Envelope air pressure design load: an approach for hygrothermal analysis of retrofitted high-rise masonry wall assemblies

Djebbar, R.; Van Reenen, D.; Kumaran, M. K.; Ruan, H.

Publisher's version / Version de l'éditeur:

2nd International Building Physics Conference, pp. 379-388, 2003-09-01

Envelope air pressure design load: an approach for hygrothermal analysis of retrofitted high-rise masonry wall assemblies

Djebbar, R.; van Reenen, D.; Kumaran, K.; Ruan, H.

NRCC-46111

A version of this document is published in / Une version de ce document se trouve dans:
Research in Building Physics, Leuven, Belgium, Sept. 14-18, 2003, pp. 379-388

Envelope Air Pressure Design Load: An Approach for Hygrothermal Analysis of Retrofitted High-Rise Masonry Wall Assemblies

R. Djebbar, D. van Reenen & M. K. Kumaran
Institute For Research in Construction – National Research Council, Ottawa, Ontario, Canada

H. Ruan
University of Ottawa – Department of Computer Science, Ottawa, Ontario, Canada

ABSTRACT: This paper presents the analytical approach to predict envelope air-pressure differential that was newly implemented into IRC's computer weather analysis tool for hygrothermal calculations *WeatherSmart-1.1*. In addition to its original features, this tool now allows obtaining in a user-friendly way yearly profiles of hourly envelope air-pressure differential for both low and high-rise buildings. Hourly envelope air-pressure profiles are derived from the knowledge of both indoor and outdoor hygrothermal design loads. *WeatherSmart-1.1* is being used within the frame work of a research project to assess effects of adding supplementary insulation and air-sealing retrofit on the long-term hygrothermal performance of different wall types used in Canadian high-rise buildings. Within the frame work of this research project, the paper also introduces how effects of moist air infiltration and exfiltration across tall building envelopes are assessed using IRC's advanced HAM model *hygIRC*.

1 I INTRODUCTION

A review of literature has shown that there is still no standard available on what design loads to use for hygrothermal analysis of building envelope performance in general and high-rise building envelope in particular. No consensus among the scientific community has yet been reached on how to impose both the hygrothermal and envelope air-pressure differential design loads on the interior and exterior boundary conditions of building envelopes for either low or high-rise buildings. A method to obtain both indoor and outdoor moisture reference years was developed and implemented in WeatherSmart-1.0 presented in Djebbar et al. (2001a,b).

Another important moisture source in both high and low-rise buildings is the moisture that is carried in and out the envelopes due to air-leakage through cracks and openings as a result of the air-pressure differential across the envelope. Predicting the envelope air-pressure differential due to the combined effects of wind, stack and mechanical ventilation is still a tedious task. One objective of the research project in which WeatherSmart was further refined was to develop an analytical approach for the envelope's air pressure differential design load that applies to high-rise moisture calculations. The model from this approach will then be implemented in IRC's weather analysis tool WeatherSmart as illustrated in Figure 1 and thereafter used to obtain the envelope air-pressure differential boundary conditions in hygIRC format for parametric analysis. A description of hygIRC, an advanced HAM model, may be found in Djebbar et al (2002a,b).

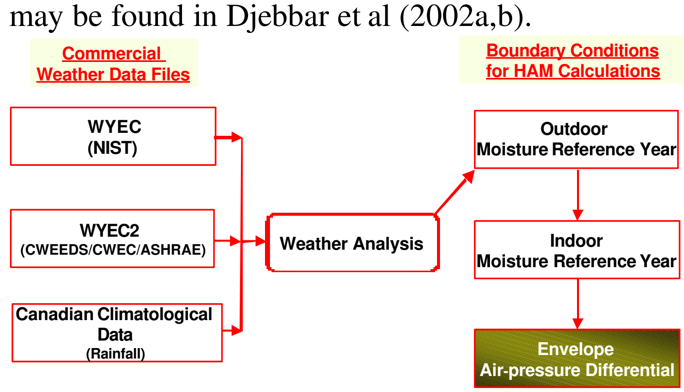

Figure 1. *WeatherSmart 1.1* flow chart

Documentation explaining how other existing HAM models handle the envelope air-pressure boundary conditions when air-leakage is considered in the hygrothermal analysis and design of building envelopes is very limited. On the other hand, most of the data available in literature on envelope's air-pressure is derived from analyses that were oriented mainly for either structural design of building envelopes or for quantifying air infiltration and ventilation in indoor spaces for IAQ and energy design of buildings. Therefore, several assumptions relevant to the hygrothermal analysis of high-rise building envelopes were adopted when the air-pressure design load computer module was added in WeatherSmart. The main assumptions are discussed in this paper.

This paper first introduces how air-leakage within porous building envelopes is modeled in hygIRC. Thereafter, follows a description of the model adopted to calculate the outdoor-induced envelope air-pressure differential due to wind loads. Finally, the approach adopted to predict indoor-induced envelope air-pressure differential is presented.

2 MODELING AIR MASS TRANSPORT WITHIN BUILDING ENVELOPES

Three main steps are systematically performed when using hygIRC for assessing the effects of air leakage on the hygrothermal performance of high-rise building envelopes. The first step consists of imposing the design load in terms of hourly envelope air-pressure differential. The second consists of selecting, depending on the problem at hand, an air-leakage path and deficiency where the moist air will flow inside the envelope. This is required to address the fact that every high-rise envelope will most probably experience air leakage during its service life due to existing imperfections in the wall assemblies. The third step consists of imposing an air permeability characteristic for the region where the air-leakage path is simulated. The value of the prescribed air permeability corresponds to the simulated level of envelope airtightness.

