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3D Heat and Air Transport Model for Predicting the Thermal Resistances of Insulated Wall Assemblies

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ABSTRACT

A Wall Energy Rating (WER) system has been proposed to account for simultaneous thermal conduction and air leakage heat losses through a full-scale insulated wall system. Determining WER requires performing two standard tests on a full-scale wall specimen: a thermal resistance test and an air leakage test. A 3D model representation of the wall specimen is developed to combine the results of these tests to obtain an accurate prediction of the wall thermal resistance (apparent R-value) under the influence of air leakage. Two types of wall configurations were tested and simulated. The first one was a standard 2" by 6" wood stud frame construction, made of spruce, spaced at 16" (406 mm) o/c in 2.4 m x 2.4 m full-scale wall specimens. The second wall configuration was similar to the first one except that it included through-wall penetrations. The cavities of the two types of wall configurations were filled with different types of insulation, namely: glass fibre batts and two different types of open cell spray polyurethane foams (light density, 6.8 and 12 kg/m³ nominal), a total of six walls.

The present 3D model was used to predict the R-values of different types of wall assemblies (with and without air leakage). This model is a new hygrothermal tool that was recently developed and benchmarked against hygIRC-2D that was previously developed at the National Research Council of Canada, Institute for Research in Construction (NRC-IRC). The 3D version of this model was benchmarked by comparing its predictions of R-values for different types of wall assemblies against the measured R-values in the Guarded Hot Box (GHB) at no air leakage. Results showed that the present model predicted R-values of six walls to within $\pm 5\%$. The 3D model was then used to investigate the effect of air leakage rate on the apparent R-values for these same walls. The results showed that the apparent R-values decreases linearly with air leakage rate less than $\sim 0.1 \text{ L}/(\text{m}^2 \cdot \text{s})$. At air leakage rate greater than $\sim 0.1 \text{ L}/(\text{m}^2 \cdot \text{s})$, the apparent R-values decreases asymptotically.

Keywords: Thermal Resistance; CFD modelling; 3 Dimensional; Spray Polyurethane Foam; Walls, Assemblies, Air Leakage.

1 INTRODUCTION

Using Polyurethane Spray Foams (SPFs) as insulation in buildings provides durable and efficient thermal barriers. The industry is promoting SPF as an effective air barrier system in addition to its thermal insulation characteristics. In an effort to address these issues, a consortium of SPF manufacturers and contractors, jointly with the National Research Council of Canada's Institute for Research in Construction, (NRC-IRC) conducted an extensive research project, called Wall Energy Rating (WER), to assess the thermal and air leakage characteristics of SPF walls. Additionally, walls with glass fibre batts insulation with lapped (unsealed) poly were also considered to investigate a range of wall performance characteristics.

A few years ago, the North American SPF industry joined forces to develop a replacement of the commonly used chlorofluorocarbon blowing agent for spray-in-place insulation foams. The introduction of a second generation of blowing agents, namely hydro-chlorofluorocarbon (HCFC) was seen as a positive step in the processing of SPF; research conducted jointly between the SPF industry and NRC on other blowing agents and their performance helped demonstrate these apparent improvements [1 and 2]. In recent years, the focus of building code and regulatory officials, professionals and researchers has shifted towards the performance of the entire wall system. In respect to SPF, the current emphasis is on the contribution of SPF and other types of insulations to the control of heat, moisture and air through wall systems.

In the WER project, a number of walls insulated with glass fibre batts and different types of SPFs were built and tested. Material characterizations were also conducted to measure the thermal conductivities of a number of SPFs. The thermal conductivities of the light density open cell foams (6.8 and 12 kg/m³) used in this project were determined according to ASTM C 518 standard [3]. The test specimen was prepared according to the procedure outlined in the ULC standard S705 on thermal insulation of spray applied rigid polyurethane foam [4]. Additionally, the thermal resistances (R-values) of these walls were determined using the NRC-IRC's Guarded Hot Box (GHB) [5] at two temperature differences across the walls (40 K and 55 K) and no air leakage (i.e. pressure differences across the wall was 0). However, to investigate the effect of air leakage on the R-values of the walls, air leakage tests were conducted for these walls over a wide range of pressure differences at room temperature.

The test method used to determine the R-value for different walls is a well-established procedure developed at NRC-IRC and forms the basis for the ASTM GHB test standard and practice [5, 6 and 7]. The air leakage test method used is in accordance with that provided in ASTM E 283 [8]. All wall samples were conditioned according to the procedure described in the CCMC Air Barrier Guide 07272 [9]. More details about the experimental setup and test procedures are available in [10, 11 and 12].

The air leakage in buildings affects both energy consumption and indoor air quality. The infiltration through air-permeable insulation materials (e.g. glass fibre) can increase the heat loss. However, infiltration may also serve to dry out the wall systems. This thermodynamic process is absent in impermeable insulation materials (e.g. closed cell SPFs).

