Heat and Moisture Modelling of Vacuum Insulated Retrofits with Experimental Validation

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Abstract. Vacuum insulation panels (VIPs) offer 8-10 times the thermal resistance of fiberglass insulation and would fit the need for a low conductivity exterior insulation. A composite insulation panel using VIPs encased in rigid foam was developed, built, and tested. Two different sizes of VIPs were used for that stage of the project, and after monitoring and evaluation, they showed contrasting results. A simulation study was performed to find the optimal VIP solution that maximized the effective thermal conductivity and minimized the mould growth potential. In total, 5 wall assemblies with VIPs used as the exterior insulation were simulated using WUFI and WUFI2D. The simulations showed that the humidity levels at the inside face of the OSB inboard of the VIPs decreased when 200 mm by 300 mm VIPs were used, but they did not reach the thermal performance thresholds of R5.28 m²K/W. The hygrothermal analysis showed that under similar conditions, a VIP insulated wall assembly would have a lower relative humidity at the sheathing surface compared to EPS and XPS. The one- and two-dimensional simulations were compared and found that WUFI Pro was capable to evaluate a VIP-insulated wall assembly.

1. Introduction

As Canada aims to reduce their greenhouse gas emissions and carbon footprint, reducing the amount of energy consumed by buildings will be a focus. In 2018, approximately two-thirds of the energy consumed by buildings in Canada was used for space heating and cooling [1]. These loads can be reduced in buildings through higher efficiency heating, ventilation, and air conditioning equipment; however, a more passive and resilient solution would be to improve the building enclosure.

Energy transfer between the conditioned environment inside the building and the outside occurs through the walls, roof, and slab. These transfers are done through conduction, convection, and radiation, but more practically through your enclosure materials like insulation and structural materials, convection through the air movement at the boundary surfaces, and circulation in wall cavities and radiation exchange between the surfaces. The most significant energy transfers are as a result of conduction and convection, which highlights the importance of building insulated and airtight wall assemblies. These aspects will be vital in reducing the emissions and carbon footprint caused by the energy consumption of buildings.

The building enclosure R-value can be improved by increasing the thickness of, preferably continuous, insulation or use a lower thermal conductivity material as the building insulation, where both strategies have benefits and drawbacks. When the insulation thickness increases, as does the total wall assembly thickness. When this incremental increase in space is taken from the interior floor area, it could result in a
substantial loss of value depending on the price per square meter of space. With a low-conductivity material as the insulation, it is possible to maintain the existing envelope thickness with improved thermal resistance. Vacuum insulation panels (VIPs) are a low-conductivity material that utilizes an evacuated porous core wrapped in an airtight metallic film. The vacuum is maintained in the panel and therefore eliminates convection inside the porous core. VIPs provide a thermal conductivity 8-10 times lower than fiberglass insulation and could insulate the building envelope above the current code requirements [2]. Their main challenges include unknown long-term performance, the inability to cut and shape on-site as well as current cost compared to typical insulation products. However, VIPs have the potential to improve the new and existing building stock by their lowering the thermal conductivity of the enclosure.

To combat these issues, it was proposed to embed the VIPs within an insulation panel, such as a composite insulation panel (CIP) or structural insulation panel (SIP). The ease of installation and quality control could be improved by incorporating VIPs into the enclosure as a system instead of sole material. The CIP and SIP could be factory-made for reliability, provide clear fastener positions, and filled with insulation between the VIPs to provide continuous insulation to the building. Since VIPs are vapour impermeable and highly insulative, the dimensions and thickness of VIPs have a great impact on the overall hygrothermal wall assembly properties and performance.

The purpose of this paper is to identify a CIP or SIP design that integrates VIPs for wood frame construction. Five sets of VIPs were selected and evaluated using experimental and numerical methods. The VIPs had differed by their geometry, thickness, and thermal conductivity. The effective R-value of the panel designs was found using experimental and numerical methods. The hygrothermal analysis was performed using a numerical hygrothermal simulation on a wall assembly in Ottawa, CA.

2. Insulation Panel Design

Beginning with the base wall assembly for the study a 2x4 wood frame was built 400 mm (16”) on-center spacing with R-1.93 m²K/W fiberglass insulation to fill the cavities. A polyethylene vapour barrier and gypsum board were installed on the interior. The CIP and SIP would be installed on the exterior to provide continuous insulation. Outboard of the CIP was a weather-resistant barrier (WRB) and vinyl siding.

