FIELD STUDY OF PERFORMANCE FACTORS OF VACUUM INSULATED PANELS IN INTERIOR RETROFIT ASSEMBLIES

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ABSTRACT
Buildings account for 36% of all U.S. energy consumption and about 70% of total electricity consumption. A significant opportunity for minimizing energy consumption is the use of increased levels of insulation, both in new construction and in deep energy retrofits (DER) to the existing building stock. Vacuum Insulated Panels (VIPs) present a unique opportunity since they possess high insulating value and a thin profile which significantly exceeds the performance of conventional insulations (Simmler, et al. 2005). Despite these advantages, the hygrothermal impacts of VIP require additional research. Specifically, the hygrothermal impacts of adhesive attachment methods in interior retrofits have not been extensively studied and thus form the basis of this research.

A field study was undertaken to assess the hygrothermal performance VIPs applied in an interior insulation retrofit to a pre-cast concrete building in Midland, Michigan (DOE Climate Zone 5). The walls were instrumented with sensors to measure temperature, moisture, and heat flux at critical locations and complemented with computational methods involving finite-element programs for both heat and moisture.

The results from the heat flux sensors were used to calculate an effective thermal resistance of the wall assemblies, with steady-state thermal analysis to assess thermal bridging effects. It was found that the thermal flanking of the VIP core reduced the effective panel to R-25.6. The results were then imported in to a hygrothermal model to determine the impacts of incidental air leakage. The hygrothermal and airflow models were calibrated with the vapour pressure readings in the assemblies. Due to the insulating properties of the VIP, but the low vapour permeance, air leakage bypassing the insulation may place moisture sensitive materials at increased risk of air leakage condensation.

OBJECTIVE
The objective of this study is to analyse the hygrothermal performance of an interior wall assembly constructed with Vacuum Insulated Panels using three different adhesive attachment methods. The focus of analysis was on determining which attachment method maximized thermal resistance and minimized concerns for moisture damage. Data were collected to validate hygrothermal models for supplemental analyses.

Recommendations are made regarding attachment methods, based on moisture performance, thermal performance, and constructability (i.e. cost, ease of installation, sequencing, etc).

SCOPE
There are two primary attachment methods for VIP: mechanical fasteners or adhesive fastening. Metal mechanical fasteners were not used in this study because they are subject to thermal bridging around the panels and risk puncturing the vacuum core in addition to not possessing intrinsic air sealing properties.
These problems can be avoided by using adhesive attachment methods. Adhesives may also provide resistance to air infiltration and moisture migration. Silicone adhesives were selected for this study.

There are three main adhesive methods of fastening the VIP assemblies: continuous adhesive, unsealed spot adhesive, and sealed spot adhesive. The first method involves troweling on a continuous layer of adhesive and bonding the VIP to the wall. The unsealed spot adhesive method consists of using spots of adhesive on the backside of the panel to fasten it to the structure while leaving a small airspace between the wall and panel assembly. The sealed spot adhesive method is similar to the unsealed spot adhesive, except a perimeter of sealant is placed around each panel to compartmentalize the air space behind it.

The conclusions from this study only extend to interior insulation retrofits with existing walls with no known pre-existing water conditions of water damage. Exterior insulation retrofits with VIP fall beyond the scope of this work.

**EXPERIMENTAL PLAN**

Three VIP test walls were built on the interior of a west-facing pre-cast concrete enclosure in a laboratory space in Midland, Michigan. The walls were instrumented with thermistors, relative humidity sensors, and heat flux transducers to obtain the thermal gradients across the walls, the vapour pressures between the VIP and the existing enclosures, and the heat flow through the center, edge, and T-intersection of the VIP. The data were collected with data logging equipment and the values were averaged over a 1 hour period. Weather data were collected from a nearby, private weather station and complemented with weather data from the Saginaw Airport.

**DESCRIPTION OF CONSTRUCTION**

The existing enclosure consisted of 178mm (7 in.) of pre-cast, concrete panel. The inside of the concrete was sealed with a vapour permeable, silicone-based sealant. The VIPs were adhered using their respective methods to the silicone sealant. The joints of the VIP assemblies were sealed with acrylic tape. After installation of the VIP assembly, a steel-stud-framed wall with gypsum wallboard (GWB) was erected and finished with latex paint. A summary of the three test walls may be found in TABLE 1.
The VIP panels consist of 25.4mm (1in.) of protective extruded polystyrene (XPS) insulation covering a fumed silica core sealed with a metallic foil. The edges were covered with 12.7mm (1/2 in.) of XPS to protect the edges.

