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SUMMARY:
This paper presents some of the results from a research project that investigates the hygrothermal (i.e. thermal and moisture) performance of the Canadian wood-frame exterior building envelope construction practices in the cities of Shanghai and Beijing (China) and Taichung (Taiwan). This study has been done using a two-dimensional hygrothermal simulation tool, hygIRC-2D. In this paper, four exterior walls and two roof constructions are exposed to the exterior climatic conditions of Shanghai. The first set of simulations is conducted with wall constructions that have no air leakage. Thereafter, two wall constructions are also simulated with various levels of air leakage through the wall assembly. The outputs from the simulations have been analyzed with the help of a moisture response indicator called RHT index. Simulation results indicate the relative performances and suitability of the different wall and roof assemblies in Shanghai. The results of this study, including those presented in this paper, have helped to develop moisture and thermal (i.e. hygrothermal) design guidelines for Canadian style wood-frame building envelope construction in China.

1. Introduction

In Canada and other parts of North America, traditional wood frame exterior building envelope construction is widely used and its ability to manage the exterior and interior moisture and thermal (i.e. hygrothermal) loads is well known from the field performance observations over the years. However, this type of building envelope construction is not traditionally used in China. Currently, Canada Wood, an association of Canadian forest industry partners including the Council of Forest Industries (COFI), is working with various levels of government and the construction sector in China to improve quality design and construction of wood-frame buildings, including the building envelope. COFI leads in Asia on behalf of Canada Wood. The ultimate objective is to develop growing and sustained markets for Canadian wood products in Asia, particularly China. However, quality assurance is not possible without knowing the consequences and the ability of the wood frame building envelope assemblies to manage the hygrothermal loads in the climatic conditions of China. This long-term performance issue becomes even harder to resolve when there is no comprehensive field performance data, as in this case.

In the absence of any credible field performance data, the National Research Council (NRC) of Canada and Canada Wood initiated a joint research project to investigate the long-term performance of alternative designs of wood-frame building envelope assemblies (walls and roofs) in Shanghai and Beijing (China) and Taichung (Taiwan) using a hygrothermal simulation tool, *hygIRC-2D*. In recent years hygrothermal simulation tools have been widely used for the evaluation of the thermal and moisture response of the building envelopes (*Mukhopadhyaya et. al.2003; Djebbar et. al. 2002, Vinha 2007*). The benchmarked two-dimensional hygrothermal simulation tool, *hygIRC-2D* (*Maref et al. 2002; Hagentoft et al. 2004*), was developed at the Institute for Research in Construction of the National Research Council Canada. Some of the simulation results for Shanghai are presented in the following sections.

1.1 Research objectives and scope

The purpose of this study is to evaluate the hygrothermal performance of alternative wood-frame building envelope designs in Shanghai (China) using the hygrothermal simulation tool *hygIRC-2D*. The numerical simulations were done on four types of exterior walls and two types of unvented roof assemblies. Initially, the roof and wall constructions were simulated assuming no air leakage through the assemblies. Subsequently, simulations with air leakage were conducted on two of the wall constructions under three assumptions of air leakage. As a result, the effects of vapour diffusion could be assessed independently of air leakage. Varying the rates of air leakage helps explain the relationship between air leakage rates and hygrothermal response.

2. . Simulation tool *hygIRC-2D*

The hygrothermal simulation tool used in this study is a computer aided numerical model, *hygIRC-2D*, that can predict the moisture response of building envelopes (*Hens 1996*). *hygIRC-2D* is continuously evolving as a research tool, developed by a group of researchers at the Institute for Research in Construction (IRC) of the National Research Council (NRC), Canada. Interested readers can refer to the publications by *Karagiozis (1997)* and *Djebbar et al., (2002)* for further details. These documents outline the formulation of the combined heat, air and moisture transport equations used in *hygIRC-2D* and the techniques used to solve them numerically. The reliability of *hygIRC-2D* outputs has been established through laboratory measurements and benchmarking exercises (*Maref et al. 2002; Hagentoft et al. 2004*). The effective use of *hygIRC-2D* to analyze and obtain meaningful results, however, demands a proper physical understanding of the problem, an appropriate definition of input parameters and the ability to judiciously interpret the outputs from the simulation tool (*Mukhopadhyaya and Kumaran, 2001; Mukhopadhyaya et al. 2001; Kumaran et al. 2003*).

