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Hygrothermal Analysis of a Vapour-Open Assembly with Vacuum Insulation Panels

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ABSTRACT
The following paper studies the year-long moisture conditions associated with vacuum insulation as the exterior insulation. The exterior insulation of one assembly was renovated by using 50.8 mm (2 inch) of expanded polystyrene (EPS) and represents the baseline performance of current common practice. Another assembly was built with 20 mm (0.7 inch) vacuum insulation panels encased in the equivalent thickness of EPS to represent a high RSI-value retrofit. The thermal performance was evaluated using a guarded hot box facility at Carleton University and the in-situ Building Envelope Test Hut at CanmetENERGY-Ottawa. The temperature, humidity and moisture content in the sheathing measurements from February 2017 to March 2018 are presented. Experimental results were compared to failure criteria outlined by ASHRAE Standard 160 to determine if the proposed building envelope system would be suitable in a cold, humid climate.

KEYWORDS
Vacuum Insulation Panel, Retrofit, Building Envelope, Hygrothermal, Experimental

INTRODUCTION

In Canada, it is estimated that a single dwelling built before 1980 consumes 25% more space conditioning energy than a dwelling built after 2010 according to the National Energy Use Database (NRCan-OEE, 2016). Considering the disparity in energy consumption between vintages, and that there are 4.5 million dwellings in Canada (Statistics Canada, 2016) built before 1984, there is a significant amount of energy that can be saved by further insulating or improving the energy performance of these existing dwellings. Since space conditioning accounts for the majority of the energy consumption in a residential building, addressing the energy flow through the envelope of the building (e.g., conduction, air leakage) may provide significant benefits. A properly sealed and well insulated envelope, which older homes often lack, can reduce the energy transfer between the conditioned space and ambient environment.

Approximately 60% of existing residential buildings in Canada were constructed before 1984 (Statistics Canada, 2016). Since some of these buildings may be poorly insulated, and/or lacking airtightness and consequently represent a large portion of the energy usage of the residential building stock, that stock is a perfect candidate for retrofit. While these buildings may need upgrades to their envelopes, simply increasing the amount of insulation on the exterior face of the envelope may not be the best practice. Instead, it may be beneficial to use high performance (e.g., high resistance) materials, such as vacuum insulation panels (VIPs), to maintain or limit the increase of wall assembly thickness. While thermal improvements are a main driver of retrofitting the building envelope, the hygrothermal aspects of the wall assembly impact its lifespan and durability.

The paper outlines the investigation of using high performance exterior insulation on two wall assemblies to address the moisture requirements and thermal performance of a building envelope while maintaining the thickness compared to standard constructions.

WALL ASSEMBLIES

Since the desired wall assembly construction is thin profiled as well as thermally and hygrothermally sufficient for a cold and humid climate, a composite insulation panel using VIPs and Type 2 expanded polystyrene (EPS) as rigid exterior insulation board was proposed. The VIPs were surrounded by the EPS such that the RSI-value of the assembly was higher than an equivalent thickness of EPS. This configuration also mitigates the risk of punctured VIPs during installation, which was a concept previously investigated (Conley, et al., 2016; Carver, et al., 2017).

Construction

Two wall assemblies used for this study were developed to represent types of construction that could impact Canadian construction. As previously stated, retrofitting the existing building stock that is currently built below the current minimum insulation levels is an area that could provide a large change in national energy consumption. The first wall assembly under investigation was a 2x4 wood stud assembly with 600 mm spacing, filled with RSI-3.3 insulation without any interior vapour barriers and has undergone an exterior retrofit. The exterior retrofit involved removing all materials to the exterior of the sheathing, applying an air barrier, adding the VIP-EPS insulation panel, adding 1x3 strapping and finishing with siding (see Figure 1). The second wall assembly represented a typical new construction in Ottawa, Canada. The wall was construction with 2x6 wood studs with 600 mm spacing filled with insulation, internal vapour barrier, 40 mm of rigid insulation, an exterior air barrier and vinyl siding (similar to Figure 1). For the high performance assembly, the VIP-EPS insulation panel was used as 40 mm of rigid insulation. Both of the wall assemblies described are attempts at creating a durable, robust and high performing assembly that can be utilized in Canadian climates and must be evaluated for their applicability to the climate.

