Identifying the critical orientation of wood-frame walls in assessing moisture risks using hygrothermal simulation

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Abstract. Hygrothermal simulations can be used as a reliable tool in analysing moisture performance. For an efficient analysis, it is important to appropriately select the wall orientation in the simulations. ASHRAE 160 recommends to using orientation with highest amount of annual wind-driven rain (WDR) and the orientation with the least annual solar radiation. The objective of this work was to identify the orientation which leads to the worst moisture performance of different wall assemblies under historical climate in different Canadian cities. Four cardinal orientations (North, East, South, and West) and orientation receiving the highest amount of annual WDR (Default) were tested in this study. The simulations were carried out assuming three scenarios of moisture loads for four different wood-frame (2x6 wood stud) wall systems that differ by their claddings: brick, fibreboard, stucco, and vinyl. With an assumption of no WDR, north facing wall always leads to the worst moisture performance. In the presence of WDR, with and without water source, default orientation leads to the worst moisture performance with few exceptions. As default orientation was based on total sum of WDR, it sometimes may not lead to worst performance and hence hourly distribution of WDR should be taken into consideration.

1. Introduction

The moisture performance of a wall depends on the various wall characteristics i.e., type of cladding, level of insulation, thickness of wall, etc. As well, it further depends on the type of climate to which it is exposed. For instance, a wall could lead to satisfactory performance in one type of climate but the same might not be true for another climate. There are many climate parameters which could impact the response of the wall. Most of these climate variables are independent of the orientation that a wall is facing but a few are directly dependent on the wall orientation. Among these outdoor climate variables, Wind Driven Rain (WDR) is one of the most important and orientation dependent boundary condition which impacts the moisture performance; it is determined by the wind speed, wind direction, rainfall, and wall orientation [1]. Water source (assumed to be a proportion of WDR) depends on the extent of deficiencies in the wall. Solar radiation is also orientation dependent boundary condition. Given the time required for hygrothermal simulations, the common practice is to select and perform the simulations on the orientation that would lead to more conservative results, i.e., leading to the highest moisture problems.

There are various methods available in literature to select the wall orientation for simulations. The most frequent method of choosing the wall orientation is based on the direction which receives the highest amount of WDR [2-6]. It is assumed that the direction receiving the highest WDR is more susceptible to moisture related problems. Zhou et al. [7] suggested using climatic index to select the
wall orientation for performing simulations. Another way of selecting this orientation is based on the orientation receiving least amount of solar radiation, as drying potential will be low and could result in the highest moisture risk. This has been the rationale of choosing the orientation for a few studies [8,9]. The orientation could also be chosen by carrying out simulation over a set of orientations and then selecting the one that leads to the worst moisture performance [10].

Most studies have suggested to use the orientation receiving the highest amount of WDR or least solar radiation for the simulations without considering the climate data, type of cladding, structure of the wall, moisture source, etc. The objective of this work was to verify these assumptions for different wall assemblies under different climates for the scenarios where: (i) WDR and water source are not considered, (ii) only WDR is considered, and (iii) WDR and water source, both are considered.

2. Methods

Hygrothermal simulations were performed to assess the effects of wall orientation on the moisture performance of wood-frame wall assemblies. Four cladding types and eleven Canadian cities were selected for analysis. Three scenarios were simulated: (i) no WDR and no water source, (ii) only WDR, and (iii) both WDR and water source. The water source considered was 1% of wind driven rain applied on the exterior side of the sheathing membrane as per ASHRAE 160 [11]. Simulations were performed for four cardinal orientations (North, East, South and West) and one default orientation (orientation with highest amount of WDR). The method used in this paper for performing Heat, Air and Moisture (HAM) simulations is similar to the one used in Aggarwal et al. [12]. In the following sections further details are provided for the various parameters used in the simulations.

2.1. Geographic locations

For the analysis, eleven cities were chosen from different provinces of Canada. Location and characteristics of the cities considered are shown in Table 1. Among the eleven cities, Vancouver is the wettest city with a moisture index (MI) of 1.93 and Calgary is the driest city with a MI of 0.37. Other cities lie between these two values.