2.1 Basic inputs and assumptions for modeling

2.1.1 Construction details

Several different wall and roof designs (Figure 1) were evaluated to compare their hygrothermal performance. Canada Wood submitted these designs, with construction details, to the IRC researchers for hygrothermal performance evaluation under Shanghai weather conditions. As mentioned earlier, simulations were first conducted with no air leakage. These include the following exterior wall designs: (i) Wall 1 – Classic cold weather wall; (ii) Wall 2 – Super E® wall; (iii) Wall 3 – Low-cost wall; (iv) Wall 4 – All climate wall; and roof designs: (v) Roof 1 – unvented truss roof with XPS and glass fibre insulation; (vi) Roof 2 – unvented truss roof with spray-on foam insulation.

2.1.2 Air leakage

To understand the effects of imperfect air barriers in the wall constructions, air leakage was introduced in the Super E® and low cost walls. An air leakage path was created through each of the wall assemblies. The air would enter/exit, depending on the nature of indoor and outdoor pressure, along a crack at the exterior top of the wood-framed wall and then travel through the insulation cavity and exit/enter at the interior bottom of the wall (Figure 2). The size of the crack was varied to simulate various levels of air leakage. This size was based on the normalized leakage area (NLA), which is the area of the crack in cm^2 divided by the area of the wall in m^2. Three levels of air leakage were examined: 0.3, 0.7, and 1.5 NLA.

The following wall and roof constructions were examined with air leakage:

- Wall 2 – Super E® Wall – 0.3, 0.7, and 1.5 NLA
- Wall 3 – Low cost wall – 0.3, 0.7, and 1.5 NLA

2.1.3 Material properties

hygIRC-2D simulation requires eight sets of material properties. These properties are air permeability, thermal conductivity, dry density, heat capacity, sorption characteristics, suction pressure, liquid diffusivity and water vapour permeability. These materials properties were obtained from the IRC/NRC's hygrothermal materials properties database (*Kumaran et al (2002); Kumaran et al (2004); Mukhopadhyaya et al (2004)*) and were determined in the IRC's Thermal Insulation and Moisture Performance Laboratory.

