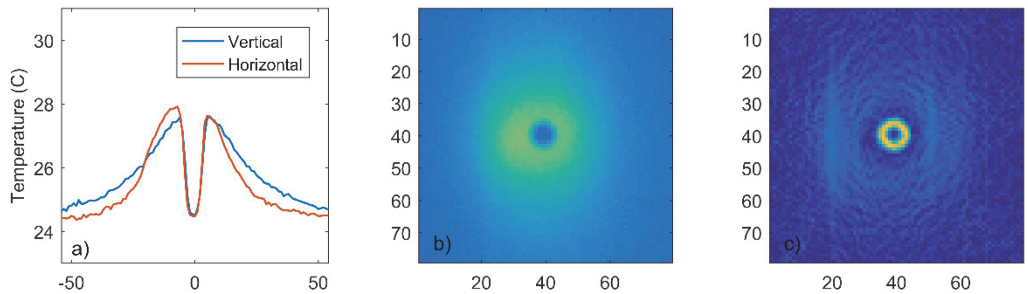

Figure 2: Temperature field recorded with laser heating using infrared camera. a) Temperature profile across the through hole center, b) Temperature field image, c) Gradient of temperature field.

After extensive studies, it was concluded that even though the location of the holes can be identified using laser heating with high accuracy, these images cannot 100% determine whether there is infiltration through the hole. Our close-up imaging did recognize through holes in the wall (Fig.2). This recognition becomes more difficult for 0.5 mm-diameter through holes. It was determined that the variation of laser wavelength and beam size has negligible effect on locating the holes as long as the heating area covers the entire hole.

iii. Infiltration Determination–Method 2

In the laser-line scanning experiment, sensible laser heating was used in attempt to use localized temperature differentials to detect infiltration. Due to the inadequacy of this method for detecting infiltration, a secondary approach was developed. This new method involved spraying a fine liquid mist onto the simulated wall surfaces. Any significant infiltration induces a phase change cooling effect on the mist in physical proximity to any wall openings. In this second detection method using spray mist, termed PECIT (Phase-change Enhanced Cooling Infrared Thermography), phase-change enhanced cooling is used, which significantly amplifies the effect of air flow (both infiltration and exfiltration). This heat transfer method works extremely well to identify infiltration and exfiltration locations with high accuracy and enhanced throughput.

iv. Test Results

We have tested the PECIT technique for through holes with diameters 1 mm to 2 mm, and diagonal lines of 0.5 mm width. Camera-wall distances of 46 cm to 200 cm have been tested to study the accuracy and throughput. During the testing, different pressure differences from 5 Pa to 20 Pa had been used to build comprehensive understanding of the capacity of the PECIT technique. Considering the real-word situations, we had tested the PECIT technique under different wind conditions: parallel, normal, and 45 degrees diagonal to the wall (wind speed: 5 km/h). The parallel wind had little effect on the diagnostics accuracy while the normal and 45 degrees wind could have positive or negative effects, depending on whether it was infiltration or exfiltration. Overall, the PCEIT worked great and provided sufficient accuracy.

(a) Effect of Camera Distance from Wall

A mock wall using the Drywall material with 5/8” thickness was used with an arrangement of holes of 0.5-2.0 mm diameter, both through and half depth as shown in Fig. 3. There were a total of 16 through holes and 16 half depth holes in this arrangement. The camera was placed at different distances of 46-166 cm away from the wall corresponding to viewing areas of 24×32-86×114 cm^2 respectively.

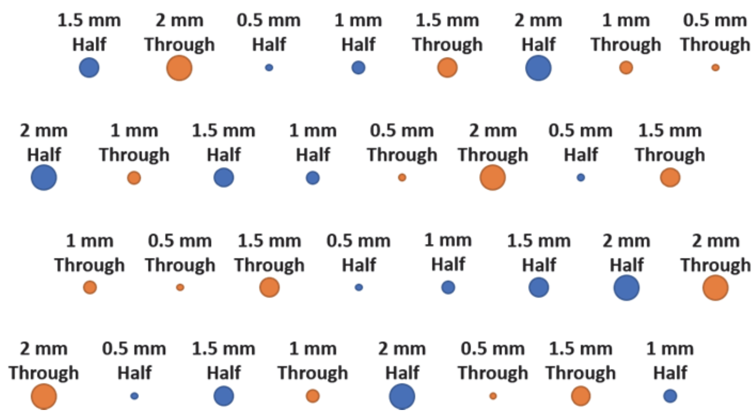

Figure 3: Arrangement of holes on the mock wall of 5/8” thick drywall.