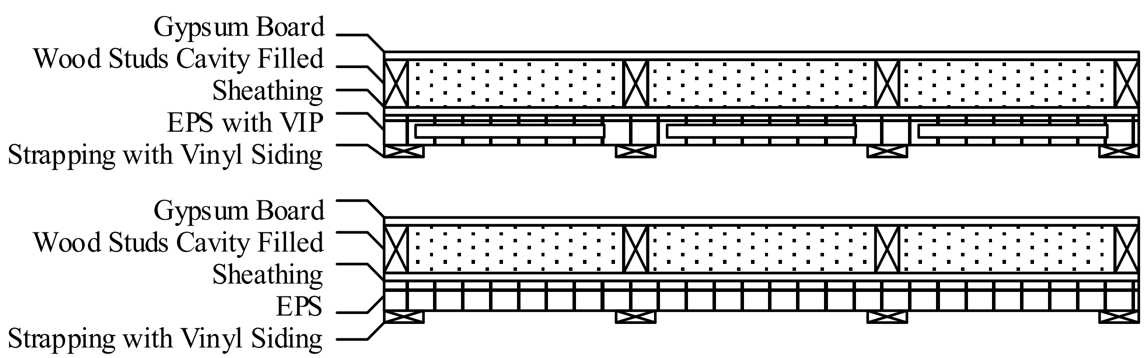

Figure 1: Cross section illustrating materials used for the wall assemblies in the study

Failure Criteria

For the wall assembly design to be considered a success, the thermal and hygrothermal goals must be met, in totality and in comparison to the baseline assemblies. These criteria were developed from standards such as ASHRAE 160 or voluntary building performance standards. The hygrothermal performance of the wall assembly is an indicator of its resilience to the wetting, and its drying potential. The following criteria is applicable for materials at temperatures between 5°C and 40°C:

1. Maintain the 30-day running average relative humidity at the sheathing below 80%;
2. Maintain the 5-day running average relative humidity at the sheathing below 98%;
3. Maintain the daily average relative humidity at the sheathing below 100%; and
4. Maintain a moisture content below 28% to eliminate the risk of mould and rot.

When the material is at a temperature below 5°C, most deterioration at high humidity levels is non-existent, while condensation and bulk wetting could still be an issue. The relative humidity set-points were developed by ASHRAE (ANSI/ASHRAE, 2016) as guidelines to minimize the risk associated with organic growth within the building envelope assembly. The moisture content of wood limits are based on studies that assessed the robustness or durability of wall assemblies and is related to the surface relative humidity.

THERMAL PERFORMANCE

The steady-state testing was performed using a guarded hot-box situated at Carleton University with the purpose of determining an accurate RSI-value of the proposed wall assemblies. The guarded hot-box, depicted schematically in Figure 2, is composed of three independently controlled chambers to force one-dimensional heat flow through the wall assembly specimen. The climate chamber is set to simulate the exterior temperature conditions (approximately -20°C) while the metering and guarded chambers have the same set-point, slightly above room temperature around 25°C, thus creating a substantial temperature difference across the specimen.

