Sensitivity analysis of hygrothermal performance of wood framed wall assembly under different climatic conditions: the impact of cladding properties

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Abstract. One of the parameters that influences the moisture performance of the wood framed wall assembly is the material properties of exterior cladding. The uncertainties of its properties, would result in a range of wall performance. The objective of this study was to investigate the impact of uncertainties in cladding material properties on moisture performance of wood framed wall assembly under different climatic conditions. A wood framed (2x6 wood stud) wall with exterior brick cladding was simulated assuming 1% rain leakage deposited on the exterior side of sheathing membrane. A parametric study was carried out to analyze the impact of the cladding properties on the moisture response of OSB. The simulations were conducted in five different cities located in different climate zones across Canada. The aim was to identify the most influential cladding property on the moisture response of OSB, i.e., mould growth index and moisture content, to the varying cladding properties under different climatic conditions i.e., different cities under historical and future conditions. In general, it was found that liquid diffusivity is the parameter that has the most influence on moisture response of OSB in all the five cities. Also, the significance of this influence varies depending on the climatic conditions.

1. Introduction

Hygrothermal simulations are widely used nowadays to predict the thermal and moisture performance of building envelopes. These simulations require various inputs such as material properties of the different wall components, climate data, boundary conditions, and initial conditions. For setting up these simulations, it is assumed that all inputs are well known, and they are not affected by any external factor or in other words, these inputs are assumed to have a deterministic value. Further, with deterministic inputs to the simulations, the deterministic outputs are obtained. However, in real world, nothing is deterministic. There is always an uncertainty associated to all the input parameters. With the associated uncertainty in the input parameters, a range of outputs is expected rather than deterministic values.

Given the inherent variability in input parameters, in order to have a more reliable performance assessment, the uncertainties should be taken into consideration. Among all the input parameters, material property must be appropriately addressed in the hygrothermal design of building constructions.
[1]. In common practice, for material property, either estimated values or mean from the experimental observations is taken as the deterministic value for performing the hygrothermal simulations. However, material properties are prone to large variation [2,3]. These uncertainties can occur due to a natural cause, manufacturing process, experimental errors, etc. The impact of uncertainties in material properties on hygrothermal performance has been the object of research in a few studies [1,4]. A study by Salonvaara et al. [1] applied the uncertainty analysis to assess the influence of material properties on the hygrothermal performance of building envelope. They simulated a stucco cladding wood framed wall and found that water content in the OSB varied more than 50% with ±20% variation in stucco properties. Zhao et al. [5] studied the effect of uncertainties in material properties of each individual component and exterior boundary coefficients on the hygrothermal performance of wood framed wall assembly located in Syracuse, New York, USA. They found that the effect of a single input variable on output is not constant but varies with time and the key variables that affect the results are also different over time. Defraeye et al. [6] studied the influence of uncertainties in heat–moisture transport properties, originating due to measurement errors on convective drying of two porous materials i.e., ceramic brick and plaster. They found that drying behaviour of ceramic brick was most sensitive to liquid transport while plaster was most sensitive to both liquid and vapor transport combined liquid and vapour transport parameters.

For most of the previous studies, the impact of variability in material properties on the hygrothermal performance was studied for a single climate conditions, i.e., considering only one city. Moreover, as per authors’ knowledge, none of the previous studies investigated how the variability in material properties may affect the wall performance in the future climate conditions. Hence, the objective of this study is twofold. Firstly, the dominance of one specific cladding property parameter was tested under different climate conditions i.e., cities belonging to different climate zones. The aim was to identify whether the most influential parameter remains consistent under different climatic conditions assuming other variables as constant. Secondly, the effect of climate change was taken into consideration. The extent of variation in hygrothermal performance due to material parameters was studied to answer the question that will the same uncertainty lead to a higher or lower change in performance under projected future climate.

2. Methods

Hygrothermal simulations were performed to assess the effects of cladding’s material properties on the moisture performance of wood-framed wall assemblies. A brick cladding wood framed wall was simulated assuming 1% rain leakage deposited on the exterior side of the sheathing membrane as per ASHRAE 160 [7]. In the following sections, further details and considerations are provided for the various parameters used in the simulations. It includes the detailed description of the geographical data of the cities considered, wall assemblies, material properties, climate data and the boundary and initial conditions. The method used in this paper for performing Heat, Air and Moisture (HAM) simulations is similar to the one used in Aggarwal et al. [8].

