THE EFFECT OF WATERPROOF COATING ON HYGROTHERMAL PERFORMANCE OF A HIGH-RISE WALL STRUCTURE

Achilles Karagiozis, Ph.D. **Mikael Salonvaara** **Kumar Kumaran, Ph.D.**

ABSTRACT

Durability and service life of a wall structure are sensitive to the wall's hygrothermal performance. Moisture sources available for the wall originate from either the interior or the exterior. From the interior, the indoor environment provides a continuous source of moisture, while from the exterior, moisture may be transferred to the wall structure by vapor diffusion or in liquid form (from condensation or wind-driven rain). Until recently, effective design tools/models to provide the effect of various design parameters or material properties on performance were not available, and even today such models are only available within the research communities.

In the LATENITE hygrothermal model, a transient two-dimensional control volume formulation is employed to numerically solve the energy and moisture content equation. Both vapor and liquid transport through each material layer are considered strongly coupled to the material properties, i.e., the sorption curves, liquid diffusivity, and vapor permeability. Latent heat generated due to moisture transport within each material layer is fully accounted for.

This paper examines the effect of waterproofing (damp-proofing) the exterior facade of a high-rise wall structure at two weather locations. The long-term performance of the walls sprayed with waterproofing substances is simulated for three years. Results are also generated for two different initial conditions—one wall starting dry and the other wet. The results show a strong influence of these two initial conditions. The yearly heat losses are also calculated, including the contributions of latent heat.

INTRODUCTION

Wind-driven rain that penetrates into structures can affect the hygrothermal performance and durability of the structure in many ways. Water in pores of building envelope materials can increase heat loss, reduce structural strength, cause cracking and spalling of the facade materials, damage the appearance of the building, and eventually increase maintenance costs.

Several different waterproof coatings exist on the market that aim at preventing rainwater damage to building envelopes. The purpose of waterproofing the exterior brick surface of a wall is to prevent rainwater from penetrating into the wall structure. The substances used for this purpose are sprayed or painted onto the wall, creating a layer that has a high resistance to liquid flow. The layer is said to have an insignificant effect on the vapor flow resistance of the surface and thus allows the structure to "breathe." To the best of the authors' knowledge, vapor resistance levels of these kinds of coatings cannot readily be found in the literature. Estimates of the properties were assumed during the simulations, and the results shown in this paper are valid only for simulated structures with these assumptions. Due to the lack of material properties of the coatings, a sensitivity analysis employing three different values for vapor permeance of the waterproofing coating was carried out. The coating was assumed to be impermeable to liquid flow.

In this paper, several simulations of the hygrothermal performance of brick cavity walls with and without waterproofing treatment are presented. Two sets of simulations were carried out—a one-dimensional ideal wall structure with and without application of the exterior coating and a two-dimensional case treated with a damp-proofing substance but with a faulty spot in the coating on the exterior surface that allowed driving rain to penetrate into the brick layer. The long-term effect of a coating on the thermal and moisture behavior of the structure is presented.

DESCRIPTION OF THE MODEL

A detailed description of the LATENITE hygrothermal model used in the analysis is given in Hens and Janssens (1993), Karagiozis (1993), Karagiozis and Kumaran (1993), and Salonvaara and Karagiozis (1994); only a brief overview is presented here. The moisture transport

Achilles Karagiozis is a research officer and **Kumar Kumaran** is a senior research officer at the National Research Council Canada, Institute for Research in Construction, Building Performance Laboratory, Ottawa, Ont. **Mikael Salonvaara** is a research scientist at the Technical Research Center of Finland, Espoo.

potentials used in the model are moisture content and vapor pressure; for energy transport, temperature is used. The equations are developed on a Cartesian rectangular coordinate system, contain explicit and implicit time discretizations, and are spatially discretized using the control volume formulation. Approximate factorization and full solution procedures are incorporated into the model to solve the differential equations in delta form.

In the model, a transient two-dimensional control volume formulation is implemented to solve each equation. The porous media transport of moisture (vapor-liquid) through each material layer is considered strongly coupled to the material properties (i.e., the sorption curves). The corresponding moisture fluxes are decomposed for each phase and are treated separately. The sets of the governing partial differential equation are thus highly nonlinear. The Newton-Raphson method for linearizing the coefficient/equations is used to provide a more direct, stronger coupling. The strong coupling between the moisture and energy transport primarily exists due to the presence of phase changes. This mechanism is dependent on material properties.

