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Stochastic modelling of hygrothermal performance of highly insulated wood framed walls

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ABSTRACT
Recent years, the majority of building codes in North America require an energy efficient envelope to improve the building energy efficiency. There are different design strategies to achieve a higher insulation level of the wood framed building envelope, such as increasing the depth of stud cavity to accommodate thicker insulation or adding an exterior insulation while keeping the depth of stud cavity unchanged. However, the highly insulated walls may lead to a higher risk of moisture problems. The deep cavity walls will reduce the temperature of the wood sheathing, which may increase the potential for condensation and mold growth. The exterior insulated walls may result in a low drying capacity of the wood sheathing if the exterior insulation has a low vapour permeance. Although hygrothermal simulations have been widely used to investigate the moisture performance of wood framed walls, the uncertainty of the input parameters may lead to discrepancies between simulation results and real performance of the walls. This paper investigates the hygrothermal performance of highly insulated wood framed walls- deep cavity wall and exterior insulated wall using a stochastic simulation approach. The uncertainties of the input parameters including the material properties, air leakage and rain leakage rates are taken into account in stochastic modelling. The mold growth risks of the walls are evaluated based on the stochastic simulation results.

KEYWORDS
Highly Insulated Wood Framed Wall, Hygrothermal Simulation, Stochastic Modelling

INTRODUCTION
Recent years, the majority of building codes in North America require an energy efficient envelope to improve the building energy efficiency. There are different design strategies to achieve a higher insulation level of wood framed building envelope, such as increasing the depth of the stud cavity to accommodate a thicker insulation or adding an exterior insulation while keeping the depth of stud cavity unchanged. However, the highly insulated walls may lead to a higher risk of moisture problems. Hygrothermal simulations have been widely used to investigate the hygrothermal performance of highly insulated walls (Maref et al., 2010; Arena et al., 2013; Parsons and Lieburn, 2013; Smegal et al., 2013; Craven and Garber-Slaght, 2014; Glass et al., 2015). However, the uncertainties of the input parameters may lead to discrepancies between simulation results and real performance of the walls. Stochastic approach has been applied to investigate the uncertainties of the input parameters and their influence, but the stochastic variables were often limited to material properties and surface transfer coefficients (Salonvaara et al., 2001; Holm and Kunzel, 2002; Zhao et al., 2011; Defraeye et al., 2013). The moisture loads such as air leakage and rain leakage were not taken into account in previous studies.

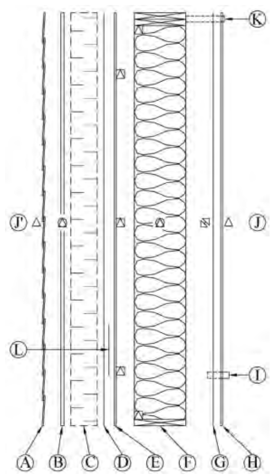
To investigate the air leakage effect on the hygrothermal performance of highly insulated wood framed walls, field measurements were conducted for three types of walls: 2x6 framed wall with fiber glass insulation, deep cavity walls and exterior insulated walls in Southern

Ontario Canada (Fox, 2014). Hygrothermal models using the mean values of the input parameters have been created and validated with the field measurements (Fox, 2014). In this paper, a stochastic approach is applied to investigate the influence of the uncertainties of input parameters including material properties, air leakage and rain leakage rates. Stochastic simulations are carried out using DELPHIN on four walls tested: 2x6 framed wall with fiberglass insulation, I-joist framed deep cavity wall with cellulose fiber insulation, polyisocyanurate exterior insulated wall and mineral wool exterior insulated wall. The mold growth risks are evaluated under the air leakage and rain leakage based on the stochastic results.

STOCHASTIC MODELING

Material properties and boundary conditions

Figure 1 shows the configuration of the walls under investigation. The material properties and their uncertainties are determined from several sources (Kumaran et al., 2003; Mukhopadhyaya et al., 2007). The hygric properties (saturation water content, vapor resistance factor and moisture diffusivity) of the OSB sheathing and insulations are considered as stochastic variables since the moisture content of OSB is used for performance evaluation.