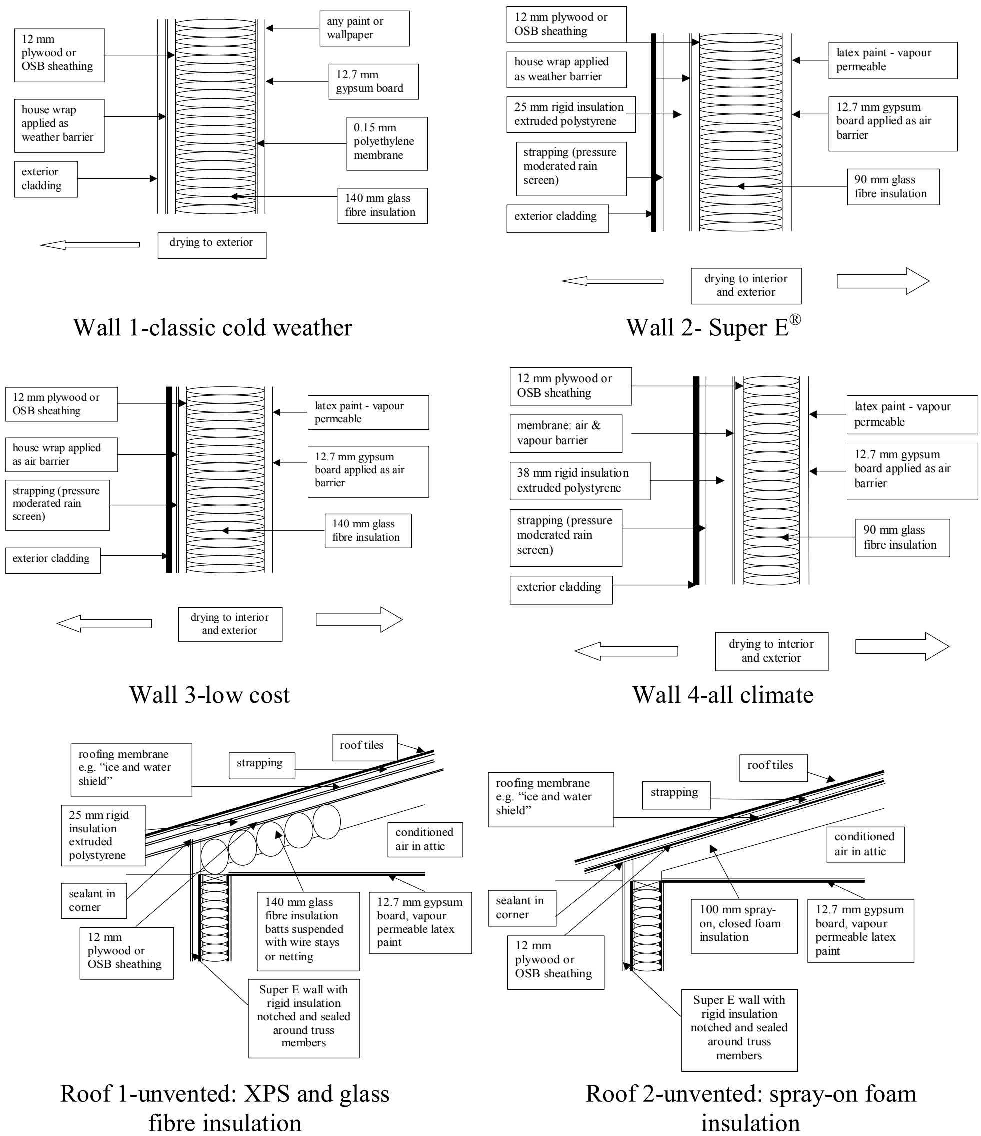

FIG 1: Walls and roofs construction details.

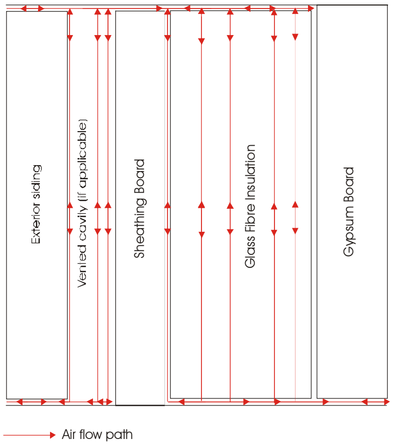

FIG 2: Schematic airflow path.

2.1.4 Environmental conditions

Hourly recorded Shanghai weather data was used as outdoor/external boundary conditions. *hygIRC-2D* requires the following hourly recorded weather components: temperature, relative humidity, wind velocity, wind direction, rainfall, solar radiation and cloud index. Weather data for the year 2003 was obtained from the weather bureau of China. Table 1 provides general climatic conditions for Shanghai.

TABLE 1: Climate+ summary of Shanghai

HDD18	1691	Extreme Mean Maximum	37° C
CDD26	164	RH Mean Coldest Month	75%
Mean Annual Temperature	16° C	RH Mean Hottest Month	83%
Extreme Minimum Temperature	-10° C	Annual Precipitation	119 cm
Extreme Maximum Temperature	39° C	Mean for Dominant Wind	3.8 m/s
Extreme Mean Minimum Temperature	-7° C	Maximum Depth of Frost	8 cm

+ Based on data from 1951 to 1980

The indoor conditions (temperature and relative humidity) used in the simulations were for a controlled indoor environment based on summer and winter seasons, identified according to the criteria specified in the 'Specifications to National (Canada) Energy Code for Houses, (*Swinton and Sander, 1994*)'. If the monthly average outdoor temperature was below 11 °C it was considered winter. If the monthly average temperature was above 11 °C it was considered summer. Indoor conditions in Shanghai were developed based on conversations with building science professionals who had knowledge of building practises in China. In the summer the indoor conditions were 25 °C temperature and 65% relative humidity. In the winter the indoor conditions were 18 °C temperature and 40% relative humidity.