The moisture transfer equation, including liquid and vapor transfer, is

$$q_M = -\rho_0 D_w(u,T)\,\nabla u - \delta_p(u,T)\,\nabla P_v \tag{1}$$

where

ρ_0 = dry density (kg/m^3),
D_w = liquid moisture diffusivity (m^2/s),
u = moisture content (kg$_w$/kg$_d$),
T = temperature (°C or K),
δ_p = vapor permeability (kg/s·m·Pa), and
P_v = vapor pressure (Pa).

Wind-driven rain is modeled as a source term on the exterior wall surface. However, the amount of water that can penetrate into the porous material is limited by the maximum allowable moisture content in the exterior material.

Problem Description

The hygrothermal performance of a brick layered cavity wall with cavity insulation was analyzed with and without the application of the exterior waterproofing. For the first set of simulations the wall was assumed to be ideal (no cracks or holes); this allowed the wall to be modeled one-dimensionally. A sensitivity analysis was carried out to determine the effect of the vapor permeance of the coating on the moisture performance. The coating was assumed to have a vapor resistance equivalent to a multiplication factor times the vapor resistance of the exterior brick layer ($\delta_p/\Delta x = 1.5\ 10^{-10}$ kg/m^2·s·Pa ≈ 2.5 perms). The multiplication factors employed were 10, 1, and 0.1, resulting in vapor permeances of $1.5\ 10^{-9}$,

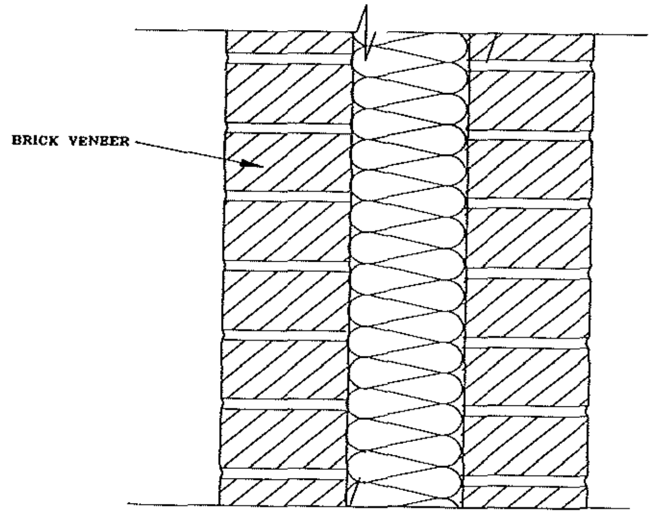

Figure 1 *The analyzed wall structure in detail. Exterior brick is 90 mm, insulation 120 mm, and interior brick 140 mm thick.*

$1.5\ 10^{-10}$, and $1.5\ 10^{-11}$ kg/m^2·s·Pa (25, 2.5, and 0.25 perms), respectively. The coating was assumed to be impermeable to liquid flow.

The high-rise wall structure selected for the numerical analysis is shown in Figure 1. The wall that is centrally located on the middle of a 10-floor building (fifth floor) is composed of the following layers from the exterior to the interior: a 90-mm facade brick, a 120-mm fiberglass board, and, finally, 140-mm red brick. In two-dimensional calculations, the height of the simulated wall section is 0.25 m. The inside surface of the wall was coated with a vapor-tight paint (permeance approximately $5{\cdot}10^{-12}$ kg/m^2·s·Pa [0.08 perms]). This produced an effect similar to that of a vapor retarder. A vapor retarder is normally required in cold climates such as Canada (Ottawa).

In two-dimensional simulations (cases with a nonideal coating), an area the size of a mortar layer on the exterior brick was not coated with waterproofing, thus allowing the wind-driven rainwater to come in contact with the brick surface. This surface was then exposed to the amount of rain that typically hits a vertical wall. This amount depends on the intensity of precipitation, wind speed, wind direction, and the location on the wall surface. Driving rain was used in the analysis as calculated by employing a commercially developed model (ASC 1993). An equation for wind-driven rain used in the hygrothermal model was created and was based on a numerical study (Karagiozis and Hadjisophocleous 1995) that presents the results generated by the wind-driven rain droplet simulations. Two series of simulations were carried out for the two-dimensional calculations. In the first series, the structure was only exposed to the direct wind-driven rain, while for the second series, the uncoated brick surface was exposed to a fall-