The VIPs were embedded into rigid insulation by creating pockets in sheets of insulation. The depth of the pockets was the same as the VIP thickness so that the surface of the VIP would be in the same plane as the top of the pocket. After the VIPs were placed in the pockets, shown in Figure 1, the surface would be flat, and a backer would be applied on top. While some VIPs were damaged during delivery, only VIPs that maintained their vacuum and rigidity were placed in the insulation panels.

![Figure 1 VIPs are placed in rigid insulation before backer boards being adhered to the panel [3].](image)

The differences between the CIP and SIP panels were the type of backer board utilized. In the case of CIPs, a 12 mm or 25 mm sheet of rigid insulation was applied as the backer. For the SIPs, a 10 mm oriented strand board (OSB) was adhered to provide the panel its structural properties. When a CIP was used, the base wall would also have a 10 mm OSB sheathing fastened to the framing. The VIPs were placed in the insulation panels to be aligned with the center of the framing cavity and to minimize the amount of area that was aligned with the studs, shown in Figure 2. By offsetting the VIPs from the framing, the insulation
panels were fastened to the sheathing or framing to ensure there was a secure connection to hold the insulation and the cladding. Fasteners needed to avoid the VIPs because the panels would lose vacuum and significantly increase their thermal conductivity. As such, markings and fastener selection are critical during installation.

![Figure 2](image)

**Figure 2** Section views of an example wall assembly with VIPs installed.

The VIPs selected for the study are listed in Table 1 and lists their dimensions and the thermal conductivity provided by the manufacturer. These VIPs are meant to provide a range of size, thickness, and thermal performance to evaluate how these could be applied to a wall assembly. A minimum of 25 mm (1”) of space was needed between VIPs for fastening purposes. The base upon which the VIPs were laid out was 2.4 m by 2.4 m (8’ x 8’) to represent a section of the home without doors, windows, or other penetrations. Also, it was presumed that these CIP and SIP panels would be applied as a 1.2 m by 2.4 m (4’x8’) panel applied horizontally. The VIP layout in the CIP and SIP designs is shown in Figure 3 and is shown as a single panel and their alignment with the woodframe.

The VIPs were oriented in the wall assembly to minimize the overlap with a stud to minimize the risk of a fastener through a VIP. However, from a thermal performance standpoint, it would be more beneficial to insulate over the studs than the cavities to minimize the thermal bridge caused by the framing. VIP sizes ranged from 863 mm (34”) to as small as 200 mm (8”). Large VIPs that overlapped the studs were compared to smaller VIPs that did not have any stud overlap.

| Panel Design | VIP Length (mm) | VIP Width (mm) | VIP Thick (mm) | Panel Type | \(\lambda_{VIP}\) (W/ m K) | %VIP Coverage | %Stud Insulated |
|--------------|----------------|----------------|---------------|------------|-----------------|--------------|----------------|
| VIP1         | 762            | 498            | 25            | CIP        | 0.0036          | 60%          | 35%            |
| VIP2         | 560            | 864            | 25            | CIP        | 0.0036          | 81%          | 65%            |
| VIP3         | 200            | 300            | 20            | CIP        | 0.0029          | 50%          | 0%             |
| VIP4         | 200            | 300            | 20            | SIP        | 0.0029          | 50%          | 0%             |
| VIP5         | 560            | 560            | 20            | SIP        | 0.0029          | 85%          | 52%            |

**Table 1** Specifications of VIPs used for the study and important insulated coverages.
VIP3 and VIP4

VIP5

Figure 3 Plan View of VIP layouts for the 5 wall assemblies. VIPs are indicated by the hatched red lines.

3. Thermal Resistance Evaluation

The wall assemblies were evaluated using a combination of steady-state guarded hot box testing and 2D heat transfer modelling. Steady-state testing was performed at Carleton University using a scaled guarded hot box that followed ASTM C1363 [4] test procedures. The wall assemblies were built and instrumented at Carleton University and were monitored for 5 days after steady-state conditions were met. THERM [5] was used to simulate the heat transfer and effective thermal resistance of the wall assemblies. In some cases, wall assemblies were evaluated using both techniques, and others were evaluated solely using THERM.

Three wall assemblies (VIP2, VIP3, VIP4) were evaluated using the guarded hot box and THERM, while the VIP1 and VIP5 were solely evaluated using THERM. Two wall profiles were modelled for each wall assembly; a VIP insulated section and a non-VIP insulated section. The effective R-value was computed using the parallel paths method, and the results are summarized in Table 2. The results showed good agreement with the guarded hot box results, and deviations could be related to material properties, specifically the VIP edge thermal bridge that was not accounted for in THERM.

