Risk of Condensation and Mould Growth in Wood-Frame Wall Systems with Different Exterior Insulations[1]

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Abstract

The National Research Council of Canada (NRC) has undertaken a research project to investigate the risk of condensation and mould growth in 2x6 wood-frame wall assemblies associated with increasing the thermal resistance (R-value) of cavity insulation for various scenarios of exterior insulation products. The project was requested by the Task Group (TG) on Properties and Position of Materials in the Building Envelope, acting on behalf of the Standing Committee on Housing and Small Buildings (SCHSB). The work originated from a Code Change Request "CCR-802" in which it was suggested that the Water Vapour Permeance (WVP) limit be raised from 60 to 300 ng/(Pa•s•m²) while leaving the limit for air leakage of building envelope materials unchanged at 0.1 L/(s•m²) at a pressure difference of 75 Pa. In response to the CCR-802, NRC undertook a research study by conducting hygrothermal modelling using hygIRC-C model. The risk of condensation and mould growth in wall assemblies with wall cavity insulation of R-19 and R-24, and with and without exterior insulation of wide ranges of R-value (4, 5 and 6 ft^2•h•^oF/BTU) and WVP (2 – 1800 ng/(Pa•s•m²)). The parametric study did not include values of WVP specific to product brands; rather, it included the values for WVP of most products currently available. This research project has led to a code change in Section 9.25 of the 2015 National Building Code of Canada (NBCC).

This paper focused on wall assemblies with stud cavity insulation of R-19, and with and without exterior insulation of R-4 and a range of WVP of 2 – 300 ng/(Pa•s•m²). The results of the hygrothermal performance was expressed using the mould index criteria, which allowed sufficient resolution to assess the risk of moisture condensation and related risk of mould growth in the wall assemblies. Also, the respective mould index criteria were selected so that those cases where assemblies comply with information provided in Table 9.25.5.2. of the 2010 NBCC would fall into an acceptable performance. The results showed that adding exterior insulation of different WVP has resulted in lower risk of condensation and mould growth than the reference wall systems (i.e. without exterior insulation). The risk of condensation and mould growth in wall assemblies with cavity insulation of R-24, and with and without exterior insulation of wide ranges of R-value and WVP will be published at a later date.

Introduction

A brief review of literature is provided on the moisture performance of the building envelope of housing and small buildings in cold climates [1-12]. Ojanen and Kumaran [1] studied the effect of over-pressurization of residential houses on the moisture performance of the building envelope for both uniform and non-uniform airflow through wall assemblies. A related question was whether a 10 Pa over-pressurization limit was acceptable for homes located across Canada. The results showed that the amount of moisture accumulation depends on the rate of exfiltration of the climatic conditions. As well, the results showed that the uniform airflow condition through the walls produced an earlier onset of wetting and faster drying than the non-uniform airflow condition (i.e. entry at interior and top of wall, exit at base of wall). The non-uniform airflow condition, however, presented more risk of moisture related damage to wall components than the uniform airflow condition. The modelling study that was

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carried out by Karagiozis and Kumaran [2] focused on moisture content of components and total moisture accumulation in walls of six different vapour retarders incorporated in a typical Canadian residential wall within three Canadian cities. No airflow was considered in that study. It was concluded that vapour control of the building envelope was important for buildings located in cold climates and in general, moisture accumulates in the wall during the heating season but dries out in the summer.

The study by Ojanen and Kumaran [3] looked at the effect of adding exterior insulation to the sheathing or using sheathing with an increased thermal resistance. In that study, the moisture accumulation due to different air leakage paths was examined as well as the effect of varying indoor relative humidity (RH) on the hygrothermal performance. The results of the simulation showed that increasing the temperature of the interior surface of the sheathing significantly reduced the amount of moisture accumulation and this in turn lead to higher tolerances for indoor RH and air leakage within the wall assembly. The study reported by Kumaran and Haysom [4] provided the basis for placement of low permeance materials within building envelopes in cold climates. The key assumption in that study was that diffuse air leakage occurred across the assembly up to the allowable code limit of 0.1 $L/(s \bullet m^2)$. Another study by Kumaran and Haysom [5] showed that by adding 25 mm of mineral fiberboard sheathing on the outside of the studs, the stud cavity was warm enough to prevent condensation on the interior face and water accumulation was reduced.

Chown and Mukhopadhyaya [6] provided a brief history of the development of air and vapour barrier provisions in the National Building Code of Canada (NBCC) since the first NBCC was published in 1941 to the most recent changes made in 2005 [13-15]. The key change in 1990 NBCC [13] was to separate the functions of air barrier and vapour retarder thus allowing for the possibility of placing low permeance materials exterior to the main thermal resistance of the wall. This change raised the possibility that someone using a low-permeance material as an air-barrier might choose to place it close to the outer surface of the wall where condensation could form on its interior face. To reduce the probability of incorrect placement, the 1990 NBCC [13] included a restriction on the location of low-permeance air barriers. These air barriers had to be placed so that the inner surface remained above the dew point of the interior air when the outside temperature was 10°C above the January design temperature. Also, that study [6] further refined the basis for placement of low-permeance materials for mild and humid climates where the expectation is that indoor RH would likely exceed 34%.

Straube [7] investigated the role of vapor barriers on hygrothermal performance with the aid of simple and transparent diffusion calculations supported by measurements from full-scale natural exposure monitoring. That study explored the phenomenon of summertime condensation, the drying of roofs and walls, and multiple vapor barrier layers as well as the importance of assessing both the interior and exterior climate. The results showed that the addition of insulated sheathing increased the temperature of the back of the sheathing and this reduced the frequency and severity of condensation due to air leakage. It was recommended that the preconceptions of many building codes, standards, and designers need to be modified to acknowledge the facts of low-permeance vapor barriers [7].

A design protocol for the application of insulating sheathing to low-rise buildings with high interior relative humidity (maximum 60%) for different locations across Canada was developed in a study by Brown et al. [8]. That study consisted of conducting parametric study using a HAM model to determine the hygrothermal performance of walls with a range of thermal insulation, air tightness and vapour permeance. For the air leakage investigated in that study, the results showed that moisture that accumulated during the heating season dried out in the non-heating season. The authors suggested that further investigations are required in order to set a threshold air leakage so as to minimize the risk of condensation. Roppel et al. [9] have undertaken modelling exercise to simulate uncontrolled indoor humidity of residential buildings. A moisture balance method was developed to estimate the indoor humidity in buildings which is an important input to the hygrothermal models.

Maref et al. [10-12] conducted a research field study at the NRC's Field Exposure of Walls Facility (FEWF) that focused on the hygrothermal and energy performance of retrofitted wall systems with added exterior insulations of different air and vapour permeance. For the purpose of comparison, a reference wall with no exterior insulation (i.e. non-retrofitted wall system) was tested. The objective was to assess the winter and summer condensation (i.e. inward moisture) within these wall systems. Results showed that the addition of an exterior insulating sheathing raised the temperatures of the stud cavity materials and maintained them above the dew point temperature of the interior air, thus reducing the likelihood and duration of interstitial condensation, within limits, but condensation can still take place during the coldest period of winter. Also, the wall systems with exterior insulation were less prone to interstitial condensation than similar wall without such exterior thermal insulation.

The objective of this paper is to use hygIRC-C model to investigate the risk of condensation and mould growth in 2x6 wood-frame wall assemblies with and without exterior insulation when these walls are subjected to different climatic conditions of Canada. This paper focuses on the case of stud cavity with R-19 insulation, an exterior insulation of R-4, and a range of water vapour permeance (WVP) of 2 – 300 ng/(Pa•s•m^2).

Numerical Simulation Model – hygIRC-C

The NRC's hygrothermal model, hygIRC-C, was used in this study to predict the risk of condensation and mould growth in wall assemblies with and without structural sheathing when these walls are subjected to different air leakage rates and different Canadian climatic conditions. This model has been validated and used in a number of projects to assess the thermal and hygrothermal performance of different components of building envelopes (roofing, wall and fenestration systems). It is important to emphasize that the predictions by such a model for the airflow, temperature, and moisture distributions within a wall assembly, when subjected to a pressure difference across the assembly (i.e. air leakage), are necessary to accurately determine the mould index in materials contained in the wall assembly.