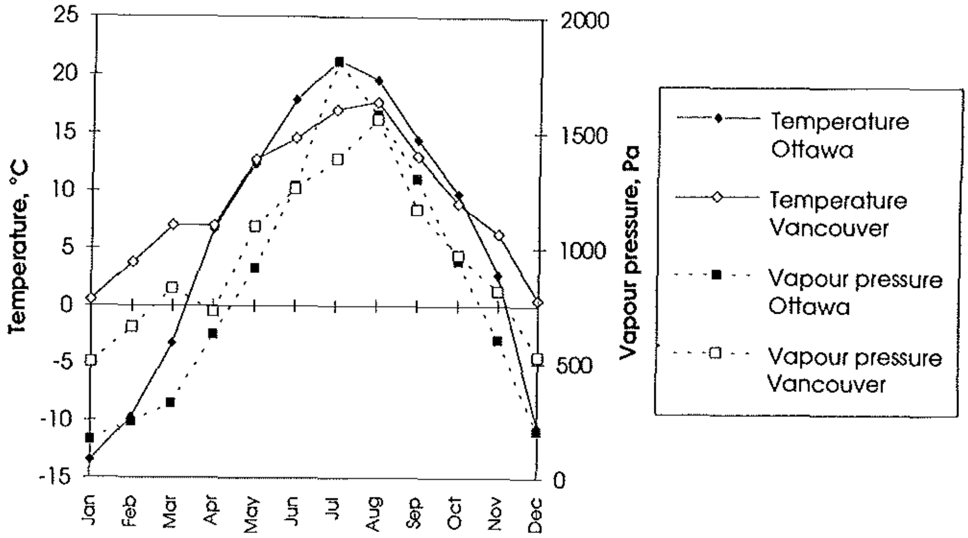

Figure 2 *The monthly average temperatures and vapor pressures in Ottawa and Vancouver weather files.*

ing film (runouts) that was assumed to give six times the amount of water in the first series.

The wall was exposed to the outside air temperature and relative humidity that varied according to the weather data from the selected locations (Vancouver and Ottawa). The simulations were carried out for a three-year exposure starting on September 7. The solar radiation and long-wave radiation from the outer surfaces of the wall were included in the analysis. In this study, no air infiltration or exfiltration was considered; thereby, the primary mode of water transmission is due to diffusion processes, both vapor and liquid transport.

BOUNDARY AND INITIAL CONDITIONS

Internal conditions were kept constant at a temperature of 21°C and a relative humidity of 40% (P_v = 997 Pa) throughout the year. The BMY (Best Meteorological Year) (AESC 1983) weather files of two Canadian cities (Ottawa and Vancouver) were used in the simulations. These one-year-long weather files were repeated during the three-year simulations, i.e., the second and third years had the same exterior boundary conditions as the first year. The monthly average temperatures and vapor pressures for Ottawa and Vancouver are shown in Figure 2. The yearly average temperatures and vapor pressures in Ottawa and Vancouver are 5.6°C, 832 Pa, and 9.1°C, 958 Pa, respectively. The total amount of driving rain when temperatures are above freezing (T > 0°C) on a vertical south-facing wall (fifth floor, center of the wall) was 79 mm and 209 mm in Ottawa and Vancouver, respectively. The total amount of precipitation was 570 and 1,124 mm in Ottawa and Vancouver, respectively. The long-term (1950-1980) average yearly precipitation is 846 mm in Ottawa and 1,329 mm in Vancouver (AESC 1993), i.e., the weather files used in the simulations had less precipitation than the average year in these locations.

TABLE 1 **Heat and Moisture Transfer Coefficients for the External and Internal Surfaces**

Property	External Surface, Without/With Dampproofing	Internal Surface
Heat transfer coefficients, W/ m^2·K	20	8
Mass transfer coefficients, kg/m^2·s·Pa		
Without coating	$1.5 \cdot 10^{-7}$	
Coating 1	$1.5 \cdot 10^{-9}$	$5.0 \cdot 10^{-12}$
Coating 2	$1.5 \cdot 10^{-10}$	
Coating 3	$1.5 \cdot 10^{-11}$	
Short-wave absorptivity	0.6	—
Long-wave emissivity	0.9	—

The modeled wall on the fifth floor of the building was facing south, i.e., the azimuth angle of the wall was 180 degrees. Both dry and wet initial conditions were investigated in this study. The exterior brick was assigned initial relative humidities[1] of 50% and 98% in the dry and wet cases, respectively. For the case of 50% RH, the initial condition corresponds to a moisture content of 0.0004 kg_w/kg_d and the case of 98% RH corresponds to 0.04 kg_w/kg_d. The initial conditions of the insulation and the interior brick were 50% RH. The maximum capillary moisture content of the bricks is 0.111 kg_w/kg_d.

The heat and mass transfer coefficients for external and internal surfaces were kept constant during the simulations in order to have comparable results in the parametric study. The coefficients are presented in Table 1. All material properties were taken from the model's data base (Karagiozis et al. 1994).

