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Application of Modeling Tool to Assess Moisture and Thermal Performance of Retrofitted Wall Assemblies

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ABSTRACT

As the stock of buildings in Canada ages, it is expected that there will be an increase in building envelope rehabilitation work. Such activities represent an ideal opportunity to add insulation and reduce air leakage to improve energy efficiency and building envelope durability. However, there is very little information available on how to assess the moisture and thermal (i.e. energy) performance of retrofitted building envelope assemblies and select the optimum retrofit options that will maximize the energy efficiency without compromising the long-term moisture performance of the retrofitted building envelopes.

This paper depicts selected results from a study that has used a two-dimensional hygrothermal simulation tool, *hygIRC-2D*, to assess thermal and moisture performance of retrofitted masonry walls used in high-rise construction. The performance analyses of three basic (i.e. base case) masonry wall systems (Brick Veneer - Steel Stud, Brick Veneer - Concrete Masonry, and Precast Concrete Panels - Steel Stud) with four retrofit options, located in the National Capital Region (Ottawa-Gatineau) of Canada, are presented in this paper.

The results from the simulations indicate that hygrothermal simulation tools can be used to evaluate the thermal and moisture performance of various wall systems and associated retrofit options. Simulations results also indicate that with specific retrofit options the energy performance of the wall system can be improved significantly without compromising the moisture response of the wall by adding insulation and reducing air-leakage in the wall assembly. However, heat or energy loss through the wall system is directly proportional to the air-leakage characteristics of the wall system.

In general, based on the results presented in this paper, it can be concluded that use of a hygrothermal simulation tool can help to identify potentially problematic retrofit strategies while more promising measures can be advanced for additional assessment through full-scale laboratory testing or field demonstration.

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1.0 INTRODUCTION

Building envelopes age and in due course of time they may require rehabilitation or retrofit to maintain effective serviceability. Considering the present status of the Canadian buildings in service, it is expected that there will be an increase in building envelope rehabilitation work in the years to come. At the same time the building construction technology and the materials used for construction have changed significantly over the years. The chance to retrofit a building envelope offers a great opportunity to upgrade it for thermal (i.e. energy) and moisture performance. These can be done by adding insulation, reducing air leakage, and improving the moisture control strategies that will enhance occupant comfort and durability of the building envelope. However, to assess the extent to which this can be done and determine the best available methods to adopt are challenging tasks for building envelope designers. There is no comprehensive methodology available that can be used for this purpose. Currently, the Institute for Research in Construction (IRC)/National Research Council (NRC) of Canada, in association with a number of Canadian government agencies, has embarked on a research program to address this concern. The main purpose of this research project is to develop a knowledge base about the thermal and moisture performance of retrofitted high-rise wall assemblies using advanced hygrothermal analysis tools. It is intended that, based on the assessment of hygrothermal analysis results, potentially problematic retrofit strategies can be identified while more promising measures can be advanced for additional assessment through full-scale laboratory testing or field demonstration. This paper presents selected preliminary results from the aforementioned study that assesses the thermal (i.e. energy) and moisture performance of retrofitted masonry wall assemblies used in high-rise construction.

2.0 RESEARCH OBJECTIVE AND SCOPE

The primary aim of this paper is to demonstrate that hygrothermal simulation tools can be used to identify the appropriate retrofit options for wall assemblies used in high-rise building construction. In order to achieve this goal heat, air and moisture (HAM) transport calculations were done, using IRC's hygrothermal simulation tool *hygIRC-2D*, to predict the moisture and thermal response of masonry wall assemblies. Three types of masonry walls were considered: (i) Brick Veneer - Steel Stud Walls (BV/SS), (ii) Brick Veneer - Concrete Masonry Unit Walls (BV/CMU), and (iii) Precast Concrete Panels - Steel Stud Walls (CV/SS).

3.0 HEAT, AIR AND MOISTURE PERFORMANCE ANALYSIS TOOL: *hygIRC-2D*

IRC's advanced hygrothermal two-dimensional modeling tool *hygIRC-2D* was used to predict the hygrothermal condition in the envelope components of the three types of wall assemblies. How heat, air and moisture transports are modeled in *hygIRC-2D* is described in the publications by Karagiozis, 1993, 1997;and Djebbar et al., 2002a. These documents outline the formulation of the combined heat, air and moisture transport equations used in *hygIRC-2D* and the techniques used to numerically solve them. The reliability of *hygIRC-2D* outputs has been established through laboratory measurements and benchmarking exercises (Maref et al. 2002).