2.1 *Air flow governing equations*

Airflow mass transport in building envelopes calculated using hygIRC is performed by solving a subset of Navier-Stokes equations. The rates of air mass transport through existing cracks, joints and deficiencies derived from Equations 1 within envelopes are mainly due to the pressure gradients across the crack and the building envelope as a whole, ∇P_a. Field velocities are derived by using a steady state approach that assumes creeping (Stokes) flow and accounts for gravity and Darcy's air viscous term. Air velocities are derived directly from Equations 2 knowing the pressure drop across the building envelope and hence across the considered crack or opening where air-leakage is simulated, ∇P_a. The envelope's total air-pressure differential is estimated in WeatherSmart using Equation 3. This approach of solving for air-mass transport is similar with what was suggested in the IEA Annex 24, Hens (1996). Once the air mass flow rates are determined, the amounts of moisture and heat that are convected by the airflow in different parts of the envelope are calculated using the moisture mass and energy balance equations that are described in Karagiozis (1997a,b) and Djebbar et al (2002a,b).

$$\nabla.\left(\tilde{n}_a(T)\vec{V}_a\right)=0 \quad (1)$$

$$\vec{V}_a = \frac{k_a(u)}{\grave{\imath}_a(T)}\left(-\nabla P_a + \tilde{n}_a\vec{g}\right) \quad (2)$$

where:

k_a	air permeability (m^2)
P_a	air pressure (Pa)
$\tilde{n}_a$	air partial density (kg/m^3)
$\grave{\imath}_a$	air dynamic viscosity (Pa s)

Gravity and air dynamic viscosity are given as input in the model. Air-permeability, k_a, is taken from IRC's materials hygrothermal properties database for each of the building envelope component considered.

The total envelope air-pressure differential across high-rise envelopes is mainly due to the combined effect of wind and indoor air induced pressure. The indoor induced air-pressure differential is in turn a result of the combination of stack effect and the operation of mechanical ventilation. The total envelope air-pressure differential, $\boldsymbol{\nabla} P_a$, is estimated by Equation 3.

$$\boldsymbol{\Delta} P_a = P_a^{out} - P_a^{in} = \boldsymbol{\Delta} P_{wind} + \boldsymbol{\Delta} P_{indoor} \quad (3)$$

With

P_a^{in}	indoor air pressure (Pa)
P_a^{out}	outdoor air pressure (Pa)
$\boldsymbol{\Delta} P_a$	total pressure difference between across the envelope (Pa)
$\boldsymbol{\Delta} P_{wind}$	wind induced pressure difference across the envelope(Pa)
$\boldsymbol{\Delta} P_{indoor}$	indoor-air induced pressure difference across the envelope(Pa)

In the following sections, the main factors affecting an envelope's air-pressure conditions that are accounted for in the newly upgraded version of WeatherSmart are presented. The calculated hourly total air-pressure differential across the envelope are included in the indoor moisture reference input files. Indoor input files include now indoor temperature and relative humidity as well as the envelope total air-pressure differential.

2.2 Input for Air-leakage Analysis

Air-leakage is a reality in all high-rise buildings. Moisture can be carried in 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 air and outdoor is assumed in each of the wall assemblies.

A schematic drawing describing the simulated air-leakage path in two example of wall assemblies that are currently addressed in on-going research project, brick veneer with steel studs (BV/SS) base case wall and one of its interior envelope retrofit option, is shown in Figures 2a and 2b.

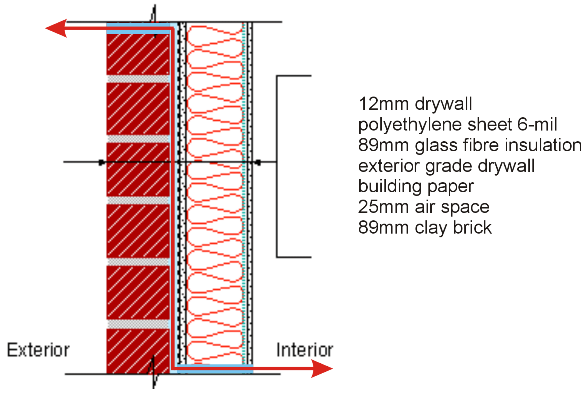

Figure 2a: Air leakage design path for BV/SS base case wall assembly

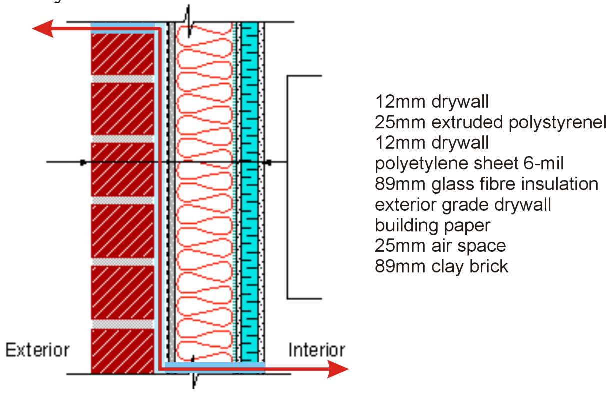

Figure 2b: Air leakage design path for BV/SS retrofitted wall assembly

The walls are simulated with an air leakage path having a 3mm crack opening (for both base case and retrofitted walls) in the bottom interior and top exterior that links the interior and exterior environments. The air-leakage paths are selected to maximize the moisture load inside the wall that may occur from wall deficiencies implying air movement from the surrounding environments. The longest possible airflow path with the greatest opportunity for condensation according to Ojanen & Kumaran (1996) are therefore assumed when assessing effects of air-leakage.