ID	Wall component
A	11 mm Fiber cement siding
B	19 mm strapping / drainage space
C	Exterior Insulation (polyisocyanurate or mineral wool)
D	SBPO air barrier and water resistive layer
E	11 mm OSB Sheathing
F	140, or 241 mm framing as required
G	6-mil polyethylene (polyisocyanurate wall has no poly)
H	12.5 mm drywall
I	Air injection port
J'-J	Sensors through wall insulation cavity
K	Air exhaust port
L	Exterior water injection wetting sheet

Figure 1 General section view of the highly insulated walls and the wall components (adapted from Fox, 2014)

The surface transfer coefficients are considered as deterministic parameters since these parameters have no significant influence on hygrohtermal performance of wood framed walls (Zhao et al., 2011). The rain deposition factor is considered as stochastic variable to reflect the variability of wind-driven rain load on façade, thus, rain leakage rate. The monitored on-site weather data is used to generate the customized weather data files for DELPHIN. The indoor climate file is also generated based on the monitored indoor temperature and relative humidity, which was maintained at 20°C and 40%RH.

Air leakage and rain leakage

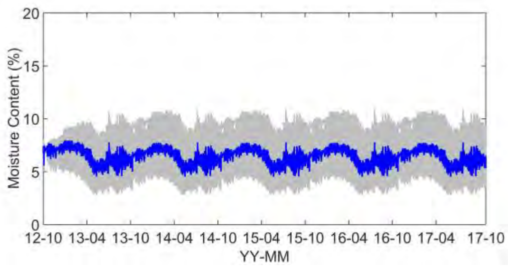
The impact of air leakage is simulated using the air infiltration method (Kunzel, 2012). By using this method, a moisture source that is equivalent to the condensing rate caused by air leakage is deposited on the interior surface of OSB sheathing. The air leakage rate (5.0 ± 3.7 $m^3/h.m^2$ under 75Pa pressure difference for walls with air barrier) is determined based on the air leakage database developed by Emmerich and Persily (2014), and converted to those under 5Pa pressure difference. Details of modeling air leakage can be found in (Wang and Ge, 2017). The rain leakage is simulated by depositing 1% of wind-driven rain on the exterior surface of OSB sheathing. The rain deposition factor is from 0.35 to 1 as prescribed in ASHRAE 160 (2016).

Generation of stochastic models

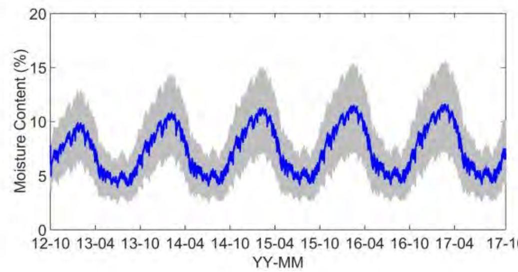
The material properties and air leakage rate are assumed to follow normal distribution to obtain the stochastic values, while the rain deposition factor is assumed to follow a uniform distribution. The stochastic models are generated for three scenarios: 1) only material properties are considered as stochastic variables; 2) material properties and air leakage rate are considered as stochastic variables; and 3) material properties and rain deposition factor are considered as stochastic variables. For each scenario, 100 stochastic models are generated using Latin Hypercube Sampling technique. Simulations are performed for five years starting from Oct. 2012.

STOCHASTIC RESULTS

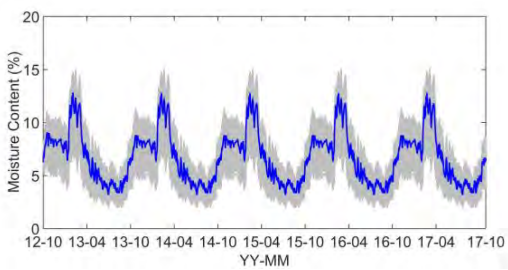
Influence of material properties



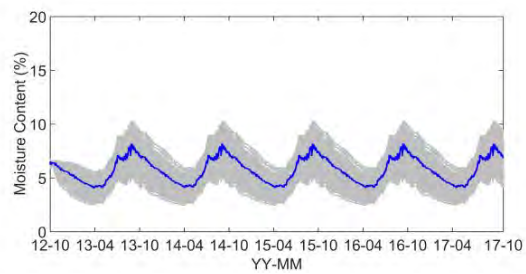
Baseline wall (2x6 framed wall)



I-joist deep cavity wall



Polyisocyanurate exterior insulated wall



Mineral wool exterior insulated wall

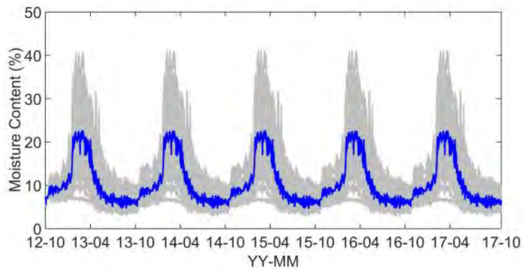
Figure 2 Stochastic results of MC with variation of material properties_south