[1]Relative humidity in pores of a material is related to moisture content via sorption isotherm.

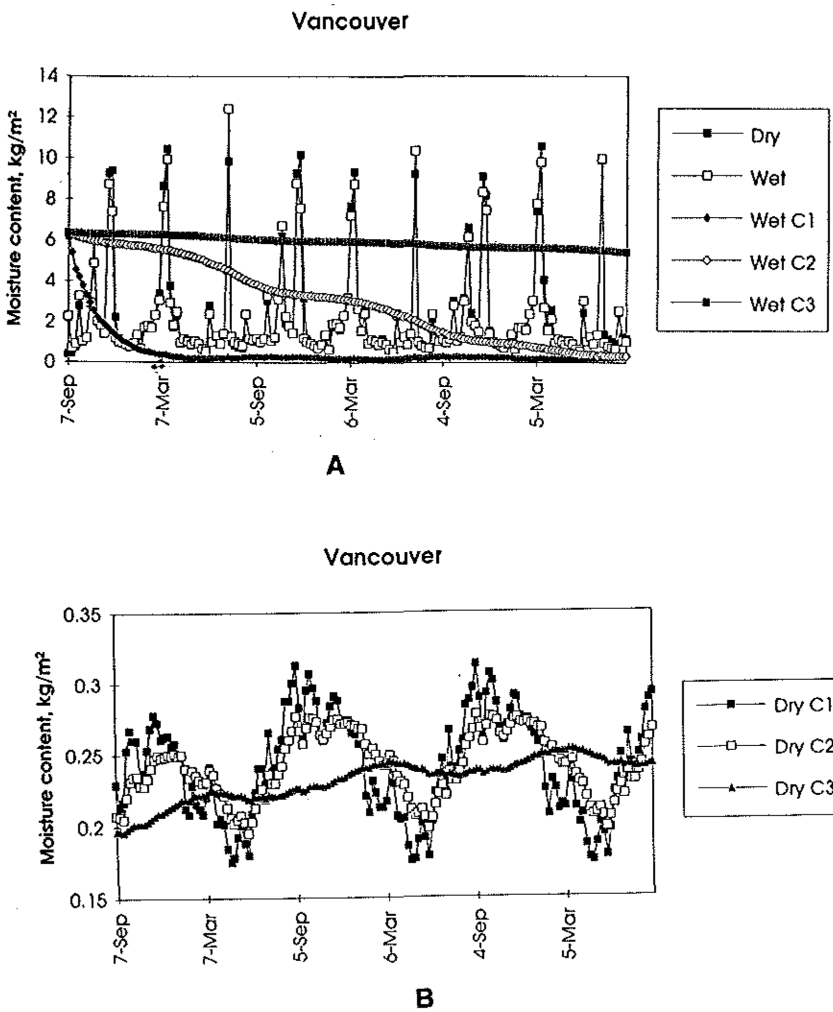

Figure 3 *Weekly average total moisture contents in dry and wet walls (initial conditions) with or without waterproofing coating for Vancouver. A = full scale, B = expanded scale for moisture content. Designations in the figures: Dry C1 = dry initial conditions, wall with coating 1; Wet C3 = wet initial conditions, wall with coating 3.*

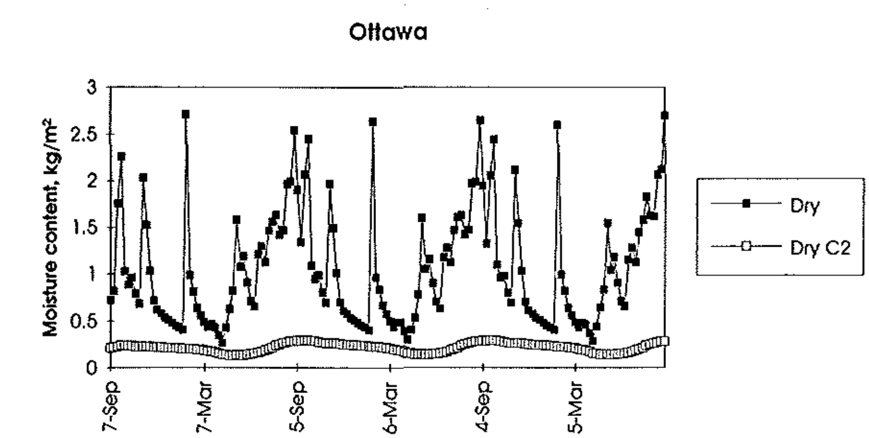

Figure 4 *The average weekly total moisture contents during a three-year period in uncoated and coated walls with dry initial conditions for Ottawa. Dry = no coating, Dry C2 = coating 2.*

RESULTS

Hygric Behavior

The water that penetrated the walls without waterproofing was shown to evaporate during dry weather periods and no yearly net accumulation was found (Figures 3 and 4, three-year calculations). The exterior brick was found to display high moisture contents during rainy periods, as depicted in Figure 3.