The air-permeability of the air-leakage path for each base case and retrofitted wall assembly was calculated according to the typical air-tightness of walls. To asses energy and moisture performance of different retrofit options, the air-tightness of all of the base case walls is assumed to be equal to 2.5 L/s m^2 at 75 Pascal. This value of air-tightness is consistent with what is reported by Proskiw & Phillips (2001) for tall residential and office buildings. Another assumption that is made for the parametric analysis is the airtightness of the retrofit option walls. A 40% airtightness increase is assumed when the base walls are either air-sealed or have undergone an interior or exterior envelope retrofit action. All of the retrofit wall options are assumed having an air-tightness of 1.5 L/s m^2 at 75 Pascal. This air-tightness increase is consistent with what is reported in the literature. Measurements performed by Shaw & Reardon (1995) on several tall Canadian office buildings show that a typical airtightness increase of 43% at 50 Pascal was achieved after the building's envelope was retrofitted.

3 WIND INDUCED ENVELOPE AIR PRESSURE DIFFERENTIAL

The wind induced envelope air-pressure differential, ΔP_{wind}, is the result of the wind pressure on external surfaces and the wind effect on the indoor air pressures. The current version of hygIRC was upgraded to account for the wind effect on the indoor air pressure. The total wind induced envelope pressure difference across the envelope is estimated using Equation 4:

$$\Delta P_{wind} = \left(C_p - C_{pi}\right)\rho_a^{out}\frac{V_a^2}{2} \qquad (4)$$

C_p external wind pressure coefficient (-)

C_{pi} internal wind-induced pressure coefficient(-)

V_a wind speed at the height considered (m/s)

ρ_a^{out} Outdoor air density (kg/m^3)

3.1 *Wind exterior air-pressure coefficients*

An extensive literature describing how to predict the external pressure coefficients, C_p, is available.

Most of the published data are related to structural analysis of the building envelope and are mainly derived from wind tunnel simulations. However a few field measurements have also provided data and more recently from CFD analysis, information has also been obtained. Values of the external wind pressure coefficients are building specific. They depend mainly on building shape, wind direction, building exposure due to nearby obstructions, vegetation and a building's terrain features. Most of the relevant data found in the literature on these coefficients are derived from rectangular buildings. They are mainly reported in terms of surface averaged C_p's for four wind-orientations relative to the building facades for all of the windward, leeward and the two side facades. For the purpose of hygrothermal analysis rectangular buildings are assumed in WeatherSmart.

Two categories of buildings are to be considered when estimating the external wind pressure coefficients: low and high-rise buildings. Several authors have reported small errors in estimating wind induced air-leakage rates in low-rise buildings when using surface averaged C_p's rather than local ones. 5% was reported by Swami & Chandra (1987-1988) and 10% by Wiren (1985). On other hand, wind pressures in high-rise buildings largely vary over the building height and the location of the envelope being considered on a given building facade. Surface averaged C_p's may induce a significant error in estimating the amount of air-leakage in tall buildings especially for those portions of envelope located at the corners.

WeatherSmart-1.1 adopts a curve fit model, resulting from an ASHRAE research project, as suggested by Swami & Chandra (1987), to predict the local external pressure coefficients of rectangular tall buildings is in. The model was derived from data obtained from wind tunnel simulations performed by Akins et al (1976-1979) on a few tall buildings having different building side and aspect ratios. The model predicts local C_p's as a function of the wind to the envelope angle, building side and aspect ratios, and the location of the envelope on the building surface. An example of local C_p's obtained using Swami & Chandra model is given in Figure 3. This example is for a 10-storey building with side and aspect ratios that are equal, i.e., a cubic building. The envelopes considered are all located at the corner of the building façade.

A harmonic trigonometric function developed by Walker and Wilson (1994) is also implemented in WeatherSmart-1.1 to predict surface averaged exterior wind pressure coefficients, $\overline{C_p}$, for both low and high-rise buildings, as described in Figure 4. Values of the four C_p s used for tall buildings are those suggested in Part 4 of the 1995 Canadian National Building Code (NBC) for flat roofed isolated and rectangular tall buildings. The values of the four C_p's used for low-rise buildings correspond to single-detached rectangular buildings suggested by Walker & Wilson (1994). This function requires knowledge of the surface averaged external wind pressure coefficients for four wind-orientations, windward, leeward and the two side walls as described in the Appendix.

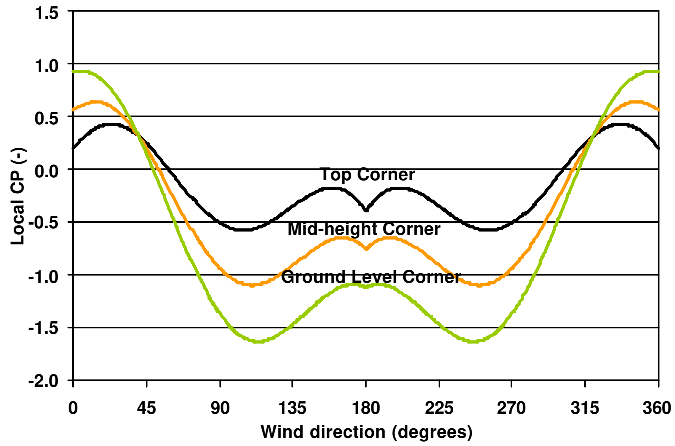

Figure 3: Local external wind pressure coefficients for three envelope elevations

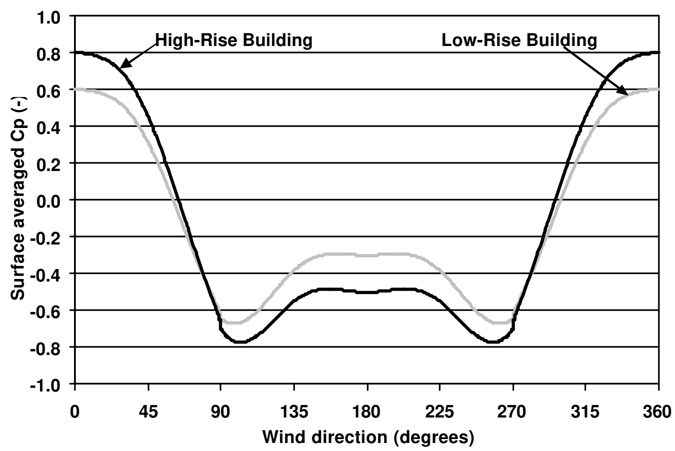

Figure 4: Surface averaged external wind pressure coefficients for low and tall buildings