**TABLE 1: SUMMARY OF ADHESIVE ATTACHMENT METHODS FOR WALLS 1, 2, AND 3**

<table>
<thead>
<tr>
<th>Attachment Method:</th>
<th>Wall 1: Continuous Adhesive</th>
<th>Wall 2: Spot Adhesive, Ventilated</th>
<th>Wall 3: Spot Adhesive, Sealed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Objective:</strong></td>
<td>Assess impact of continuously applied adhesive on moisture effects.</td>
<td>Assess the impact of incidental air leaks behind the VIP panel.</td>
<td>Assess the performance of the assembly including an interstitial air space between the VIP and the existing structure.</td>
</tr>
<tr>
<td><strong>Notes:</strong></td>
<td>Three heat-flow sensors were installed on the panels to measure heat flux at the center of panel, edge of panel, and at the T-intersection of three panels.</td>
<td>Blocks between the floor and ceiling were installed to ensure a continuous air loop into the stud space. Holes were drilled in the GWB to ensure communication of the interstitial cavity with the interior laboratory air.</td>
<td>A metal pipe penetrated an area of the test sample. The area was carefully sealed with silicone to suppress any airflow. The sensors were located at a distance from the pipe.</td>
</tr>
</tbody>
</table>

The VIP panels consist of 25.4mm (1in.) of protective extruded polystyrene (XPS) insulation covering a fumed silica core sealed with a metallic foil. The edges were covered with 12.7mm (1/2 in.) of XPS to protect the edges.

**INSTRUMENTATION PLAN**

The thermal performance of each assembly was monitored with thermistors, which were installed at each adjoining layer in the construction of the wall from exterior to interior to create a thermal profile. Thermistors were also installed at the top and bottom of the VIP assembly terminus to measure thermal bridging effects of floor and ceiling slabs. Thermistors were installed vertically to measure the effects of temperature stratification along the height of the walls.

Relative humidity sensors were installed between the VIP and concrete panels and inside the stud space. This provided information on the vapour pressure gradient and the level of exchange of interstitial and indoor air.

Heat flux sensors were installed at the center, edge, and T-intersection of the panel in Wall Assembly 1 with the continuous adhesive layer. The heat flux sensor was installed flush by coring out the required depth in the XPS protective layer. The layout of the sensors may be found in FIGURE 1. With the exception of the heat flux sensors, all of the sensors were lined-up vertically through the wall section.

The resulting data were collected with data logging equipment and the values were averaged over a 1 hour period. Weather data were collected from a nearby, private weather station and complemented with weather data from the Saginaw Airport.
### FIGURE 1: WALL SENSORS LAYOUT FOR WALLS 1 AND 2/3

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Wall 1 Sensor Layout</th>
<th>Wall 2 and 3 Sensor Layout</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp Sensor</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>RH &amp; Temp Sensor</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Heat Flux Xducer</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Strain Gauge</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

### FIGURE 2: HEAT FLUX SENSOR INSTALLED AT T-INTERSECTION

### FIGURE 3: SAMPLE RH AND TEMPERATURE SENSORS
RESULTS

Data collection started at the completion of the assembly on March 1, 2012 and has continued through the publication of this paper. In addition to the global data set, data from the middle of January 2013 were selected for additional analysis, because a large variation in outdoor temperature was experienced (-17°C to 10°C). The large temperature variation provides an effective illustration of the temperature impacts on the various layers in the wall assembly, especially since thermal mass effects are prominent.

THERMAL EFFECTS

The wall assemblies were analyzed on the basis of temperature profiles collected from the installed thermistors and the recorded heat flux readings from the heat flux sensors. The temperature profiles through the center of each wall are shown below, in FIGURE 4.

![Wall 1- Trowel Adhesive](#)

![Wall 2- Spot Adhesive- Vented](#)

![Wall 3 - Spot Adhesive- Sealed](#)

**FIGURE 4: WALL 1, 2, AND 3 TEMPERATURE PROFILES**

The temperature data indicate minor variations in temperature profiles for the three assemblies. The thermal mass effects of the pre-cast concrete can be clearly observed when comparing the exterior concrete temperature to that of the exterior of the VIP. With regards to heat flows, the results from the heat flux sensors are shown in FIGURE 5.
The Center of Panel sensor recorded a more stable heat flux throughout the year compared to the edge and panel intersection sensors. This suggests that thermal bridging is in fact occurring along the edges of the panels.

HYGRIC EFFECTS

Temperatures and relative humidity readings were collected in the interface between the VIP and the concrete wall. These values were used to calculate the vapour pressure using the Hyland-Wexler equation, accounting for both vapour pressures above and below 0°C (32°F). Vapour pressure was used in lieu of the relative humidity, due to the sensitivity of the relative humidity readings to variations in temperature.