3. Simulation results

A significant amount of data was generated by *hygIRC-2D* simulations and subsequently post-processed for the detailed evaluation of the hygrothermal response of the building envelopes (*Mukhopadhyaya and van Reenen 2007*). For relative comparison of hygrothermal performance of the building envelope assembly, a novel hygrothermal performance indicator was used in this study as described in the following paragraphs.

3.1 RHT index – hygrothermal performance indicator

It is widely accepted that building materials are subject to deterioration under the combined effects of temperature and moisture. The most deleterious conditions are those in which moderate or high temperature is coupled with high humidity for extended periods *(Nofal and Morris 2003)*. This study uses a novel long-term hygrothermal response indicator, called the RHT index, derived from the relative humidity (RH) and temperature (T) conditions inside the building envelope cross section over a period of time for any specific area of the cross-section. The RHT index is an indicator used to quantify and compare the hygrothermal response of the wall assembly. This index captures the duration of moisture and thermal conditions coexisting above threshold RH and T levels. RH and T are given linear weight in the RHT index. It is to be noted that for many materials this may not always be the case when assessing their long-term performance while subjected to varying and elevated moisture conditions. A different weighting for RH and T can be determined only through controlled long-term experiments. The RHT index as defined in this study is:

$$\textit{Cumulative } RHT=\sum(RH-RH_X)\times(T-T_X) \qquad (1)$$

for $RH>RH_X\%$ and $T>T_X$°C at every hour of the simulation.

Where, RH_X and T_X are the threshold values for relative humidity and temperature respectively.

In this set of simulations two sets of threshold levels were used. The first set was with an RH of 80% at 0 °C temperature, hereafter referred as RHT80. The second set was with an RH of 95% at 0 °C temperature, hereafter referred as RHT95. The cumulative RHT was a summation done on an hourly basis for the final two years of the simulation.

During any time step when either or both $RH \le RH_X$ % and $T \le T_X$ °C, the RHT value for that time step is zero. A schematic diagram for the generation of RHT index value is shown in Figure 3. The results presented in the following section use the cumulative two-year RHT index as a single-value hygrothermal response indicator. A higher value of RHT index indicates a greater potential for moisture-related deterioration. It is to be noted here that two different walls with similar cumulative RHT values can still have very different hygrothermal responses. At the same time, climates or conditions that seem intuitively to be quite different can produce similar cumulative RHT values. It is also to be mentioned here that the threshold RHT index value that borders a safe and unsafe hygrothermal design of a wall system is yet to be defined. IRC researchers will work on this issue in the coming days.

4. Discussion

Computer simulations for each assembly design were subsequently processed to produce the following graphical displays: (i) RHT Analysis for 80% RH and 0°C; (ii) RHT Analysis for 95% RH and 0°C; (iii) moisture accumulation in each product or material component over the review period; (iv) total moisture and moisture content (%) in the wood components over the review period; (v) temperature and relative humidity in the wood components over the review period. Because it is impossible to present all the analytical information in this paper, only brief discussion on significant observations is presented in the following paragraphs. Readers may wish to refer to the publication (*Mukhopadhyaya and van Reenen 2007*) for the entire information.

4.1 Walls with no air leakage

The hygrothermal simulations of the wall assemblies with *hygIRC-2D* indicate that *Wall 1* (classic cold weather) has an area of intense hygrothermal loading (*i.e.* higher RHT index values) along the interior side of the poly sheet (Figure 4). The moisture contents in the top and bottom plates are higher than the other three wall types. The maximum moisture content in the bottom plate reaches a value of approximately 21% and remains at this level for several months during the summer (Figure 5). The other wall cross-sections remain near 15 % moisture content, reaching a maximum of 17%. The higher RHT values and moisture content in the top and bottom plates indicate a higher potential of moisture related damage to this *Wall 1* cross-section.