Feustel and Kendon [13] conducted a comprehensive review of various methods and models on the prediction and measurement of infiltration for building systems. The phenomenon of infiltration heat recovery inside the building envelope was first experimentally studied by Bhattacharyya and Claridge [14]. In this study, a modified calibrated hot box with the associated instrumentation was designed and constructed for testing a single stud cavity filled with glass fibre. The standard ASTM calibrated hot box method ASTM C976-82 [15] was modified to incorporate air flow through the test specimen. Several configurations of the wall specimen with different positions of inlet and outlet holes were tested at different infiltration flow rates [14].

Buchanan and Sherman [16] presented 2D and 3D CFD numerical model for the heat recovery in the building envelope. The model incorporated the heat transfer and airflow in the room, as well as that in the porous building envelope. Also, they developed a simple mathematical model to predict the heat recovery factor. The mathematical model agreed with the CFD results over a large range of infiltration rates. A similar 2D CFD model was presented by Abadie et al. [17], except that a boundary layer flow was considered instead of the whole indoor airflow field. This study showed the important effect of the external boundary layers on conduction and infiltration heat loads.

Recently, Qiu and Haghighat [18] developed a numerical model to investigate airflow and heat transfer in porous building material. After that model was benchmarked by comparing its predictions against the model of Buchanan and Sherman [16], and experimental data [19], it was used to investigate the thermal performance of the diffusive building envelope. In that study [18], numerical simulations were carried out to determine the contribution of air infiltration to the heat gain/loss through the “diffusive layer” representation of the building envelope. Additionally, they developed a simplified analytical model to determine the thermal performance of that layer. In that study, the whole wall was divided into ventilated and non-ventilated areas, and the ventilated area was modeled by adopting a uniform velocity distribution. They compared the results obtained by the numerical model and the simple analytical model. It was shown that the analytical model can accurately predict the performance of a diffusive building envelope.

The ultimate objective of the WER project is to develop a WER procedure that can be used as a simple tool for building designers and construction professionals. Both the accuracy and applicability of the developed WER procedure was enhanced by choosing a wide the range of different variables that can affect the wall thermal performance. As a result, some walls were constructed with penetration and other without penetration. Additionally, some walls were intentionally not sealed to represent leaky walls in order to cover a wide range of air leakage rate at different pressure difference across the walls. A brief outline of the WER project objectives and a limited set of results of two walls were

presented in an earlier paper [10] and test results of six walls were presented in a subsequent paper [11]. Two of these walls were intentionally constructed with some deficiencies to represent leaky walls for the purpose of development the WER procedure. These two walls (WER-1 and WER-5) were insulated with glass fibre. The air barrier featured poly that was lapped at a joint and penetrations were not sealed. Note that these two walls do not meet all the air barrier requirements of Canadian National Building Code (NBC) 2005 [20]. The other four walls were insulated with medium density closed cell SPF (34.9 to 46.3 kg/m³). The purpose of this study was not to compare the performance of the insulation products but the performance of airtight system versus leaky system regardless of the type of insulations. In a third paper [12], additional details on the testing program for another six walls was presented, in addition to a brief description of the analytical approach used to determine the Wall Energy Rating (WER) of insulated wall assemblies. Four of the six walls were insulated using light density open cell SPF (6.8 and 12 kg/m³). The remaining two walls were reference walls (WER-1 and WER-5, [11]).

The objective of this paper is to report on the development of the 3D numerical approach that was developed and on the results of 3D numerical simulations for walls with and without penetration from which was derived the R-values with and without air leakage. These simulations were conducted using the recently developed 3D hygrothermal model that solves simultaneously the highly nonlinear constitutive equations for Heat, Air and Moisture (HAM) transfer through materials. Using this model, the predictions of the R-values for different types of walls are compared with those measured from tests conducted in the GHB at zero air leakage. Following viable results in predicting the R-values at no air leakage, a parametric study was then conducted to predict the apparent R-values at different leakage rates that were measured for each wall assembly. The work in this project is progressing and the plan is to test and conduct 3D simulations for additional walls; this will help further develop and refine the WER procedure, which, it is expected, could be used as a simple tool for building designers and construction professionals. The WER procedure could also be used to assess whether specific wall configurations comply with current or future energy code requirements.

2 Need for 3D Heat and Air Transport Model

The heat flow through a wall assembly involves a multi-dimensional heat exchange within the wall. The multi-dimensional effect on the heat transfer through the wall becomes significant in a wall subjected to a large temperature difference (e.g. 40 - 55 K). This is due to the effect of thermal bridges that are created by wood frames. Also, in the case of a wall with a penetration, the wood frame around the penetration will create more thermal bridges. Air movement through the wall assembly is expected when pressure difference exists across the wall. The rate of air movement through a wall due to air leakage depends on the air tightness of the wall assembly as well as the air permeability of the different wall components. It is important to note that air movement through walls adds a convective heat transfer component when determining the overall degree of heat transfer across the wall.

