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Review of Design Guidelines for Pressure Equalized Rainscreen Walls

Appupillai Baskaran

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Review of Design Guidelines for Pressure Equalized Rainscreen Walls

ABSTRACT

Controlling rain penetration in the building envelope is a continuing task for building engineers and architects. In 1963, Garden introduced the "Open Rainscreen" principle, in which external wind pressure, one of the forces that contributes to rain penetration, is controlled by equalizing it with internal cavity pressure through venting. As pressure equalization is the key element of the process, these walls are known as Pressure Equalized Rainscreen Walls (PER). Application of this wall multiplied rapidly and it is considered the most reliable tool to control rain penetration. Yet few designers seem to have a clear knowledge or rules of designing such walls; thus the problem of rain penetration is not prevented totally.

This report presents results of the first phase of an ongoing research project to develop design guidelines for PER walls, in order to help architects, engineers and building envelope designers. Part of this has been accomplished in two ways: First, the existing studies are scrutinized and useful design guidelines are extracted. During this review, more emphases is placed on research results that are dedicated to design guidelines than on data illustrating fundamental PER wall behavior. Second, a research project has been initiated at IRC/NRC, consisting of experiments and computer modelling to study the performance of PER walls. Recently experiments were performed on a wall assembly consisting of reinforced brick-wythes (1.5 x 2.1 m), steel frame (100 mm), cavity (100 mm) and gypsum board (13 mm) and exposed to simulated cyclic loading conditions. A variety of venting conditions were achieved by opening/closing the wall head joints. Performance of this wall was also modelled in a computer by assuming steady state flow conditions for the wind loading and using an iterative procedure adapted to calculate the unknown cavity pressure. Computed results are compared with the experimental data and observations are highlighted.

Based on the knowledge gathered from the preliminary experimental studies and computer modelling, the directions for further research to generate comprehensive design guidelines have been identified.
ACKNOWLEDGMENT

The author is indebted to Dr. S.A. Barakat, Mr. W.C. Brown and Mr. W.A. Dalgliesh for their valuable input during the preparation of the report. The author also acknowledges the contribution of Mr. G.F. Poirier, who conducted the experiments for the data presented in the report.
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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Controlling rain penetration of the building envelope is a continuing design problem for building engineers and architects. In fact, to cause rain penetration three conditions must prevail:

a) there must be water on the wall surface;

b) there must be an opening on the wall through which water can enter; and

c) there must be a force to move the water through the opening.

Driving forces for water entry were identified in the past and they are also displayed in Fig. 1. These include:

a) kinetic energy,

b) surface tension,

c) gravity,

d) capillary action, and

e) wind-induced pressure difference.

Details for the mechanism of these forces are well documented elsewhere [Garden (1964) and Birkeland (1968)]. By far the most common form of rain penetration is due to wind-induced pressure difference (Killip and Cheetham, 1984). When exterior air pressure is greater than the building internal pressure, rainwater can penetrate through openings, joints and imperfect seals. As wind is one of the major causes for rain penetration, basic concepts of wind effects on the building envelope are summarized in Appendix 1.

In the past, attempts were made to control rain penetration. One of the techniques that had been developed in the 1960's and applied rapidly thereafter is the "Open Rainscreen Principle." Before proceeding to the details, the other forms of wall constructions that are developed to eliminate the problem of rain penetration will be defined. This has been performed with a dual aim of distinguishing the operation of other walls from the Open Rainscreen principle and also to understand the advantages of Open Rainscreen walls. Considered walls include: face sealed
Figure 1  Driving Forces on a Pressure Equalized Rainscreen Wall (Garden 1964)
wall, cavity wall, and back-ventilated wall. Both the face sealed and cavity walls are common worldwide, whereas the back-ventilated walls are mainly used in Europe.

1) FACE SEALED WALL

A wall system in which rain penetration is prevented by sealing the joints and openings, rather than eliminating the forces that drive the water inwards.

2) CAVITY WALL

Water migration from the building exterior to the interior is diverted by introducing a cavity between the layers. The water entering through the cladding is collected and drained at the cavity bottom.