Videos were recorded using the infrared camera and the results were summarized as shown in Table 1. Throughout different tests, it was noticed that the PECIT method essentially did not pick up any of the non-through holes as potential infiltration/exfiltration areas and the focus was only on recognition of through holes. This table shows the number of holes recognized with this method out of a total of 12 holes (x/12) as well as the time needed for them to be visible after the spraying was finished (@s). It is worth noting that as shown by the no pressure difference tests, the detection is solely reliant on the air flow through the infiltration areas. Note here the 0.5 mm through holes are not included in detection accuracy counting since in real-world situations, 0.5 mm wide diagonal lines are more realistic. 0.5 mm wide diagonal lines will be addressed in other testing reported later.

Table 1: **Number of recognized holes and time needed for detection at different camera distances and pressure differences.**

Camera Distance [cm]	46	61	76	91	106	121	136	151	166
Viewing Area [cm^2]	24×32	32×42	40×53	47×63	55×73	62×83	70×94	79×105	86×114
Infiltration at 15 Pa	12/12 @ 28 s	10/12 @ 27 s	10/12 @ 32 s	10/12 @ 13 s	12/12 @ 20 s	9/12 @ 32 s	8/12 @ 34 s	8/12 @ 28 s	8/12 @ 30 s
Exfiltration at 15 Pa	12/12 @ 6 s [1]	12/12 @ 9 s	12/12 @ 9 s [2]	12/12 @ 8 s	12/12 @ 18 s	12/12 @ 19 s [2]	12/12 @ 18 s	12/12 @ 22 s	12/12 @ 20 s
0 Pa	None	None	None	None	None	None	None	None	N/A

[1] 3/4 of the 0.5 mm holes are detected. [2] 1/4 of the 0.5 mm holes are detected.

Images of 4 of the cases reported in Table 1 are shown in Fig. 4 demonstrating a sample of temperature field recordings. It can be seen from this image that a clearer visualization of exfiltration is possible as compared to infiltration.

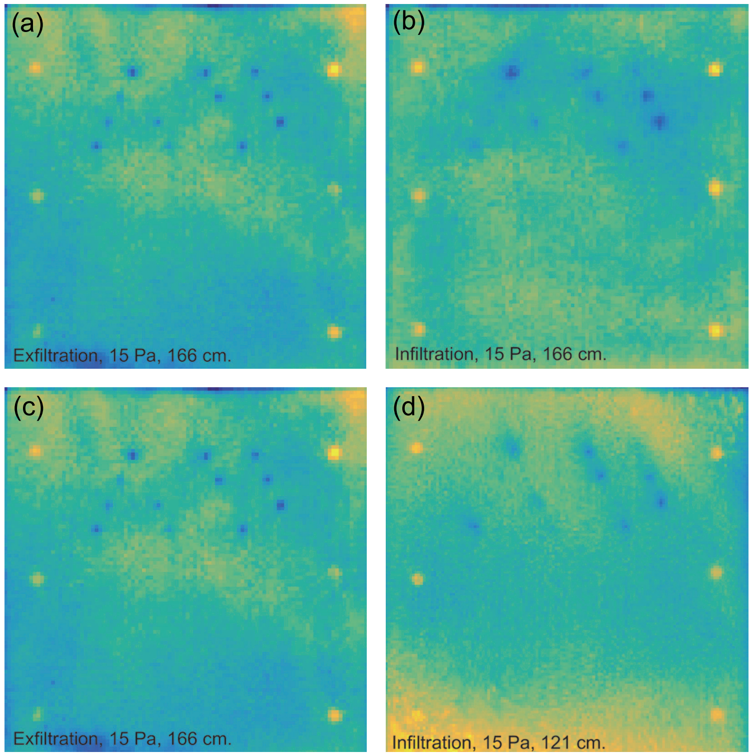

Figure 4: Temperature field recordings of different cases studied.

These results show that even at the longest distance studied, very good detection is possible since almost all the missed holes were 0.5 and 1.0 mm holes and the larger holes are consistently detected. For infiltration, we could achieve 100% accuracy at 46 cm and 106 cm distance. Future better control of water spray is expected to improve the success rate. For exfiltration, we could achieve 100% accuracy even at the longest distance of 166 cm.

(b) Effect of Pressure Difference

Research was conducted to find how sensitive to the pressure difference the PECIT technique is by setting the camera at the farthest distance (166 cm) and varying the pressure difference from 5-20 Pa. Results are given in Table 2 showing that for exfiltration, even a 5 Pa pressure difference is enough for visualization whereas for infiltration, the number of detected holes increases as the pressure difference increases.