| City       | Latitude | Longitude | HDD18 | MI  | CZ | Annual rain (mm) |
|------------|----------|-----------|-------|-----|----|------------------|
| Calgary    | 51.0°    | -114.0°   | 5000  | 0.37| 7A | 325              |
| Charlottetown | 46.2°   | -63.1°    | 4460  | 1.09| 6  | 900              |
| Halifax    | 44.6°    | -63.5°    | 4000  | 1.49| 6  | 1350             |
| Moncton    | 46.0°    | -64.7°    | 4680  | 1.02| 6  | 850              |
| Montreal   | 45.5°    | -73.5°    | 4200  | 0.93| 6  | 830              |
| Ottawa     | 45.2°    | -75.4°    | 4440  | 0.84| 6  | 750              |
| Saskatoon  | 52.1°    | -106.6°   | 5700  | 0.41| 7A | 265              |
| 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             |
| Winnipeg   | 49.9°    | -97.1°    | 5670  | 0.58| 7A | 415              |

2.2. Weather data and default 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. [13]. Fifteen different runs (each containing 31 years) are available for each city based on different set of initial conditions used for generating the modeled climate data. Among those fifteen runs, the median run based on Moisture Index (MI) was selected for each city. Later, the wettest year based on the MI ranking was chosen from the median run. Table 2 shows the median run, the wettest year, and the corresponding default orientation (for the wettest year) for the cities under consideration.

| City       | Median run, the wettest year, and default orientation for each city. |
2.3. Wall configuration
The modeled building was assumed to be 3.5-storey tall (10-m height) and located in a suburban setting. The wall construction type is a lightweight wood frame wall assembly with four different claddings: brick (90 mm), fibreboard (10.5 mm), stucco (19 mm), and vinyl (1.1 mm). The wall was assumed to be perfectly airtight. Other wall components are:

- Sheathing membrane (30 Minute asphalt impregnated kraft paper, 0.22 mm)
- Exterior grade wood-based sheathing panel (OSB, 11 mm)
- Insulation within vertical stud cavities (glass fibre batt insulation, 140 mm)
- Vapor barrier (polyethylene sheet, 0.15 mm)
- Interior finish (gypsum panel with latex primer and 1 coat of latex paint, 12.7 mm)

A drainage cavity was added for brick and vinyl cladding with a dimension of 25 mm and 2 mm, respectively, for all the cities. For fibreboard, there was no cavity and for stucco, a cavity of 10 mm was assumed only for the cities of Vancouver and St. John’s based on the recommendation of NBCC for cities with MI and heating degree days (HDD) above a certain level (HDD18 < 3400 and MI > 0.9 or HDD18 > 3400 and MI > 1) [14]. For all the scenarios where a drainage cavity was present and for vinyl wall, a conservative value of air change per hour (ACH) of 2 was used. This ACH value of 2 is largely underestimated for the case of vinyl cladding. In fact, the design of vinyl with holes and the installation with untighten joints permit higher flow rate in the air space created by the vinyl profile [15].

2.4. Simulation tool
In this study, 1D simulations were performed using a state-of-the-art hygrothermal modelling software, Delphin 5.9. Material properties 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 twice.

2.5. Boundary conditions
Indoor temperature and relative humidity were assumed constant with values being 21º C and 50%, respectively. The indoor exchange coefficient for heat conduction was set to 8 W/m²K and the indoor vapor diffusion coefficient was set to 3*10⁻⁸ s/m.

The WDR in a specific direction was computed using the ASHRAE method, assuming $F_E$ and $F_D$ equal to 1 as per ASHRAE 160 [11].

$$ WDR = R_h \times F_E \times F_D \times 0.2 \times V_{10} \times \cos \theta $$

Where, $R_h$ is the horizontal rainfall amount (kg m⁻² h⁻¹); $F_E$ is the rain exposure factor; $F_D$ is the rain deposition factor; $V_{10}$ is the wind speed at 10 m above ground (ms⁻¹); $\theta$ is the angle between the wind direction and the normal to the façade. Outdoor boundary conditions and parameters used for defining them are shown in Table 3.

Table 3. Outdoor boundary conditions and radiation coefficients.
| Type                                | Value                                      |
|-------------------------------------|--------------------------------------------|
| Outdoor convective heat transfer coefficient | $5 + 7.2v^{0.78}$                        |
| Outdoor vapor transfer coefficient  | $3 \times 10^{-8} + 4.392 \times 10^{-8}v^{0.78}$ |
| 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)

2.6. Performance indicators
There are several performance attributes, criteria and evaluation processes that can be used to analyze the results obtained from hygrothermal simulations [16]. In this study, moisture content (MC) and mould growth index (MoI) were chosen as performance indicators. Absolute MC was considered over the entire thickness of OSB. The MoI was computed at the exterior layer of the OSB sheathing (0.1-mm thick) using the method proposed by Ojanen et al. [17]. The calculations were made assuming the “sensitive class” for OSB and a decline factor of 0.5 (assuming significant decline) when the conditions become unfavorable for mould growth. Four performance indicators i.e., maximum MC, average MC, maximum MoI and average MoI were used to compare the performance of wall assembly facing different orientations.