3.1. Input Data for *hygIRC-2D*

The reliability and applicability of the results obtained from hygrothermal simulations depend greatly on the quality and appropriateness of the input parameters. Various important input parameters as required for this study are described in the following paragraphs.

3.1.1 *Construction of the Walls*. The construction details of three types of masonry walls and four retrofit options for each wall are shown in Figures 1, 2 and 3 for Brick Veneer - Steel Stud Walls (BV/SS), Brick Veneer - Concrete Masonry Unit Walls (BV/CMU) and Precast Concrete Panels - Steel Stud Walls (CV/SS), respectively. Each wall has been analyzed for five distinct cases: (i) Base case (i.e. original wall before retrofit as shown in Figures 1a, 2a and 3a), (ii) Interior retrofit option – I (as shown in Figures 1b, 2b and 3b), (iii) Interior retrofit option – II (as shown in Figures 1c, 2c and 3c), (iv) Exterior retrofit option (as shown in Figures 1d, 2d and 3d), and (v) Air sealing retrofit option (as shown in Figures 1e, 2e and 3e). All walls have a height of 2.5 m and all calculations are done for a unit one-meter width of walls. Hence, the walls are 2500 mm high x 1000 mm wide, having a surface area of 2.5 m^2.

3.1.2 Hygrothermal Properties of Materials. One of the major sets if input parameters for *hygIRC-2D* simulations are the hygrothermal properties of the construction materials that form part of the wall assembly. Eight sets of material properties are required for *hygIRC-2D* simulation: air permeability, thermal conductivity, dry density, heat capacity, sorption characteristics, suction pressure, liquid diffusivity and water vapour permeability. Most of the materials used in the construction of the walls were available in the IRC/NRC's database and had been determined in the IRC's Thermal and Moisture Performance Laboratory following standard test procedures (Kumaran et al. 2002). However, for the brick veneer cladding of both BV/SS and BV/CMU walls, the properties used were calculated by performing surface averaging of the combination of both red brick and mortar properties. Typical thickness for both brick units and mortar joints were then used for these calculations. All materials considered are also representative of currently available building materials commonly used in North America.

3.1.3 Environmental Design Loads. The outdoor hygrothermal loads, for three years of simulation, used were for the moisture reference years (MRYs) identified by Djebbar et al., 2002a, 1986 as the initiation year and 1984 as the critical year for the National Capital Region (NCR). The building type considered in this paper was tall multi-unit residential building (MURB). Most residential buildings are not equipped to control the indoor environment. The Kirkwood Avenue building (Ottawa, ON, Canada) monitored by IRC is such an example. The one-year indoor environment data (hourly temperature and relative humidity records), repeated for three years, obtained from the Kirkwood Avenue building, as shown in Figure 4, were used as indoor environment design load.

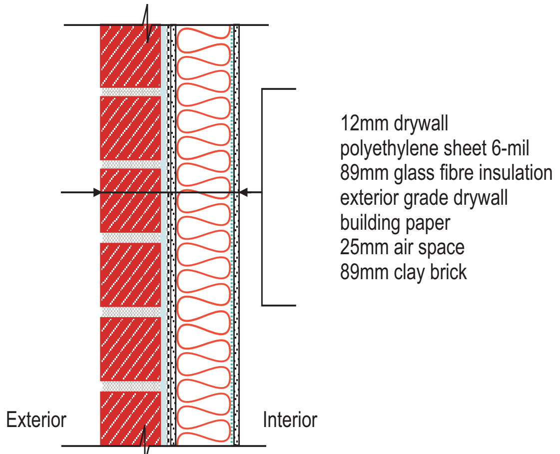
3.1.4 Input for Air-leakage Analysis. Air-leakage was considered for all cases for which simulations were performed in this study. Moisture can be carried into and out of the walls due to indoor air exfiltration or outdoor air infiltration depending on the envelope air-pressure differential gradients. An air-leakage path linking the indoor and outdoor air was assumed in each of the wall assemblies. Schematic drawings describing the simulated air-leakage path for three types of wall are given in Figures 1e, 2e and 3e.