The hygIRC-C model simultaneously solves the highly nonlinear two-dimensional and three-dimensional Heat, Air and Moisture (HAM) equations in building components. The HAM equations were discretized using the Finite Element Method (FEM). The model has been extensively benchmarked in a number of other projects and has been used in several related studies to assess the thermal and hygrothermal performance of wall and roofing systems.

In a previous project entitled "Wall Energy Rating, WER", the three-dimensional version of the model was used to conduct numerical simulations for different full-scale 2x6 wood-frame wall assemblies incorporating, or not, penetrations representative of a window installation, such that the effective thermal resistance (R-value) of the assemblies could be predicted, taking into consideration air leakage across the assembly. The stud cavity of these walls incorporated open cell spray polyurethane foam, closed cell spray polyurethane foam or glass fibre insulation. The predicted R-values for these walls were in good agreement (within ± 5% [17]) with the measured R-values that were obtained from testing in the NRC's Guarded Hot Box (GHB) according to the ASTM C-1363 test method [33].

The model was also benchmarked against GHB test results according to the ASTM C-1363 test method [33] and heat flow meter according to the ASTM C-518 test method [34], and then used to conduct numerical simulations to investigate the effect of foil emissivity on the effective thermal resistance of different wall systems with foil bonded to different types of thermal insulations placed in furred-airspace assemblies, in which the foil was adjacent to the airspace [19, 21-25]. The accurate calculations of the airflow and temperature distributions within the test specimens resulted in that the predictions of the model for the R-values were in good agreements with the measured R-values (within the uncertainties of the experimental data, see [21, 23-25] for more details). Furthermore, the model was used to determine the reductions in the R-values of specimens as a result of increasing the foil emissivity due to water vapour condensation and/or dust accumulation on the surface of the foil.

In a number of previous studies by Saber [27-31], the model was used to conduct numerical simulations to predict the airflow and temperature distributions as well as the R-values of vertical, horizontal and inclined enclosed airspaces, subjected to different directions of heat flow. The predicted R-values were compared with the R-values for enclosed airspaces of different thicknesses and operating conditions as provided in the ASHRAE handbook of fundamentals [35]. In those studies the dependence of the R-value on a wide range of the airspace aspect ratio (i.e. ratio of the length or height of the airspace to its thickness) of the enclosed airspace was also investigated. Additionally, practical correlations were developed for determining the R-values of enclosed airspaces of different thicknesses, and for a wide range of values for various parameters, namely, aspect ratio, temperature difference, average temperature, and emissivity of the different surfaces of the airspaces [27-31]. These correlations are ready to be implemented in energy simulations models such as Energy Plus, ESP-r and DOE.

Also, the model was benchmarked and thereafter used to assess the effect of thermal mass on the thermal performance of Insulated Concrete Form (ICF) wall systems when placed in NRC-Construction's Field Exposure of Walls Facility (FEWF) and subjected to yearly periods of local Canadian climate [20]. Results showed that the predictions of the model for the temperature and heat flux distributions within the ICF wall systems were in good agreements with the test data. As well, the model was benchmarked against field data obtained in the NRC's FEWF of highly insulated residential wood-frame construction in which Vacuum Insulation Panels (VIPs) were used as the primary insulation components; the results from this work showed that the model predictions were in good agreement with the test data [32].

More recently, the hygIRC-C model was benchmarked against test results of a number of samples of Exterior Insulation and Finishing Systems (EIFS) [36]. The test results were obtained using the NRC's Guarded-Hot-Plate (GHP) apparatus in accordance of the ASTM C-177 test method [37]. The accurate calculations of the airflow and temperature distribution within the test specimens had resulted that the model predictions for the R-values of different samples were in good agreements with the test results (within ±5%). Thereafter, the model was used to investigate the effect of air leakage due to infiltration and exfiltration on the effective R-values of different EIFS assemblies, subjected to different climatic conditions. The results of that study will be published at a later date. The studies above focused on predicting the thermal performance of different types of walls; however, no account was made for moisture transport across the wall assemblies.

In instances where the model has been used to account for moisture transport across wall assemblies, the model predicted the drying rate of a number of wall assemblies subjected to different outdoor and indoor boundary conditions [18] in which there was a significant vapor drive across the wall assemblies. The model predictions were in good agreement with the experimental measurements of the drying and drying rate of the assembly with respect to the shape of the drying curve and the length of time predicted for drying. Additionally, the predicted average moisture content of the different wall assemblies over the test periods were in good agreement, all being within ±5% of those measured experimentally [18].

With respect to the prediction of the hygrothermal performance of roofing systems, the present model was used to investigate the moisture accumulation and energy performance of reflective (white coloured) and non-reflective (black coloured) roofing systems that were subjected to different climatic conditions of North America [26]. The results of these studies showed that the climatic conditions of St John's and Saskatoon resulted in a high risk of long-term moisture accumulation in the white roofing systems. In case of climatic conditions in which white roofing systems have no risk of moisture accumulation, however, the results of those studies provided the amount of energy saving due to using white roofing systems compared to using black roofing systems [26].

In a recent study to investigate the risk of condensation in wood-frame wall assemblies that is similar to this study, the model was benchmarked against field data of three highly insulated residential 2x6 wood-frame constructions with fibrous cavity insulation of R-24 when placed in NRC's FEWF. The three wall systems have different types of exterior insulations, namely: (a) of EPS of 1 inch thick, (b) 2 inch XPS of 2 inch thick, and (c) rock wool insulation of 3 inch thick. The results showed that the model predictions were in good agreement with the test data. The results of that study will be published at a later date.

Having previously benchmarked the hygIRC-C model to several tests undertaken in field and controlled laboratory conditions, this model was used with confidence in this study to investigate the risk of condensation and mould growth in different wall assemblies with and without structural sheathing when these walls were subjected different Canadian climatic conditions. The description of the wall assemblies and simulation parameters are provided next.

Simulation Conditions and Parameters

This section briefly provides the different simulation conditions and parameters that were used to conduct the numerical simulations for different wall assemblies with and without structural sheathing shown, respectively, in Figure 1 and Figure 2. The full details about the rationale for the selection of the simulation conditions and parameters are available in [39]. The different wall configurations have nominal insulation in the stud cavity (referred to as inboard insulation) of either R-19 or R-24, as well as for each of the exterior insulation (referred to as outboard insulation) conditions that may vary from R-0 or R-0.62, depending on whether the wall incorporates a structural sheathing, to values of R-4, R-5, and R-6. The list of wall assemblies with structural sheathing is given in Table 1 and that without structural sheathing is given in Table 2. These tables provide information as regards the ranges of R-value and WVP of the outboard insulation of different wall configurations incorporating or not, structural sheathing. As indicated earlier, this paper focuses only on wall assemblies with cavity insulation of R-19, and with and without exterior insulation of R-4 and a range of WVP of 2 – 300 ng/(Pa•s•m²).

Vapour Barrier Conditions

As provided in Subsection 9.25.4 of the NBCC [16], the current maximum allowable WVP value for vapour barriers is 60 ng/(Pa•s•m²). While it is recognized that there are product choices with much lower values of WVP, the selection of materials having this value for WVP for this parametric study is expected to maximize inward and outward vapour drive.

Air Leakage Conditions

All cases were modeled with some air flow introduced through openings into the assembly, as this is a likely scenario given the imperfections of the air barrier system of wall assemblies. Additionally, completing the investigation without considering the effects of air leakage would not create useful results in terms of assessing the risk to the formation of condensation in wall assemblies given that air leakage of indoor air to the wall assembly (i.e. exfiltration) is the primary cause for the formation of condensation in the assembly itself (for example, see the experimental study by Maref et al. [10-12]).

The modeling assumed that the path for air movement is initiated at the interior and is introduced at the bottom of the wall and thereafter moisture is deposited along the interior face of the sheathing panel and exits through the top of the wall. This air leakage path, shown in Figure 1 and Figure 2, was one of the scenarios used in the study by Ojanen and Kumaran [38] in which it was assumed that air would move through imperfections that existed at the wall top plate and the joint between the interior face of the exterior sheathing and the exterior of the top plate.

The air leakage rate for all cases of different climatic conditions was set to 0.1 L/(s•m²) at 75 Pa, which was an assumption used in at least one previous study (see e.g. [38]). The impact of this assumption on the hygrothermal performance was investigated in a sensitivity analysis, by modeling a wall assembly with different air leakage rates from which would be derived the least performing and most vulnerable wall assembly with respect to the formation of condensation and the risk to the formation of mould within the assembly. As will be indicated later, the results of that sensitivity study supported the selection of 0.1 L/(s•m²) at 75 Pa as a means of challenging the wall system with a large amount of moisture ingress.