3.2 *Wind induced indoor air-pressure*

Wind effects on the indoor air pressure is mainly depending on the envelope air-tightness and nature of the distribution of openings in the building. Default value assumed in WeatherSmart for internal wind induced pressure coefficient C_{pi} in high-rise building is equal to - 0.26. This value, suggested by Kato et al (1997), is a result of a full-scale measurement of wind-induced internal pressures in a 29-story building. The authors confirmed that this value of C_{pi} was found constant over the building's height. This value is at a mid-range between $C_{pi} = -0.3$ that is suggested in Part 4 of the 1995 NBC, and C_{pi} = - 0.2 suggested in Chapter 16 on airflow around buildings of the 2001 ASHRAE Handbook of Fundamentals for openings uniformly distributed in all four walls of the building.

3.3 *Wind speed at a specific height*

Several models are available on how to predict the effective wind speed at a particular height. The wind speed, V_a, at the envelope height considered, *H*, is calculated in WeatherSmart according to Equation 5 as suggested in Part 4 of the 1995 NBC.

$$V_a(H) = V_{10}\sqrt{C_{eH}} \qquad (5)$$

with

$$C_{eH} = a\left(\frac{H}{Z_c}\right)^b$$

where

V_{10}	reference wind speed determined at a height of 10m above ground in a open exposure terrain (measured at the nearby meteorological weather stations) (m/s)
C_{eH}	exposure factor reflecting changes in wind speed and height, and also effects of variations in the surrounding terrain and topography (non-dimensional)
H	height above ground in (m)
Z_c, a and b	three constant values depending on the nature of the building wind exposure

Buildings, both commercial and residential, are assumed to be located in suburban and urban areas in centers of large towns. Therefore, the mid-range values of the exposure factor coefficients suggested in Part 4 of the 1995 NBC for Z_c, a and b are assumed as default. Other exposure options for buildings are also implemented in WeatherSmart for which the values of Z_c, a and b are provided.

4 INDOOR ENVIRONMENT INDUCED ENVELOPE AIR PRESSURE DIFFERENTIAL

There are mainly two categories of buildings one can consider when estimating the indoor-induced envelope air-pressure differential for the purpose of carrying out long-term hygrothermal calculations. The first category of buildings are those where the indoor air pressure is continuously managed. The indoor-induced envelope air pressure differential can be set equal to the known operating pressure drop for these buildings. In the second category of buildings, the indoor-air pressure difference is not managed and is a function of the outdoor weather, airtightness of exterior building envelope and the different interior airflow resistances. These later type of building, most probably, constitute the majority of existing tall buildings.

In buildings where indoor air-pressure is not managed, the indoor induced air pressure difference across the envelope, ΔP_{indoor}, is a result of both the stack effect that is significant in tall buildings located in cold climates, and also to the mechanical ventilation.

Two main effects that the mechanical ventilation has on the hygrothermal performance of envelopes are accounted for in WeatherSmart. First, mechanical ventilation influences the levels of indoor air humidity. This aspect was addressed in the previous version of WeatherSmart-1.0, see Djebbar et al (2001a,b). Secondly, mechanical ventilation introduces a pressure difference across the building envelope, ΔP_{mv}. This later effect is addressed in WeatherSmart-1.1 and is discussed in the following section.

It is extremely difficult to quantify the envelope's indoor air pressure differential over a long period of time due to mechanical ventilation in isolation of the two other factors affecting air pressure difference, which are due to the wind and stack effects. Actually, very little data exist where typical pressure differences due to only mechanical ventilation are reported in the literature. One of the objectives in developing WeatherSmart was to be able to assess the effect of mechanical ventilation on the long-term hygrothermal performance of different wall assemblies. An alternative approach is to separate the effects of stack pressure from the mechanically induced pressure. The indoor-induced air pressure difference, ΔP_{indoor}, may be estimated by superimposing the stack and the mechanical ventilation effects as shown in Equation 6.

$$\Delta P_{indoor} = \Delta P_{stack} + \Delta P_{mv} \qquad (6)$$

Where

ΔP_{stack}	pressure drop across the envelope due to the stack effect (Pa)
ΔP_{mv}	indoor induced pressure drop across the envelope in the absence of outdoor wind and stack effects (due to mechanical ventilation) (Pa)

How the two envelop air-pressure differential components ΔP_{stack} and ΔP_{mv} are modeled in WatherSmart-1.1 is discussed in the following sections.

4.1 *Envelope air-pressure differential due to stack effect*

For long-term hygrothermal analysis, stack effect is a major component in the driving forces inducing air-leakage through building envelopes as illustrated in Figures 5a to 5c. Stack pressure across envelopes exists as long as there is always a temperature and humidity gradient between indoor and outdoor environment. Stack air-pressure differential in tall buildings at a specific height depends mainly on: (*i*) the difference between indoor and outdoor air-density due to air temperature gradients; (*ii*) distribution of the openings and cracks on the building facades, and (*iii*) on the airflow resistance of the exterior walls relative to the airflow resistance between floors, i.e. interior and exterior air-tightness of the building considered. A simple formula , Equation 7, suggested by Tamura & Wilson (1966-1967a) and one that is now recommended in Chapter 26 on ventilation and infiltration of the 2001 ASHRAE Handbook of fundaments is used in *WeatherSmart-1.1* to predict envelope air-pressure differential due to stack effect.