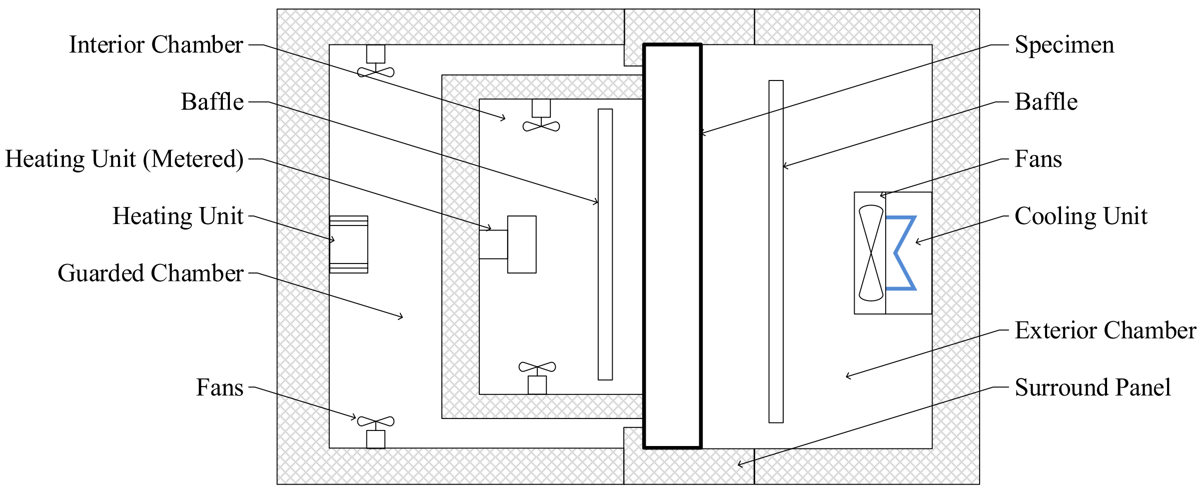

Figure 2: Schematic of the guarded hot-box at Carleton University

The electric heaters installed within the metering chamber are the only source of energy input to the area, and are therefore accurately monitored for the duration of the test period. Additionally, the interior and exterior surface temperatures are measured during the test period to find the effective RSI-value of the wall assembly through Equation (1), where ΔT is the temperature difference between surfaces in °C, A is the known area of the metering chamber in m^2, t is the test period in seconds, and E is the energy input to the metering chamber in J.

$$RSI = \frac{\Delta T \cdot A \cdot t}{E} \tag{1}$$

The effective RSI-value of the wall assembly can be calculated from the measured data after steady-state is reached. Defined by ASTM C-1363, these test conditions are met when five consecutive test periods:

- The average specimen surface temperature in either chamber did not vary by more than ±0.25°C.
- The average energy input to the metering chamber did not vary by more than ± 1%.

For this study, the wall assemblies were evaluated in the guarded hot-box and results were compiled into Table 1. The assemblies that were tested performed below the failure criteria previously described, however, the baseline values were improved by increasing the RSI-value by 31% and 21% for new construction and retrofit construction, respectively. It should be noted that the nominal values provided for the baseline assemblies do not incorporate thermal bridges from the vertical framing members, and constitute a highest permissible value, while the values calculated from the guarded hot-box experiments are the effective RSI-values, which would be a lowest possible RSI-value.

Table 1: Summary of steady-state effective RSI-value from guarded hot-box testing

Assembly	New Construction (m^2K/W)	Retrofit (m^2K/W)
Baseline	4.8 (nominal)	4.2 (nominal)
High Performance	6.3 (effective)	5.1 (effective)

HYGROTHERMAL PERFORMANCE

The hygrothermal assessment of the wall assemblies were conducted at the CanmetENERGY Building Envelope Test Hut (CE-BETH) in Ottawa, Canada. The test facility monitors the moisture and thermal conditions of wall assemblies by controlling the interior conditions and exposing the exterior to ambient conditions for a prolonged period of time. Instrumentation is placed within each specimen to monitor the moisture content, relative humidity, temperature and heat flux at various interfaces and materials within the assembly. The measured values were compared to failure criteria and the durability of the assembly was assess for the climate. Measurements were taken at 5 minute intervals and averaged over the hour to reduce the number of data points and have a better comparison for weather data. The instrumentation points are shown in Figure 3, which are identical for the new construction and retrofit wall assemblies.

