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Use of hygrothermal numerical modelling to identify optimal retrofit options for -rise buildings

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Abstract
Using numerical modelling to simulate and predict the hygrothermal (i.e., combined thermal and moisture) performance of building envelopes is very recent. Key questions include: how to model accurately coupled heat-air and capillary moisture transports in building envelope components; a satisfactory definition of a set of representative environmental boundary conditions to be used for long-term hygrothermal calculations; how to characterize the moisture- and temperature-dependent properties; the effect of aging and cyclic environmental conditions on porous building materials; and how to develop sound criteria to predict the moisture durability of building envelope components. This paper presents the findings of a research project involving detailed hygrothermal modelling. The heat, air and moisture results demonstrated that the in-house model could be adapted successfully for high-rise building calculations. The findings also show how the long-term hygrothermal performance of typical wall systems can be assessed using numerical modelling. A short description of an advanced in-house heat, air and moisture model, hygIRC, is also presented.

Key words:

1. Introduction
It is projected that most of Canada's aging high-rise building stock will require some sort of building envelope retrofit in the near future to enhance and extend service life. One of the most problematic issues with both low and high buildings is the premature degradation of the exterior building shell due to the effect of moisture within the porous building envelope. Higher levels of moisture and temperature over time in ill-designed building envelopes cause many of the degradation factors affecting service life. The addition of insulation when retrofitting existing building structures or the reduction of air leakage can alter the heat, air and moisture regimes within these assemblies. In some cases, performance is improved, in others it is not. Predicting the impact of supplementary insulation and air-sealing retrofits can be challenging as hygrothermal properties, assembly characteristics and indoor-outdoor environmental conditions must be considered. A research project at the Institute for Research in Construction (IRC) addressed some of these questions. The main objective was to adapt the IRC's existing in-house model, hygIRC, to assess the long-term effects of various high-rise wall designs and post-retrofit conditions, specific weather, ventilation and the indoor environment. The first task was to assess the reliability of the adapted hygIRC. To do this, a significant number of simulations were performed: five base case wall systems and the corresponding retrofit options (Djebbar et al., 2002). The five walls are typical of the exterior envelopes used in Canadian commercial and residential high-rise buildings. The parametric analysis was conducted by simulating the hygrothermal response of the walls when subjected to the outdoor climate of five Canadian geographical locations and two types of indoor environment. This paper presents the basic governing equations embedded in the in-house model and the results of the parametric analysis performed within the frame of the research project.

2. Hygrothermal mathematical model

equations (PDEs) of heat-air and moisture mass transfer in porous building materials. The model is based on three physical laws: Fick, Fourier and Darcy's laws. The moisture contents in the building envelope components are obtained by solving vapour diffusion and capillary liquid moisture mass balance, PDE 1. Temperatures as well as the heat fluxes through the envelope components are derived from PDE 2. Field velocities are derived by using creeping (Stokes) flow in a porous media type of approach. PDE 3 and Equation 4 are solved to derive the field velocities. The model is continuously upgraded, benchmarked and validated. LATENITE, the earlier version of hygIRC was benchmarked during the International Energy Agency-Annex 24 activities by performing inter-model round robin comparisons (Hens, 1996). Recently, a series of drying experimental laboratory tests to validate hygIRC were conducted within a consortium project by Maref et al. (2002). The results showed good agreement between the experiments and the simulations. More details on the in-house hygrothermal model, hygIRC, may be found in (Karagiozis and Kumaran, 1993), (Salonvaara and Karagiozis, 1994) and (Djebbar et al., 2002).