In the present study, the air leakage rate (Q) as a function of the total pressure difference across the wall assemblies (ΔP_{tot}) is given as:

$$Q = \xi \left(a \, \Delta P_{tot}^{n} \right) \tag{1}$$

Where, the coefficient '*a*' and exponent '*n*' in Eq. (1) are listed in Table 3. The multiplication factor 'ξ' in Eq. (1) allowed applying different air leakage rates at 75 Pa. For example, $\xi = 0.0$ and 1.0 for the cases of the air leakage rate of 0.0 and 0.1 L/(s•m²), respectively. The full details of the approach to simulation of air leakage in different wall assemblies are available in [39]. As provided in [39], the higher the exfiltration rate is the greater the risk of condensation and subsequent mould growth. For each climatic location, the weather data of different climatic conditions was analyzed to identify the orientation of the wall assembly yielding the highest exfiltration rate. In this study, all numerical simulations were conducted for the wall assemblies of the third storey of low-rise buildings that face the direction yielding highest exfiltration rate and which is assumed represents the worst case scenario (see [39] for more details).

Outdoor Conditions

The different wall assemblies were subjected to different climate conditions of four different locations across Canada and having differing values of Heating Degree Days (HDD18) and Moisture Index (MI), namely:

- Vancouver, BC (mild, wet, HDD18 = from 2600 to 3100, MI = 1.44),
- St John's, NL (cold, wet, HDD18 = 4800, MI = 1.41),
- Ottawa, ON (cold, dry, HDD18 = 4440 - 4500, MI = 0.84), and
- Edmonton, AB (cold, dry, HDD18 = 5120, MI = 0.48).

Walls were assumed to be shaded to minimize the impact of solar-driven moisture ingress into the assembly and to minimize the solar drying effect on the wall. However, diffuse radiation was taken into consideration.

Indoor Conditions

Regarding to the indoor moisture load, the Task Group (TG) on Low Permeance Materials proposed that the water vapour pressure difference across the wall assembly (from indoor to outdoor) correspond to a moisture load of 5.2 g/m³, which is consistent with previous studies, in which a moisture load of 7.1 L/day was chosen for a one storey, floor area of 80 m², with indoor temperature of 21°C, water vapour pressure difference close to 700 Pa, and 0.3 ACH by mechanical ventilation. In this case, $\Delta P_v = P_{v,indoor} - P_{v,outdoor} = 700$ Pa. Because the condition of $\Delta P_v = 700$ Pa could result in a quite high relative humidity (RH_{ind}), which at times exceeded 100%, the TG on Low Permeance Materials recommended using this condition but the value of RH_{ind} was capped at 70% (see [39] for more details). Regarding to the indoor temperature, cooling was to be used when the interior temperature reached 25°C to minimize summer condensation scenarios; such scenarios have not been fully addressed in the building envelope requirements of Part 9 of the NBCC 2010 [16]. Other indoor conditions were set according to that provided in the ASHRAE Standard 160 [40] with respect to recommendations for conditioned space.

Simulation Period

Hygrothermal simulations were conducted for a period of two years where the first year corresponded to an average year (conditioning year, where equal drying and wetting potential exists (MI)) and the second year corresponded to a wet year. The weather data of the different locations were obtained from the NRC's weather database.

Material Properties

The hygrothermal properties of all material layers were obtained from the NRC's material database. However, the hygrothermal simulations were conducted using constant R-value and constant Water Vapour Permeance (WVP) for the exterior insulation as provided in Table 1 and Table 2. The thickness of the exterior insulation for the different values R-value and WVP were taken as 1 inch. These values may not correspond with existing building products currently available on the market, but are instead selected to develop the necessary data in the region of interest (high inboard R-value, low outboard R-value, and medium permeance) from which to discern any trends as regards to the potential for the formation of condensation in the wall assembly.

A sheathing panel made of OSB 7/16 inch (11 mm) thick was considered for all wall assemblies with structural sheathing that are listed in Table 1. Glass [41] compiled the available data for the WVP of OSB (11 mm thick) and the recommended values of WVP of OSB as a function of relative humidity that were used in the numerical simulations are shown in Figure 3. A summary of simulated parameters and conditions that were used in the numerical modeling for all wall assemblies is provided in Table 3.

Acceptable Performance

The modeling results for each case were expressed using the mould index (M) criteria developed by Hukka and Viitanen [42], Viitanen and Ojanen [43], and Ojanen et al. [44]. The selected mould index criteria allowed sufficient resolution to assess the risk of moisture condensation in those cases where the modeled assembly currently does not have to comply with the information provided in Table 9.25.5.2 of the NBCC 2010 [16] or where the modeled assembly does not comply, but the requirements apply. The descriptions of the mould index levels are provided in Table 4 [42-44].

The most recent mould model by Ojanen et al. [44] was used in this study to determine the mould index of different materials of the wall assemblies shown in Figure 1 and Figure 2. In that model [44], the sensitivity of different construction materials for mould growth was classified in four sensitivity classes, namely: very sensitive, sensitive, medium resistant and resistant (see Table 5). Table 6 provides the assumed correspondence of sensitivity class for materials located within the wall assembly modelled in this study. More specifically, the sensitivity class for the top and bottom plates, OSB layer and foam layer was considered "Sensitive", whereas the sensitivity class of the materials for cavity insulation (fiber-based), drywall and membranes was considered "Medium Resistant".

Approach for Assessing the Overall Performance

The simulation results derived for different wall assemblies, subjected to different climatic conditions are presented on basis of a simple form using the following two parameters:

- Overall average mould index at different locations in the wall at which mould may grow. The list of these locations is provided Table 9 of the reference [39] for walls with and without structural sheathing.
- Overall maximum mould index at different locations in the wall at which mould may grow.

The two parameters above were determined based on a simulation period of two years, i.e., simulation of the average year followed by a wet year for the location of interest. The overall average mould index is the average value obtained from the average mould index at all locations within the assembly [39]. Whereas the overall maximum mould index is given by the average value of the maximum mould index values at all locations within the assembly [39].

Results and Discussion

In this section, the influences of different parameters that affect the hygrothermal performance of wall assemblies are discussed. The list of wall assemblies with structural sheathing is provided in Table 1 and the list of wall assemblies without structural sheathing is provided in Table 2. In this study, in instances where the units for the WVP and R-value are not reported, the units for each of these parameters are, respectively, as ng/(Pa•s•m²) and ft^2•h•^{o}F/BTU. The different parameters affecting the hygrothermal performance of wall assemblies are discussed next.

Effect of Air leakage Rate on the Risk of Mould Growth

A parametric study was conducted to investigate the effect of the air leakage rate on the hygrothermal performance of wall assemblies with and without structural sheathing. This parametric study was conducted to investigate the risk of mould growth in a wall assembly and permit identifying within the assembly the locations of likely mould growth given the different air leakage rates to which was subjected. In these analyses, the full amount of the air leakage rate given by Eq. (1) (i.e. ξ = 100%) and different percentages of that value (ξ = 0%, 10%, 25%, 50% and 75%) were considered.

A detailed example of these analyses was given in reference [39] for a wall assembly with structural sheathing, Wall 104, as shown in Figure 4. The contour shown in Figure 4b is a snapshot for the relative humidity within the different layers of the wall assembly when subjected to the climate of Ottawa over a period of two years and for the case of ξ = 100% (i.e. full amount of air leakage rate). Figure 4b shows the locations within the wall assembly at risk for the formation of condensation; these are predicted to occur at the top portion and bottom portion of the wall assembly in proximity to the exit and entry points for the air leakage through the wall assembly.

A series of figures illustrating the variation in average value of relative humidity of specific sections of Wall 104 as a function of air leakage rate when subjected to a period of two years of Ottawa climate are provided in reference [39] which included the average RH profiles at different locations within the wall assembly, namely: (a) entire OSB layer, (b) 45 cm high portion at the bottom of the OSB layer, (c) interface between OSB and fibre-based cavity insulation, (d) 45 cm high at the bottom portion of OSB – fibre interface, (e) entire bottom plate, (f) interface between top plate and fibre-based cavity insulation, (g) interface between OSB and exterior insulation, and (h) 45 cm high at the bottom portion of the OSB – exterior insulation interface. At these locations, the results showed that at air leakage rates of 75% and 100% of 0.1 L/(s•m²) at 75 Pa there was a risk for mould growth in the wall assembly. However, at air leakage rates of 50% or less no risk of mould growth was evident at these locations [39].