3) BACK VENTILATED WALL

In this approach, rainwater is allowed through the cladding and no attempts made to minimize the effect of wind pressure differentials. Instead, the cavity behind the cladding is drained. Moreover circulating air from the bottom to the top of the wall helps the rapid evaporation of any rainwater deposited on the inner leaf.

4) OPEN RAINSCREEN WALL

Open rainscreen wall is a system composed of two layers, separated by an air space. The air space is deliberately vented to the outside to attenuate the wind-induced pressure differential, one of the major driving forces causing the rain penetration, while keeping the inner part of the wall airtight. Thus the cavity pressure is equalized with the external air pressure through venting. As "Pressure Equalization" is the key element of the process, and also to distinguish from other types of rainscreen walls, such walls are named as "PRESSURE EQUALIZED RAINSCREEN" walls (hereafter abbreviated as PER walls). In PER walls, joints are also designed using the pressure equalization principle to give a high degree of protection against rainwater entry caused by all other forces (ref: Fig.1).
As outlined above, in all wall systems except PER walls, none of the driving forces are completely prevented or fully eliminated. In addition, PER walls have numerous advantages over other forms of wall construction and a few of them are listed below:

1) A wall design with the face seal approach will require continuous inspection and maintenance, as the sealants are susceptible to deterioration from solar radiation, freeze/thaw cycles, thermal wall movements, building motion, etc., and the effectiveness is highly dependent on the quality of workmanship. The seal may perform well for only a short period of time compared to the building life.

2) The problems of tolerance and cyclic thermal movements in the cladding assembly are less critical with PER wall than with fully-sealed walls.

3) In the air barrier system, the insulation can be placed on the outer face of the structural element, reducing thermal bridging to the other structural components such as floor slabs and columns. This maintains a constant temperature on the structural element and minimizes the risk of condensation and thermal bridges.

4) In an open rainscreen wall assembly, the outer portion of the wall is partially relieved from the external loading and thus it may be designed with lightweight and attractive materials such as glass. This enhances the appearance of a building.

1.2 DESIGN COMPONENTS OF A PRESSURE EQUALIZED RAINSCREEN WALL

There are mainly three components in a PER wall assembly; exterior, air-space and interior, respectively known as rainscreen, cavity and air-barrier system. These are illustrated in Fig. 2. Each component has number of sub-components and they are listed below.

1.2.1 Rainscreen

Rainscreen is the exterior side of a PER wall assembly. It is also called cladding or rainscreen cladding. It can be made of brick-veneer, precast-concrete, glass or sometimes aluminium. It not only prevents rain, but also regulates heat, light, pollutants, sound, fire and other
Wind Driven Rain

Air Barrier System
1) Effective leakage area
2) Air barrier design loads
3) Air barrier stiffness
4) Air barrier fasteners

Pressure Equalization Cavity
1) Cavity depth
2) Compartment size
3) Design loads on seals

Building Exterior

Wind Driven Rain

Air Barrier System

Rainscreen

1) Total venting area
2) Venting location
3) Venting dimension
4) Rainscreen design loads
5) Rainscreen stiffness

Pressure Equalization Cavity

Building Interior

Figure 2 Components of a Pressure Equalized Rainscreen Wall
environmental factors. However, the design details listed below consider only the rain penetration aspect:

(a) total venting area,
(b) venting location,
(c) venting size,
(d) protective measures for venting,
(e) design loads for rainscreen,and
(f) stiffness of the rainscreen.

1.2.2 Cavity

Space between the exterior and interior is known as the cavity or air-space. It is usually partially or fully filled with insulating materials. The design aspects of a cavity include:

(a) Depth of the cavity,
(b) Compartmentation,
(c) Design loads on the compartment seals, and
(e) Specification of the insulating materials.