Figure 5 shows the total moisture contents as a function of time during the third year of the simulated period for a wall in Vancouver when driving rain is either taken into account or ignored in the simulations. The moisture contents in walls without rain were at maximum 0.32 kg/wall-m^2, whereas walls with rain occasionally had more than 12 kg of moisture per wall-m^2 (Figure 5). The results show clearly that rain penetration can be far more important than vapor diffusion fluxes when considering the moisture behavior of building structures.

The relative humidity distributions in the walls after 1 month, 2 months, and 12 months from the beginning of the simulations (September 7) are shown in Figure 6. The walls with waterproofing (even the one with high vapor permeance) show lower moisture contents throughout the simulated years (dry initial conditions, Figure 6) because the most significant source for moisture increases in the wall is *wind-driven rain*. The walls with no coating reach the balance with the environment within a few weeks. The moisture contents in the initially wet walls with a coating eventually approach the moisture contents in the dry walls, but drying out the initial moisture contents may take years depending on the vapor permeance of the coating.

For the case of the initially wet exterior brick, the drying period of the wall was prolonged in the case with the waterproofed walls. The wall with coating 3, the lowest vapor permeance, took approximately 30 years (extrapolated estimation) to dry out the initial moisture contents (Figure 3). The dry-

Vancouver

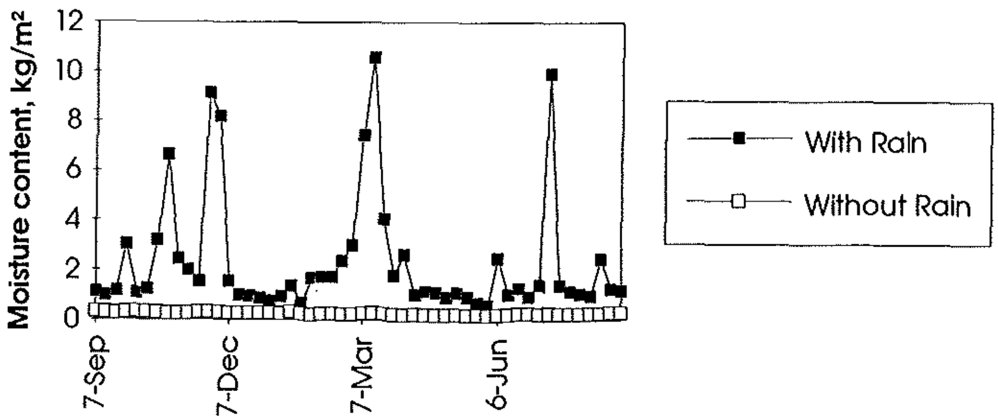

Figure 5 The average weekly total moisture contents during the third year in uncoated walls for Vancouver when moisture behavior is calculated with or without wind-driven rain hitting the wall surface.

ing periods for cases with coatings 2 and 1 were three years and six months, respectively. The only way for moisture to dry out was through the coating, since these walls did not have cavity ventilation and the vapor permeance of the interior surface was very low ($5 \cdot 10^{-12}$ kg/$m^2 \cdot s \cdot Pa$ [0.08 perms]).

The ideally coated dry walls (no cracks or defects, high or low vapor permeance coating) had low moisture contents throughout the years, and no moisture problems are likely to occur as long as the coating is not damaged. The initial moisture contents in the dry walls were lower than the average yearly moisture contents, which results in slightly increasing moisture contents for the case with low vapor permeability coating (dry C3).

The wall with an opening defect in the coating (coating 2) allowed moisture to accumulate in the wall structure. The coating does not allow liquid water penetration, which creates a falling film of water. This effect was approximated by multiplying the amount of rain that reaches the crack surface by six. This factor is an estimation, and it can be much higher, depending on the location of the crack on the wall. The total amount of moisture in the structure at the end of the first year was considerably higher than at the beginning of the year (Figure 7), but after the first year, a moisture balance is found and no further yearly accumulation occurs. The liquid moisture flow during rainy periods through the small opening can be higher than evaporation through the opening and the coated surface during dry periods. The effect of a crack on moisture migration into the structure is shown in Figure 8. The exterior brick is highly permeable to liquid moisture transfer and even a small crack or opening in the waterproofing may result in yearly moisture accumulation.