$$\Delta P_{stack} = \gamma \ \Delta P_s \qquad (7)$$

with

$$\Delta P_s = -g\left(\tilde{n}_a^{out} - \tilde{n}_a^{in}\right)\left(H - H_n\right)$$

where

ΔP_{stack} actual pressure difference due to the gradient of outdoor and indoor air temperatures

ΔP_s theoretical maximum pressure difference due to the gradient of outdoor and indoor air temperatures for buildings with no internal partitions or negligible internal airflow resistance

γ ratio of the actual stack pressure to the theoretical maximum stack pressure. Also called thermal draft coefficient due to inter-floors airflow resistance

H elevation of the wall considered (m)

H_n elevation of the neutral pressure level (m)

$\tilde{n}_a^{in}$ indoor moist air density (kg/m^3)

$\tilde{n}_a^{out}$ outdoor moist air density (kg/m^3)

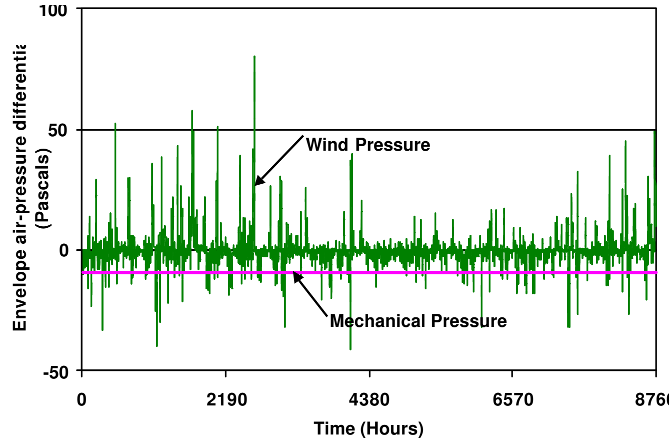

Figure 5a. Components of the total envelope air-pressure differential. Model of a design load for envelope air-pressure differential. The envelope is oriented east and is located at the top corner of a 10-storey residential building in Toronto. 0.35 ACH supply type of mechanical ventilation is assumed.

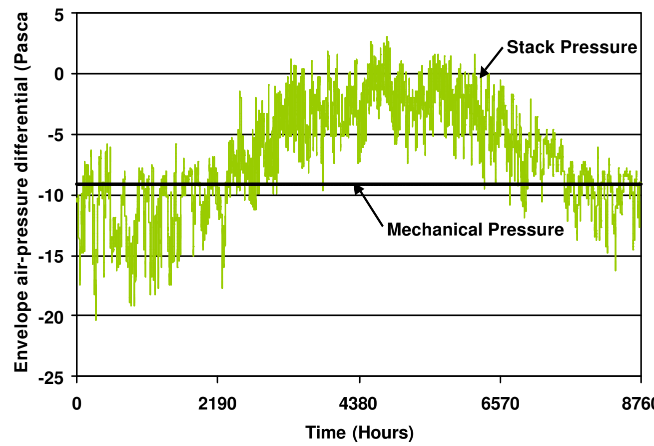

Figure 5b. Components of the total envelope air-pressure differential. Model of a design load for envelope air-pressure differential. The envelope is oriented east and is located at the top corner of a 10-storey residential building in Toronto. 0.35 ACH supply type of mechanical ventilation is assumed.

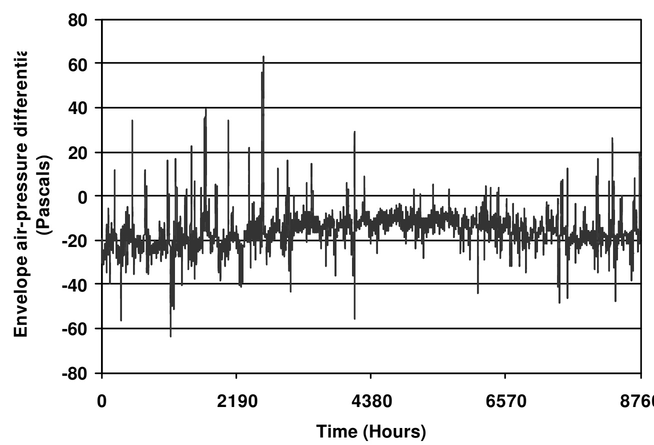

Figure 5c. Total envelope air pressure differential. Model of a design load for envelope air-pressure differential. The envelope is oriented east and is located at the top corner of a 10-storey residential building in Toronto. 0.35 ACH supply type of mechanical ventilation is assumed.

Outdoor and indoor air densities $\tilde{n}_{out}$ and $\tilde{n}_{in}$ are functions of local barometric pressure, temperature and humidity ratio. They are calculated assuming ideal gas law relationships, as described in Equation 8. The outdoor and indoor absolute temperatures, T_{out} and T_{in}, and the relative humidity ϕ_{out} and ϕ_{in} used to estimate the moist air densities are obtained from the indoor and outdoor environment condition input files, i.e., the indoor and outdoor moisture reference years, see Figure 1.

$$\tilde{n} = \left(\frac{1}{\nu}\right)(1 + W) \tag{8}$$

with

$$\nu = \frac{R\,T\,(1 + 1.6078\,W)}{28.964\,p}$$

$$W = 0.62198\left(\frac{p_w}{p - p_w}\right); \qquad \phi = \left.\frac{p_w}{p_{w,s}}\right|_{T,p}$$

where

- ν moist air specific volume (m^3/ kg (dry air))
- W humidity ratio/ moisture content kg (water vapour)/kg (dry air)
- p total moist air mixture barometric pressure (Pa)
- p_w partial pressure of water vapour (Pa)
- $p_{w,s}$ partial pressure of water vapour at saturation (Pa)
- R universal gas constant for dry air (8.314 J/ mol K)
- ϕ relative humidity (-)
- T absolute indoor or outdoor (K)

The water vapour pressure at saturation, $p_{w,s}$, is calculated according to the correlation in Chapter 6 of the 1997 ASHRAE Handbook of Fundamentals on Psychrometrics. The indoor and outdoor absolute temperatures T_{out} and T_{in} are also used to estimate $p_{w,s}$.