2.1. Geographic locations and wall orientation

| City       | Latitude | Longitude | HDD18 | MI | CZ | Annual rain (mm) |
|------------|----------|-----------|-------|----|----|------------------|
| Calgary    | 51.0°    | -114.0°   | 5000  | 0.37| 7A | 325              |
| Ottawa     | 45.2°    | -75.4°    | 4440  | 0.84| 6  | 750              |
| St. John’s | 47.5°    | -52.7°    | 4800  | 1.41| 6  | 1200             |
| Toronto    | 43.6°    | -79.3°    | 3800  | 0.87| 5  | 730              |
| Vancouver  | 49.2°    | -123.1°   | 3100  | 1.93| 4  | 1850             |

HDD: heating degree days below 18°C, MI: moisture Index, CZ: climate zone

For the analysis, five cities were chosen from different provinces of Canada based on moisture index (MI). Location and characteristics of the cities are shown in Table 1. Among the five cities, Vancouver
is the wettest city with a MI of 1.93 and Calgary is the driest city with a MI of 0.37 [9]. The MI of other cities is between these two values.

2.2. Wall configuration

The modeled building was assumed to be a 3.5-storey tall (10 m height) located in a suburban area. Light weight wood framed wall assembly with brick cladding was simulated and the wall was assumed to be perfectly airtight. A detailed description of chosen wall assembly is shown in Figure 1. The material properties were obtained from the NRC hygrothermal material property database [10]. For the air cavity, the same value of Air Changes per Hour (ACH) of 10 was used for each city and climate scenario.

![Figure 1. Description of the wall assembly with brick masonry veneer cladding.](image)

2.3. Climate data and wall orientation

The climate data used for the present study includes hourly values of climate variables, which are necessary to undertake hygrothermal simulations. The procedure for generating these data can be found in Gaur et al. [11]. The data include hourly values for 31 consecutive years: from 1986-2016 for historical period and from 2062-2092 for future period. The data for future period was generated assuming an increase of 3.5° C in global temperature by the end of the century.

15 different realizations (with 31 years in each realization) per time period were available for each city based on different set of initial conditions used for generating the climate data. Among 15 realizations, MI was calculated based on 31 years data for each realization and the one with median MI was selected for each city. Later, the wettest year (among 31 years) based on MI ranking was chosen from the median climate realization. The simulations were run for the orientation receiving highest amount of annual wind-driven rain. Table 2 shows the climatic realization with median MI, the wettest year in that climatic realization, and the corresponding wall orientation (for the wettest year) used for simulations for the cities under consideration.

| City       | Median realization | Wettest year (Historical) | Wall Orientation (Historical) | Wettest year (Future) | Wall Orientation (Future) |
|------------|--------------------|----------------------------|--------------------------------|-----------------------|---------------------------|
| Calgary    | 10                 | 2016                       | 292.5° (WNW)                   | 2063                  | 315° (NW)                 |
| Ottawa     | 10                 | 1991                       | 22.5° (NNE)                    | 2070                  | 67.5° (ENE)               |
| St. John’s | 6                  | 1994                       | 202.5° (SSW)                   | 2069                  | 202.5° (SSW)              |
| Toronto    | 15                 | 1994                       | 202.5° (SSW)                   | 2079                  | 67.5° (ENE)               |
| Vancouver  | 4                  | 1994                       | 157.5° (SSE)                   | 2066                  | 157.5° (SSE)              |
2.4. Boundary conditions
Indoor temperature and relative humidity (RH) were assumed constant with values being 21°C and 50% respectively. As the wall was assumed to be airtight (no air leakage) and with the presence of vapor barrier, varying the indoor RH does not affect the response of the component’s outboard insulation. The indoor exchange coefficient for heat conduction was set to 8 W/m²K and the indoor vapor diffusion coefficient was set to 1.52*10⁻⁸ s/m.

Outdoor convective heat transfer coefficient was calculated as per the EN ISO 6946 standard [12]. The details of parameters used to calculate outdoor boundary conditions are given in Table 3.

| Type                                | Value                |
|-------------------------------------|----------------------|
| Outdoor convective heat transfer coefficient | 4 + 4. v          |
| Outdoor vapor transfer coefficient   | 2.44 * 10⁻⁸ + 2.44 * 10⁻⁸, v |
| Ground shortwave reflection          | 0.1                  |
| Shortwave surface absorption         | 0.6                  |
| Ground longwave emission coefficient | 0.9                  |
| Surface longwave emission coefficient| 0.9                  |

v: wind speed (m/s)

2.5. Simulation tool
In this study, simulations were performed using a well-established hygrothermal modelling software, Delphin 5.9. Material properties, such as liquid diffusivity and vapor permeability, were defined as the function of volumetric moisture content and climate data was entered as individual files for each climate variable. For simulations, each year selected for analysis was repeated three times.