The air leakage paths through the wall assembly are quite complicated. Figure 1 shows a schematic of air leakage paths through a wall assembly. In the air leakage tests, all wall perimeters were sealed. As such, for a given pressure difference across the wall, air enters the wall assembly at low temperature (e.g. -20°C or -35°C) through a 3 mm air gap between the two OSB sheathing boards. After the air finds its way through the wall, it exits mainly through the electrical outlet box located in the drywall. Because of the different shapes and locations of the 3 mm gap between the two OSB boards and the electrical outlet box, the air can move through the wall in vertical, horizontal and lateral directions (3D movement).

While air moves through the wall, it carries a quantity of heat that depends not only on the leakage rate but also on the temperature difference across the wall system. The air paths and movements within the wall assembly could be through the thermal insulation (the case of open cell SPF or glass fibre), through openings in construction (due to tolerances in installation practice), cracks, and due to material imperfections. The openings that occur due to construction tolerances results in air gaps between all solid-solid interfaces of the different wall components through which air can pass (studs – OSB, studs-top plate, studs-bottom plate, studs-gypsum board interfaces). Note that the amount of heat carried by the air depends on its local velocity. For example, a high local air velocity would result in a large effect in the local temperature distribution within the wall. In order to accurately predict both the temperature and heat flux distributions, and hence determine the wall thermal resistance, an accurate prediction for the velocity field in the wall is needed. However, to capture the multi-dimensional effects on the heat transfer and air flow through different wall assemblies (with and without penetration) there is a need to develop a 3D model to be used for evaluating the thermal performance of different wall systems.

Recently, a hygrothermal model (2D and 3D) that uses COMSOL as a solver was developed at NRC-IRC. This model solves simultaneously the highly nonlinear 2D and 3D Heat, Air and Moisture (HAM) transport equations. These equations were discretized using the Finite Element Method (FEM). The use of the FEM is important as it permits modeling complicated wall geometries with less discretizing errors. The present model accounts for surface-to-surface radiation (e.g. foundation wall system with low emissivity of foil bonded to expanded polystyrene foam in a furred-airspace assembly [20]). Recently, the 2D version of the present model was used to conduct numerical simulations in order to investigate the effect of the emissivity of foil on the effective thermal resistance of a foundation wall system with foil bonded to expanded polystyrene foam in a furred assembly with airspace next to the foil [20]. In this work, no moisture transport was accounted for in predicting the thermal performance of different types of walls. The heat and air transport equations in the different material layers are presented next.

3 Governing Equations

The continuity and momentum equations for air flow through porous medium are given as [22]:

Mass balance equation: $\varepsilon \frac{\partial \rho_f}{\partial t} = -\nabla \cdot \rho_f \vec{v}_f$ (1)

Darcy's law: $\vec{v}_f = -\frac{k_f}{\mu_f} (\nabla P - \rho_f \vec{g})$, (2)

where: P is the air pressure (Pa), $\vec{g}$ is vector of acceleration due to gravity (m^2/s), $\vec{v}_f$ is Darcy velocity vector of the air (m/s), ρ_f is air density (kg/m^3), ε is material porosity, k_f is air permeability (m^2), and μ_f is air dynamic viscosity (Pa.s). When Eqs. (1) and (2) are combined, the equation of motion of air through porous medium is rewritten as:

$$\varepsilon \frac{\partial \rho_f}{\partial t} = \nabla \cdot \left(\frac{\rho_f k_f}{\mu_f} (\nabla P - \rho_f \vec{g}) \right) \quad (3)$$

In the airspace (air gaps layers, electrical outlet box), the continuity equation and momentum equation (compressible Navier-Stokes equation) are respectively given as [22]:

$$\frac{\partial \rho_f}{\partial t} = -\nabla \cdot \rho_f \vec{v}_f, \text{ and} \quad (4)$$

$$\rho_f \frac{\partial \vec{v}_f}{\partial t} + \rho_f \vec{v}_f \cdot \nabla \vec{v}_f = -\nabla P + \nabla \cdot \left(\mu_f (\nabla \vec{v}_f + (\nabla \vec{v}_f)^T) - \frac{2}{3} \mu_f (\nabla \cdot \vec{v}_f) I \right) + \rho_f \vec{g}, \quad (5)$$

where, I is a 3x3 unit matrix

The energy equation in porous media is obtained from local volume averaging. An averaging volume should be sized small enough in order to not filter global flow structures but it should be large enough so as to guarantee containing both fluid and solid phases everywhere in the structure at all times. Such volume is called a Representative Elementary Volume, REV (see Figure 2). The volume-averaged energy equation for the fluid phase inside an REV is given in terms of fluid temperature, T_f , and solid temperature, T_s , as:

$$\frac{\partial}{\partial t} (\varepsilon \rho_f C_{p_f} T_f) + \nabla \cdot (\rho_f C_{p_f} \vec{v}_f T_f) = \nabla \cdot (\varepsilon \lambda_f \nabla T_f) + h_{sf} \alpha_{sf} (T_s - T_f) + q'''_{\text{source/sink}}, \quad (6)$$

where: C_{p_f} is the air specific heat ($\text{J}/(\text{kg} \cdot \text{K})$), λ_f is the air thermal conductivity ($\text{W}/(\text{m} \cdot \text{K})$), h_{sf} is the interfacial heat transfer coefficient ($\text{W}/(\text{m}^2 \cdot \text{K})$), α_{sf} is the specific surface area of the solid-fluid interface inside REV (m^2/m^3), and $q'''_{\text{source/sink}}$ is the volumetric heat source/sink (e.g. due to condensation/evaporation inside the REV) (W/m^3). Similarly, for the solid phase inside an REV, its volume-averaged energy equation is:

$$\frac{\partial}{\partial t} ((1 - \varepsilon) \rho_s C_{p_s} T_s) = \nabla \cdot ((1 - \varepsilon) \lambda_s \nabla T_s) - h_{sf} \alpha_{sf} (T_s - T_f) \quad (7)$$

The subscript s in the above equation refers to the solid phase. The second term on the RHS in Eqs. (6) and (7) was used to achieve the full coupling between the two energy equations of solid and fluid phases. It also represents the energy exchange between the two phases due to temperature difference between solid and fluid inside the REV.

In many practical applications, the temperature difference between the solid and fluid phases inside an REV is much smaller than the global scale temperature variation [23, 24]. This condition is met if the REV is much smaller compared to global length scale [25]. Under this condition, the temperatures of the fluid and solid phases could be assumed equal to the local thermodynamic equilibrium temperature, T . In other words, the local thermal equilibrium between the two phases inside an REV is assumed to occur. Based on this assumption, the energy equations for the fluid and solid phases (Eqs. (6) and (7)) are combined to one energy equation as:

$$\frac{\partial}{\partial t} ((\varepsilon \rho_f C p_f + (1 - \varepsilon) \rho_s C p_s) T) + \nabla \cdot (\rho_f C p_f \vec{v}_f T) = \nabla \cdot ((\varepsilon \lambda_f + (1 - \varepsilon) \lambda_s) \nabla T) + q'''_{\text{source/sink}} \quad (8)$$

In building applications, the range of the temperature difference across different building components is not large. As such, $C p_f$, $C p_s$, and ρ_s can be assumed constants (i.e. independent of temperature). Based on this assumption, the combination of the fluid mass balance equation given by Eq. (1) and the energy equation given by Eq. (8) leads to:

$$\rho_o C p_{\text{eff}} \frac{\partial T}{\partial t} + \rho_f C p_f \vec{v}_f \cdot \nabla T = \nabla \cdot (\lambda_{\text{eff}} \nabla T) + q'''_{\text{source/sink}} \quad (9)$$

where $\lambda_{\text{eff}} = \varepsilon \lambda_f + (1 - \varepsilon) \lambda_s$, and $C p_{\text{eff}} = C p_s + \varepsilon C p_f (\rho_f / \rho_o)$

The parameters $\rho_o = (1 - \varepsilon) \rho_s$, λ_{eff} and $C p_{\text{eff}}$ in Eq. (9) are the matrix density, effective thermal conductivity and effective specific heat, respectively, for a porous material. These parameters are measurable and obtained from material characterization. In the case of airspace, however, the energy equation is also given by Eq. (9) where $\varepsilon = 1$. In this case, $\lambda_{\text{eff}} = \lambda_f$ and $\rho_o C p_{\text{eff}} = \rho_f C p_f$.

Since no moisture transport was considered in this work, the last term on the RHS of Eq. (9) was neglected. The first term on the RHS of Eq. (9) accounts for heat transport by conduction. Also, the second term on the LHS of this equation accounts for heat transport by convection, where the velocity vector, $\vec{v}_f$, is given by Eq. (2) in the case of porous media and Eq. (5) in the case of airspace. In order to predict the wall thermal resistance (R-value), Eqs. (1), (2) and (9) for porous media, and Eqs. (4), (5) and (9) for airspace are solved simultaneously at the steady state condition, where only the effective thermal conductivity λ_{eff} (see Eq. (9)), and air permeability, k_f , of different material layers are need.

4 Benchmark the Present Model

Since the present model has 2D and 3D capabilities, its 2D capability was activated to compare its predictions against the hygIRC-2D model that previously developed at NRC-IRC [26 and 27]. Figure 3 shows a test case for a horizontal cut through a wall specimen and the different material layers. Note that symbol (M-xx) in this figure specifies the material ID number in the NRC-IRC database of the material properties. Also, this figure shows the boundary conditions that have been used in this test case.