All the walls have an air-leakage path with a 3mm crack opening (for both base-case and retrofitted walls) in the bottom interior and top exterior to link the interior and exterior environment. For the Precast Concrete Panels - Steel Stud Walls (CV/SS), an air space of 3mm was assumed just on the interior side of the cladding to allow for the connection between the indoor and outdoor air. The air-leakage paths were selected to maximize the moisture load inside walls that may occur from wall deficiencies implying air movement from the surrounding environment. The longest possible airflow path with the greatest opportunity for condensation, therefore, was assumed in this study.

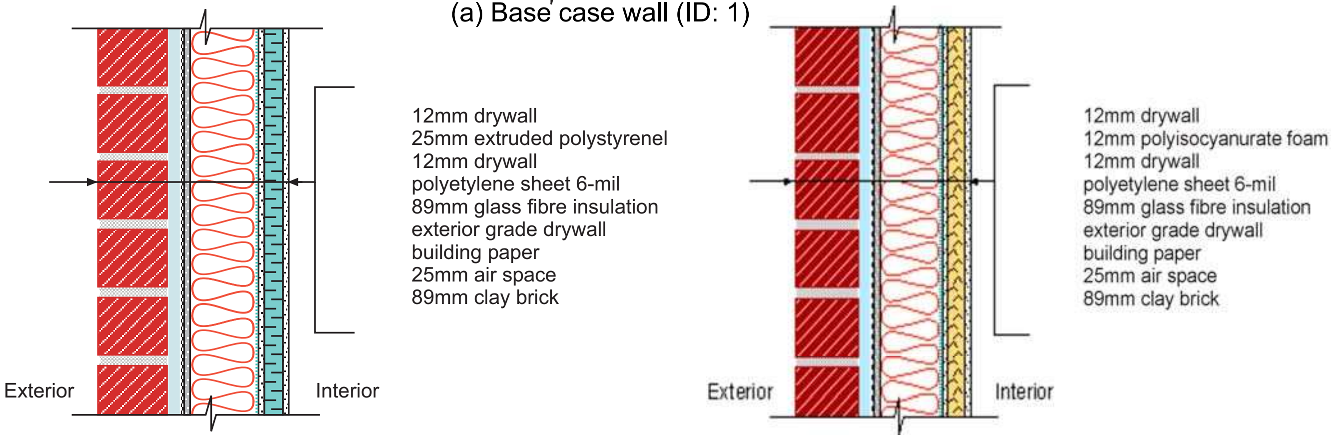
The air permeability of the path for each base-case and retrofitted wall assembly was calculated according to the assumed air-tightness of walls. For the present parametric study, the air-tightness of all three base case walls was assumed to be equal 2.5 L/s.m^2 at 75 Pascals (Pa). This value of air-tightness is consistent with what is reported by Proskiw and Phillips (2001) for tall MURBs (Multi-Unit Residential Buildings). Another assumption made for the parametric analysis was the air-tightness of the retrofit option walls. For the present study, a minimum of 40% air-tightness increase was assumed when the base walls were either air-sealed or have had an interior or exterior retrofit. This air-tightness increase is consistent with what is reported in the literature. Measurements performed by Shaw and Reardon (1995) on a select number of tall office buildings located in Canada show that typical air-tightness increase of 43% at 50 Pa was achieved after building envelopes were retrofitted.

The walls were assumed to be located at the top corner of a 10-storey building facing the prevailing wind direction during rain events of the location considered. For the National Capital Region the prevailing wind direction during rain events was found to be east. The main driving potential for the airflow through the envelope cracks is the total pressure drop across the crack itself and the envelope in general. The total pressure drop across the envelope is the combination of the wind-induced pressure, stack effect and the indoor mechanical-induced pressure. How these three mechanisms are modelled for this study is described in *Djebbar et al. 2002a.* A constant 5 Pa mechanical, indoor over-pressure above the atmospheric pressure to the exterior was maintained during the whole simulation period. To estimate the pressure drop across the envelope due to the stack effect, the neutral pressure level was assumed to be at mid-height on the building. Heat and mass transfer across the top and bottom wall surfaces to the slabs were assumed to be negligible.

3.1.5 Simulation Duration. Two-dimensional hygrothermal calculations using *hygIRC-2D* were carried out over three years of the simulation period (1095 days/26280 hours). One initiation weather year (1986) was followed by two critical weather year (1984) conditions.