After conducting the numerical simulations for all wall assemblies with and without structural sheathing listed in Table 1 and Table 2, the critical locations inside the wall assembly at risk of mould growth were identified. These locations are provided in Table 9 of the reference [39]. At these locations, the Mould Index (M) was calculated for different wall assemblies on the basis of the mould sensitivity classes of the different materials layers within the wall assembly as provided in Table 6. It is important to point out that the locations within the wall assemblies at risk of condensation and mould growth (see [39]) are based on the air leakage path that is considered in this study and shown in Figure 1 and Figure 2. Considering a different air leakage path, however, would result in different locations within the wall assemblies at risk of condensation and mould growth.

Another example showing the effect of air leakage rate on the hygrothermal performance is provided for the Wall 104 with structural sheathing (cavity insulation of R-19 and exterior insulation of R-4 and WVP = 60, see Table 1) but when this wall is subjected to the climate of Edmonton, which is the coldest climate (HDD18 = 5120) among the other climates investigated in this study. Figure 5 and Figure 6, respectively, show the overall average mould index (M_{AVG}) and maximum mould index (M_{MAX}) for different percentages of the air leakage rate of ξ = 0% (no air leakage), 10%, 25%, 50%, 75% and 100%. As well, these figures shows M_{AVG} and M_{MAX} of the reference wall (REF1, no exterior insulation) for the case of ξ = 100%. As shown in these figures for ξ = 100%, the values of M_{AVG} and M_{MAX} for the Wall 104 are 42% and 35% lower than that for the reference wall, REF1. For Wall 104, decreasing the air leakage rate resulted in decreasing the risk of condensation and mould growth. For example, the values of M_{AVG} and M_{MAX} for the case of ξ = 50% are 43% and 54% of the values of M_{AVG} and M_{MAX}, respectively, for the case of ξ =

100%. Note that at a pressure difference (ΔP) of 75 Pa, ξ = 50% corresponds to an air leakage of 0.05 L/(s•m²) whereas ξ = 100% corresponds an air leakage rate of 0.1 L/(s•m²). Furthermore, Figure 5 and Figure 6 show that for the case of ξ = 25% or less, the values of the mould index are negligible (i.e. no risk of condensation). As the value of the air leakage rate of 0.1 L/(s•m²) at ΔP = 75 Pa showed a higher risk of condensation, it was used to conduct the numerical simulations for all wall assemblies shown in Table 1 and Table 2 in order to investigate the effect of the R-value and WVP of the exterior insulation on the hygrothermal performance of these wall assemblies (see [39] for more details).

Effect of WVP of the Exterior Insulation on the Risk of Mould Growth

For wall assemblies with structural sheathing, Figure 7 shows comparison of the overall average mould index for the reference wall REF1 and other four walls with exterior insulation of R-4 but with different WVP of 2 (wall 102), 60 (wall 104), 90 (wall 106), and 300 (wall 207) when these walls were subjected to the climatic conditions of Edmonton. The exterior insulation of R-4 helped to maintain the wall cavity warmer than the case of no exterior insulation, as would be expected. As such, the overall average mould index in the walls 102, 104, 106 and 207 as shown in Figure 7 is lower than that in reference wall REF1 (no exterior insulation).

On a side note, Figure 3 shows that the WVP of the OSB sheathing increases by increasing its Relative Humidity (RH). For example, the WVP of the OSB increases from 4.37 US perm (250 ng/(Pa•s•m²)) to 7.57 US perm (433 ng/(Pa•s•m²)) as its RH increases from 80% to 100%. In addition to the high moisture storage capacity of the OSB compared to other construction materials (e.g. EPS, XPS, fibre), at high RH of the OSB that would cause mould growth (i.e. above 80% [42, 43, 44]), the rate of moisture flux inside the OSB increases as its RH increases. In other words, moisture moves inside the OSB with lower resistance at higher RH levels. In case of adding exterior insulation in the walls 102, 104, 106 and 207, the WVP of this insulation played an insignificant role in moisture transport. As shown in Figure 7, increasing the WVP of the exterior insulation from 2 to 300 resulted in an insignificant change in the mould index.

For wall assemblies without structural sheathing, Figure 8 shows comparisons of the overall average mould index for the reference wall REF3 (foam insulation of R-0.62 and WVP = 60) and other four walls with foam insulation of R-4 but with different WVP of 2 (wall 101), 60 (wall 103), 90 (wall 105), and 300 (wall 201) when these walls were subjected to the climatic conditions of Edmonton. As shown in this figure, for the same value of WVP of the foam insulation (WVP = 60 for walls REF3 and 103), the foam insulation of R-4 resulted in lower mould index than that in the reference wall REF3 (foam insulation of R-0.62) due to warmer wall cavity in the former than in the latter. Furthermore, for the same R-value of the foam insulation (i.e. R-4), Figure 8 shows that the foam with higher WVP resulted in lower mould index. For example, the overall average mould index decreases by 15% as the foam WVP increases from 2 (Wall 101) to 300 (Wall 201).

For the same R-value and WVP of the exterior insulation, the overall average mould index of a wall with structural sheathing (Figure 7) is lower than that for a wall without structural sheathing (Figure 8). A series of figures to compare the mould index during the simulation period (2 years) at different locations in wall assemblies (with and without structure sheathing) at which mould may grow is available in [39].

Effect of Geographical Locations on the Risk of Mould Growth

The hygrothermal performance for different wall assemblies with and without structural sheathing (see Table 1 and Table 2) were obtained when these walls were subjected to the climate of four Canadian cities each differing in geographical location and that included: Ottawa (ON), Edmonton (AB), Vancouver (BC) and St. John's (NL). The primary environmental parameters that greatly affect the hygrothermal performance are:

- The outdoor temperature which can be represented by the Heating Degree Days (HDD). The greater the number of HDD the higher the risk for mould growth in a wall assembly. Among other geographical locations, Edmonton has the highest HDD (HDD = 5120), followed by St John's (HDD = 4800).

- The outdoor relative humidity which can be represented by the Moisture Index (MI). The higher the value of MI, the smaller the drying potential of a wall assembly and hence, the higher the risk of mould growth. Among other geographical locations, Vancouver has the highest MI (MI = 1.44), followed by St John's (MI = 1.41).
- The wind speed. The higher the wind speed, the greater the air leakage rate across the wall assembly, and hence, the higher the risk for mould growth within the wall assembly as indicated earlier. Details of the air leakage rates of the different geographical locations are provided in reference [39]. Among other geographical locations, St John's has the highest air leakage rate.

Figure 9 shows comparison of the overall average mould index for walls with structural sheathing when subjected to different climatic conditions. Similar comparison of the overall average mould index for walls without structural sheathing is provided in Figure 10. As shown in these figures, the combined effects of the three environmental parameters, listed above, have brought about, in the case of walls subjected to the climatic conditions of Ottawa, the lowest value of mould index, whereas the highest value of mould index can be found for walls subjected to the climatic conditions of St John's. For example, the overall average mould indexes for the reference wall REF1 (with structural sheathing) are 1.09, 1.89, 2.30 and 2.97 for the climatic conditions of Ottawa, Edmonton, Vancouver and St John's, respectively (Figure 9). For the reference wall REF3 (without structural sheathing), the overall average mould indexes are 1.60, 2.47, 2.72 and 3.42 for the climatic conditions of Ottawa, Edmonton, Vancouver and St John's, respectively (Figure 10). More details about the dependence of the mould index on time during the period of simulation (2 years) at different locations in the wall assemblies with and without structure sheathing and subjected to different climatic conditions are available in [39].