Figure 4 shows the temperature contours in this horizontal cut obtained using hygIRC-2D [28] and the present 2D model. As shown in this figure, both models predict the same temperature distribution. Furthermore, as shown in Table 1, the calculated heat fluxes (on the top, bottom, left and right sides) and the R-value using hygIRC-2D and the present 2D model are identical. Other test cases using the 2D capability of the present model were carried out and the obtained results were compared against the hygIRC-2D model. The results showed that the predictions of both models are in good agreement. Another step for benchmarking the present 3D model was taken by comparing its predictions for the R-values of six wall specimens against the measured R-values in the Guarded Hot Box (GHB). The descriptions of these walls and the material properties used in the numerical simulations are presented next.

5 Description of Wall Specimens

Six wall specimens were constructed according to common North American construction industry practice. All walls were built according to the CCMC Air Barrier Guide 07272 [9]. Table 2 provides a brief description of these walls. Figure 5 and Figure 6 show wall specimens with and without penetration, respectively, illustrating the construction details. The six walls listed in Table 2 were built using the conventional 2" by 6" (38 mm by 138 mm) wood stud frame construction. The studs were spaced at 406 mm (16") on center with double top plates and a single bottom plate. A 19 mm stud was used at each end of the wall. Two reference walls were lapped poly, no sealing of penetrations and the insulation not contributing to the air barrier (WER-1 and WER-5) and the other four walls (WER-AA, WER-BB, WER-CC and WER-DD) were insulated with two light densities, open cell SPF insulations (6.8 and 12 kg/m³). Three walls were opaque (WER-1, WER-AA and WER-CC) and other three included penetrations (WER-5, WER-BB and WER-DD) to simulate a window (see Figure 7 for the details of the window). Thermal test and air leakage test were conducted for these walls and the results of these tests are available in [12].

WER-1 and WER-5 were built to field installation practices to illustrate the Wall Energy Rating with poor air tightness, including the following detailing choices:

- Part 9 of the National Building Code of Canada (NBC) 2005 [20] requires one of two options be followed for air barrier continuity between 2 sheets of poly for the air barrier:
 1. Sealing the joint
 2. Lapping the joint by not less than 100 mm and clamping between framing members and rigid panels

We chose the second option, with the understanding that it is likely less effective in controlling air leakage.

- NBC 2005 [20] also requires sealing of windows, piping, ducting and electrical boxes to maintain the integrity of the air barrier.

We purposely did none of these.

So WER-1 and WER-5 do not meet all of the air barrier requirements of NBC 2005 [20].

The present 3D model was used at steady-state condition to predict the R-values of different wall specimens with and without air leakage. At steady-state condition, however, the only material properties needed for the numerical simulations are the effective thermal conductivity (λ_{eff} , see Eq. 9) and air permeability (k_f) of the different material layers. These properties are listed in Table 3. All material properties shown in this table except the effective thermal conductivities of the open cell SPF insulations were obtained from Kumaran et al. [29]. The effective thermal conductivity of the open cell foams were measured at the NRC-IRC's material characterization laboratory. The test method used to measure the thermal conductivity was ASTM C 518 [3].

6 Assumptions, Boundary Conditions, and 3D Simulations

This section presents the assumptions, boundary conditions and the steps of conducting numerical simulation using the present 3D model for different walls with and without penetration. Each wall specimen was made of a number of material layers. Before conducting thermal tests in the GHB, all wall samples before and after conditioning were tested at room temperature to determine their air leakage performance at different pressure differential across the wall according to ASTM E283 (ASTM 1997) (see references [10], [11] and [12] for more details). The extraneous air leakage (system air leakage) was determined for each wall assembly. After many modifications in the NRC-IRC's air leakage tester, the system has approximately zero extraneous air leakage. All perimeter boundaries of each wall assembly were sealed (i.e. no air transport, $\vec{n} \bullet \vec{v}_f = 0$). As such, for a given pressure difference across the wall assembly, the air enters the wall specimen through a 3 mm air gap between the two OSB sheathing boards and exits through the electrical outlet box (see Figure 5 and Figure 6 for a wall without and with penetration, respectively).

Figure 1 shows the air leakage paths through the wall assembly. It was assumed that there is a 1 mm air gap to represent construction tolerance at all solid-solid interfaces, namely: studs-OSB, studs-gypsum board, studs-top plate, and studs-bottom plate interfaces. In the case of wall specimens with penetrations, the window wood frame adds more construction tolerances than wall specimen without penetrations. As such, for the same pressure difference across the wall, the measured air leakage rate in the wall with penetrations was higher than that for wall without penetration (see reference [12] for more details). Consequently, it is expected that the R-value of a wall specimen with penetrations would be lower than that for wall without penetrations due to the greater number of thermal bridges and higher air leakage rate in the former as compared to the latter. In all wall assemblies, it was assumed that the thermal insulations were in good contact with other wall components (the glass fibre batts were friction fit with other wall components, and the open cell foams were sprayed-in-place).