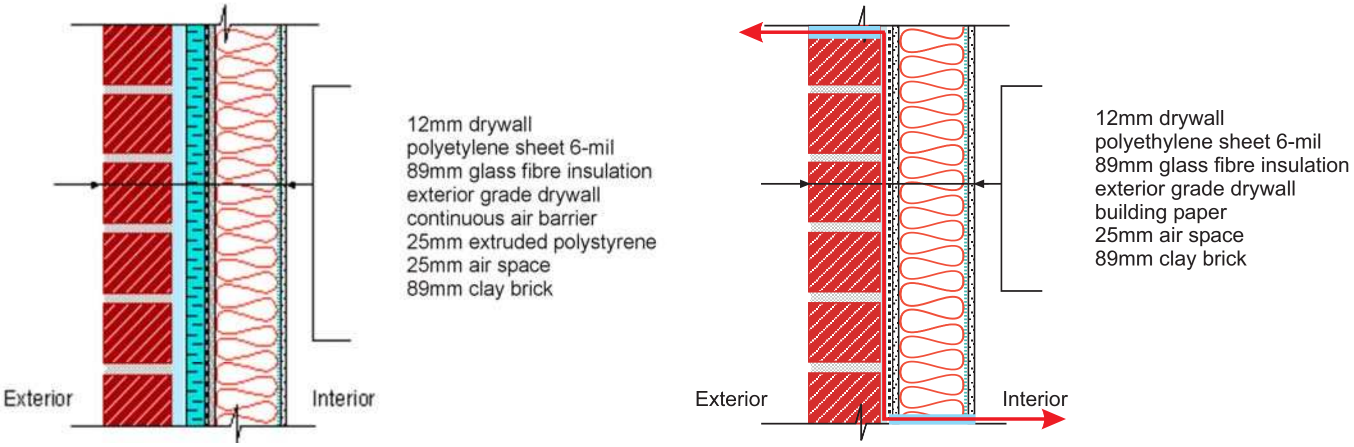


(a) Base case wall (ID: 1)



(b) Interior retrofit (ID: 1A)

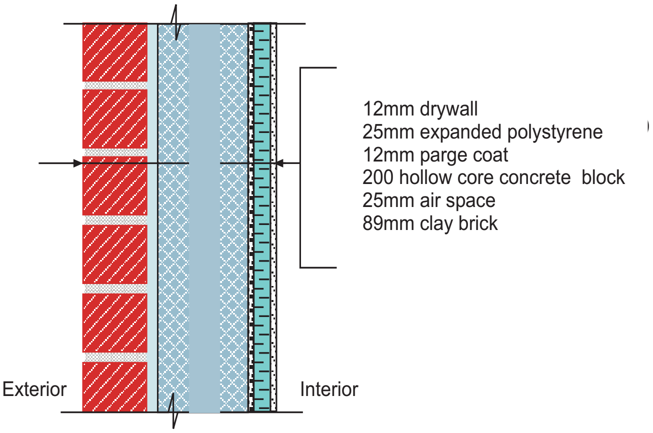
(c) Interior retrofit (ID: 1B)



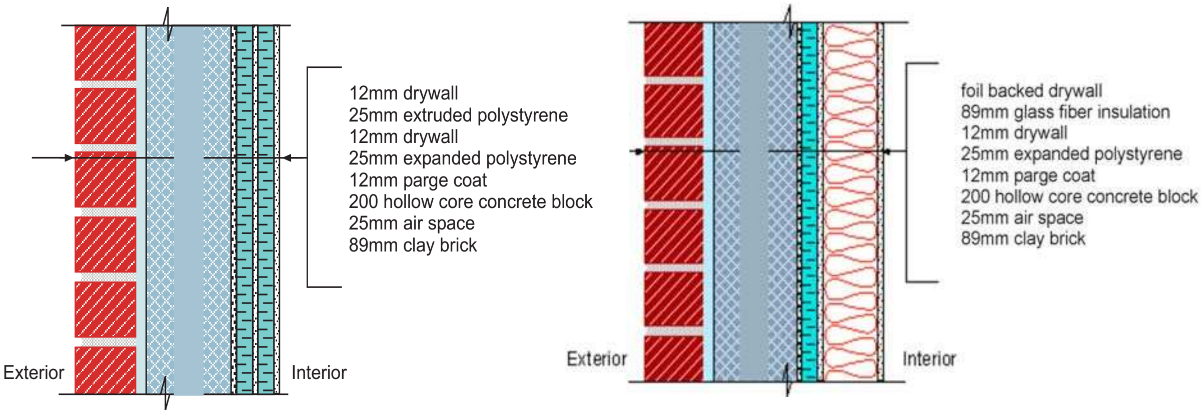
(d) Exterior retrofit (ID: 1C)