Summary

Numerical simulations were conducted using the hygIRC-C model to investigate the risk of condensation and mould growth of different 2x6 wood-frame wall assemblies with and without structural sheathing, and subjected to different Canadian climatic conditions. This paper focused on wall assemblies with cavity insulation of R-19, and with and without exterior insulation of R-4 and a range of water vapour permeance of 2 – 300 ng/(Pa•s•m²). The modeling results for different wall assemblies were expressed using the mould index criteria. The most recent model by Ojanen et al. [44] was used to determine the expected value of the mould index for different materials within the wall assemblies. The simulation results were presented on the basis of a simple form using the the overall average mould index and the overall maximum mould index. Sensitivity analysis was conducted to investigate the effect of different air leakage rates on the hygrothermal performance of wall assemblies. Based on the air leakage path that was considered in this study, the simulation results showed that the critical locations inside the wall assembly at risk of mould growth are the top and bottom portions of the wall assembly. Considering a different air leakage path, however, could result in different locations within the wall assemblies at risk of condensation and mould growth. The Results showed that decreasing the air leakage rate resulted in lower risk of condensation and mould growth. The values for the overall average mould index of walls configured with structural sheathing are lower than that of walls configured without structural sheathing. St John's appears to have the most severe climate in comparison to the other three locations investigated (Ottawa, Edmonton, and Vancouver); the greatest values of the overall average mould index of the wall configurations amongst the four locations occurred in this location.

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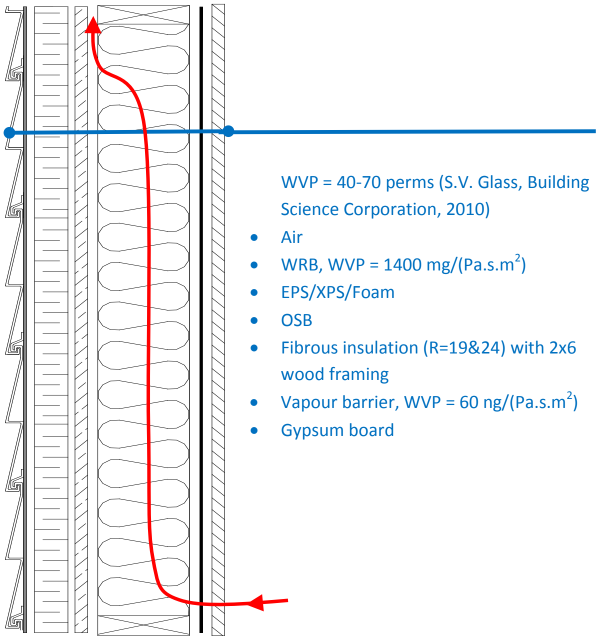


Figure 1. Schematic of wall assembly configuration showing different component layers and assumed path of air flow through assembly; wall assembly includes structural sheathing

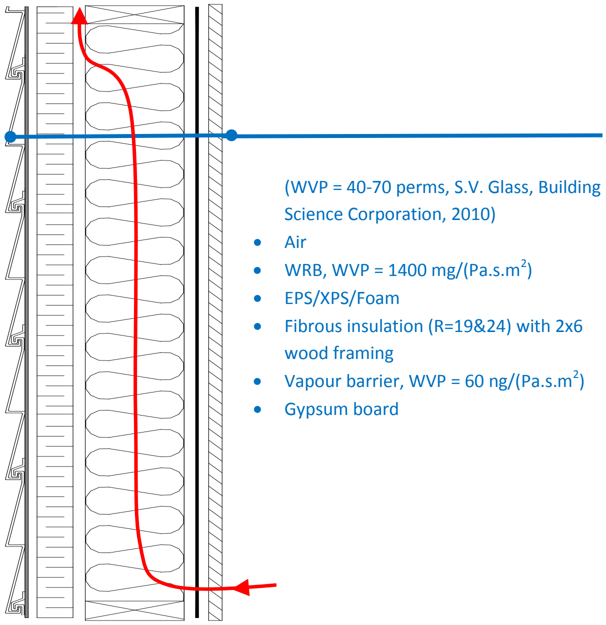


Figure 2. Schematic of wall assembly configuration showing different component layers and assumed path of air flow through assembly; wall assembly does not include structural sheathing

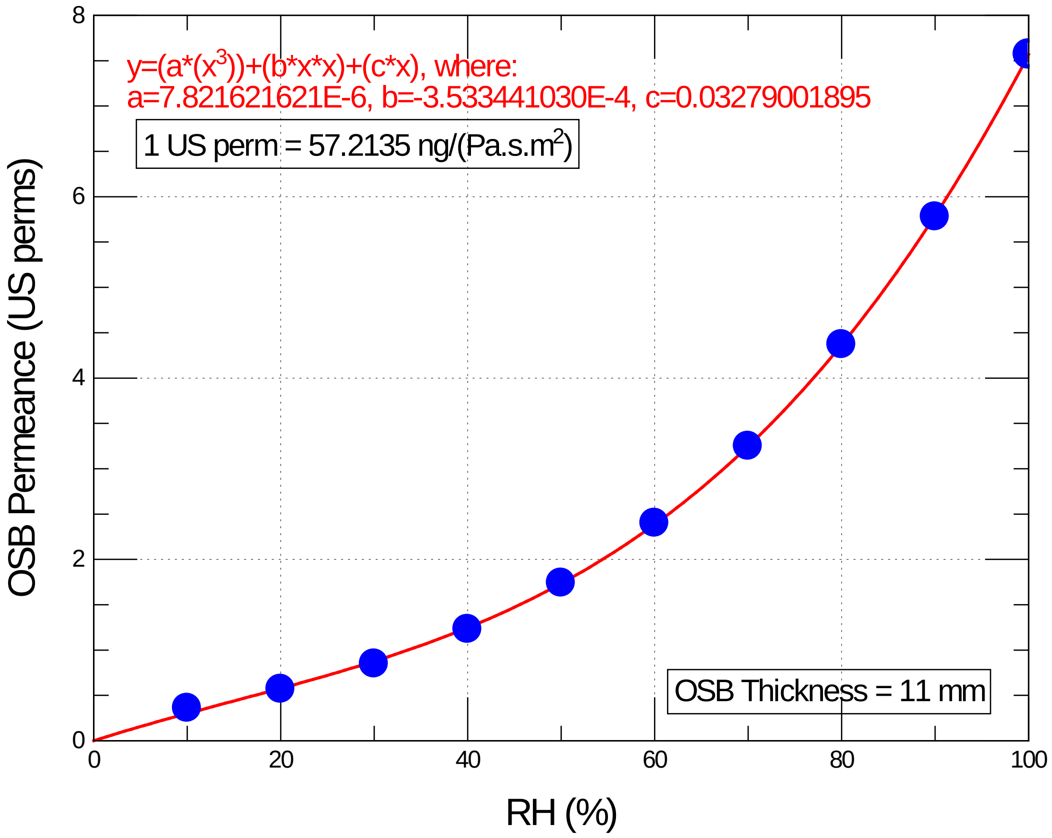
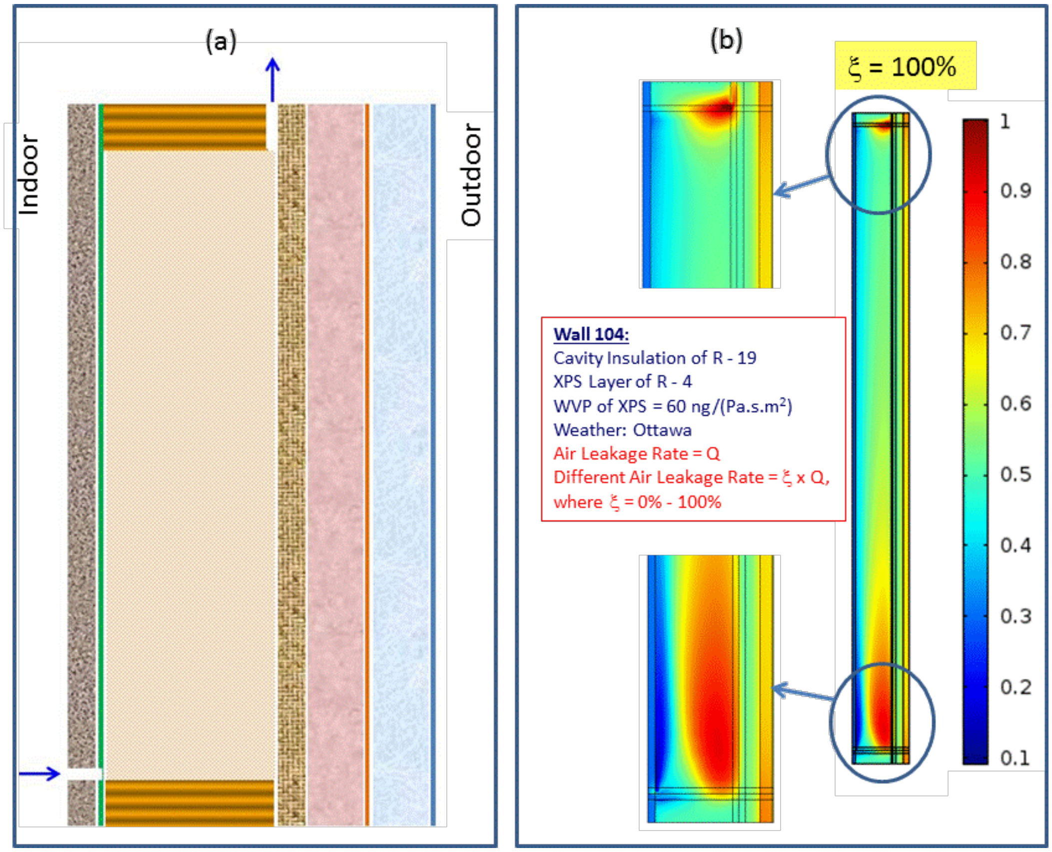