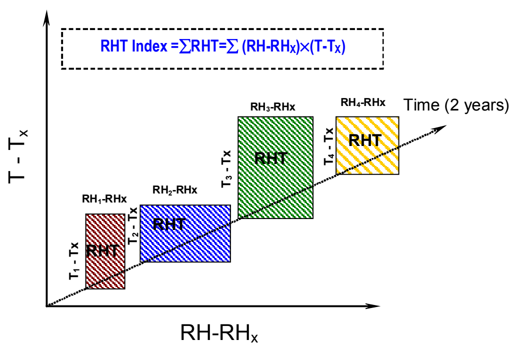

FIG 3: Schematic diagram to explain RHT Index calculation.

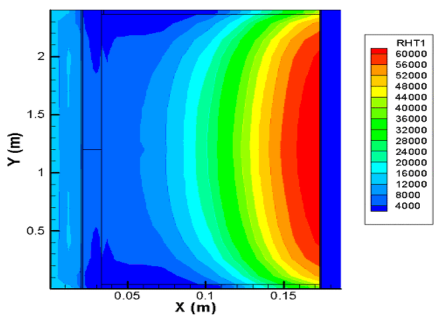

FIG. 4: Wall 1 - RHT analysis for 80% RH and 0 °C

4.2 Roofs

Two unvented roofs (Figure 1) examined here are *Roof 1* (traditional truss with rigid, XPS foam over and glass fibre insulation under sheathing) and *Roof 2* (traditional truss with spray-on foam insulation under sheathing). The hygrothermal analyses, using *hygIRC-2D*, compares the two roofs. Whilst the highest values of RHT indices in both roofs are in the roof tiles, roof 2 shows a higher RHT index in the area of the plywood sheathing and immediately below the sheathing (Figures 6 and 7).

When looking at the total moisture content in the two roofs, *Roof 2* has a higher total value of moisture accumulation for most of the year under consideration (Figures 8 and 9). *Roof 2* shows significantly higher moisture content in the wood components of the roof, i.e., plywood sheathing and upper truss chords (Figures 10 and 11). The plywood, moisture content in *Roof 1* generally varies between 8% and 14% while in *Roof 2* it is approximately 5% higher for most of the year, (Figure 10). An estimate of the moisture content in the truss chords was derived from the relative humidity in the insu