The continuous adhesive assembly exhibited widely variable vapour pressures. The variations in the vapour pressure are likely a result of the temperature changes in the wall assembly, as the RH sensor was effectively isolated from moisture sources. The vapour pressures in the sealed spot adhesive assembly in Wall 3 are less variable, and the vapour pressures in the vented assembly in Wall 2 are nearly equivalent to those of the interior. The vapour pressure gradients were calculated and plotted in FIGURE 6. The gradient indicates the direction or drive of water vapour flow across the assembly.
A vapour pressure gradient near zero indicates a connection to the interior laboratory space. Wall 2 shows such a connection. The continuous adhesive assembly in Wall 1 demonstrates a clear disconnect from the interior conditions, as shown with the high peak vapour pressure differentials.

ANALYSIS AND DISCUSSION

THERMAL PERFORMANCE

Previous research has indicated that thermal bridging through VIP panels with metallic foil composites can be significant. To assess the effective thermal performance of the VIP, the heat flux sensors were positioned to capture the heat flow through the center of the panel, the edge of the panel, and at the intersection of three panels (a T-intersection). Because these are point-specific measurements, a linear thermal transmittance approach was used to ascribe a component R-value to the “center” and “edge” of the panels, as shown in FIGURE 7. The limits of the edge effects were established by two-dimensional, steady state thermal modeling and were used to determine the respective area-weights for the panel R-values. The results of the thermal modeling, including temperature and heat flux distributions, are shown in FIGURE 8.

![FIGURE 7: EDGE AND INTERSECTION HEAT FLUX SENSOR BREAKDOWN](Image)

As data were collected for $R_{center}$ and $R_{heat flux}$ for both the edge and intersection locations, the effective R-value of $R_{edge}$ can be obtained.

$$\frac{1}{R_{sensor}} = \frac{\alpha}{A_{sensor}} \cdot \left( \frac{1}{R_{edge}} \right) + \frac{\beta}{A_{sensor}} \cdot \left( \frac{1}{R_{center}} \right)$$

$R_{edge} = \left[ \left( \frac{1}{R_{sensor}} - \frac{\beta}{A_{sensor}} \cdot \left( \frac{1}{R_{center}} \right) \right) \cdot \frac{A_{sensor}}{A_{sensor}} \right]^{-1}$
FIGURE 8: TEMPERATURE AND HEAT FLUX DISTRIBUTION ACROSS VIP COMPOSITE PANEL

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Thermal Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W·m⁻¹·°K⁻¹</td>
</tr>
<tr>
<td>Extruded Polystyrene</td>
<td>0.0242</td>
</tr>
<tr>
<td>MF-3 VIP Foil</td>
<td>1.0</td>
</tr>
<tr>
<td>Fumed Silica Core</td>
<td>0.0037</td>
</tr>
</tbody>
</table>

TABLE 2: MATERIAL PROPERTIES

Very high heat fluxes along the foil were obtained from the thermal modeling. This suggests that the heat flow passing through the XPS end caps is bypassed by the foil wrapping the VIP core. Based on the steady-state heat flow simulations, it was found that the edge effects do not extend beyond 20mm into the interior of the VIP panel. The results are shown in TABLE 3.

<table>
<thead>
<tr>
<th>RSI-value (R-value)</th>
<th>Winter</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>01/12/2012 0:00</td>
<td>01/06/2012 0:00</td>
</tr>
<tr>
<td></td>
<td>01/03/2013 0:00</td>
<td>31/08/2012 0:00</td>
</tr>
<tr>
<td>Center of Panel</td>
<td>4.7 (26.9)</td>
<td>4.9 (27.5)</td>
</tr>
<tr>
<td>Panel Intersection</td>
<td>1.8 (10.2)</td>
<td>2.0 (11.4)</td>
</tr>
<tr>
<td>Panel Edge</td>
<td>2.1 (11.9)</td>
<td>2.4 (13.4)</td>
</tr>
<tr>
<td>R-Value Effective</td>
<td>4.5 (25.6)</td>
<td>4.5 (25.4)</td>
</tr>
</tbody>
</table>

TABLE 3: CALCULATED EFFECTIVE R-VALUES FOR WINTER AND SUMMER DATA
A sensitivity analysis was conducted to assess the difference in R-value when the limits of the edge effects were modified. The maximum agreement is 10% (assuming no edge effect to the maximum radius of the heat flux sensor). However, from the derived edge effect (20mm) to the radius of the heat flux sensor, the calculated agreement is only 2.6%. The ratio of center to edge R-values agrees well with thermal testing from Childs, et al. (2013).