Figure 3. WVP of OSB of 11 mm thick that used in numerical simulations



Wall 104:
Cavity Insulation of R - 19
XPS Layer of R - 4
WVP of XPS = 60 ng/(Pa.s.m^2)
Weather: Ottawa
Air Leakage Rate = Q
Different Air Leakage Rate = ξ x Q,
where ξ = 0% - 100%

Figure 4. Schematic of Wall 104 and contours of the relative humidity showing the locations at high risk of condensation

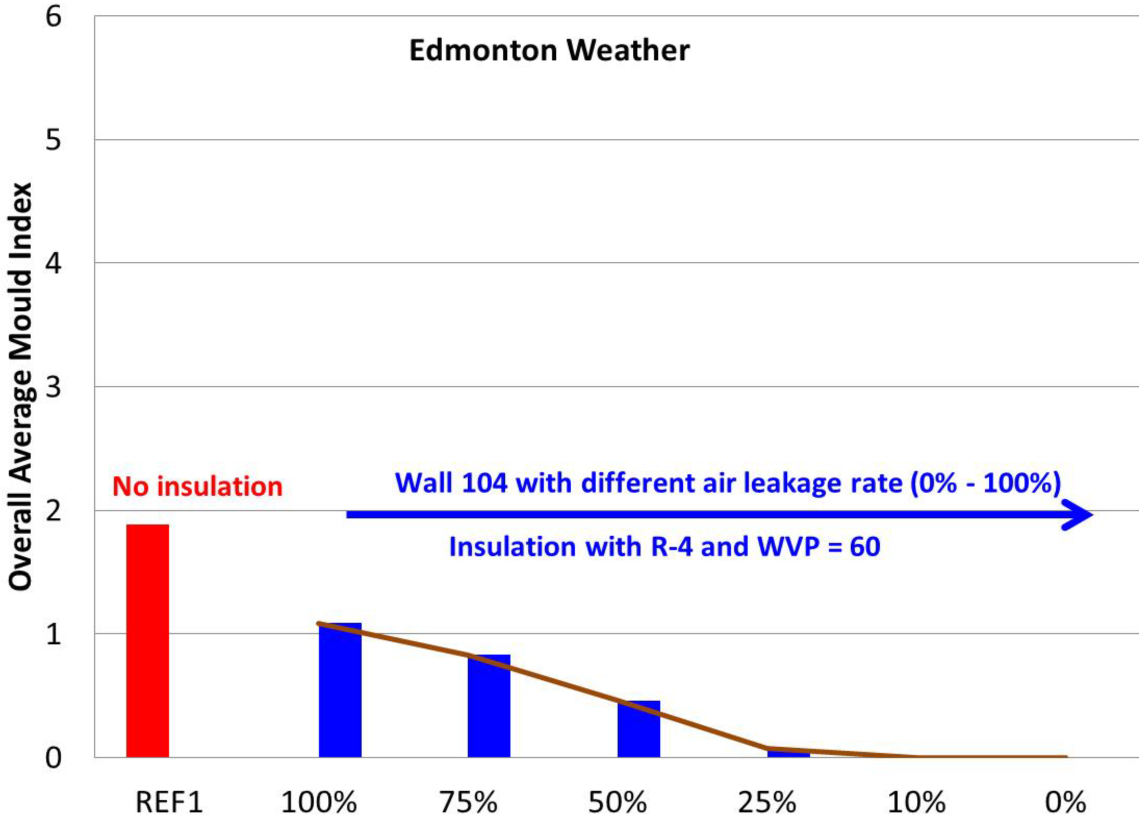


Figure 5. Effect of air leakage rate on the overall average mould index of Wall 104 with structural sheathing

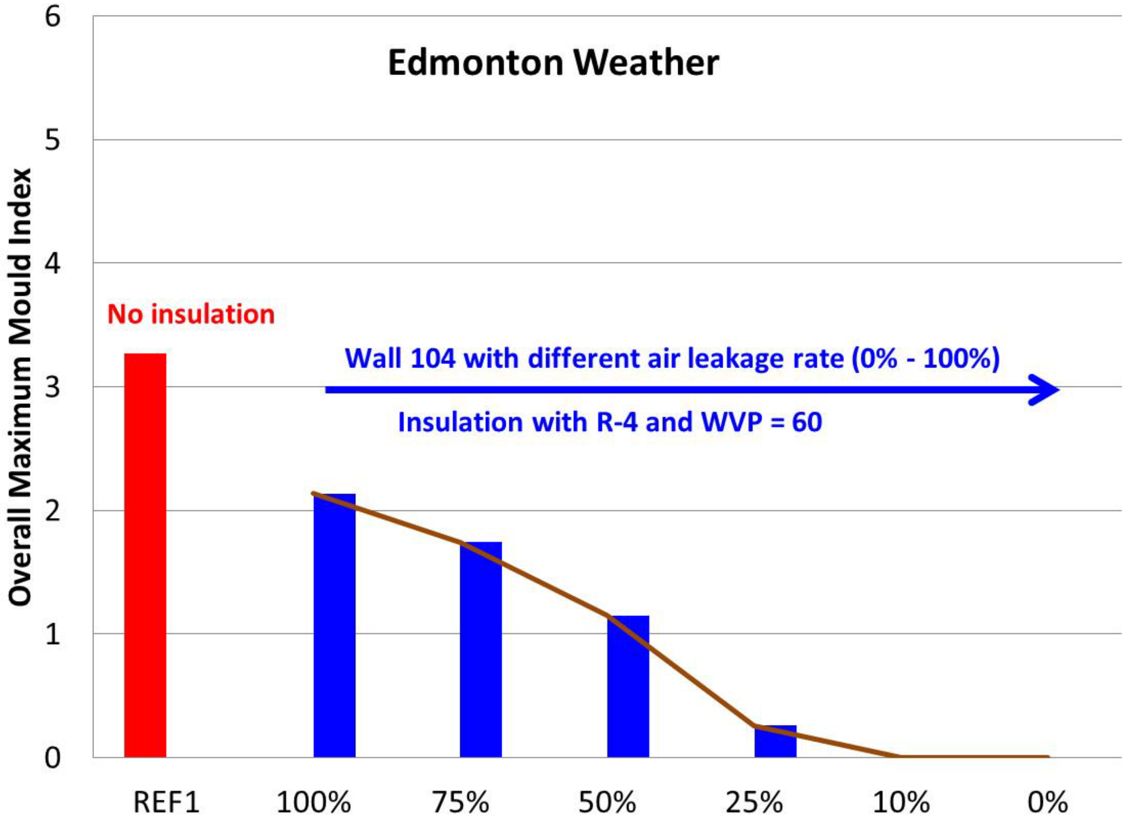


Figure 6. Effect of air leakage rate on the overall maximum mould index of Wall 104 with structural sheathing