Table 2: Effect of pressure difference on detection of infiltration/exfiltration areas.

Exfiltration, 5 Pa	Infiltration, 5 Pa	Infiltration, 10 Pa	Infiltration, 15 Pa	Infiltration, 20 Pa
12 / 12 @ 9 s [1]	None	6 / 12 @ 32 s	8 / 12 @ 31 s	10 / 12 @ 30 s

[1] 1/4 of the 0.5 mm holes are detected.

(c) Detection of Diagonal Lines

The above approach was somewhat modified after these results were obtained, since it was apparent that this method may only fail for smaller sizes of defects (0.5 mm holes). Per discussion with DOE program managers, a new mock wall was prepared with diagonal lines rather than holes. The diagonal lines have a 0.5 mm width and 4-6 mm length as shown in Fig. 5 with a total of 11 through and 6 not through and an extra very large slot on the top left due to manufacturing issues.

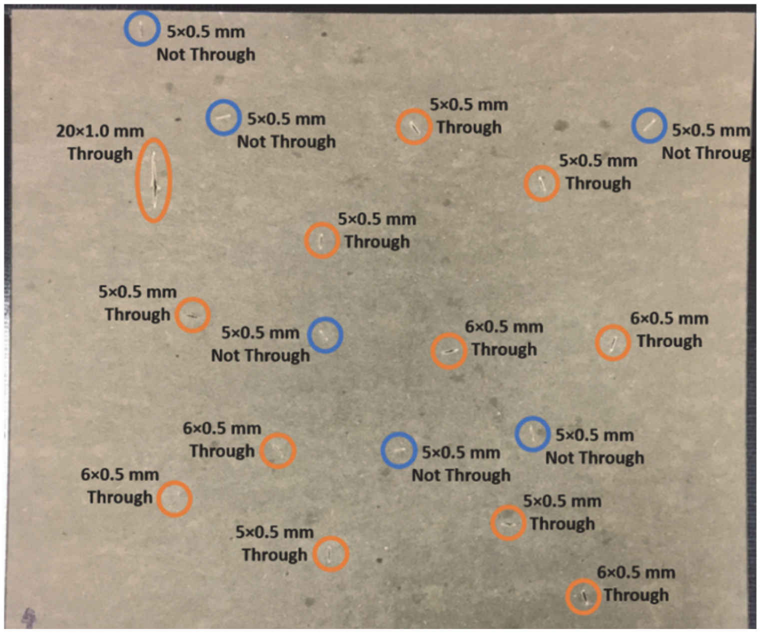

Figure 5: Mock wall with diagonal lines of 0.5 mm width on Drywall with 5/8" thickness.

In addition, it was realized that the consistency in spraying is important and a new electric paint sprayer was used for the following tests. Results of these tests are shown in Table 3 with sample images for 3 studied cases shown in Fig. 6.

Table 3: Detection of diagonal lines at various camera distances and pressure differences for infiltration and exfiltration.

Camera distance, pressure difference	**1.5 m, 5 Pa**	**1.5 m, 10 Pa**	**1.5 m, 15 Pa**	**2.0 m, 5 Pa**	**2.0 m, 10 Pa**	**2.0 m, 15 Pa**
Infiltration	7/12 @ 31 s	11/12 @ 18 s	12/12 @ 6 s	7/12 @ 31 s [1]	11/12 @ 25 s [2]	11/12 @ 17 s
Exfiltration	12/12 @ 4 s	12/12 @ 10 s	N/A	10/12 @ 13 s	12/12 @ 8 s	N/A

[1] 4/6 Not through slots are recognized as infiltration zones.
[2] 2/6 Not through slots are recognized as infiltration zones.

As can be seen from Table 3, the spray cooling method worked excellent at 15 Pa pressure difference that is the stretch goal for the initially proposed laser line-scanning and simultaneous infrared temperature imaging approach and worked even in the lower range of pressure difference. It is worth mentioning that for the 2 m distance tests, the mock wall was placed on the corner of the images to ensure that there was no bias in detection in the edges of image. A detection rate of 90% for both infiltration and exfiltration at 10 Pa pressure difference was achieved with a maximum of 25 s video recording.