(e) Air sealing retrofit (ID: 1D)

Figure 1 Brick Veneer - Steel Stud Walls (BV/SS)

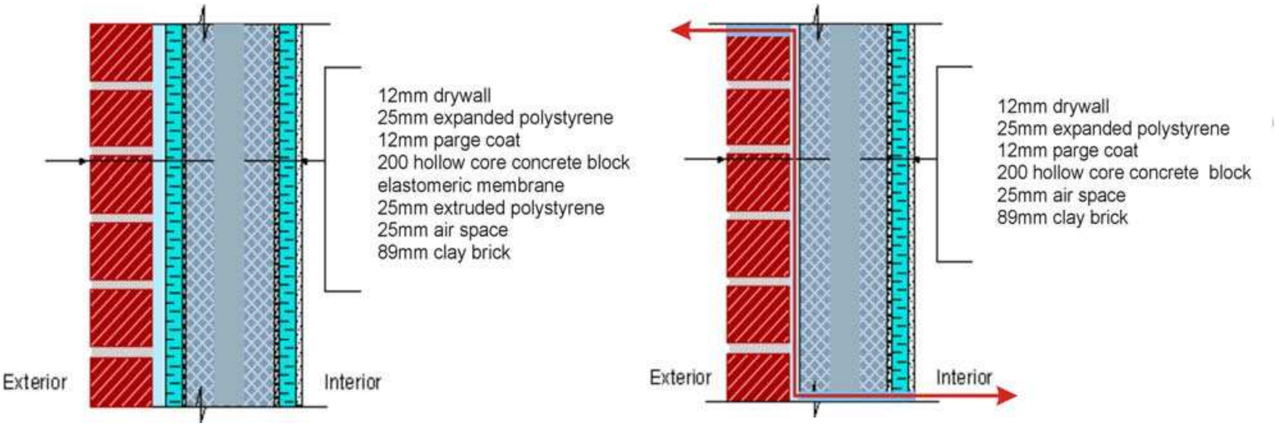


(a) Base case wall (ID: 2)



(b) Interior retrofit (ID: 2A)

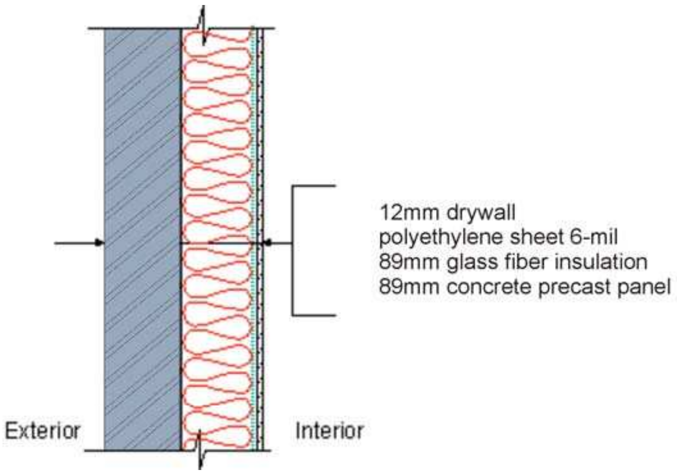
(c) Interior retrofit (ID: 2B)



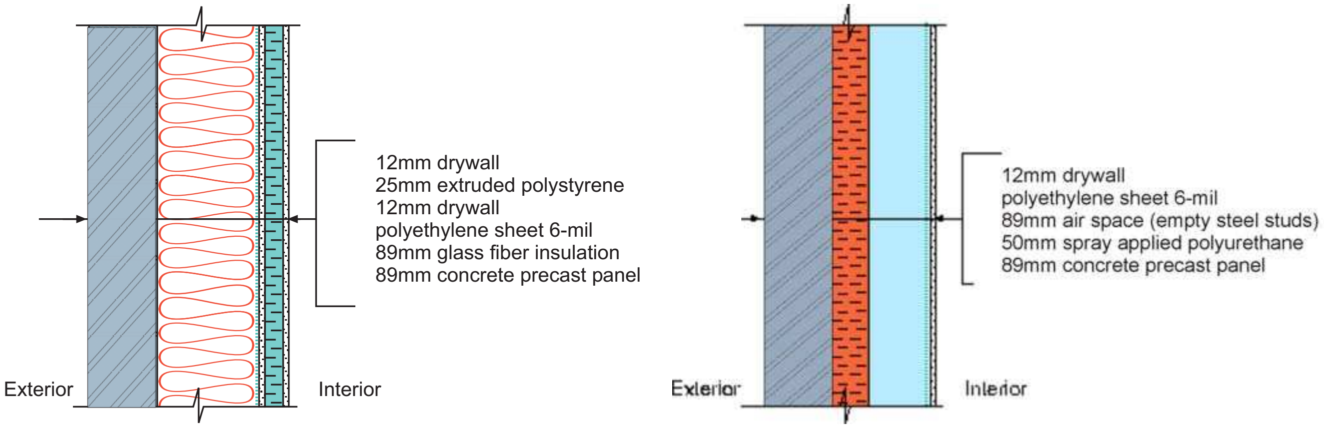
(d) Exterior retrofit (ID: 2C)