The neutral pressure level, H_n, is the elevation at which inside and outside pressures across the envelope are equal. Location of H_n is specific to each building depending on the opening distribution on the whole building facades and building internal compartimentation. Measurements reported by Tamura & Wilson (1966-1967a) on a few tall buildings indicated that the neutral pressure elevation level ranged from 0.3 to 0.7 of total building height. Therefore, the neutral pressure level is assumed per default in WeatherSmart to be at mid-height of buildings.

The thermal draft coefficient, γ, represents the ratio of actual to theoretical pressure difference. Actual pressure difference depends on the resistances to flow of both exterior and interior separations, such as partitions, floor constructions and walls and shafts. Values of γ are also building specific. Tamura & Wilson (1967) reported that these ratios ranged between 0.82 to 0.91 when the ventilation system was turned off, and for the same buildings γ ranged between 0.63 to 0.82 when the ventilation system was operating. As when, there was a good equilibrium between exhaust and supply ventilation. When calculating the envelope total air-pressure differential γ is assumed equal to 0.86 per default when mechanical ventilation is not considered and 0.72 when mechanical ventilation is accounted for.

Using these assumptions an example of a yearly profile of hourly envelope air-pressure differential calculated with WeatherSmart-1.1 for Toronto Moisture reference year 1972 (Djebbar et al 2001b) is given in Figures 5a-5c. For this example the mechanical ventilation is considered operating. The indoor air-humidity corresponding to a two-bedroom type of indoor air-humidity class moisture, i.e., indoor moisture generation of 12 L/day with 0.35ACH mechanical ventilation and a room corresponding to $100m^3$.

4.2 *Envelope air-pressure differential due to mechanical ventilation*

There are mainly three types of mechanical ventilation systems that are used: extract, supply and balanced ventilation. Extract ventilation systems remove air from the indoor space generating positive pressure drops towards the interior. The envelope air-pressure differential, ΔP_{mv}, is positive in this case according to hygIRC convention for the signs of pressure drop, see Equation 3. Supply ventilation systems carry outdoor air inside the space causing a pressure drop across the envelope towards the exterior, ΔP_{mv} generated is negative in this case. Balanced ventilation combines extract and supply systems using different air duct networks inside buildings. Balanced mechanical ventilation optimistically does not change the pressure across the envelopes. However, sometimes a slight imbalance may be introduced intentionally or non-intentionally causing either a positive or negative pressure drop across the envelope. ΔP_{mv} is not considered in WeatherSmart-1.1 when balanced mechanical ventilation is addressed. The difference in the envelope air-pressure generated by the three types of mechanical ventilation could be very significant especially for very air-tight envelopes, as shown in Figure 6. The example reported on Figure 6 is for tall office buildings.

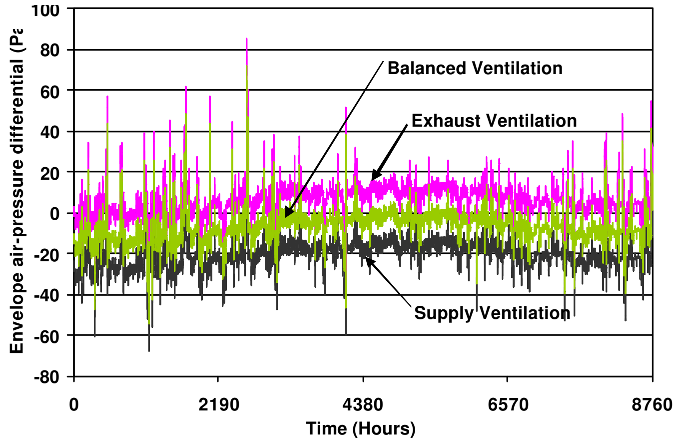

Figure 6. Model of a design load for envelope air-pressure differential when assessing effect of the type of mechanical ventilation. The envelope is oriented east and is located at the top corner of a 10-storey residential building in Toronto. Leakage coefficient=0.15 L/s m^2 Pa$^{0.65}$. Ventilation rate of 0.35 ACH mechanical are assumed for supply and exhaust types of mechanical ventilation. Controlled indoor air humidity type of building is used for indoor hygrothermal loads.

Very few data are available that correlate the envelope air-pressure differential to the operating mechanical ventilation. As a first order of approximation, Liddament (1986) suggested the use of the traditional exponential flow equation for estimating the envelope air-pressure differential due to mechanical ventilation as given in Equation 9. The envelope air-pressure differential is a function of amount of the ventilation rate carried in or out of the indoor space by mechanical means. The flow coefficient, k_t, and exponent, n, in Equation 9 are those determined by whole building pressurization/depressurization type of testing. Airflow rate and the flow coefficient and exponent should correspond to the same zone of testing for which testing has been performed.

$$\left(\Delta P_{mv}\right)^n = \frac{Q_{mv}}{k_t\, S_e} \qquad (9)$$

where

k_t total building leakage coefficient (also called flow coefficient) (m^3/s m^2 Pa^n)

n flow exponent (non-dimensional)

S_e surface area of the exterior envelope considered (m^2)

Q_{mv} airflow rate carried in or out of the building (m^3/s)

Values of k_t and n are buildings specific reflecting the air-tightness of the exterior envelope being considered. Proskiw & Phillips (2001) have gathered published data on air-tightness characteristics of large buildings from different countries including Canada. The authors reported the normalized leakage rate at an envelope air pressure differential of 75 Pa (NLR$_{75}$) for different types of buildings including both residential and non-residential high-rise buildings. The mean NLR$_{75}$ values given by the authors are reported in the second column of Table 1. These mean values of total leakage coefficients, k_t, obtained from overall air-leakage tests in Canada on whole buildings with the total envelope area used for calculation are implemented in WeatherSmart-1.1 as default values. Values of the total mean leakage coefficients reported in the third column of Table 1 are calculated by assuming a flow exponent n of 0.65. This value of the flow exponent is consistent with what is suggested by Tamura and Shaw (1976) for tall office buildings and equivalent to 0.67 that is suggested by Walker and Wilson (1998) for typical residential buildings.