Thermal Behavior

The exterior waterproofing has a significant effect on rainwater penetration into the wall structure. The layer does not allow rainwater to penetrate into the wall, and the initially dry ideal walls stay dry throughout the test period. Small differences in the moisture contents of the initially dry walls with different waterproofing coatings were caused by differences in vapor diffusion fluxes.

The thermal conductivity of each of the material layers is a function of moisture content. Walls without waterproofing occasionally have higher moisture contents in the exterior layers, which may result in a decrease in the thermal resistance of the wall and therefore in an increase of heat loss. In these analyzed walls, the effect of the increased thermal conductivity due to moisture in the exterior brick was insignificant when compared to the total thermal resistance of the wall.

The water that is absorbed in liquid form by the exterior brick during rainy periods can eventually be evaporated outward, and the latent heat involved in this process also further increases the heat loss. Moisture that comes into the wall in the vapor phase and is absorbed by the structure does not affect the long-term average heat flux unless yearly accumulation (or drying) occurs. However, instantaneous heat fluxes may be influenced by the phase changes of vapor or liquid. Walls with the three different vapor permeance coatings (coatings 1, 2, and 3) were found to have approximately the same yearly heat losses (negligible differences). If the waterproof coating behaves ideally and does not allow liquid water to migrate into the wall, substantial savings in heating energy loss can be expected in walls with dry initial conditions. The analyzed wall structure was found to have 8% lower heat losses with a coating than without in Vancouver. The results are valid only for south-facing walls that are exposed to solar radiation and should not be generalized to other directions.

For the case of the initially wet exterior brick, the drying period for the walls coated with the waterproofing substance was substantially prolonged. In the initially wet walls, the moisture that was trapped inside the wall and allowed to travel between the exterior and interior bricks across the insulation layer may have increased instantaneous heat fluxes within the cavity.