(e) Air sealing retrofit (ID: 2D)

Figure 2 Brick Veneer - Concrete Masonry Unit Walls (BV/CMU)

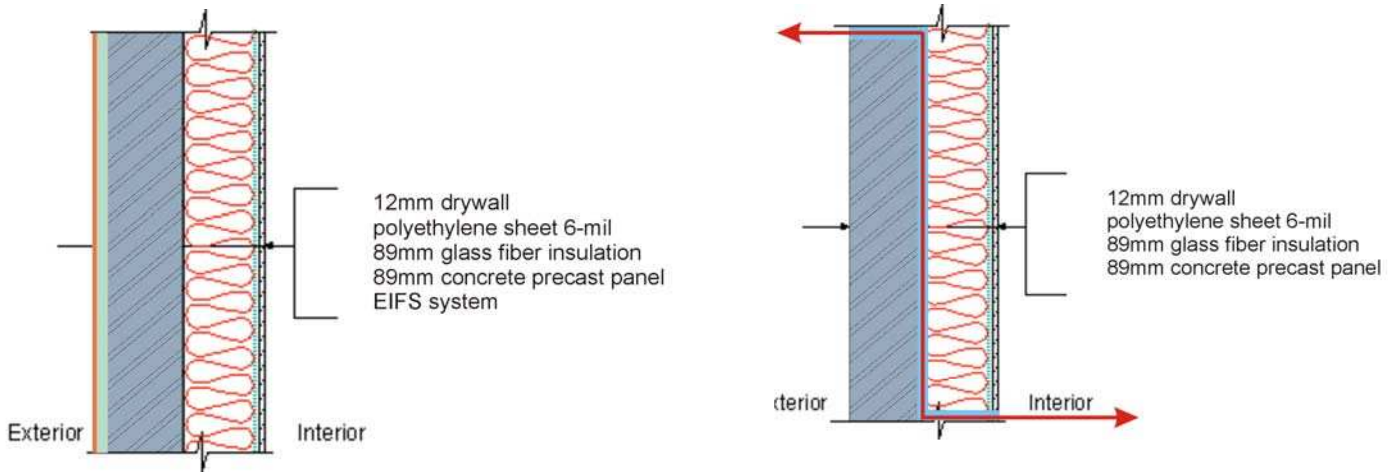


(a) Base case wall (ID: 3)



(b) Interior retrofit (ID: 3A)

(c) Interior retrofit (ID: 3B)



(d) Exterior retrofit (ID: 3C)

(e) Air sealing retrofit (ID: 3D)

Figure 3 Precast Concrete Panels - Steel Stud Walls (CV/SS)