The boundary conditions used to solve the air transport equation are: (a) inlet boundary at the exterior surface of the 3 mm air gap between the OSB layers with prescribed uniform velocity. This velocity was calculated from the measured air leakage rate at a given

pressure differential across the wall, and (b) outlet boundary at the exterior surface of electric box with prescribed pressure of 101 kPa. To check the air mass balance at steady state condition, however, the predicted air mass flow rate at the outlet of the electrical box was equal to the air mass flow rate at the 3 mm air gap between the two OSB layers. Because the shape and the location of the 3 mm air gap and the electrical outlet box are quite different, the air moves through the wall specimen in all directions (x-, y-, and z-direction, see Figure 1).

The boundary conditions used to solve the heat transport equation are: (a) adiabatic (i.e. no heat losses, $\vec{n} \bullet k \nabla T = 0$) on all perimeter boundaries, (b) convective boundary condition on the outdoor wall surface with prescribed air temperature and heat transfer coefficient of -20°C and 8 W/(m²K), respectively, and (c) convective boundary condition on the indoor wall surface with prescribed air temperature and heat transfer coefficient of +20°C and 8 W/(m²K), respectively. In this study, the effects of wind and thermal radiation on both outdoor and indoor surfaces of the wall were neglected. Although the present 3D model has the capability of handling hygrothermal properties as a function of temperature, the thermal conductivities of the different material layers were taken as being constant. This is because the measured thermal conductivities were very nearly constant within the temperature range that was used in conducting the thermal tests in the GHB (see [12] for more details).

In all wall specimens, it was assumed that the thermal insulations were uniformly distributed in the stud cavities. In the case of wall with open cell SPF, small air voids were observed in the foams. Because the thermal conductivity of the air (~0.025 W/(m.K)) is comparable with the values of the thermal conductivities of these foams (see Table 3), the small air voids in the foams would not have a significant effect on the R-values. The type of mesh used in the numerical simulations is tetrahedral elements. Several mesh size were tested to identify the mesh size needed to obtain a mesh-independent solution. In the numerical simulation, the convergence criteria were set to 10⁻⁶. The temperature contours and air velocity field in a wall specimen with and without penetrations is provided next.

7 Heat Transfer and Air Flow in Wall Specimens with and without Penetrations

Figure 8 & Figure 9, and Figure 10 & Figure 11 show the air velocity field in a wall specimen without penetration (WER-1) and with penetration (WER-5), respectively, for measured leakage rates at a pressure difference across the wall of 75 Pa. In these figures, the highly 3-dimensional nature of the air leakage flows through the wall can be easily recognized. The length of the velocity arrows is proportional to the magnitude of the resultant velocity, v_{res} ($v_{res} = \sqrt{u^2 + v^2 + w^2}$). The air enters the wall specimen through the 3 mm air gap between the OSB sheathing boards at -20°C. Then, it flows through the wall and eventually exits the wall assembly through the electrical outlet box. As shown in these figures, the local air velocity and its direction vary within the wall specimen. The effects of the air flow through these wall specimens on the local temperature distribution are shown Figure 12 and Figure 13. These figures show the temperature

contours in a slice passing through the middle of the wall assemblies at a leakage rate corresponding to $\Delta P = 75$ Pa. As shown in these figures, the local value of the air velocity greatly affects the local temperature distribution in the wall. For example, the region around the entry points of the air into the wall assembly has the lowest temperatures. Accurate prediction of the apparent R-value for a wall assembly requires capturing the three-dimensional effect on both the air flow and heat transfer through the wall assembly. The comparison of the present 3D predictions for the R-values of the six wall specimens listed in Table 2 against the measured R-values are presented next.

8 Results and Discussion

The present 3D model was used to predict the R-values for the six wall assemblies shown in Table 2 with and without air leakage. As indicated earlier, the test method used to determine the R-values of all wall specimens is based on the ASTM GHB test standard and practice [5 and 7]. Details of the measurements of R-values and air leakages for different wall specimens are available in [10, 11, and 12]. Figure 14 and Figure 15 show sample results of the measured R-values in the GHB for the wall specimens WER-AA, WER-BB, respectively, with open cell SPF as thermal insulations. The steady state condition was achieved after ~ 10 hours. As shown in these figures, about $2/3$ of the collected data for R-values falls within 1σ (where, σ = standard deviation value in $\text{m}^2\text{K/W}$). The mean R-values for WER-AA and WER-BB were 3.59 and 3.30 $\text{m}^2\text{K/W}$, respectively. The corresponding standard deviation values of the measured R-values were 0.10 and 0.08 $\text{m}^2\text{K/W}$, respectively. The 1σ corresponds to a deviation from the mean R-values of $\pm 2.8\%$, and $\pm 2.5\%$, for WER-AA and WER-BB, respectively. These figures clearly show that the uncertainty in most of the collected data for R-values was $\sim \pm 6\%$ (see Elmahdy, [5]).