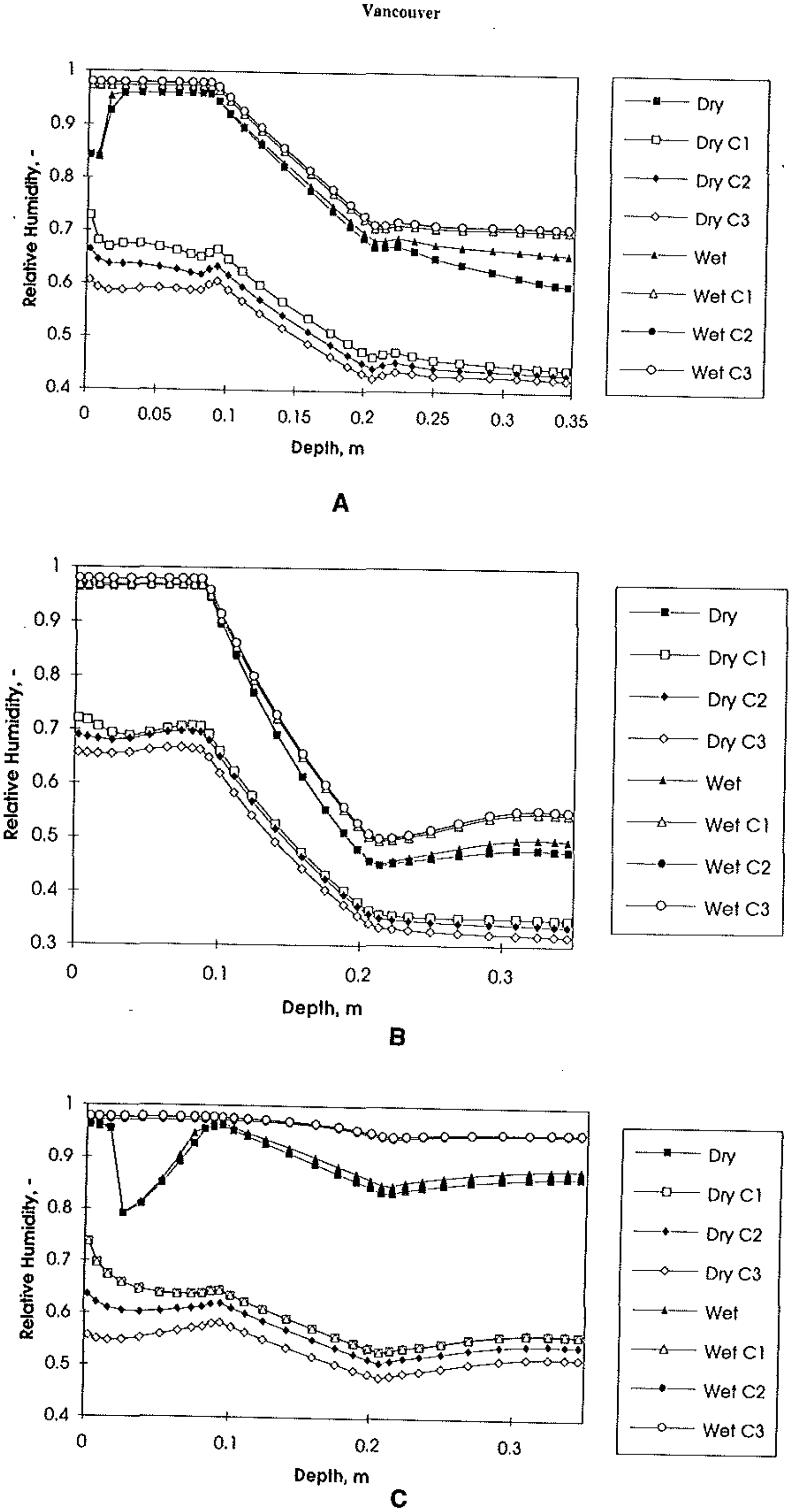

Figure 6 The relative humidity distributions in the wall during the first year (drying period) for different cases. Date: Beginning of A = October, B = November, and C = September (one year from the start of the calculations). Designations in the figures: Dry C1 = dry initial conditions, wall with coating 1. Depth is the distance from the exterior surface.

This phenomenon does not necessarily increase the net heat loss through the wall (or heat loss of the building) since latent heat flux is carried inward and outward, depending on the boundary conditions (e.g., diurnal variations of temperature); the thermal mass dampens the variations, thus the net effect can be minimal.

The effect of driving rain on the yearly heat loss through the wall structure was +9% for the wall facing south in Vancouver and +2% for the same wall in Ottawa. The yearly amount of driving rain calculated from the weather files using wind speed, wind direction, and hourly precipitation was 2.6 times more in Vancouver than in Ottawa for a south-facing wall. This explains the stronger influence of rainwater penetration on the heat losses in Vancouver.

The differences between the long-term heat losses of the ideally coated walls (one-dimensional calculations) and the wall with a crack (two-dimensional) in the exterior surface were negligible, even though the wall with a crack had higher moisture contents. The uncoated walls absorb rainwater and allow more moisture to evaporate through the exterior surface. Thus, in these walls, the primary reason for increases in heat losses was the wind-driven rain and liquid absorption-evaporation cycles.

CONCLUSIONS

This study showed the influence of rain on thermal and moisture performance in walls. The waterproof coating used in cold climates (with the assumed material properties) proved to be an effective method to control water penetration into the structure when applied to a brick cavity wall with a vapor retarder. However, the underlying assumption is that the coating was maintained without the existence of cracks. The calculated moisture contents in the walls were low throughout the years and

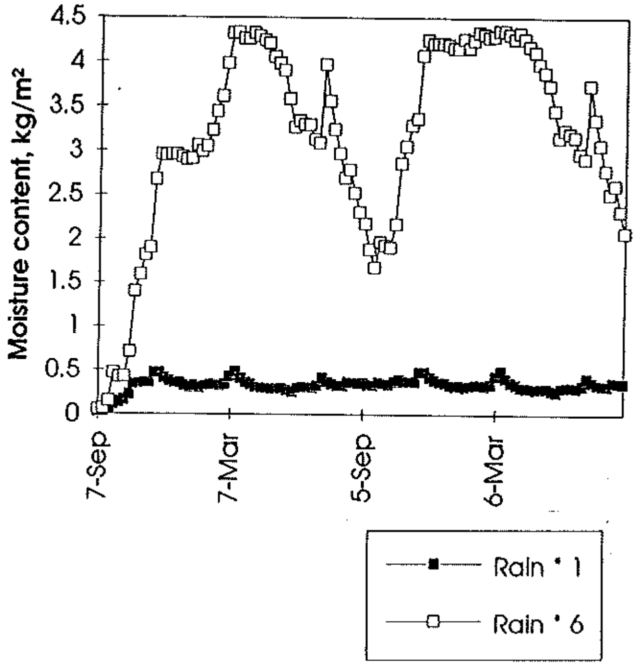

*Figure 7 The average weekly total moisture contents for a two-year period in different two-dimensional cases. Rain *1 means that the opening in the exterior coating gets only the amount of wind-driven rain that hits the wall surface. Rain *6 means that the coating does not allow liquid water penetration, which creates a falling film of water that flows past the crack.*