The remaining panel designs were well above the thermal resistance threshold. The panels varied in VIP thickness, VIP coverage, and stud coverage. VIP1 panel design cleared the thermal performance threshold, with a 25 mm VIP integrated into the CIP design. With only 60% VIP coverage and 35% stud coverage, this layout provided a slight improvement in thermal performance and ample spacing for fasteners. VIP2 design had the highest effective R-value but also the highest percentage of VIP insulating studs. With 25 mm VIPs and high coverage ratios, this design did not balance the performance and constructability. The VIP3 and VIP4 thermal performance did not exceed the R-5.28 m²K/W threshold and would therefore require a thicker VIP layer or increase the VIP coverage area. The main benefit from those two designs was also its biggest drawback. The VIPs were all located in the cavity, and therefore would not be at risk of errant fasteners or puncture during application. However, the thermal bridges caused by the framing limited the panel performance. Therefore, the VIP performance, size, or thickness to improve it above the threshold.

Finally, VIP5 was a hybrid between VIP1 and VIP2. The design was changed to a SIP design and used a 20 mm VIP with lower thermal conductivity. Additionally, the square VIP shape minimized the perimeter and would lower the thermal bridge at the VIP edge. The thermal performance met the target, and there was spacing for fastening.

| Table 2 Effective Thermal Resistance Results |
|---------------------------------------------|
| VIP1 | VIP2 | VIP3 | VIP4 | VIP5 |
| Guarded Hot Box (m²K/W) | -- | 8.90 | 5.20 | 5.20 | -- |
| THERM (m²K/W) | 6.04 | 8.50 | 5.45 | 5.45 | 7.03 |
| % Difference | -- | 4% | 1% | 1% | -- |
4. Hygrothermal Evaluation

The hygrothermal evaluation was performed through a numerical study using WUFI Pro and WUFI 2D [6] models. The objective is to ensure that the wetting and drying mechanisms in the proposed wall assemblies were balanced over 3 years and the assemblies did not present a moisture-related risk. WUFI Pro was used to simulate the 1D heat air and moisture (HAM) flows through the proposed wall assemblies. The relative humidity and temperature at the sheathing were compared between the two simulation types.

4.1. Material Properties

The material properties were selected from WUFI’s Generic North American Materials data for the simulations, including the material properties for VIPs. The wall assembly was composed using the same materials and thickness as Figure 2, except the OSB sheathing was divided into 3 layers to refine the numerical grid along with the sensitive layers. Otherwise, the numerical grid in the remaining materials was generated by the software under a “Fine” grid setting.

4.2. Initial Conditions, Moisture Load, Air Exchange

The simulation inputs that the most impact on the hygrothermal calculations are the building orientation, initial moisture conditions, the moisture sources in the assembly, and air leakage in the assembly [7]. A North building orientation was selected since the orientation would not receive any solar exposure as the cities in question lie in the Northern hemisphere and would have the least amount of drying potential. The moisture modelling guideline suggested an initial relative humidity of 80% and 20°C and was used in this study because it was thought to be a high end of expected conditions.

Moisture sources were placed interior to the cladding acting as the moisture shedding layer and behind the weather-resistant barrier. These sources accounted for rain penetrating the assembly and were 1% and 0.1% of hourly rainfall, respectively. Instead of inserting every airflow that would exist in the assembly, a simplification was made. Two air changes were inserted to represent air infiltration and exfiltration at the sheathing surface. These sources were 5 mm air gaps and 10 ACH connected to the boundary conditions.

4.3. Simulation Boundary Conditions

The boundary conditions used followed the guidelines provided by the inputs. The interior temperature and relative humidity were set as annual sine curves. The conditions were set as 21°C±1°C and 50%±10% RH over the annum. The day of peak temperature and relative humidity was set to June 3rd and August 16th, respectively. The ASHRAE Year 1 Ottawa, CA weather files were selected for the outdoor boundary condition. The file is the most severe weather concerning moisture over ten years and yields overly conservative results when simulated over many years. The 2D simulations utilized the same boundary conditions, air and moisture sources, and material properties as the previous simulations.