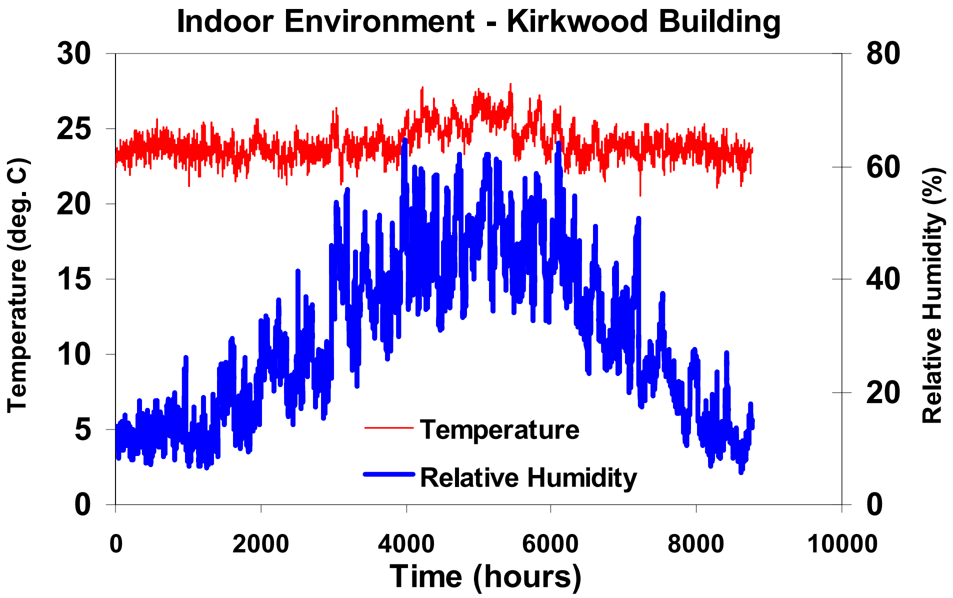


Figure 4 Indoor Environment – Kirkwood Avenue Building (Ottawa, ON, Canada)

4.0 ENERGY AND MOISTURE SIMULATION RESULTS

Two-dimensional hygrothermal simulations using *hygIRC-2D* were carried out for three basic types of walls and four retrofit options for each type of wall (Figures 1, 2 and 3). A significant amount of data were generated from these simulations and subsequently post-processed for the detailed evaluation of the simulated hygrothermal response of the wall assemblies. Comprehensive details of the simulations and the outputs were documented in a report authored by Djebbar et al. 2002b, and the approach adopted for the analysis has been published in a paper by Djebbar et al. 2002c. Further analyses of these results were done by Nofal and Tariku (2002) and subsequently documented in a report. However, the following paragraphs aim primarily to summarise the results of airflow and heat flux analysis for all three types of wall assemblies located in the National Capital Region. Interested readers should refer to the aforementioned documents for detailed outputs and analyses of results.

4.1 Airflow Analysis

Statistical analysis on the air-leakage rate was performed for the third year of simulation, (i.e., from hours 17521 to 26280) and results are summarized in Table 1 for the National Capital Region. It can be clearly established from these results that the air-leakage rates predicted for the base-case walls (Wall ID 1, 2 and 3) are consistently higher than those of the retrofitted walls. This simply reflects the fact that the retrofit walls are assumed to be minimum 40% more airtight than the base case walls through the assumed air-leakage path. However, retrofitted Precast Concrete Panels - Steel Stud Walls (CV/SS) with ID 3B and 3C generated the highest improvement in the yearly air-leakage. Comparison of the yearly infiltration and exfiltration air-leakage rates indicates that, except for a couple of times (i.e. approximately 87 hour times a year) when the outside wind pressure was strong enough to generate outdoor air infiltration, only exfiltration was taking place in all the walls. This is explained by the fact that the simulated walls are assumed to be located at the top corner of a 10-storey building. At this location, stack effects and the yearly, constant, imposed indoor-mechanical pressure of +5 Pa generated a continuous positive pressure drop to the exterior and a net exfiltration airflow. In general it can be said that hygrothermal simulations could identify the relative improved performance of various retrofitted wall systems.

4.2 Heat-flux Analysis

The decrease in the total heat loss in the retrofit options when adding insulation is reported in the fourth column of Table 2. Values for the yearly heat balance including both heat loss and gain are in the third column of Table 2. Results clearly show that all the retrofit strategies effectively reduced the energy loss through the building envelope predicted for the corresponding base case walls by 40% to 44% for the Brick Veneer - Steel Stud (BV/SS) walls, 36% to 45% for the Brick Veneer - Concrete Masonry Unit (BV/CMU) walls, and 25% to 83% for the Precast Concrete Panels - Steel Stud (CV/SS) walls. The retrofitted Precast Concrete Panels - Steel Stud Walls (CV/SS) identified as 3B and 3C produced the highest improvement in the reduction of energy loss. Interestingly, these are the same walls that showed the highest improvement in the reduction of air-leakage. Moreover, the percentage reduction in air-leakage, as shown in Table 1, for each retrofitted wall assembly is almost the same percentage reduction in heat or energy loss, as shown in Table 2. These observations clearly indicate that there is a strong and direct relationship between air-leakage and energy performance of the wall assembly.