To determine the impact of airflow in the ventilated wall (Wall 2), an effective R-value can be obtained by first estimating the amount of air leaking and then applying the following equation:

$$R_{\text{effective}} = \left( U_{\text{airflow}} + \frac{1}{R_{\text{conduction}}} \right)^{-1}$$

The effects of air leakage are approximated by assuming a range of airflows behind the cavity, attributing an equivalent R-value reduction to the airflow and verifying the effective R-value of the assembly. This is obtained by the following equation:

$$U_{\text{airflow}} = \frac{Q \rho c_p}{A}$$

Where $A$ is the area of the cladding behind which air is flowing, $Q$ is the volumetric flowrate of the ventilation air, $\rho$ is the air density, and $c_p$ is the specific heat capacity of the air. Hygrothermal modelling, as described in the next section provided an air leakage estimate of approximately 0.05 L·s⁻¹·m⁻². The effective conductance is thus 0.0105 m²·K·W⁻¹. This airflow de-rates the panel R-value of RSI-4.5 (R-25.6) down to RSI-3.5 (R-20.1), a 21% decrease. However, the airflow calculations are subject to construction parameters, such as wall height, ventilation gap widths, and the degree of obstruction in the air space and may differ for other walls. Sealed and compartmentalized panels, as in Wall 3, are not subject to this de-rating.

**Moisture Effects**

Measured data from the test wall showed very low vapour pressures throughout the winter months. Upon inspection, interstitial vapour pressures are so low because the laboratory relative humidity averaged approximately 20% throughout the winter, with a low of 15% in February. With such low relative humidity, the ventilated test wall was not exposed to significant moisture loads that may be found in other interior environments. Consequently, to assess moisture effects for increased moisture loads, a hygrothermal model was calibrated to match the measured data. The air changes per hour (ACH) of the ventilated space were modified until good agreement was achieved. The results of the weekly averaged difference in vapour pressures between the modeled and measured data are shown in FIGURE 9.
The difference between calculated and modeled peak vapour pressure can be attributed to the lack of adequate solar radiation data for the modeling software. In warmer months with increased sunlight to the west-facing wall, the difference between measured and modeled vapour pressures is greater than during the colder months.

In general, good agreement has been shown between the modeled and calculated vapour pressures. In an effort to further align results and assign a cause for the divergence, the quantity of air leakage behind the ventilated air space in Wall 2 was varied in the modeling software and it was determined that 50ACH resulted in very good agreement with the calculated data. This corresponds to roughly 0.05L·m⁻²·s⁻¹ in airflow rate. Due to the thermal resistance of the panels and the low vapour permeance, this air leakage may place moisture sensitive materials at increased risk of air leakage condensation damage.

CONCLUSIONS

High-performance buildings are required to reduce energy consumption and environmental degradation. Vacuum insulated panels or VIPs are one product that provide superior thermal performance in a compact package. To assess the hygrothermal performance of VIPs, a test wall was constructed with three different adhesive attachment methods on the inside of a pre-cast concrete building in Midland, Michigan. The three adhesive attachment methods used a continuous, trowel-applied adhesive, spot-applied adhesives with perimeter sealant, and spot-applied adhesives with a ventilated cavity.

The thermal analysis indicated that the actual R-value of the VIP, when accounting for thermal bridging around the evacuated fumed silica core, was approximately RSI-4.5 (R-25.6). This decreases to RSI-3.5 (R-20) if a ventilated airspace is located behind the VIP, as in the unsealed, spot-adhered wall.

None of the three walls exhibited elevated relative humidities in the interstitial cavity space. However, this was a result of extremely dry interior winter conditions. Based on the level of connection in the ventilated wall, it is believed that some air leakage condensation may create moisture concerns if interior relative humidities were maintained at higher levels. It is not anticipated that the sealed or spot-adhered wall would
suffer any levels of air leakage condensation unless a seal was discontinuous. There should be no occurrence of air leakage condensation in the continuous adhesive wall.

Based on the hygrothermal performance of the walls and the resources required for construction, the following conclusions are made:

- **Constructability**: Wall 2 was faster to build than Wall 3. Wall 1 required the most labour and material to construct.

- **Moisture Performance**: Wall 1 is less prone to moisture concerns than Walls 2 or 3. Wall 2 may be susceptible to moisture problems if the interior vapour pressure becomes elevated in the winter.

- **Thermal Performance**: Wall 1 is not subject to any convective looping or ventilation. It performs better than either Walls 2 or 3. Wall 2 suffers from de-rated thermal performance from the air flowing through the cavity.

Due to its superior moisture and thermal performance, it is recommended that a fully-adhered adhesive attachment approach be used for interior retrofits with VIP panels.

**REFERENCES**

ASHRAE. 2009. *Handbook of fundamentals*. ASHRAE, Atlanta, GA.


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