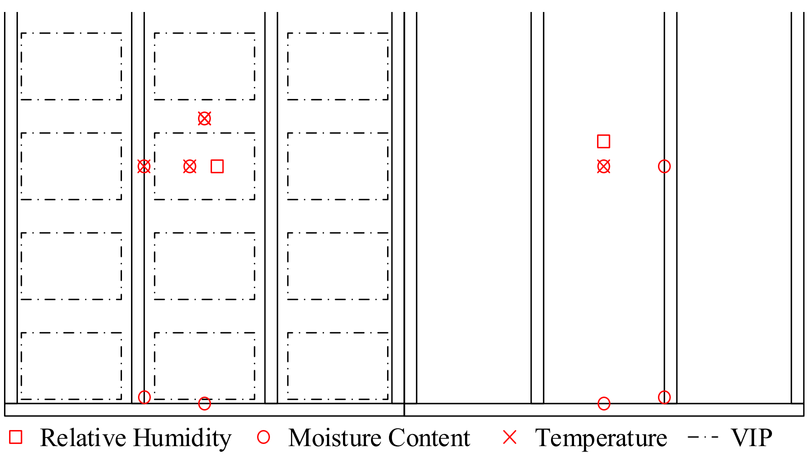

Figure 3: Plan view of instrumentation placed at the sheathing of bottom half of the assemblies

The durability of the wall assemblies were monitored from February 2017 to February 2018, however they were installed at the test facility beginning in December 2016. Therefore, the assemblies were exposed to a heating seasons worth of moisture loads prior to when the data acquisition began. During installation, various sensors were place on the sheathing surface and vertical framing members to assess the moisture content, temperature and relative humidity of the materials.

The interior conditions of the facility have different set-points for the heating and cooling seasons. During the heating season, the facility maintains an indoor air temperature of 24°C and a relative humidity between 35% and 40%. During the cooling season, the indoor air temperature is maintained at 20°C but the relative humidity may reach up to 70%. The lack of dehumidification in the space aligns with ASHRAE 160 interior design humidity for daily average outdoor temperatures 20°C or greater, which is experienced in Ottawa. For the one year test period, the interior temperature and relative humidity of CE-BETH is presented in Figure 4.Note that there were control and power issues during the monitoring program that caused dips in temperature and relative humidity.

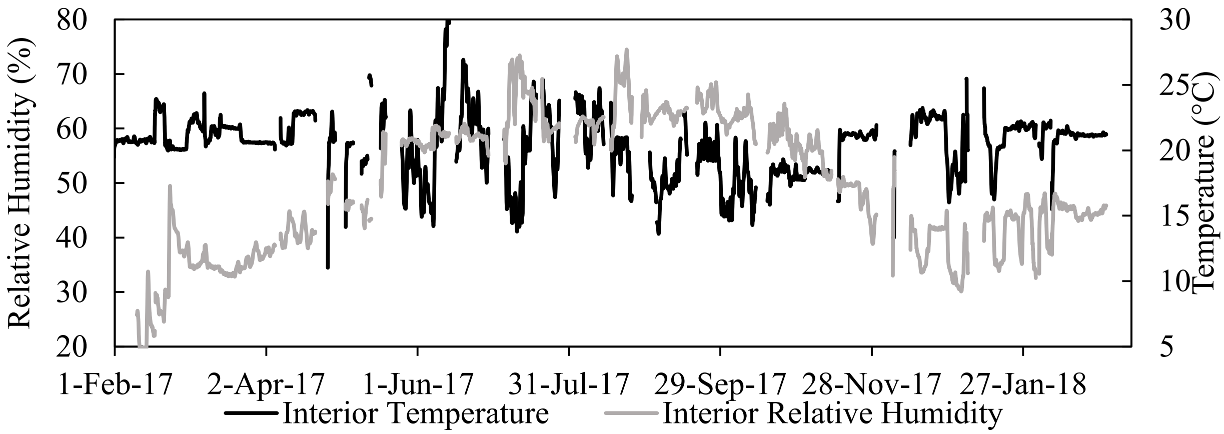

Figure 4: CE-BETH interior conditions for the February 2017 through February 2018