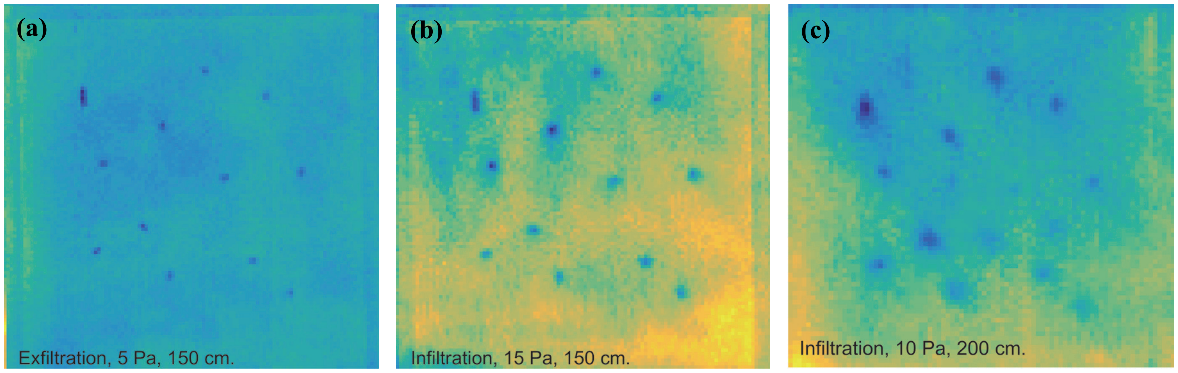

Figure 6: Temperature field recordings with diagonal lines of 0.5 mm width.

(d) Effect of wind

In this part, we conducted work to address one very important issue: applying the PECIT technique from outside of a building which requires some insight into the effect of weather, specifically wind that does affect the evaporation of water. Three different wind directions of normal, parallel, and angled about 45 degrees at a speed of 5 km/h were tested for both the 5 and 15 Pa pressure difference at the 2 m distance. Results are given in Table 4 with a set of sample images shown in Fig. 5.

Table 4: Effect of different directions of wind on detection rate of diagonal lines.

	Normal, 5 Pa	**Normal, 15 Pa**	**Angled, 5 Pa**	**Angled, 15 Pa**	**Parallel, 5 Pa**	**Parallel, 15 Pa**
Infiltration	10/12 @ 6 s	12/12 @ 7 s	7/12 @ 9 s	12/12 @ 5 s	9/12 @ 7 s [1]	11/12 @ 12 s
Exfiltration	6/12 @ 15 s	9/12 @ 5 s	8/12 @ 12 s	12/12 @ 8 s	11/12 @ 12 s	12/12 @ 9 s

[1] 3/6 Not through slots are recognized as infiltration zones.

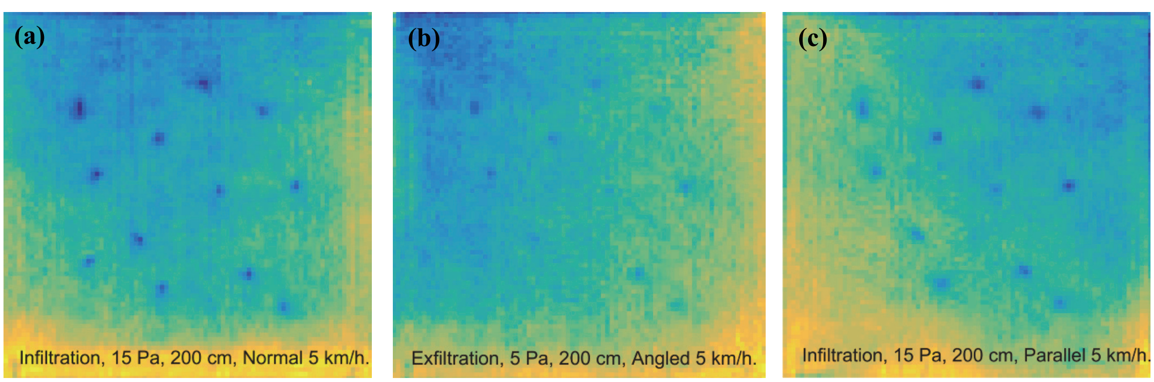

Figure 7: Temperature field recordings in presence of wind.

Comparison of the results of Table 4 with Table 3 reveals very interesting features of this method. As can be seen, presence of wind generally helps with a faster detection of holes in the case of infiltration. This is due to the fact that wind increase the air flow through the diagonal lines. It is also apparent that the number of detected holes is higher with a normal wind direction at 5 Pa pressure difference as compared to no wind. In contrast, the exfiltration results suffer in presence of normal or angled wind, even though a parallel wind direction does not affect the accuracy of method. These results suggest that a local normal air blower can be used for detection enhancement if infiltration is expected rather than exfiltration.