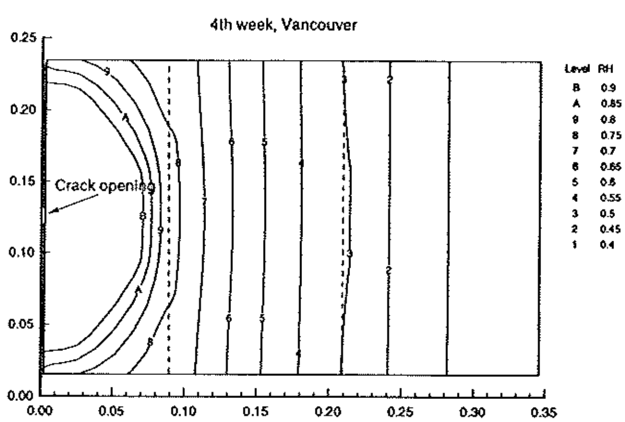

Figure 8 Relative humidity contours after four weeks of simulation for the wall structure with a crack in the coating. The height of the crack is 8 mm, and it is located in the middle of the outside (left) surface. The dashed lines show the interfaces between the brick and the insulation.

no moisture problems were found to develop. However, if cracks in the surface coating develop, yearly moisture accumulation in the walls in climates such as that in Vancouver can be expected if the coating has low vapor permeance.

The walls without waterproofing displayed higher average yearly heat losses than those with the coating (+2% in Ottawa, +9% in Vancouver). This was mainly caused by the latent heat effects of absorbed moisture from wind-driven rain and partly by the increase in thermal conductivities.

The results clearly show that computer models used in investigating hygrothermal behavior of building structures should have the capabilities to handle rain penetration. Rain penetration can be far more important than ambient surface diffusion fluxes in estimating the moisture behavior of building structures. The moisture contents in walls when calculated without rain were at maximum 0.32 kg/wall-m^2, whereas walls with rain occasionally had more than 12 kg of moisture per wall-m^2 (in Vancouver, Figure 5).

The results provided in this paper are only applicable to the specific materials that were chosen. Furthermore, the vapor permeabilities of the coating layers used in the simulations were estimated due to lack of experimental data. Further modeling research is needed to determine the applicability of the exterior surface coating on building envelopes in cold climates for different facade and wall configurations. Special care should be taken not to apply any coating with low vapor permeance on wet walls that do not have proper cavity ventilation.

ACKNOWLEDGMENT

This work was partially supported by Canada Mortgage and Housing Corporation (CMHC) under a joint research project. CMHC's support is greatly appreciated.

NOMENCLATURE

List of Symbols

D_w = moisture diffusivity (m^2/s [ft^2/s])
q_M = total moisture flux (kg/m^2·s [lb/s·ft^2])
P_v = vapor pressure (Pa [lbf/ft^2])
RH = relative humidity
T = temperature (°C [°F])
t = time (s)
u = moisture content of material (kg$_w$/kg$_d$ [lb$_w$/lb$_d$])

Greek Symbols

ρ_o = dry density of porous material (kg/m^3 [lb/ft^3])
δ_p = vapor permeability (kg/s·Pa·m)

REFERENCES

AESC. 1983. *Environment Canada, Canadian climate normals*, vol. 3. Downsview, Ont.: Atmospheric Environment Service of Canada.

ASC. 1993. Theory documentation for TASCflow, version 2.2. Waterloo, Ont., Canada: Advanced Scientific Computing Ltd.

Hens, H., and A. Janssens. 1993. Inquiry on HAMCAT CODES. International Energy Agency, Heat, Air and Moisture

Transfer in Insulated Envelope Parts, Report Annex 24, Task 1, Modeling.

Karagiozis, A. 1993. Overview of the 2-D hygrothermal heat-moisture transport model LATENITE. Internal IRC/BPL Report.

Karagiozis, A., and G. Hadjisophocleous. 1995. Wind-driven rain on high-rise buildings. Submitted to *Thermal Performance of Exterior Envelopes of Buildings* VI, Clearwater, Fla.

Karagiozis, A., and K. Kumaran. 1993. Computer models for hygrothermal modeling of building envelopes. Montreal: CFD Society of Canada.

Karagiozis, A., M. Salonvaara, and K. Kumaran. 1994. LATENITE hygrothermal material property database. IEA Annex 24 Report T1-CA-94/04. Trondheim, Norway.

Salonvaara, M., and A. Karagiozis. 1994. Moisture transport in building envelopes using an approximate factorization solution method. Toronto: CFD Society of Canada.