1.2.3 Air-barrier System

This lies on the interior side of the wall system, facing the occupied space of a building. Mostly the air barrier system combines both vapor and air barrier functions with structural support and building paper. In addition to its function of preventing heat and air flow, it may carry decorative coatings or films on the interior side. To perform pressure equalization, design details of the following aspects are necessary:

(a) Effective Leakage area,
(b) Design loads on the air-barrier,
(c) Fasteners on the air-barrier, and
(d) Stiffness of the air-barrier.
1.3 SCOPE OF THE REPORT

PER walls are considered one of the most reliable tools to control rain penetration. While the PER wall concept is not new to building engineers, few designers seem to have a clear knowledge of how to design a PER wall and thus the problem of water migration is not prevented totally. The cause of these failures is not the principle of PER walls, but is due to a combination of factors:

(a) misunderstanding the behavior of PER walls with respect to other forms of wall construction,
(b) inappropriate or 'partially digested' design methods,
(c) lack of consistent and ready to use design guidelines,and
(d) lack of research efforts in identifying the critical parameters.

The main objective of the report is to extract from existing literature, current design guidelines for PER walls in order to help architects, engineers and building envelope designers. During this process, more emphases is focused on the research results dedicated to the design guidelines than on the data illustrating fundamental PER wall behavior.

Secondly, a research project is in progress at the Institute for Research in Construction, National Research Council Canada (IRC/NRC) to develop design guidelines for the PER walls. This initiative includes experiments and computations. For the former, various PER test specimens will be constructed of common wall construction materials and their performance will be assessed using the Dynamic Loading Facility (DLF) of IRC/NRC. Recently a wall assembly consisting of a reinforced brick-wythe (1.5 x 2.1 m), steel frame (100 mm), cavity (100 mm) and gypsum board (13 mm) has been constructed. It has been exposed to simulated cyclic loading conditions using the DLF. A variety of venting conditions were achieved by closing/opening the wall head joints. Behavior of the PER wall has also been modelled in the computer by assuming a steady external flow condition and the cavity pressure calculated through an iterating algorithm. The results from the computer modelling and experimental data are analyzed here and some design observations are also highlighted.
As mentioned before, this report is not reviewing the state-of-the-art. Neither experimental details nor theoretical developments of the existing research are elaborated; only their applications are reviewed. It is believed that this report:

(a) helps to understand the scientific principles of a PER wall;
(b) reviews design guidelines for a PER wall assembly; and
(c) identifies the directions for systematic further research in this area.

The report is partitioned into five chapters and two appendices. Chapter 2 reviews the existing design guidelines and presents in-depth discussions on current research efforts. Chapter 3 summarizes, in a comprehensive manner, the available design guidelines for a PER wall system. Transitions in research, advantages and disadvantages of different approaches are summarized in Chapter 4, while the references are listed in Chapter 5.
CHAPTER 2

REVIEW OF DESIGN INFORMATION

This chapter presents the various studies in chronological order. After presenting the essential features from each study, a summary is presented containing the extracted design information. The presented design information have not been checked or verified and readers are requested to refer the original publication for further details.

2.1 REVIEW OF EXISTING RESEARCH

In 1963, Kirby Garden first introduced the principle of "Open Rainscreen" to building engineers. The significance of the study by Garden lies in the formulation of basic design guidelines, which have been subsequently modified on several occasions to deal with the complicated interaction between rain and wall system. Most of the existing design guidelines of today are based on his continuous work on this topic [Garden(1964) and (1968)]. According to him, successful application of the open rainscreen technique requires:

(a) protected vent holes in the rainscreen, to minimize the wind-induced air pressure difference which acts across the rainscreen;
(b) an effective and continuous air barrier on the internal side of the cavity;
(c) cavities subdivided into a series of compartments, permeating equalization of the non uniform wind pressure distribution around the building; and
(d) joints in the assembly that are also designed using the PER principle, to give a high degree of resistance to rain penetration caused by various forces, as listed in chapter 1.

Extracted design information

A minimum diameter of 10 mm is necessary for vent holes; they should be placed at the bottom of the wall to facilitate drainage and all vent holes of a compartment should be placed at the same height.
The width of cavity should be about 25 mm.

Regarding the segmentation or compartmentalization of the cavity, it was proposed that "until further pertinent information becomes available," vertical closures should be provided at each outside corner of a building and at 1.2 m intervals for about 6 m from the corners. Horizontal closures should be positioned up to 9 m on centers over the total wall area.