$$\rho_o \frac{\partial(u)}{\partial t} + \nabla.\left(-\rho_o D_w \nabla u + K_w \rho_w \vec{g} - \delta_p \nabla P_v + \rho_v \vec{V}_a \right) = Q_m \quad (1)$$

$$\frac{\partial\left(\rho_T C_p T \right)}{\partial t} + \nabla.\left(\rho_a C_{pa} \vec{V}_a T\right) = \nabla(\lambda \nabla T) + L_v\left(\nabla.\left(\rho_o \delta_p \nabla P_v\right)\right) - L_{ice}\left(\rho_o u \frac{\partial f_l}{\partial t} \right) + Q_h$$

$$\nabla.\left(\rho_a \vec{V}_a\right) = 0$$

$$0 = -\nabla P_a + \rho_a \vec{g} - \frac{\mu_a}{k_a} \vec{V}_a$$

Where u is moisture content (kg moisture)/(kg dry material). K_w, liquid moisture permeability (kg/m s Pa). Q_m moisture source volumetric rate ((kg moisture /s)/m^3). Q_h, heat source volumetric rate (W/m^3). Q_m and Q_h account for the moisture and thermal sources at the indoor and outdoor boundary conditions as well as the internal moisture and thermal sources respectively. Pv vapor moisture pressure (Pa). $\vec{V}a$ air velocity vector (m/s). ρ_a air partial density (kg/m^3). ρ_o density of the dry porous material (kg/m^3). ρ_w liquid moisture partial density (kg/m^3). D_w liquid moisture diffusivity (m^2/s). δ_p vapor water permeability (kg/ m s Pa). Pa air pressure (Pa). μa air dynamic viscosity (Pa s). Cp effective specific heat capacity (J/kg K). Cpa dry-air specific heat capacity (J/kg K). f_l liquid fraction having a value from 0 to 1. λ Effective thermal conductivity (W/m K). L_v enthalpy of evaporation/condensation (J/kg). L_{ice} enthalpy of freeze/thaw (J/kg). ρ_T actual total density of the material including moisture contribution (kg/m^3). The IRC's materials hygrothermal properties database was used to solve the governing equations. The approach adopted to apply the long-term indoor and outdoor boundary conditions may be found in (Djebbar et al., 2001) and (Djebbar et al., 2002)

3. Simulations results

over three years (i.e., 1095 days equivalent to 26 280 hours). The walls are assumed to be located at the top corner of a 10-storey building facing the prevailing wind direction during rain events at the considered geographical location. The moisture and thermal conditions at the start of the simulations are 80% relative humidity and 5°C in all the wall components. Heat and mass transfer across the top and bottom wall surfaces to the slabs are assumed negligible and are not considered in the parametric analysis. A number of simulations were carried out to ensure results independent of the initial moisture conditions of the wall assemblies. (See Figure 2.)

One-dimensional results:

walls (BV/SS); brick veneer with hollow core concrete masonry unit back-up walls (BV/CMU); pre-cast concrete walls with steel stud back-up walls (CV/SS); thin stone veneer with solid concrete masonry unit back-up walls (SV/CMU); and load-bearing masonry wall systems with a stone veneer (SV/BMU). The performance of the wall systems was assessed for five Canadian geographical locations. The results reflected correctly the weather features of the five locations considered in this study. (See Figure 3.) Higher moisture levels in walls were obtained consistently in the coastal areas, Vancouver and Halifax (Shearwater), and lower moisture levels in the prairies, in Winnipeg. Vancouver and Halifax (Shearwater) both had a poor yearly drying-out potential and higher wind-driven moisture loads. Winnipeg was at the other end of the spectrum in terms of weather hygrothermal loads. Thermal analysis of the simulation results predicted correctly a higher total heat loss in Winnipeg during the winter for all the walls considered. Winnipeg has the higher heating degree hours among the five cities. Effects as a result of the type of materials were also consistently predicted in all the calculations. The hygrothermal properties of extremely porous brick were used in the simulations for two brick veneer walls considered in the study: BV/SS and BV/CMU walls. In all the base case and retrofit options of the two wall systems, higher moisture levels and accumulations were predicted in the brick cladding material. (See Figure 4.). The CV/SS base case and its corresponding retrofit walls were subjected to both a controlled and uncontrolled indoor air-humidity environment. The simulation results predicted correctly the fact that only the interior finish drywall is affected by indoor moisture levels. This is the case of perfectly airtight walls with the vapour barrier fully performing its task as assumed in the 1D parametric analysis. The BV/SS, BV/CMU and CV/SS wall systems were subjected to an uncontrolled indoor environment, implying higher moisture levels during the cooling season. A significant moisture contribution in the total heat balance in the three wall systems was predicted. (See Figure 5.) These results were expected. The indoor environment model used implies that extreme outdoor moisture conditions generate proportional conditions in the indoor air. Therefore, a simultaneous extreme moisture load results on both sides of the walls.