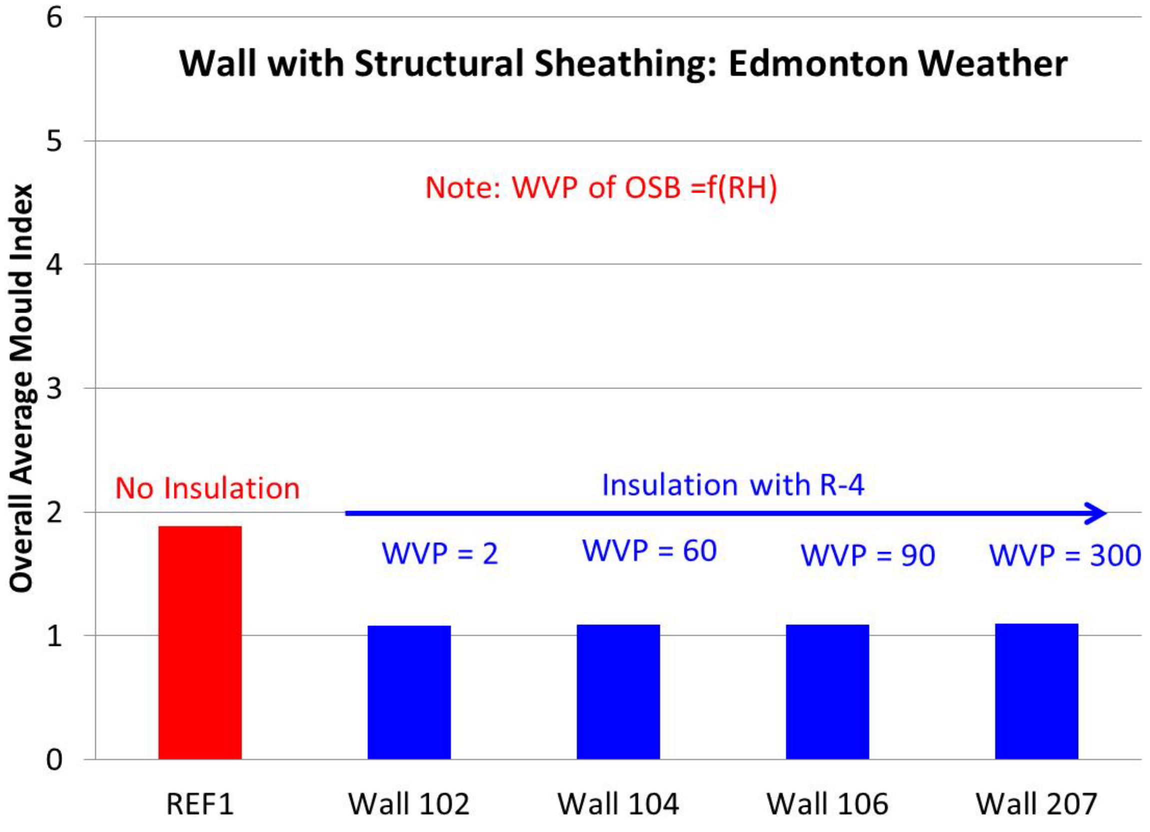


Figure 7. Effect of WVP on the overall average mould index of walls with structural sheathing

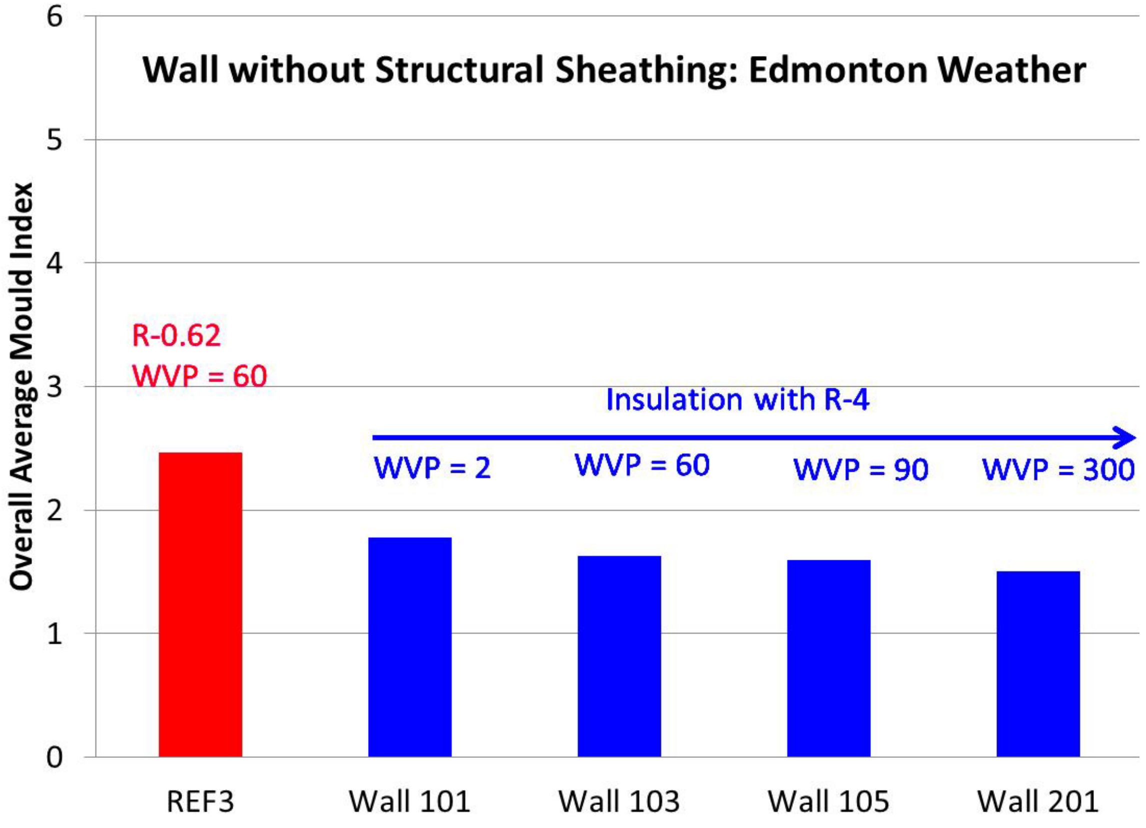


Figure 8. Effect of WVP on the overall average mould index of walls without structural sheathing

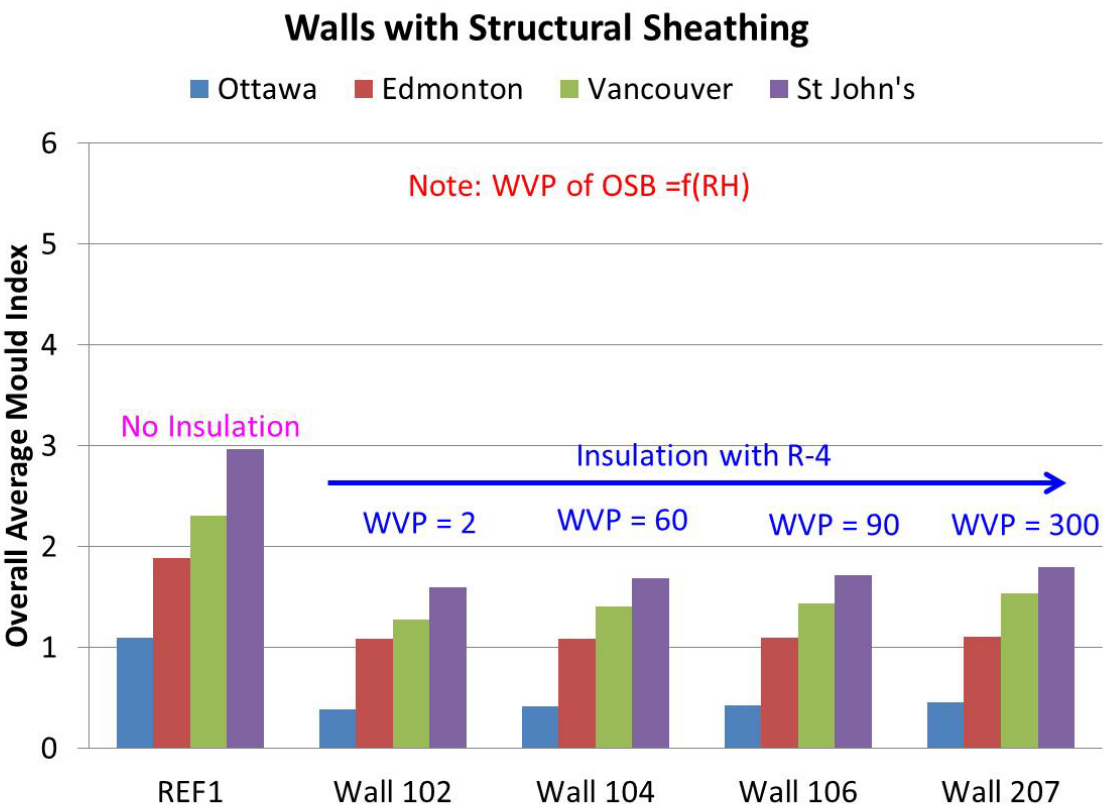


Figure 9. Effect of climatic conditions on the overall average mould index for walls with structural sheathing