Because the thermal conductivity of the studs is greater than that of the different types of thermal insulations (see Table 3), these studs act as thermal bridges. In the case of wall specimens with penetrations, a greater number of thermal bridges exist as a result of the window wood frame (Figure 7). As such, the wall specimens with penetration results in lower R-values than that without penetration. For example, the stud cavities of both WER-AA (opaque wall) and WER-BB (wall with penetration) were filled by the same type of thermal insulation (open cell foam). The predicted and measured R-values for WER-AA were 3.44, and 3.59 $\text{m}^2\text{K/W}$, respectively. For WER-BB, however, the predicted and measured R-value (3.28, and 3.30 $\text{m}^2\text{K/W}$, respectively) were lower than that for WER-AA (see Figure 14 and Figure 15). Figure 16 shows a comparison between the predicted R-values using the present 3D model and the measured R-values for the six wall specimens listed in Table 2 at no air leakage. As shown in this figure, the predicted R-values for all wall are in good agreement with the measured ones (within $\pm 5\%$).

After gaining confidence in the present 3D model in predicting R-values at no air leakage, it was then used to predict the apparent R-values at different air leakage rates for the six wall specimens. The CCMC Air Barrier Guide [9] sets the maximum allowable air leakage rate for the product to be labeled as “air barrier”. This limit is set at 0.05 $\text{L}/(\text{m}^2\cdot\text{s})$ at pressure difference, $\Delta P = 75$ Pa for higher indoor relative humidity

environments. In order to investigate the dependence of the apparent R-value of a wall system on the air leakage rate, the numerical simulations were conducted for a wide range of pressure difference across the wall. The apparent R-value for the wall specimens with glass fibre as thermal insulation (WER-1 and WER-5) was obtained at ΔP across the wall of 75 and 150 Pa. However, for wall specimens with light density open cell SPFs (WER-AA, WER-BB, WER-CC, and WER-DD), the apparent R-value was calculated at a different ΔP up to 600 Pa. Given that the air leakage rate increases linearly with ΔP (see reference [12] for more details), the values of the air leakage rates at a ΔP greater than 175 Pa were obtained by linear extrapolation. The predicted apparent R-values for the walls with open cell SPFs and glass fibre are shown in Figure 17 and Figure 18, respectively. As shown in these figures, the apparent R-values decrease as the air leakage rate increases. Within the range of air leakage rate of 0 - ~ 0.1 L/(m².s), the apparent R-values decreases linearly with air leakage rate (see Figure 17). On the other hand, for air leakage rate greater than ~ 0.1 L/(m².s), the apparent R-values decreases asymptotically. To show the dependence of apparent R-value of different wall assemblies on the air leakage rate, a dimensionless parameter is introduced (β). This parameter is defined as the ratio of R-value at a given air leakage rate (RSI_L) to the R-value at no air leakage (RSI_0):

$$\beta = RSI_L / RSI_0 \quad (10)$$

Practically, the value of $(1 - \beta)$ represents the reduction in the wall R-value due to air leakage ($\beta \leq 1.0$). Figure 19 shows the dependence of the dimensionless β -values on the air leakage rate (ξ) for the six wall specimens (Table 2). As shown in this figure, the β -value decreases linearly as ξ increases from 0 to ~ 0.1 L/(m².s) (see the black-dashed line in this figure). However, for ξ greater than ~ 0.1 L/(m².s), the β -values decreases exponentially. Furthermore, Figure 19 shows that all β -values for these walls collapsed nicely on a single line, which can be represented as:

$$\beta = \exp(a \xi^b + c \xi^d), \quad (11)$$

where,

ξ = air leakage rate in L/(m².s),

$a = -1.85 (\text{m}^2.\text{s}/\text{L})^{0.95}$, and $b = 0.95$, $c = 0.36 (\text{m}^2.\text{s}/\text{L})^{2.79}$ and $d = 2.79$

Note that the calculated β -values using the expressions above goes to 1.0 as the air leakage rate, ξ , approaches to 0.0. The calculated β -values using the above expression for different air leakage rates of the six walls with and without penetration were within $\pm 3\%$.