		Base case BV/CMU wall	Retrofitted BV/CMU wall
Minimum leakage rate (L/s m^2)	**exfiltration**	**1.6 10^{-4}**	**1.3 10^{-4}**
	infiltration	**4.1 10^{-4}**	**8.2 10^{-4}**
Maximum leakage rate (L/s m^2)	**exfiltration**	**7.37**	**6.3**
	infiltraion	**6.09**	**5.2**
Mean leakage rate (L/s m^2)	**exfiltration**	**0.94**	**0.81**
	infiltration	**0.84**	**0.72**
Yearly total leakage rate (L/ m^2)	**exfiltration**	**2.78 10^{+7}**	**2.38 0^{+7}**
	infiltration	**1.71 10^{+6}**	**1.49 10^{+6}**
Airflow direction (%)	**exfiltration**	**93**	**93**
	infiltration	**7**	**7**

Table 1: Air leakage rates: statistics for year 3 of simulations

Two-dimensional results:

7.) This is expected, since the retrofitted BV/CMU wall is more thermal-resistant than the BV/CMU base case wall. The temperature levels in the interior components increase when they are part of the BV/CMU wall compared to when they are part of the base case BV/CMU wall. More warm components have a greater moisture absorption and retention capacity. The 2D analysis also showed that the moisture effects of air leakage were important in the components that are more air permeable, such as the expanded polystyrene in the two walls and glass fiber insulation in the retrofitted wall. (See Figure 8.) The importance of the air-leakage in the total energy balance of the two walls was also demonstrated by the 2D results. (See Figure 9.) The contribution in the energy loss through the wall components due to air-leakage was found comparable to the energy loss through the dry heat transfer (i.e., pure heat conduction transfer).

4. Summary

5. Acknowledgments

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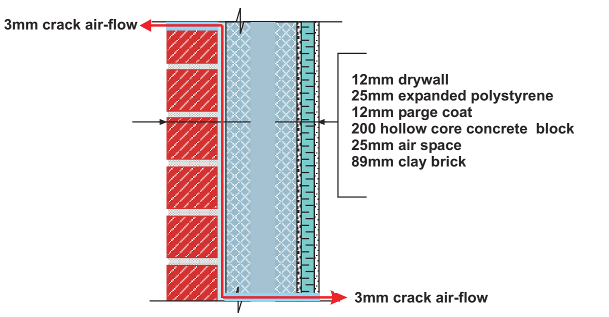