2.6. Initial conditions
The initial conditions for temperature and relative humidity were set, respectively, to 21°C and 80% for all wall components.

2.7. Material property
Material properties under investigation included liquid diffusivity (LD), sorption curve (SC) and vapor permeability (VP). Simulations were performed considering the baseline case along with upper and lower levels for each material property (for brick) for each city i.e., 3 for each material property (9 in total). The properties for the cladding material were varied based on the measurement uncertainties as per Kumaran et al. [10], i.e., a variation of ±50%, ±45% and ±20% from the baseline case was assumed for LD, SC, and VP, respectively (Figure 2). Properties of other layers of the wall assembly are shown in Table 4.

Figure 2. Uncertainty on liquid diffusivity (LD), sorption curve (SC), vapor permeability (VP) of red matt clay brick: 1 and 2 refer to lower and upper limits of the parameter.
Table 4. Material properties of various layer for brick cladding wood frame wall assembly.

| Material                         | Dry density (kg/m³) | Specific heat capacity (J/kgK) | Thermal conductivity (W/mK) | Porosity (m³/m³) |
|---------------------------------|---------------------|-------------------------------|----------------------------|-----------------|
| Brick                           | 1900                | 800                           | 0.5                        | 0.21            |
| Sheathing membrane              | 909                 | 1256                          | 0.15                       | 0.0005          |
| OSB                             | 600                 | 1880                          | 0.09                       | 0.9             |
| Glass fiber batt insulation      | 11.5                | 840                           | 0.04                       | 0.99            |
| Vapor barrier                   | 1256                | 840                           | 0.15                       | 1e-6            |
| Gypsum+Primer+Latex             | 700                 | 870                           | 0.16                       | 0.39            |

2.8. Performance indicators

Two performance indicators i.e., moisture content (MC) and the mould growth index (MoI) were used to assess the moisture performance of the wall assembly. MC was calculated for the entire OSB layer and MoI was calculated at the exterior side of OSB (0.1-mm thick layer). The MoI was computed using the empirical formula proposed by Ojanen et al. [13]. The calculations were made assuming the “sensitive class” for OSB and a decline factor of 0.1 when the conditions become unfavourable for mould growth. Average of MC and MoI (over 3 years) values were used as the two indicators to make the sensitivity analysis.

3. Results and discussion

Figure 3 shows the hourly profiles of MC in the OSB sheathing for the wall under historical period in Calgary. The results are shown for varying level of LD, SC, and VP where “1” and “2” correspond to lower level and upper level of parameter, respectively. It was observed that higher value of LD results in higher value of MC. LD has the highest effect on increasing MC, followed by SC and VP. Similar trends were observed in MC and MoI for all five cities under both historical and future climate scenarios.

![Figure 3. Hourly variation of moisture content (MC) in the OSB layer for three levels of (a) Liquid diffusivity (LD), (b) Sorption curve (SC), and (c) Vapor permeability (VP) for brick cladding under historical climate (His) in Calgary: 1 and 2 refer to lower and upper limits of the parameter.](image_url)

To simplify the comparison of results, average MC and MoI (over 3 years) were calculated to analyse the impact of cladding properties variations. For this, the average for the extremes levels of variations were calculated and a relative increase with respect to lower level was noted (equation 1). Here, “I” can be either MC or MoI.

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Sensitivity\ indicator, SI = \frac{I_{LD2} - I_{LD1}}{I_{LD1}} \tag{1}
\]

E.g., from Figure 3, difference between average MC for LD2 and LD1 (LD2-LD1) was divided by the average MC for LD1 to obtain the relative percentage change in the performance indicator when the
material properties are varied. In general, the property that leads to a higher variation has a significant influence on the performance indicator.

Figure 4(a) and 4(b) shows the relative change in the MC and MoI when varying the material properties under historical climatic condition. It is evident that the liquid diffusivity is the most influential parameter, to the exception of Vancouver. Between the two performance indicators, a higher variation was noted for MoI. It should be noted here that when the MoI was insignificant (0.1 or smaller), the calculation was made assuming 0.1 as MoI to avoid the sudden increase in the % change (because of lower denominator). This assumption is justified by the fact that, when MoI is below a certain level (0.1 in this case), the variation in its value does not indicate significant variation in mould growth performance, for example, MoI of 0.01 would be similar to MoI of 0.09. Further, the effect of varying the VP remained insignificant and it proved to be the cladding property which has the least effect on the hygrothermal performance for all the cities. For Vancouver, it was observed that SC was more significant than LD. This may be explained by the fact that a higher rain and temperature in Vancouver as compared to other cities lead to very humid conditions in the drainage cavity. Further, the RH in drainage cavity for the wall with SC2 brick was around 90% and it was 84% for SC1 brick. The higher humidity in the drainage cavity might explain the high MC and MoI in the OSB.