4.4. Simulation Period

The simulation period was based on the model reaching a repeatable annual result. This would ensure that the initial conditions are no longer a factor in the calculated RH and temperature, and the calculated conditions are only varying due to the boundary conditions. The simulations were run over 3 years, simulation, two years longer than the modelling guideline suggested because it was found that in some cases the results were not repeated annually. The 2D simulation period was 1 year.

4.5. Grid, Convergence, and Errors

The simulations were numerically successful when the number of convergence errors is 0, and the total water content between the interior and exterior boundaries was in balance. If the simulation results were outside of those bounds, the numerical grid was revised, and the simulation was run again.

4.6. Monitoring Positions

After the 1D simulations were computed, and convergence criteria were met, the interior and exterior nodes of the OSB sheathing were analyzed. The transient temperature and relative humidity from the nodes were
analyzed. The proposed wall assemblies would experience 2D HAM flow in practice, WUFI 2D was used to verify the accuracy of simplification using WUFI Pro. The same materials were monitored in the 2D assembly.

5. Comparison of Assemblies

WUFI Pro simulations were carried out for a wall insulated with EPS, XPS, a CIP with VIPs, and SIP with VIPs. The simulations were simplified to a one-dimensional cross-section to assess the weakest point in the assembly from a moisture perspective. The WUFI library was used for the material properties, including the VIPs. The only alteration was the VIP thermal conductivity was adjusted to reflect the VIPs used in the study. The relative humidity, vapour pressure difference, and moisture content for the inside and outside surface of the OSB sheathing were plotted in Figure 4 and Figure 5 respectively.

![Figure 4](image-url)

**Figure 4** Hygrothermal data of the inner sheathing surface for various exterior insulations.

The relative humidity and moisture content results showed that the inner surface of the OSB would be most susceptible to mould growth. Additionally, the EPS or XPS presented a higher risk for mould growth considering the calculated moisture content and vapour pressure plotted in Figure 5 were higher than the same metrics for the VIP insulated sheathing. The vapour pressure difference between the two OSB surfaces (positive value indicates vapour pressure differential towards the exterior) showed that the panel drying towards the exterior during most of the year. However, since in practice these effects would be occurring in two or three dimensions, a WUFI 2D model was created to determine whether a 1D simplification was acceptable.
The mould index of each wall design was calculated using the relative humidity and temperature at the OSB from the WUFI Pro models. The predicted intensity of mould growth was calculated for both surfaces of the OSB using the mathematic-empirical models developed by Viitanen and Ojanen [8]. The surfaces were not exposed to conditions that would offer mould growth potential. As such, the peak mould index was 0 for all the surfaces and the wall assemblies passed the final design criteria.
The 2D model showed a variation in relative humidity along with the sheathing, plotted in Figure 6. This gradient was largest during the heating season and was nearly nonexistent during the cooling season. The comparison between the WUFI Pro and WUFI 2D hygrothermal models showed that over that after the initial moisture was redistributed, there was very little difference between the relative humidity at the sheathing. The gradient in relative humidity can be explained by the warmer temperature based on the lower conductivity of the exterior insulation. A deeper investigation of the impact of the initial conditions is needed but the annual wetting and drying from the exterior climate provided similar results from both models. Given that a WUFI 2D model required hours to complete the simulation compared to minutes for an assembly in WUFI Pro, a WUFI Pro model could be suitable for evaluating the wall assemblies.

6. Conclusions
In conclusion, it was apparent that building CIP and SIPs with embedded VIPs could be used to create safe, insulated wall assemblies. The effective R-value for a variety of VIP sizes and thicknesses was found to be greater than R 5.2 m²K/W, which would be above a code-built assembly today. And with sufficient care and attention to construction details, a 50 mm CIP or SIP could exceed R 7.0 m²K/W on a woodframed assembly with insulated cavities.

The hygrothermal results from WUFI Pro and WUFI 2D modelling showed promising results for long-term resilience. The VIPs offered high thermal resistance per unit thickness and the sheathing insulated with VIPs had lower moisture contents and relative humidity compared to the sections insulated by EPS or XPS.

Future work for this project would be incorporating the VIP5 panel into in-situ testing, as well as determining how to handle penetrations through the assembly. The VIP5 panel was found to be the optimum for heat and moisture performance since it used square VIPs for limiting thermal bridging around the VIP itself and used the SIP to improve the panel rigidity for easier handling on-site. Also, the long-term thermal conductivity of the VIPs is currently a question, and accelerated ageing of the panels used for this work is underway to determine their lifetime thermal conductivity.

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