3. Results and discussion
The results are presented firstly for the cases without WDR and water source, secondly for the case with WDR only, and finally for the case with WDR and water source. For the first two cases i.e., no WDR and WDR without water source, it was observed that there was negligible MoI for most of the cities, claddings, and orientations (considerable MC, though). This further results in an insignificant difference of MoI for comparing the results with different orientations. For the case with WDR and water source, there was a considerable difference among different orientations to analyze the impact of wall orientation. Moreover, the results with MoI were consistent with MC and hence to compare the effect of wall orientation for all the analyzed WDR scenarios, only the results obtained using maximum MC are discussed in detail.

3.1. Cases with no WDR and water source
In this scenario, it was found that for all the cities, irrespective of the cladding type, the highest value of maximum MC was observed when the wall is facing the north orientation. This is due to the significantly lower amount of solar radiation in the north direction for northern hemisphere. The results are consistent with the one found by Lepage et al. [18].

3.2. Cases with WDR but no water source
In this section, the results are discussed where WDR was taken into consideration while assuming no deficiency in the cladding leading to water penetration. Table 4 shows the result for maximum MC in the OSB layer for brick cladding wall in all the eleven cities. In general, it was observed that unlike the case with no WDR and water source, where the north orientation always leads to the worst performance irrespective of city or cladding, in this case, the results were not as consistent.

It was observed that in 7 out of 11 cities (Table 4), the default orientation resulted in the worst performance. Four cities, i.e., Moncton, Montreal, Saskatoon, and Winnipeg, performed worst in an orientation other than the default. However, the difference in maximum MC between the default orientation and the orientation with highest maximum MC was not significant, with the exception of Montreal. For Montreal, it was observed that there was a significant difference in the maximum MC for default (0°) and the direction with highest maximum MC, i.e., east (90°).
Table 4. Maximum Moisture content (MC) values in the OSB layer for brick cladding with WDR but no water source.

| City        | Default orientation | Orientation with Max. MC |
|-------------|---------------------|-------------------------|
|             | Orientation        | Max. MC (kg)            | Orientation | Max. MC (kg) |
| Calgary     | 292.5° (WNW)       | 0.68                    | 292.5° (Default) | 0.68        |
| Charlottetown| 157.5° (SSE)      | 1.61                    | 157.5° (Default) | 1.61        |
| Halifax     | 180° (South)       | 1.69                    | 180° (Default)  | 1.69        |
| Moncton     | 22.5° (NNE)        | 1.52                    | 90° (East)     | 1.62        |
| Montreal    | 0° (North)         | 0.86                    | 90° (East)     | 1.67        |
| Ottawa      | 22.5° (NNE)        | 0.96                    | 22.5° (Default) | 0.96        |
| Saskatoon   | 22.5° (NNE)        | 0.80                    | 90° (East)     | 0.84        |
| St. John’s  | 202.5° (SSW)       | 1.48                    | 202.5° (Default) | 1.48        |
| Toronto     | 202.5° (SSW)       | 0.71                    | 202.5° (Default) | 0.71        |
| Vancouver   | 157.5° (SSE)       | 1.71                    | 157.5° (Default) | 1.71        |
| Winnipeg    | 67.5° (ENE)        | 1.08                    | 90° (East)     | 1.18        |

Figure 1. Hourly and cumulative distribution of WDR for 4 cities for default and orientation with highest maximum moisture content (MC) (def: default orientation, actual: orientation with highest max. MC, cum: cumulative).

A closer look at the distribution of WDR (Figure 1) in Montreal showed that highest sum of WDR in north (default) was because of a few singular high intense rain events in this direction. North orientation has a few spikes which mean that there were few hours in the year when there was high WDR intensity in this direction. Peaks representing the higher WDR load is actually less of a concern in terms of durability. This is because of the reason that as water absorption capacity of the cladding is limited and with a great amount of WDR during a short span of time, most of the water is going to be drained off and will not affect the wall performance to a large extent. A further analysis showed that the spikes make around 70% of the total WDR that had occurred throughout the year in that direction. On the other hand, for the other direction although the overall sum remains low, the distribution of WDR was steady throughout the year. The actual sum of WDR remained higher for north direction but a steadier distribution of rain in other directions resulted in worst performance in that direction. It was further observed that among the many available years in the run, only the chosen year (wettest year) for Montreal holds this exceptional distribution of WDR and hence resulted in this anomalous behavior.
In terms of different claddings (Figure 2), maximum MC was highest for stucco cladding. Moreover, for fibreboard and vinyl cladding, the results were similar irrespective of the orientation. The maximum MC in OSB for these two claddings were lower than brick and stucco claddings. Vinyl being impermeable to water did not allow any vapor transport and hence behave as if there was no WDR. On the other hand, for fibreboard, for similar thicknesses of investigated cladding materials, it has the highest vapor permeance and hence drying capacity. The balance between wetting and drying for fibreboard makes the results indistinguishable and lead to similar value of MC for all the orientations.