Figure 2 shows the stochastic results of OSB moisture content of the south-facing walls with only the material properties are treated as stochastic variables. The blue curve is the base case, which uses the mean values of the input parameters. The grey curves are the stochastic results. The highly insulated walls generally have higher MC level and more significant seasonal variation (increasing in winter and decreasing in summer) than the baseline wall except for mineral wool exterior insulated wall, which has similar MC level to the baseline wall but different seasonal variations (increasing from spring to summer but decreasing starting from fall to winter). The MC of I-joist wall has an upward trend with a highest value of 12$\pm$4%, which is slightly higher than the polyisocyanurate insulated wall. The highest MC of the baseline wall is 8$\pm$3%, which is similar to the mineral wool exterior insulated wall. The highest moisture content is below 20% for all the walls.

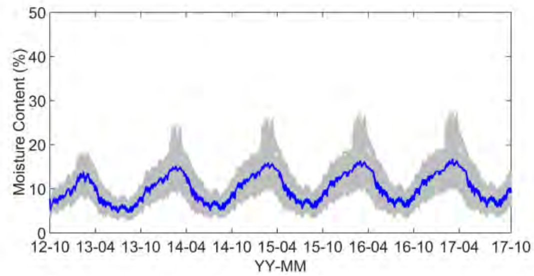
Influence of air leakage

There is no condensation caused by air leakage for the exterior insulated walls and the MC profiles of OSB are the same as those presented in Figure 2, therefore, only the results of south facing baseline wall and I-joist wall are presented. It can be observed from Figure 3 that the influence of air leakage is more significant for the baseline wall than for the I-joist wall. The highest MC of baseline wall is 23$\pm$17%, which is much higher than that of I-joist wall 17$\pm$8%.

For the baseline wall, 75% of the stochastic cases have highest MC exceeding 20%, but only 35% of stochastic cases of I-joist wall have highest MC exceeding 20%. The I-joist wall performs better than the baseline wall because the cellulose fiber in I-joist wall has a higher moisture storage capacity than fiberglass in the baseline wall, and the cellulose fiber is able to absorb the moisture carried by the air leakage and reduces the amount of moisture reached the OSB sheathing.



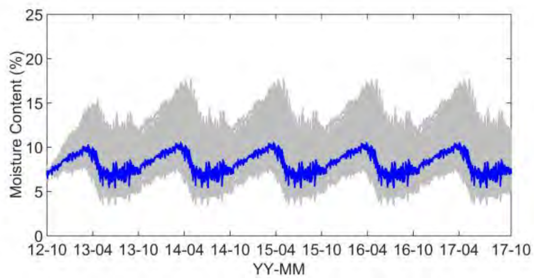
Baseline wall (2x6 framed wall)



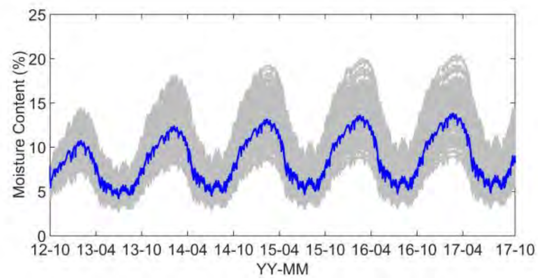
I-joist deep cavity wall

Figure 3 Stochastic results of MC with variation of material prperties and air leakage rate_south

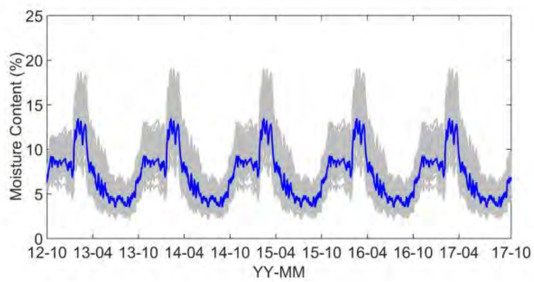
Influence of rain leakage



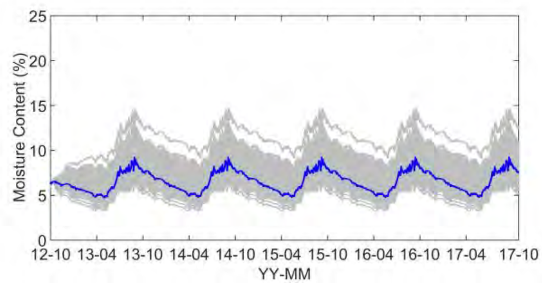
Baseline wall (2x6 framed wall)