9 Conclusions

3D numerical simulations were conducted using the present model for different walls with and without penetrations to predict the R-values with and without air leakage. The

2D capability of the present model was used to compare its predictions against the hygIRC-2D model, previously developed at NRC-IRC. The results showed that the predictions of both models are in good agreement. After gaining confidence in the present model, its 3D capability was used to predict the R-values of six wall specimens with and without penetrations at no air leakage. Two of these walls were insulated with glass fibre (reference walls) with an unsealed poly – air barrier that resulted in high rates of air leakage. The other four walls were insulated using light density open cell SPF (6.8 and 12 kg/m³) with sealed double top plates that resulted in good air tightness. The predicted R-values for these walls were in good agreement with the measured R-values in the Guarded Hot Box (GHB) (within $\pm 5\%$). The present 3D model was also used to predict the apparent R-values at different air leakage rates corresponding to pressure differences across the six wall specimens up to 600 Pa. Results showed that the apparent R-value decreases linearly as air leakage rate increases within the range 0 - $\sim 1.0 \text{ L}/(\text{m}^2 \cdot \text{s})$, and decreases exponentially for air leakage rate greater than $\sim 0.1 \text{ L}/(\text{m}^2 \cdot \text{s})$.

The results obtained for wall R-values with and without air leakage for the six walls presented in this paper, as well as for other walls that used medium density closed cell SPFs as thermal insulation [10, 11], and new walls that are currently being built and tested at NRC-IRC, will be used to develop a simple engineering correlation for determining the Wall Energy Rating (WER) number for different types of wall systems. The results of these efforts will be the subject for future publications.

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Table 1. Comparison of the calculated heat fluxes and R-value using hygIRC-2D and present 2D model for the test case shown in Figure 3

Parameter	hygIRC-2D	Present 2D model
Average heat flux at Left side (W/m ²)	20.08	20.09
Average heat flux at right side (W/m ²)	20.08	20.09
Average heat flux at top side (W/m ²)	0.00	0.00
Average heat flux at bottom side (W/m ²)	0.00	0.00
R-value (m ² K/W)	2.49	2.49

Table 2. A brief summary of wall description

Wall	Wall Description	Comments
WER-1	Poly-wrapped glass fibre (without penetration)	Poly sheets are over-lapped and sealed
WER-5	Poly-wrapped glass fibre (with penetration)	Same as above
WER-AA	Open cell foam (without penetration)	Foam is applied in the full cavity
WER-BB	Open cell foam (with penetration)	Same as above
WER-CC	Open cell foam (without penetration)	Same as above
WER-DD	Open cell foam (with penetration)	Same as above

Table 3. Effective Thermal conductivity and air permeability of the different layer of the six wall specimens [29]

Wall Layer	Effective Thermal conductivity, $\lambda_{eff} = \varepsilon\lambda_f + (1-\varepsilon)\lambda_s$ W/(m.K)	Air permeability, k_f (m ²)
Spruce (wood frame)	0.09	7.08E-16
OSB (sheathing board)	0.09	3.12E-14
Gypsum board	0.159	5.66E-14
Glass Fibre Batts (WER-1, WER-5)	0.039	3.54E-09
OCF (WER-AA, WER-BB)	0.0352*	5.95E-14
OCF (WER-CC, WER-DD)	0.0388*	5.95E-14
XPS (penetration)	0.0289	1.42E-25

* Measured in this project according to ASTM C 518 [3].

Figure 1. A schematic showing the air leakage paths through a wall system

Figure 2. Schematic of Representative Elementary Volume (REV) in porous media

Figure 3. A horizontal cut through a wall showing different materials and boundary conditions

Figure 4. Comparison of the temperature contours using hygIRC-2D and present 2D model for the test case shown in Figure 3

Figure 5. 3D presentation of wall specimen without penetration

Figure 6. 3D presentation of wall specimen with penetration

Figure 7. Window assembly for wall with penetrations

Figure 8. Isometric view of the air velocity arrows in WER-1 at 75 Pa

Figure 9. Different views of the air velocity arrows in WER-1 at 75 Pa

Figure 10. Isometric view of the air velocity arrows in WER-5 at 75 Pa

Figure 11. Different views of the air velocity arrows in WER-5 at 75 Pa

Figure 12. Temperature contours in a lateral slice passing through the middle of the wall WER-1 at a leakage rate corresponding to 75 Pa

Figure 13. Temperature contours in a lateral slice passing through the middle of the wall WER-5 at a leakage rate corresponding to 75 Pa

Figure 14. Measured R-value at steady state condition for WER-AA ($\Delta P = 0$ Pa)

Figure 15. Measured R-value at steady state condition for WER-BB ($\Delta P = 0$ Pa)

Figure 16. Comparison of the predicted R-values with measured ones for the six walls

Figure 17. Effect of the air leakage on the apparent R-value of open cell SPF wall assemblies

Figure 18. Effect of the air leakage on the apparent R-value glass fibre wall assemblies

Figure 19. Dependence of the dimensionless R-value (β) on the air leakage rate for different wall assemblies.