3.3. Cases with WDR and water source

In this scenario, WDR and water source were considered. Table 5 shows, for the brick cladding, maximum MC in the OSB layer obtained with the default orientation and with the orientation having maximum MC in different cities. For all the cities except Moncton, Montreal, and Winnipeg, default orientation led to the worst moisture performance.

Table 5. Maximum moisture content (MC) in the OSB layer for brick cladding with WDR and water source.

| City     | Default orientation | Orientation with Max. MC |
|----------|---------------------|--------------------------|
|          | Orientation         | Max. MC (kg)             | Orientation | Max. MC (kg) |
| Calgary  | 292.5° (WNW)        | 1.02                     | 292.5° (Default) | 1.02 |
| Charlott. | 157.5° (SSE)        | 1.74                     | 157.5° (Default) | 1.74 |
| Halifax  | 180° (South)        | 1.92                     | 180° (Default)  | 1.92 |
| Moncton  | 22.5° (NNE)         | 1.85                     | 0° (North)     | 1.87 |
| Montreal | 0° (North)          | 1.33                     | 180° (South)   | 1.94 |
| Ottawa   | 22.5° (NNE)         | 1.35                     | 22.5° (Default) | 1.35 |
| Saskatoon| 22.5° (NNE)         | 1.16                     | 22.5° (Default) | 1.16 |
| St. John’s | 202.5° (SSW)       | 1.86                     | 202.5° (Default) | 1.86 |
| Toronto  | 202.5° (SSW)        | 1.16                     | 202.5° (Default) | 1.16 |
| Vancouver| 157.5° (SSE)        | 2.39                     | 157.5° (Default) | 2.39 |
| Winnipeg | 67.5° (ENE)         | 1.80                     | 90° (East)     | 1.92 |

The wall performed worst in north and east direction for Moncton and Winnipeg, respectively. However, the difference in the maximum MC for the default and the direction with highest maximum MC (approximately 5%) was not significant. Among the claddings (Figure 3), OSB for vinyl cladding showed the highest value of accumulated moisture content. This is because that vinyl is highly...
impermeable and does not allow the water deposited on the sheathing membrane to dry to the exterior. As well, a lower ACH in the drainage cavity further aids the slower drying and hence the moisture remained there for a long time leading to highest maximum MC among the claddings considered.

Figure 3. Maximum moisture content (MC) of OSB layer for 3 cities with WDR and water source.

In terms of orientation leading to the worst performance, the default orientation proved to be the worst orientation for all the claddings except for brick cladding in Montreal. It can be said that, choosing the default orientation based on the highest WDR is a good assumption to some extent. However, as seen for the case of brick cladding in Montreal (section 3.2), it is important to analyze the distribution of WDR instead of relying only on the cumulative sum.

4. Conclusion
The results were obtained by considering rain scenario (no WDR, only WDR and WDR with water source), four cladding types, eleven cities belonging to different climate zones and assuming low ACH in the drainage cavity.

The main findings are as follows:
- In the absence of WDR, for all the selected cities, north orientation led to the worst performance with respect to maximum accumulated moisture in the OSB irrespective of the cladding material because of the least amount of incident solar radiation in north (northern hemisphere).
- In the presence of WDR but no water source, four out of eleven cities perform worst in an orientation other than default.
- When WDR and water source, both are assumed to be present, it was found that most of the times, the orientation receiving the highest amount of WDR lead to the worst performance.

There were few exceptions in the results because of the WDR distribution throughout the year. Incidences when an intense rain spell occurred could sometimes lead to the unreliable results. This high rain event leads to a greater sum of WDR in the year but in actual is less of a concern in terms of durability of the wall as water absorption capacity of the cladding is limited and most of the water is going to be drained off. It is recommended that in addition to looking the direction with highest sum of WDR, it is equally important to analyze the hourly distribution of WDR in all the directions.

Furthermore, the present study only accounts for results obtained using the historical climate across different cities in Canada without considering the effect of climate change. Under projected climate, with higher expected precipitation, the response of the wall might change, and this will be included in a future study.

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