These results show that except for an outlier case of normal wind and 15 Pa pressure difference for exfiltration, no major drawback on detection rate occurs in presence of wind. For the 5 Pa pressure difference however, presence of wind can decrease the number of detected infiltration/exfiltration zones. Further tests are required for finding the limits of this method at higher wind speeds.

(e) Development of new liquid for hydrophobic wall infiltration/exfiltration diagnostics

One of the concerns regarding the applicability of PECIT was due to its usage of water for detection. Exterior of a building needs to be waterproof and widely used materials such as caulk are hydrophobic. To study this issue, the surface of the mock wall was treated by Flex Seal Spray-On Sealant and tested with water and a solution of Finish® Jet-Dry® (dish wash) as surfactant. The surfactant solution wets the surface in contrast to water. The PECIT method was applied to the treated mock wall using both water and surfactant solution and results are presented in Table 3. It shows that despite the presence of the droplets on the surface, detection on hydrophobic surfaces is accurate since the size of these droplets at the required amounts of water is extremely small. Using a surfactant is an alternative approach that shows successful results and makes detection of the air leak areas faster.

Table 5: Waterproof surface test results.

	Infiltration, 10 Pa	Exfiltration, 10 Pa	Infiltration, 15 Pa	Exfiltration 15 Pa
Water	**11/12 @ 22 s**	**12/12 @ 22 s**	**11/12 @ 22 s**	**12/12 @**
Jet-Dry (Dish wash)	**11/11 @ 11 s**	**12/12 @ 8 s**	**N/A**	**N/A**

v. Conclusions

In conclusion, the PECIT technique has been proved to recognize infiltration and exfiltration zones of 0.5 mm in one dimension at pressure differences of 10 Pa and above with higher than 90% accuracy. With the camera placed at 2 m from the wall, a total area of 1.46 m^2 (1.04×1.40) can be diagnosed one time with a maximum required time of 25 s for videography. This will require 0.105 liters of water sprayed on the surface which takes 18 seconds with the current paint sprayer. Under wind conditions, the PECIT is still applicable with its performance either reduced or improved, depending on the wind direction and the type of air leaking: infiltration or exfiltration. When the wind is parallel to the wall, the detection accuracy is affected very little. When the wind is going against the wall, infiltration detection accuracy will be improved dramatically while the exfiltration detection could be reduced by a limited extent. For hydrophobic wall surfaces, water with very low concentration of surfactant will make the liquid wet the surface nicely and the detection accuracy was not compromised.

For the Go/No-Go criteria, the PECIT technique has either met or exceeded the original goals for the laser line-scanning and simultaneous infrared temperature imaging approach as detailed in Table 6. In conclusion, our achievement even exceeded the stretch goal set in the Go/No-Go decision points. In the goals of the project, the proposed throughput was 30 m^2/h for the laser line-scanning and simultaneous infrared temperature imaging approach. The PECIT technique has been extensively tested and found that its throughput can reach 120 m^2/h, which is 4 times the proposed one. A product requirement document (PRD) had been developed based on the PECIT technique and is in the process of review and improvement.

For commercialization and market penetration, we had developed non-disclosure agreement (NDA) and had meetings with Systemworks and Homestar Iowa. These meetings provided insights into market viability, challenges and hurdles, and industry feedback for further technology improvement, such as ensuring that the diagnostic technique would work for envelope transition areas where wind effects may also be more challenging. Also, we had interacted with Office of Intellectual Property and Technology Transfer of Iowa State University and had a meeting for idea disclosure and patent application.

Table 6: Laboratory performance metrics of PECIT compared to proposal goals.

	Proposal	**Stretch Goal**	**Laboratory Exfiltration**	**Laboratory Infiltration**
System cost	< $7,000		$6,295	
Throughput	30 m^2/h (320 ft^2/h)		120 m^2/h (1300 ft^2/h)	
Leak area size	**0.5 - 1.0 mm (0.02 – 0.04 in)**			
Accuracy	>80%	>70%	100%	>90%
Pressure	50 Pa (0.007 psi)	15 Pa (0.002 psi)	10 Pa (0.0015 psi)	10 Pa (0.0015 psi)
Leak area size	**1.0 - 2.0 mm (0.04 – 0.08 in)**			
Accuracy	>90%	>80%	100%	100%
Pressure	50 Pa (0.007 psi)	15 Pa (0.002 psi)	10 Pa (0.0015 psi)	10 Pa (0.0015 psi)

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