Table 1. Airtightness values based on building type (reported by Proskiw and Phillips 2001, from testing of Canadian tall buildings

Building type	Mean NLR$_{75}$ (L/s m^2)	k_t (L/s m^2 Pa$^{0.65}$)
Residential	3.19	0.193
Office	2.48	0.15
Schools	1.48	0.089
Commercial	1.35	0.082
Institutional	0.86	0.052

The flow exponent, n, is assumed the same in WeatherSmart for both types of buildings, residential and non-residential buildings. The flow exponent is assumed equal to 0.65.

Shaw & Jones (1979) have reported very small deviations when estimating air-leakage rates in one school building when performing both pressurization and suction types of air-leakage testing. Hence as a first degree of approximation, k_t and n are kept the same when simulating either extract or supply type of mechanical ventilation systems, for both commercial and residential types of buildings.

Values of the ventilation airflow rates, Q_{mv}, used in Equation 9 are assumed in WeatherSmart to be equal to the required levels of ventilation rate for indoor air quality. In other words, in the absence of natural ventilation due to stack and wind effects, the minimum ventilation rates for IAQ requirements are assumed to be provided by mechanical ventilation devices. Table 2 of the ASHRAE standard 62 on "Ventilation for Acceptable Indoor Air Quality" provides ventilation rates for a wide range of building types. For the purpose of carrying out hygrothermal analysis, a ventilation rate corresponding to 0.35 ACH is assumed for both residential and commercial buildings as suggested by the 2001

ASHRAE standard 62 for living areas in residential facilities.

5 SUMMARY

An analytical model to predict an envelope's air-pressure differential was developed as a result of an extensive review of published literature. This model constitutes an upgrade of the previous approach that was used as boundary conditions in hygIRC simulations. An approach on how to predict the three main components of the total envelope air-pressure, wind, stack and mechanical ventilation induced pressures was developed and the main details for high-rise building applications are presented in this paper. This approach allows assessing several parameters that affect the hygrothermal performance of wall assemblies such as the height and location of the wall assembly on the building facade, type of ventilation used whether it is supply, balanced or exhaust type of ventilation.

This approach has allowed adapting IRC's hygrothemal model, hygIRC, to deal specifically with envelope air-pressure differential of high-rise buildings. For example, wind induced air-pressure differential can now be estimated by accounting for the location of the envelope on the building façade. Local external wind pressure coefficients are used rather than surface averaged values. This is important when height effects on the hygrothermal performance of envelopes are taken into consideration. Wind effects on the interior air-pressures are also now accounted for. Correction is made when estimating the total wind induced air-pressure differential. The building shape and geometry also affect the magnitude of pressure coefficients and is an important parameter when estimating the wind induced pressure on the envelope. Usually residential apartment buildings have a more rectangular shape whereas commercial office buildings have a more square geometry. The newly implemented model for pressure coefficients accounts for the nature of the building side and aspect ratios. The model for stack pressure calculation was also upgraded to correct for the indoor airflow resistance due to building internal compartmentation. The theoretical maximum stack pressure that is usually estimated assuming no internal airflow is actually reduced due to the internal airflow resistance inside buildings. An approach for estimating the envelope air-pressure due to the different type of typically used mechanical ventilation systems was also developed. This approach is used when the effect of the type of ventilation on the hygrothermal performance of the walls is assessed.

This general approach to predict the three components of envelope air-pressure is currently implemented in the recent version of IRC's weather analysis tool WeatherSmart 1.1. WeatherSmart-1.1 now allows conversion of, in a user-friendly way, multi-decades of commercial weather data into appropriate indoor and outdoor (*i*) thermal, (*ii*) moisture and (*iii*) envelope air-pressure differential loads for long-term moisture calculations. The outputs from WeatherSmart 1.1 include hourly envelope air-pressure differential and are part of hygIRC's indoor input files.

ACKNOWLEDGEMENTS

The authors would like to thank C.Y. Shaw and J.T. Reardon from IRC/NRC for their input. This work was partially funded by Canada Mortgage and Housing Corporation (CMHC), Natural Resources Canada (NRCan) and Public Works and Government Services Canada (PWGSC) but the views expressed here those of NRC and the participants, CMHC, NRCan and PWGSC accepts no responsibility for them.

REFERENCES

Akins, R.E. & Cermak, J.E. 1976."Wind pressures on buildings", Fluid Mechanics and wind engineering program, Colorado State university, IRN13606347, 1976.

Akins, R.E., Peterka, J.A. & Cermak J.E. 1979. "Averaged pressure coefficients for rectangular buildings", Proc, Fifth International Conference, Fort Collins, CC. Pergamon Press, NY, pp 369-380, 1979

Djebbar, R., van Reenen, D. & Kumaran, M.K. 2001a. "Indoor and Outdoor weather Analysis Tool for Hygrothermal Modelling", 8th Conference on Building Science and Technology, Toronto, Ontario, Feb, 2001), pp.139-157, 2001

Djebbar, R., van Reenen. D., & Kumaran M. K., 2001.b. "Environmental boundary conditions for long-term hygrothermal calculations", Proc. 8th International conference on building envelopes, Clearwater Beach, Florida, USA, Dec 2001.