Figure 1a. Building envelope's components of the BV/CMU base case wall system

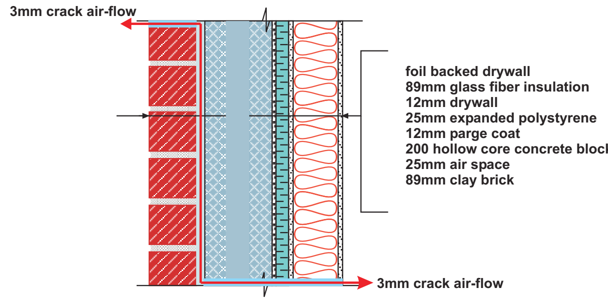

Figure 1b. Building envelope's components of the BV/CMU retrofitted wall system

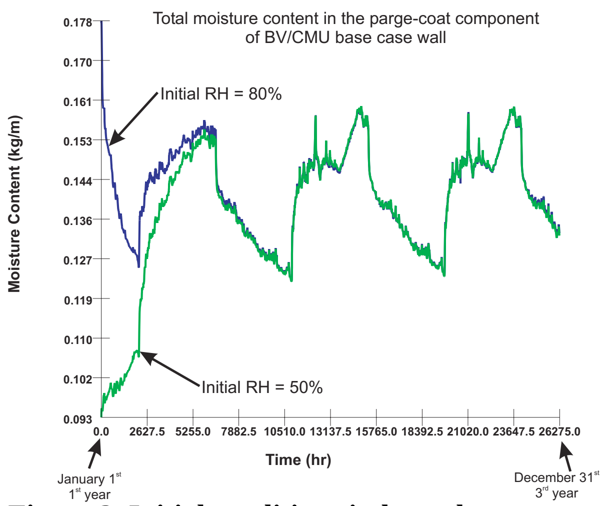

Figure 2. Initial conditions independence

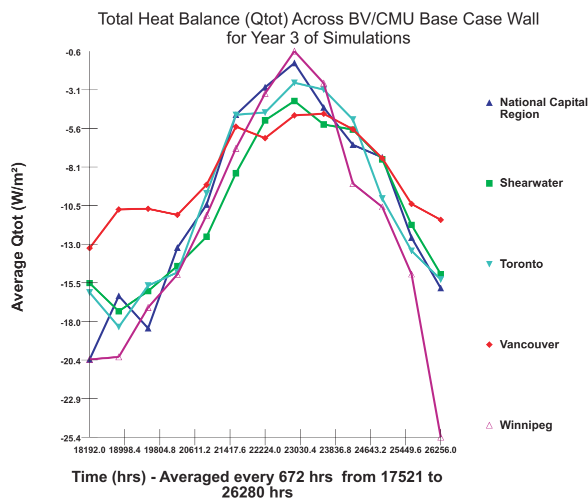

Figure 3. Weather effect analysis

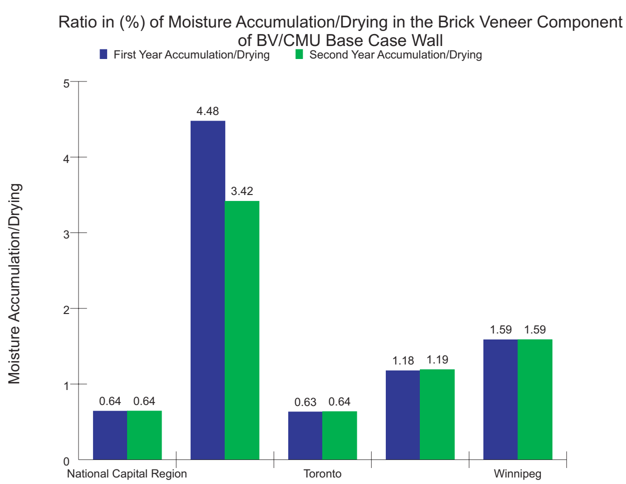

Figure 4. Components moisture performance

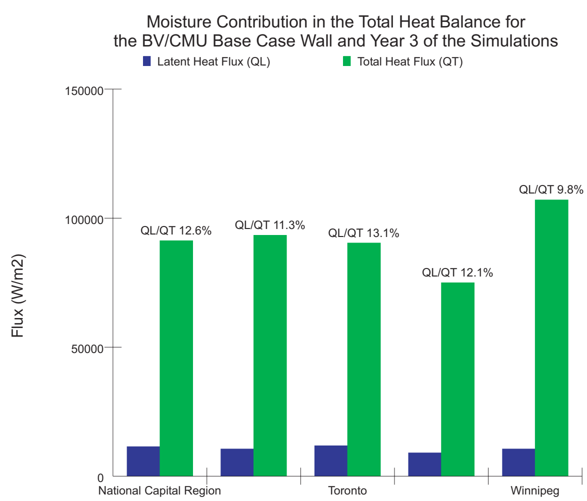