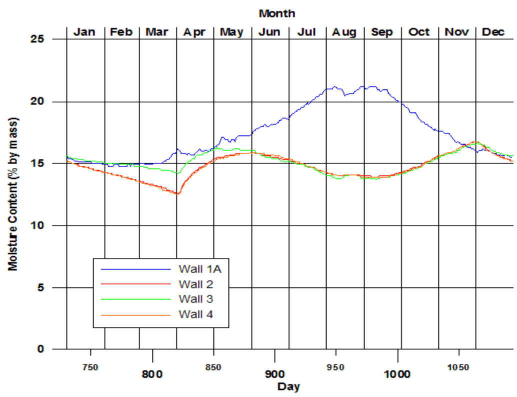

FIG. 5: Average moisture content in bottom plate

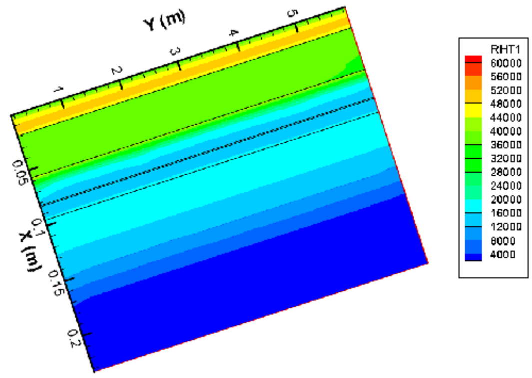

FIG. 6: Roof 1 - RHT analysis for 80% RH and 0°C

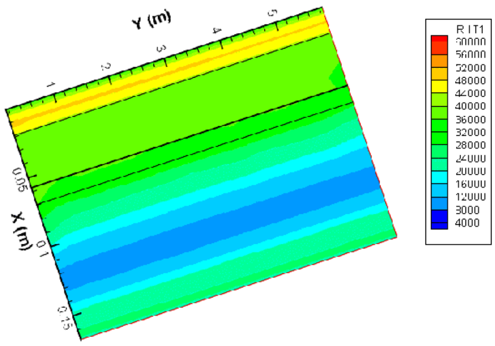

FIG. 7: Roof 2 - RHT analysis for 80% RH and 0°C

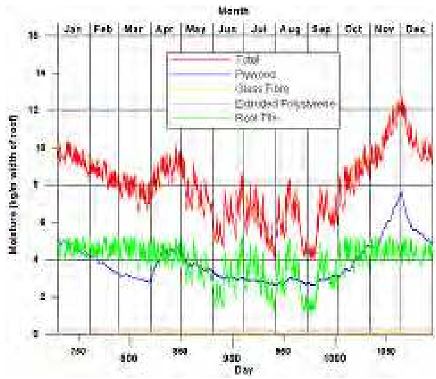

FIG. 8: Moisture accumulation in components of roof 1

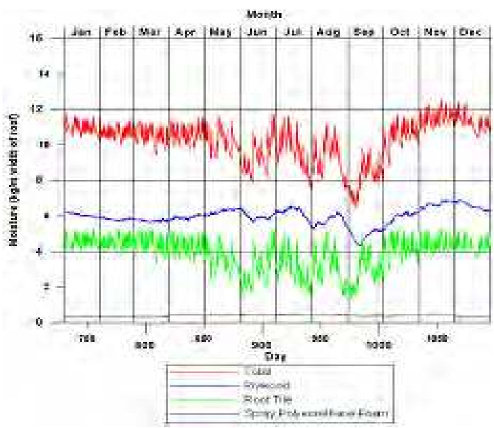

FIG. 9: Moisture accumulation in components of roof 2

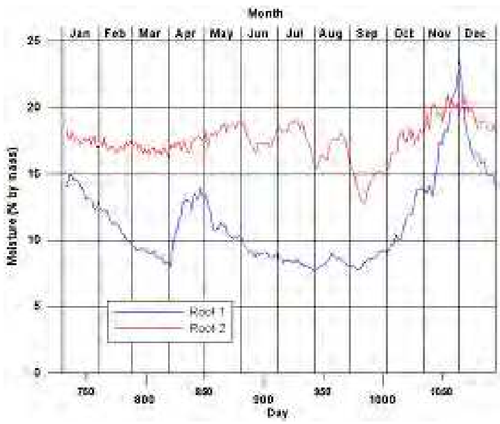

FIG. 10: Roofs-average moisture content in plywood

4.3 Walls with air leakage

Three levels of air leakage (0.3, 0.7, and 1.5 NLA) were examined on *Wall 2* and *Wall 3*. The RHT analyses from hygrothermal simulations show interesting results for *Wall 3* (Figures 12, 13 and 14). There is an area of high hygrothermal loading (i.e. high RHT index) on the interior side of the bottom plate for all three levels of leakage. This area of high hygrothermal loading becomes larger as the level of the air leakage increases. The moisture content in the bottom plate reaches the highest level, and increases with more air leakage (Figure 15).