Djebbar, R., Kumaran, M.K., Van Reenen, D. & Tariku, F. 2002a. Hygrothermal Modeling of Building Envelope Retrofit Measures in Multi-Unit Residential and Commercial Office Buildings, Client Final Report, pp. 187, 2002 (B-1110.3)

Djebbar, R., Kumaran, M.K., Van Reenen, D. & Tariku, F. 2002b, "Use of hygrothermal numerical modeling to identify optimal retrofit options for high-rise buildings,"12th International Heat Transfer Conference (Grenoble, France, 2002-08-18), pp. 165-170, Sep, 2002 (NRCC-46032)

Hens, H. 1996. Final Report, Volume 1, Task 1: Modeling. International Energy Agency, Energy Conservation in Buildings and Community Systems Program, Annex 24 Heat, Air and Moisture Transfer in Insulated Envelope Parts (HAMTIE). Laboratorium Bouwfysica, K.U.-Leuven, Belgium.

Karagiozis, A. N. 1997a. "Porous media transport in building systems". Canadian CFD Society Conference, Victoria, BC, pp 7-21 to 7-25

Karagiozis, A.N. 1997b. "Analysis of the hygrothermal behaviour of residential high-rise building components". IRC/NRC Client report number A-3052.4

Kato, N., Niihori, Y., Kurita, T. & Ohkuma, T. 1997 ."Full-scale measurement of wind-induced internal pressures in a high-rise building", Journal of wind Engineering and Industrial Aerodynamics, Vol 69 – 71, pp. 619-630

Liddament, M. W. "Air infiltration calculation techniques- An applications guide", IEA- Annex V, Air Infiltration and Ventilation Centre, Bracknell, Great Britain, June 1986.

Magee, R. J., MacDonald. R. A & Shaw C. Y., 1999. "Measurement of overall and component leakages at the Brooke Claxton Building". Rept. NRCC/Institute for Research in Construction, Ottawa, Ontario, March 1999.

Ojanen, T. & Kumaran, M.K. 1996. "Effect of exfiltration on the hygrothermal behaviour of a residential wall assembly", Journal of Thermal Insulation and building Envelopes, 19, pp. 215-227, 1996

Proskiw, G. & Phillips, B. 2001. "Airtightness characteristics of large buildings", Proc of the 8th Conference on Building Science and Technology, pp 257-270, Feb 22-23, Toronto, Ontario, 2001.

Shaw, C.Y & Jones, L. 1979. "Air-tightness and air infiltration of school buildings", ASHRAE transactions, Vol. 85, Part 1, 1979, pp. 85-95.

Shaw, C. Y & Reardon J.T. 1995. "Changes in airtightness levels of six office buildings", ASTM STP 1255, pp. 47-57, 1995.

Swami, M.V & Chandra, S. 1987. "Procedures for calculating natural ventilation airflow rates in buildings", ASHRAE Final Report FSEC-CR-163-86, ASHRAE Research Project 448-RP, March 1987.

Swami, M.V & Chandra, S. 1988. "Correlations for pressure distribution on buildings and calculation of natural-ventilation airflow", ASHRAE Transactions (94) 1, pp 243-266, 1988.

Tamura, G.T & Wilson A. G. 1966. "Pressure differences for a nine-story building as a result of chimney effect and ventilation system operation", ASHRAE Transactions 72(1):180, pp-180-189, 1966.

Tamura, G.T & Wilson A. G. 1967a "Pressure differences caused by chimney effect in three high buildings". ASHRAE Transactions 73(2), pp II.1.1 – II.1.10,

Tamura, G.T. & C.Y. Shaw. 1976b. "Studies on exterior wall airtightness and air infiltration of tall buildings. ASHRAE Transactions 82(1): 122. 1976

User's Guide – National Building Code. 1995. Structural Commentaries (Part 4), pp 9-42 Canadian Commission on Building and Fire Codes. National Research Council of Canada.

Walker, I.S & Wilson, D.J. 1994. "Practical methods for improving estimates of natural ventilation rates". 15th AIVC Conference, Bruxton, Great Britain 27-30 September, pp 517-525,.

Walker, I.S & Wilson, D.J. 1998. "Field validation of algebraic equations for stack and wind driven air infiltration calculations", Journal of HVAC&R Research, Vol. 4, No. 2, April 1998

APPENDIX

Walker and Wilson (1994) model to predict surface averaged external wind pressure coefficients ($\overline{C_p}$) function of the angle between the normal of the envelope and the wind direction (θ):

$$\overline{C_p}(\theta)=\frac{1}{2}\left[\begin{array}{l}\left(\left(\overline{C_p}(1)+\overline{C_p}(2)\right)\left(\cos^2(\theta)\right)\right)^{1/4}+\left(\overline{C_p}(1)-\overline{C_p}(2)\right)\left(\cos(\theta)\right)^{3/4}+\\+\left(\left(\overline{C_p}(3)+\overline{C_p}(4)\right)\left(\sin^2(\theta)\right)\right)^2+\left(\overline{C_p}(3)-\overline{C_p}(4)\right)\sin(\theta)\end{array}\right]$$

where

θ	angle measured clockwise between the wind direction and the normal of the wall
$\overline{C_p}(1)$	surface averaged $\overline{C_p}$ when the wind is at 0°, i.e., the C_p on the windward wall
$\overline{C_p}(2)$	surface averaged $\overline{C_p}$ when the wind is at 180°, i.e., the C_p on the leeward wall
$\overline{C_p}(3)$	surface averaged $\overline{C_p}$ when the wind is at 90°, i.e., the C_p on the side wall with wind blowing from the left
$\overline{C_p}(4)$	surface averaged $\overline{C_p}$ when the wind is at 270°, i.e., the C_p on the side wall with wind blowing from the right