Figure 5. moisture impact on thermal performance

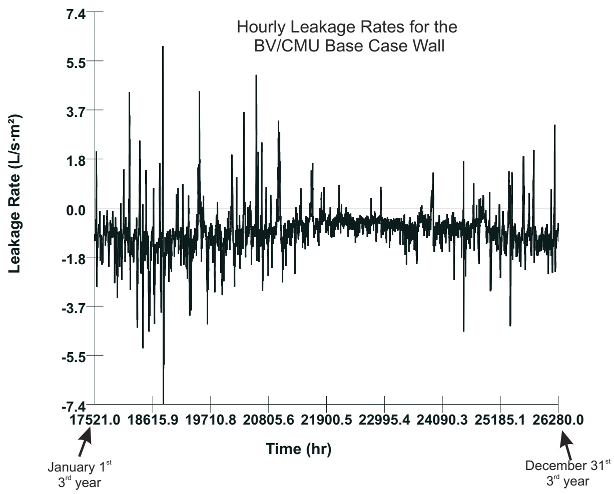

Figure 6. Air leakage rates analysis. Positive-negative leakage rates means air infiltration-exfiltration

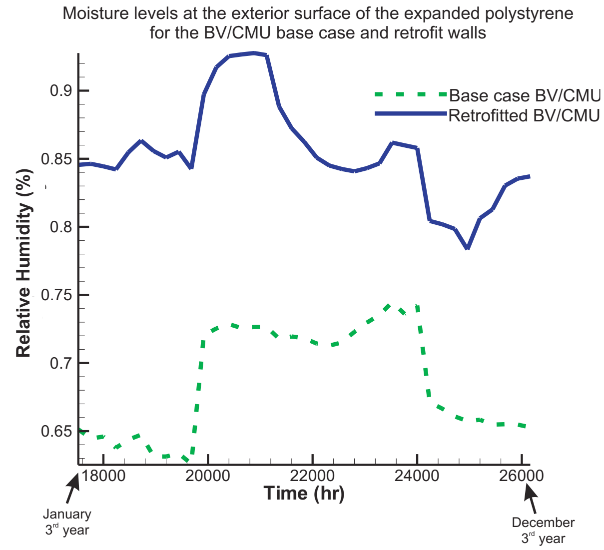

Figure 7. Moisture spatial analysis of the post-retrofit condition

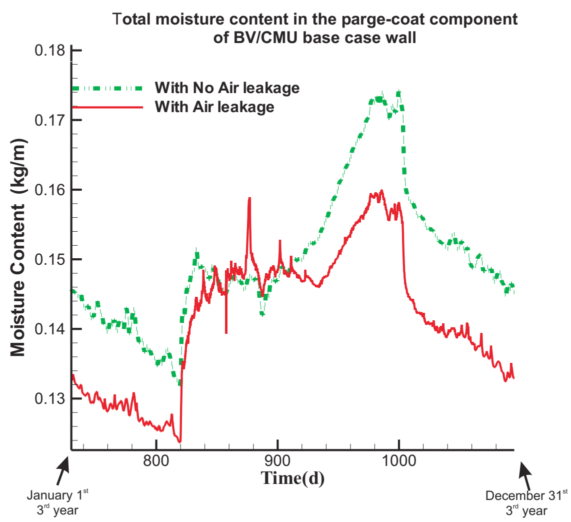

Figure 8. Analysis of the air-leakage effect on moisture performance

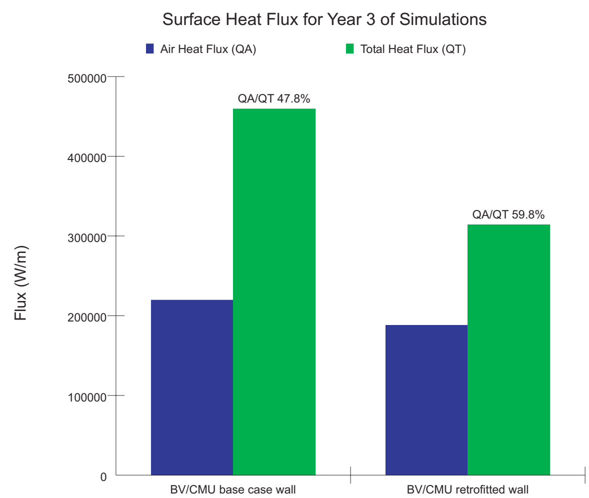

Figure 9. Heat flux analysis