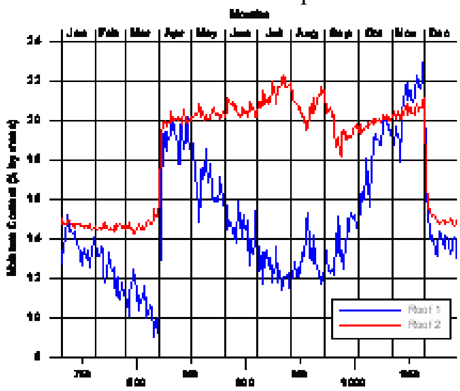

FIG. 11: Roofs - estimate of moisture content in rafters

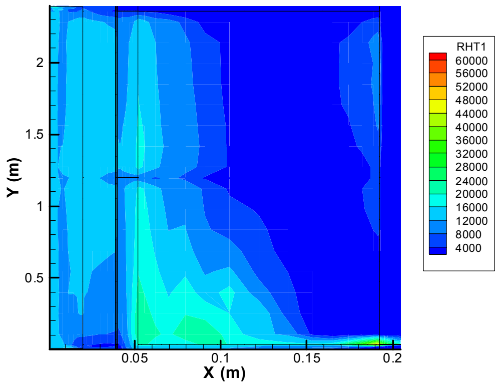

FIG. 12: Wall 3 - 0.3 NLA

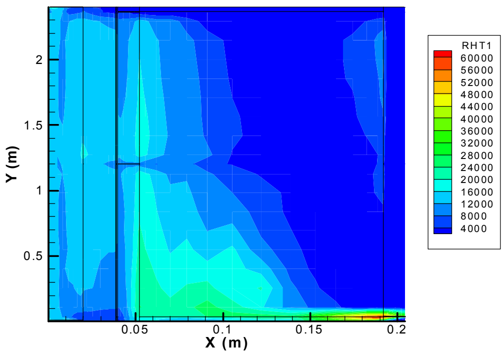

FIG. 13: Wall 3 - 0.7 NLA

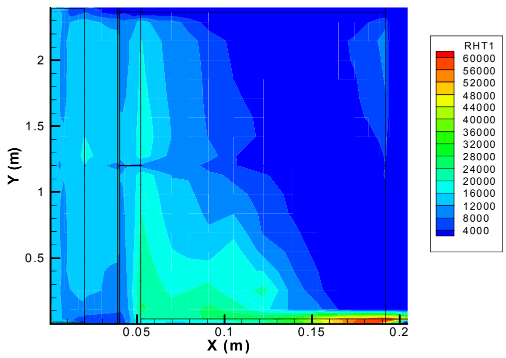

FIG. 14: Wall 3 - 1.5 NLA

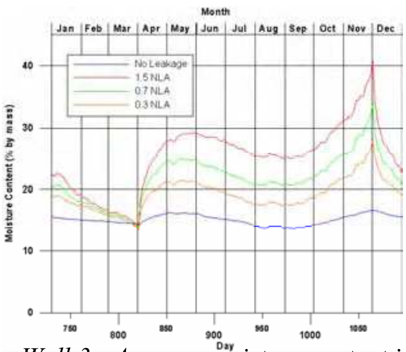

FIG. 15: Wall 3 - Average moisture content in bottom plate

5. Conclusions

- Under conditions with no air leakage, the hygrothermal simulation with *hygIRC-2D* indicates that the classic cold weather wall, as constructed in Canada, has the highest intensity of overall hygrothermal response.
- Air leakage condition has been simulated in both the Super E® wall, and the low cost wall. These simulations show increasing the air leakage through the wall assembly results in higher levels of moisture in the bottom plate.

- The unvented roof simulations show that roof tile is the most vulnerable to high temperatures and moisture levels. The roof with rigid, XPS foam over and glass fibre insulation under the sheathing has resulted in lower moisture contents in the wood components of the construction.

6. References

Djebbar, R., Kumaran, M.K., Van Reenen, D. and Tariku, F. (2002). Hygrothermal Modelling of Building Envelope Retrofit Measures in Multi-unit Residential and Commercial Office Buildings. IRC/NRC, *National Research Council*, Ottawa, Canada, Client Final Report B-1110.3, pp. 187.

Hagentoft, C-E., Adan, O., Adl-Zarrabi, B., Becker, R.; Brocken, H., Carmeliet, J., Djebbar, R., Funk, M., Grunewald, J., Hens, H., Kumaran, M.K., Roels, S., Kalagasidis, A.S., Shamir, D. (2004). Assessment Method of Numerical Prediction Models for Combined Heat, Air and Moisture Transfer in Building Components: Benchmarks for One-dimensional Cases. *Journal of Thermal Envelope and Building Science*, v. 27, no. 4, April 2004, pp. 327-352.