I-joist deep cavity wall



Polyisocyanurate exterior insulated wall



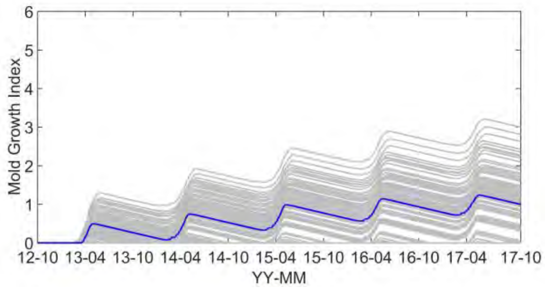
Mineral wool exterior insulated wall

Figure 4 Stochastic results of MC with variation of material prperties and rain factor_south

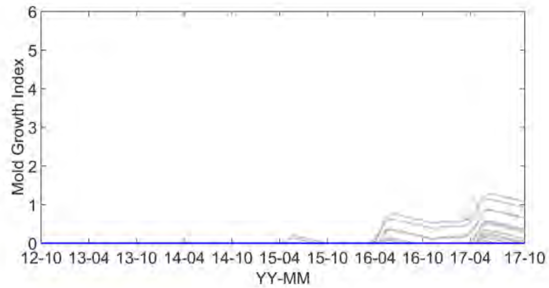
Since the south orientation receives higher wind-driven rain than the north orientation, the results for south oriented walls are presented in Figure 4. It can be seen that the impact of rain leakage is less significant than air leakage. The highest MC of the baseline wall is $12\pm5\%$, the base case is lower than average because the rain deposition factor in base case is 0.35, which is lower than the average value. The highest MC of I-joist wall is $15\pm5\%$, which is slightly higher than the baseline wall. The MC level of polyisocyanurate wall is similar to I-joist wall, but has no upward trend. The mineral wool wall has the lowest MC level, which is $10\pm4\%$. All the walls under rain leakage scenario have moisture content lower than 20%.

Mold growth index

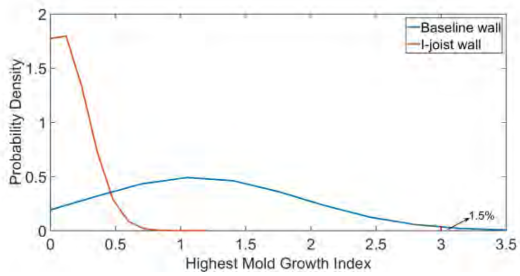
Figure 5 shows the mold growth index over 5 years and probability density function of the 5 years' highest mold growth index for the baseline wall and I-joist wall under air leakage scenario. It can be found that the mold growth index for the baseline wall increases gradually from 0 up to 1.6±1.6. The 5 years' highest mold growth index has 1.5% probability higher than 3, which exceeds the threshold (visually detectable mold growth) prescribed in ASHRAE 160 (2016). For the I-joist wall the highest mold growth index is about 1.2, which indicates there is no risk of detectable mold growth.



Baseline wall



I-joist wall



Probability density function of highest mold growth index

Figure 5 Mold growth index of baseline wall and I-joist wall under air leakage

CONCLUSION

This paper investigates the hygrothermal performance of highly insulated walls, i.e. I-joist framed deep cavity wall and exterior insulated walls, compared to a conventional 2x6 framed wall with fiberglass insulation (baseline wall) through stochastic approach with consideration of the uncertainties of material properties, air leakage and rain leakage rates. The main findings of this paper are:

- The uncertainties of material properties in I-joist wall and polyisocyanurate exterior insulated wall (low exterior vapour permeance) lead to greater variations of MC of OSB than that in the baseline wall and mineral wool exterior insulated wall (high exterior vapour permeance). Without air leakage or rain leakage, the uncertainty of material properties does not lead to mould growth risk in the walls investigated.
- The air leakage has no influence on the exterior insulated walls using air infiltration simulation method. The MC of OSB in the baseline wall is more sensitive to air leakage than that in the I-joist wall with cellulose fiber. The mold growth risk of the baseline wall is higher than the I-joist wall under air leakage.
- Under climatic condition of South Ontario, the influence of rain leakage is less significant than air leakage for the baseline wall and I-joist wall, while the influence of rain leakage is more significant than air leakage for the exterior insulated walls. The MC of OSB in polyisocyanurate wall has higher uncertainty than that in mineral wool wall under simulated rain leakage, while all the walls studied do not have mold growth risks under simulated rain leakage.

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