4.3 Moisture Accumulation/drying Analysis

Ratios for the total moisture content in walls are presented in Table 2 (column 5th and 6th). Moisture accumulation or drying is quantified by comparing the daily average total moisture content of the walls obtained on the last day (December 31) for each of the three years of the simulation period. Two values are obtained for each wall system for the first and second year accumulation/drying. The first year accumulation/drying value compares the daily average total moisture content in the wall systems on December 31 of the first and second years of the simulation period. The second year accumulation/drying value compares the daily average total moisture content in the wall systems on December 31 for the first and third years of the simulation period. The first year value gives a one-year net accumulation/drying during the second year of the simulation period. The second year value gives the net accumulation/drying during the last two years of the simulation period. As can be seen in Table 2, no major total moisture accumulation over two years was predicted when the walls were subjected to the indoor and outdoor hygrothermal loads considered in the present study. However, it is to be noted that in one wall (simulation ID: 1137-51, Wall ID: 3-B) the total moisture accumulation increased by 11% and this increment was the maximum achieved of all walls simulated. At this stage it is difficult to predict the severity of this moisture response without further localized moisture response analysis of different wall components. Further work is being carried out at this moment on this issue and will be reported in due course.

Table 1 Air-leakage analysis for 3rd year of simulation

Simulation ID	Wall ID	Mean Leakage Rates ($L/s.m^2$)		Yearly Air Leakage (L/m)	% Reduced	Airflow Direction (%)	
		Exfiltration	Infiltration			Exfiltration	Infiltration
B1137-39	1	14	5	119456	Base Case	99	1
B1137-40	1-A	8	3	67236	44	99	1
B1137-41	1-B	8	3	68580	43	99	1
B1137-42	1-C	8	3	68141	43	99	1
B1137-43	1-D	8	3	71245	40	99	1
B1137-44	2	13	5	113450	Base Case	99	1
B1137-45	2-A	8	3	68038	40	99	1
B1137-46	2-B	7	3	62264	45	99	1
B1137-47	2-C	7	3	61680	46	99	1
B1137-48	2-D	8	3	72082	37	99	1
B1137-49	3	9	4	80066	Base Case	99	1
B1137-50	3-A	7	3	56714	29	99	1
B1137-51	3-B	2	1	16362	80	99	1
B1137-52	3-C	2	1	13959	83	99	1
B1137-53	3-D	7	3	60005	25	99	1

Table 2 Thermal performance and moisture accumulation

Simulation ID	Wall ID	Yearly Heat Balance (W/m^2)	Heat Balance Reduction (%)	Moisture Accumulation/ Drying	
				1st Year	2nd Year
B1137-39	1	5009084	Base Case	1.00	1.00
B1137-40	1-A	2822943	44	0.98	0.98
B1137-41	1-B	2879823	43	0.98	0.98
B1137-42	1-C	2860997	43	0.98	0.98
B1137-43	1-D	2992066	40	0.98	0.98
B1137-44	2	4764246	Base Case	1.00	1.00
B1137-45	2-A	2860624	40	0.98	0.98
B1137-46	2-B	2616048	45	0.98	0.98
B1137-47	2-C	2596809	45	0.98	0.97
B1137-48	2-D	3034047	36	0.98	0.98
B1137-49	3	3388419	Base Case	0.97	0.97
B1137-50	3-A	2407353	29	0.92	0.92
B1137-51	3-B	715092	79	1.10	1.11
B1137-52	3-C	595325	82	0.99	0.99
B1137-53	3-D	2552624	25	0.92	0.92

5.0 SUMMARY OF OBSERVATIONS

The results from hygrothermal simulations and the discussion on the results presented in this paper bring out many interesting observations that can be very useful for the building envelope designers. However, these results are preliminary in nature. Further investigations are in progress and more critical interpretations will be reported in due course. Nevertheless the following observations can be made from these interim results.

(i) Advanced hygrothermal simulation tools can be used to evaluate the thermal (i.e. energy) and moisture performance of various wall systems and associated retrofit options.

(ii) Simulation results show that the energy performance of the wall system can be improved significantly without compromising the moisture response of the wall by adding insulation and reducing air-leakage in the wall assembly.

(iii) The heat or energy loss through the wall system is directly proportional to the air-leakage characteristics of the wall system. Reduction of air-leakage helps to minimize the heat or energy loss across the wall cross-section.

6.0 ACKNOWLEDGEMENT

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