Figure 4. Percent change in moisture content (MC) and mould growth index (MoI) under historical (His) and future (Fut) periods for variation in liquid diffusivity (LD), sorption curve (SC), and vapor permeability (VP) in the five cities considered.

A similar analysis was made for future climate and the results are shown in Figure 4(c) and 4(d). Similar to the results under the historical climate, the trend remained the same i.e., LD and VP proved to be the most and least influential material property. Moreover, the MoI had a higher change than MC. In terms of cities, it was observed that except Vancouver, the results are consistent for all other four cities. For Vancouver, similar explanation holds true as explained earlier for the results under historical climate. Under future climates, the influence of LD and SC on MoI becomes more significant for Ottawa and Toronto, while less significant for Vancouver, compared to historical climate.

To investigate the impact of the climate change, a comparison was made between the % changes as obtained from historical and future simulation results using the ratio defined in equation 2.

$$\text{Ratio (Fut/His)} = \frac{S_I_{\text{Fut}}}{S_I_{\text{His}}}$$  \hspace{1cm} (2)
A ratio greater than 1 implies that the effect of changing the material properties is more dominating in future. This ratio was computed for both MC and MoI. Since VP does not have a significant impact on the performance, the analysis was limited to only LD and SC.

![Graph showing ratio of percent change in moisture content (MC) and mould growth index (MoI) under future (Fut) and historical (His) climate.](image)

**Figure 5.** Ratio of percent change in (a) moisture content (MC), (b) mould growth index (MoI) under future (Fut) and historical (His) climate for variation in liquid diffusivity (LD) and sorption curve (SC) for five cities.

Figure 5 shows the ratio of % change for future and historical climate. It was observed that for most of the cases, the ratio remained greater than 1, meaning the effect of varying the material properties is higher under future climate. A significant increase was found for Ottawa and Toronto when MoI was used as performance indicator because of higher rain in future. For Calgary, the material properties affect the performance more significantly in historical climate than future as indicated by a ratio lower than 1. For Vancouver and St. John’s, it was observed that the ratio remained close to unity for MoI, meaning that impact under future climate remained more or less the same. As Vancouver and St. John’s are rainy cities and hence the MC and MoI remained significantly high in historical climate and a higher rain in future, could not bring a significant variation in performance indicator values, thus the ratio remained close to unity. For other cities, the values remained lower in historical climate and a significant variation in the results was observed with a more severe climate in future, resulting in a higher future to historical ratio.

4. Conclusion

The hygic properties of brick (liquid diffusivity, sorption curve and vapor permeability) are prone to uncertainties due to multiple reasons. One among these reasons is uncertainties originating due to measurement errors. This uncertainty can be as high as ±50% in the single material property but it might not be the case that all these properties equally impact the wall performance. It was found that the liquid diffusivity and vapor permeability prove to be the most and least influential respectively, when analysing the variation in hygrothermal response of wall due to the uncertainties. A similar trend was observed for 5 Canadian cities with different climatic conditions and two performance indicators (average moisture content and average mould index). Generally speaking, extreme level of liquid diffusivity led to an average moisture content increase around 12% (ranging 5%-24%) and an average mould growth index increase around 32% (ranging 6%-47%) depending on different climatic conditions. Similar values stand at 5% (ranging 0%-14%) for moisture content and 20% (ranging 0%-84%) for mould growth index for extreme levels of sorption curve, while the variation caused by vapor permeability is negligible (around 0.25%). For dry city like Calgary, the effect of measurement uncertainties was not significant (around 10%). The highest variation was observed for cities like Ottawa and Toronto, the variation was found to be around 40% for historical and more than 100% for future climate.

The effect of climate change was also taken into consideration to investigate the extent of change in performance for the given uncertainty in the material properties. With a higher temperature and rain along with the higher uncertainty in projected future climate, the variation in the results under future climate was more significant. This study did not consider the variability in properties of other wall
components, uncertainties in other simulation parameters, and the interaction among different parameters. These will be included in a future study.

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