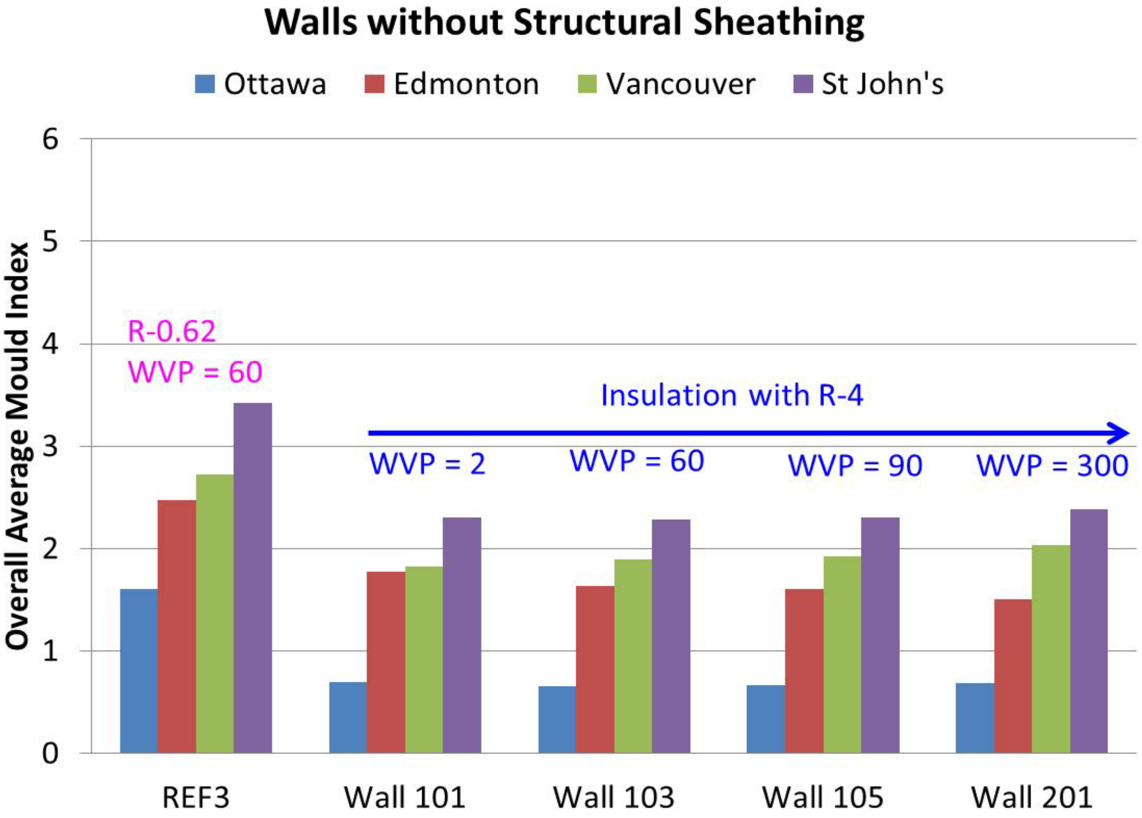


Figure 10. Effect of climatic conditions on the overall average mould index for walls without structural sheathing

Table 1. Wall assemblies with structural sheathing

Walls with Structural Sheathing			
Cavity Insulation		**Exterior Insulation**	
R-19	**R-24**	**R (ft^2.h.^{o}F/BTU)**	**WVP (ng/Pa•s•m^2)**
REF1	**REF2**	**None**	**None**
Wall 102	Wall 120	4	2
Wall 219	Wall 222	4	45
Wall 104	Wall 122	4	60
Wall 106	Wall 124	4	90
Wall 231	Wall 234	4	200
Wall 207	Wall 210	4	300
Wall 243	Wall 246	4	1800
Wall 108	Wall 126	5	2
Wall 220	Wall 223	5	45
Wall 110	Wall 128	5	60
Wall 112	Wall 130	5	90
Wall 232	Wall 235	5	200
Wall 208	Wall 211	5	300
Wall 244	Wall 247	5	1800
Wall 114	Wall 132	6	2
Wall 221	Wall 224	6	45
Wall 116	Wall 134	6	60
Wall 118	Wall 136	6	90
Wall 233	Wall 236	6	200
Wall 209	Wall 212	6	300
Wall 245	Wall 248	6	1800

Table 2. Wall assemblies without structural sheathing

Walls without Structural Sheathing			
Cavity Insulation		**Exterior Insulation**	
R-19	**R-24**	**R (ft^2.h.^{o}F/BTU)**	**WVP (ng/Pa•s•m^2)**
REF3	**REF4**	**0.62$^{\#}$**	**60**
REF3-N1	**REF4-N1**	**0.62$^{\#}$**	**2**
REF3-N2	**REF4-N2**	**0.62$^{\#}$**	**90**
REF3-N3	**REF4-N3**	**0.62$^{\#}$**	**300**
Wall 101	Wall 119	4	2
Wall 213	Wall 216	4	45
Wall 103	Wall 121	4	60
Wall 105	Wall 123	4	90
Wall 225	Wall 228	4	200
Wall 201	Wall 204	4	300
Wall 237	Wall 240	4	1800
Wall 107	Wall 125	5	2
Wall 214	Wall 217	5	45
Wall 109	Wall 127	5	60
Wall 111	Wall 129	5	90
Wall 226	Wall 229	5	200
Wall 202	Wall 205	5	300
Wall 238	Wall 241	5	1800
Wall 113	Wall 131	6	2
Wall 215	Wall 218	6	45
Wall 115	Wall 133	6	60
Wall 117	Wall 135	6	90
Wall 227	Wall 230	6	200
Wall 203	Wall 206	6	300
Wall 239	Wall 242	6	1800

R-value of the exterior insulation of R-0.62 is the same R-value as the OSB layer of 11 mm thick.

Table 3. Summary of simulated parameters and conditions

Criteria	Assumptions/Conditions
Pressure exponent, n, Eq. (1)	0.7 (see [39])
Pressure coefficient, a, Eq. (1)	0.00487 $L/(s \bullet m^2 \bullet Pa^{0.7})$ (see [39])
Predominant wall orientation	Facing the highest exfiltration rate
ΔP for stack effect	Top storey of a 3-storey building to maximize the effect of exfiltration
ΔP for ventilation	Assume depressurization/pressurization from ventilation source is negligible
Air leakage rate	Corresponds to 0.1 $L/(s \bullet m^2)$ at 75 Pa
Interior moisture load	Constant water vapour pressure difference, ΔP_v = 700 Pa and capped at 70% RH
WVP of OSB	Function of the RH ranging from 0-100% as recommended by Glass [41]
Modeling period	Two years – Jan to Dec: one average year followed by one wet year
Geographical locations	Ottawa, Edmonton, Vancouver and St John's

Table 4. Description of mould index (M) levels [42-44]

M	Mould Index (M) Description of Growth Rate
0	No growth
1	Small amounts of mould on surface (microscope), initial stages of local growth
2	Several local mould growth colonies on surface (microscope)
3	Visual findings of mould on surface, < 10% coverage, or < 50% coverage of mould (microscope)
4	Visual findings of mould on surface, 10%–50% coverage, or > 50% coverage of mould (microscope)
5	Plenty of growth on surface, > 50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

Table 5. Mould growth sensitivity classes and some corresponding materials [44]

Sensitivity Class	Materials	RH_{min} (%)#
Very Sensitive	Pine sapwood	80
Sensitive	Glued wooden boards, PUR with paper surface, spruce	80
Medium Resistant	Concrete, aerated and cellular concrete, glass wool, polyester wool	85
Resistant	PUR with polished surface	85

\# Minimum relative humidity needed for mould growth

Table 6. Mould growth sensitivity classes for different materials of wall assemblies shown in Figure 1 and Figure 2

Sensitivity Class	Material Layers of Wall Assemblies	RH_{min} (%)#
Very Sensitive		80
Sensitive	Top plate, bottom plate, OSB, foam	80
Medium Resistant	Fibre, gypsum, membranes	85
Resistant		85

\# Minimum relative humidity needed for mould growth