During the test period, the moisture content in the sheathing and vertical framing members were measured through resistance based instruments. In Figure 5, the moisture content of four locations in the high performance assembly designed for new constructions were plotted for the duration of the test period. The VIP and EPS labels are moisture content pins in the sheathing aligned to the labelled material outboard. The temperature of the sheathing aligned with a VIP is plotted to show the temperature dependence of the moisture content. The moisture contents in the assembly did not exceed 20%, except for a brief period in November and December, where the temperature decreased rapidly.

The findings suggests that the building envelope would pass the hygrothermal failure criteria outline, however, the assemblies would need to undergo further observation to ensure that the increasing trend of moisture content does not continue over time. An acceptable level of drying potential is shown for the 2017 annum, but with 2018 data, conclusive determinations can be made about the assembly and its feasibility in the environment.

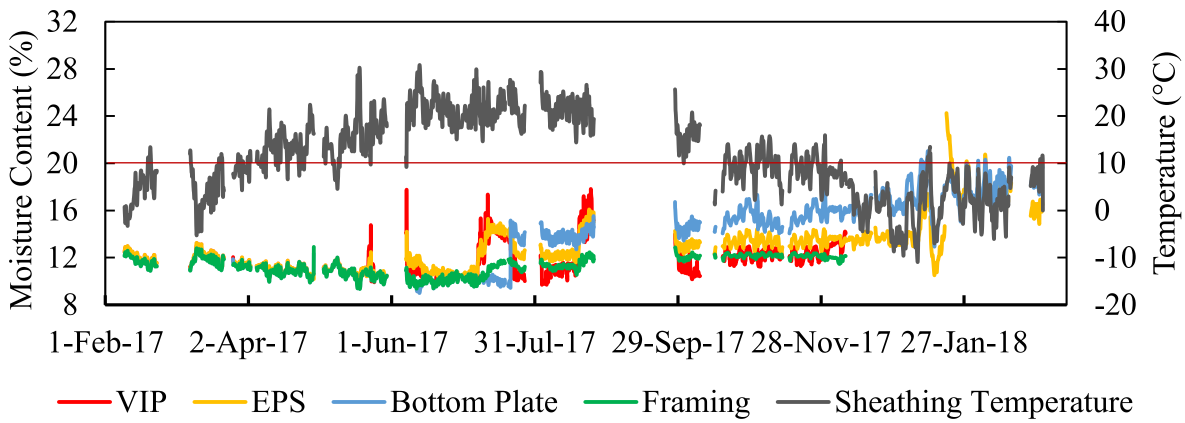

Figure 5: Monitored moisture content within the new construction wall assembly

CONCLUSION

In conclusion, two wall assemblies with VIPs were evaluated under steady-state and in-situ conditions in Ottawa, Canada. The thermal performance of the proposed assembly increased the thermal resistance by up to 32% compared to the baseline assembly. The hygrothermal parameters of the assemblies were and continue to be monitored and measured. After the first year of data collected, the wall assemblies passed the failure criteria outlined, however, it remains too early to make conclusive determinations about the durability and robustness of the wall assemblies in this climate.

The hygrothermal measurements continue to be logged, while the computer simulations will be used to verify the results from CE-BETH. After the in-situ study in Ottawa is completed and simulations are compared to the experimental data, the wall assemblies will be compared to other climates across Canada to ensure they are sufficiently robust and durable. Afterwards, hygrothermal simulations will be used to determine the sensitivity of the proposed assembly to parameters such as, interior relative humidity, sun exposure and varying weather files.

ACKNOWLEDGEMENTS

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