Hens, H. (1996). Heat, air and moisture transport, Final Report, Vol. 1, Task 1: Modelling, *International Energy Agency*, Annex 24, Laboratorium Bouwfysica, K. U.-Leuven, Belgium.

Karagiozis, A. (1997). Analysis of the Hygrothermal Behaviour of Residential High-rise Building Components. Client Report A-3052.4, IRC/NRC, *National Research Council Canada*, Ottawa.

Kumaran, K., Lackey, J., Normandin, N., Tariku, F and van Reenen, D. (2004). A Thermal and Moisture Transport Property Database for Common Building and Insulating Materials, Final Report from *ASHRAE Research Project 1018-RP*, pp. 1-229.

Kumaran, K., Lackey, J., Normandin, N., van Reenen, D. and Tariku, F. (2002). Summary report from Task 3 of MEWS project. Institute for Research in Construction, *National Research Council*, Ottawa, Canada, (NRCC-45369), pp. 1-68.

Kumaran M. K., Mukhopadhyaya P., Cornick S. M., Lacasse, M. A., Maref W., Rousseau M., Nofal M., Quirt J. D. & Dalgliesh W. A. (2003). An Integrated Methodology to Develop Moisture Management Strategies for Exterior Wall Systems. *9th Conference on Building Science and Technology*, Vancouver, Canada, pp. 16.

Maref, W., Kumaran, M. K., Lacasse, M. A. Swinton, M. C. and van Reenen, D. (2002). Advanced Hygrothermal Model hygIRC: Laboratory Measurements and Benchmarking. *12th International Heat Transfer Conference*, Grenoble, France, pp. 1-6.

Mukhopadhyaya, P., Lackey J., Normandin N., Tariku F., and van Reenen, D. (2004). Hygrothermal Performance of Building Envelope Retrofit Options: Task 1 - A Thermal and Moisture Transport Property Database, IRC/NRC, *National Research Council Canada*, Ottawa, Client Final Report, pp. 1-37, (B-1137.5).

Mukhopadhyaya, P. and Kumaran, M. K. (2001). Prediction of Moisture Response of Wood Frame Walls Using IRC's Advanced Hygrothermal Model (hygIRC). *2nd Annual Conference on Durability and Disaster Mitigation in Wood-Frame Housing*, pp. 221-226.

Mukhopadhyaya, P. Kumaran, M. K. van Reenen, D. and Tariku F. (2001). Influence of Sheathing Membrane and Vapour Barrier on Hygrothermal Response of Stucco Walls, *International Conference on Building Envelope Systems and Technologies (ICBEST)*, Vol. 1, pp. 269-274.

Mukhopadhyaya, P., Kumaran, K., Rousseau, M., Tariku, F. van Reenen, D., and Dalgliesh, W.A. (2003). Application of Hygrothermal Analyses to Optimise Exterior Wall Design, *Research in Building Physics*, Sept. 14-18, Lueven, Belgium, pp. 417-426.

Mukhopadhyaya, P., and van Reenen, D. (2007). Assessment of Moisture Performance of Wood-frame Walls in China and Taiwan, IRC/NRC, *National Research Council Canada*, Ottawa, Client Final Report, pp. 1-176, (B1083.1).

Nofal, M. and Morris, P.I. (2003). Criteria for Unacceptable Damage on Wood Systems, *Japan-Canada Conference on Building Envelope*, Vancouver, Canada, 6/4/2003, pp. 1-14.

Swinton, M.C.; Sander, D.M., 1994. "Trade-off Compliance for Houses: Specifications for Calculation Procedures for Demonstrating Compliance to the National Energy Code for Houses using Trade-offs", pp. 46, March 01,(NRCC-39861).

Vinha, J. 2007, Hygrothermal Performance of Timber-Framed External Walls in Finnish Climatic Conditions: A Method for Determining the sufficient Water Vapour Resistance of the Interior Lining of a Wall Assembly, Ph.D. Thesis, Tampere University of Technology.