When reviewing Garden's work, Latta (1973) proposed a theory for pressure equalization based on the incompressible continuity equation. This has been considered as the first theoretical work for the pressure equalization phenomenon. The wall system was idealized as an air chamber as shown in Fig. 3. For simplicity, all the openings in the outside of the chamber have been grouped together to form one single hole; the same has been followed for the inner wall. Representing the openings on the outside and inside as vent and leakage holes, respectively, and assuming them to be sharp edged orifices, the flow rate can be written as:

\[ Q_v \propto A_v \sqrt{\Delta P_o} \]  \hspace{1cm} (1)
\[ Q_l \propto A_l \sqrt{\Delta P_i} \]  \hspace{1cm} (2)

By applying the continuity condition:

\[ Q_v = Q_l \]  \hspace{1cm} (3)
\[ A_v \sqrt{\Delta P_o} = A_l \sqrt{\Delta P_i} \]  \hspace{1cm} (4)
Figure 3  Simplified Model for Pressure Equalization  
(Latta 1973)
\[ \Delta P_i = \Delta P_0 \left( \frac{A_v}{A_L} \right)^2 \]  \hspace{1cm} (5)

From equation (5), it can be seen that the relative venting area changes the relative pressure difference with the square of their ratios. If the venting area is 10 times greater than the aggregate size of the leakage area of the inner wall, the pressure drop across the outer wall will be only \(1/100\) of the inner wall. Thus, for any outside pressure drop, only about 1 percent will not be taken by the cavity and for practical purposes, this may be considered as the acceptable pressure equalized condition. However, the above discussion is valid only for steady wind loading under the assumption of the orifice flow conditions.

Latta also calculated the amount of air passes into the chamber by using the standard gas law equation:

\[ \frac{\text{Pressure} \times \text{Volume}}{\text{Temperature}} = \text{Constant} \] \hspace{1cm} (6)

Assuming a constant temperature prevails in the cavity and outside, the above equation can be written as:

\[ P_1 V_1 = P_2 V_2 \] \hspace{1cm} (7)

Take \(P_1\) and \(V_1\) as air pressure and volume, respectively, at normal atmospheric conditions. Then, for any design pressure \(P_2\), one can calculate the new volume, \(V_2\), and the volume change \((V_1 - V_2)\). The venting area should be sufficient enough to provide pressure equalization for this change in the air volume.
Under steady wind conditions, to obtain acceptable pressure equalization, a venting area 10 times as large as the leakage area is required.

In 1984, Killip and Cheetham presented a technical paper reviewing the prevention of rain entry through external walls and joints by means of pressure equalization. They also performed simplified experiments to measure the pressures in the cavity for various combinations of venting to leakage area; the results are shown in Fig. 4. The figure also contains theoretical results based on Latta’s equation (5), which deviates significantly from the experimental data. Killip and Cheetham questioned Latta’s incompressibility assumption for air movements in the cavity and the assumption of equating cracks and capillary pores to sharp edged orifices.

Based on Kimura’s (1977) equation for air flow rates through cracks, an amended theory for pressure drop across the rainscreen under steady external loading conditions was proposed by Killip and Cheetham as follows:

\[ \Delta P_i = \Delta P_o \left( \frac{a_v D_v}{a_L D_L} \right) \]  

where:

- \( a \) is the crack coefficients and
- \( D \) is the characteristic dimension of the cracks.

It is also reported by Killip and Cheetham that equation (8) takes account of the three dimensionality characteristic of the flow through real cracks and joints and the compressible nature of air movements in cavities. However, knowledge of the crack coefficients is necessary to validate the newly proposed theory.
Figure 4  Comparison of (Killip and Cheetham's 1984) Results with (Latta's Theory 1973)
Extracted design information

Venting area should be between 25 and 40 times larger than the area of leakage in the air barrier.

From June 1983 to October 1984, field testing on the Place Air Canada building, a high rise office building in downtown Montreal, was undertaken by Dalgliesh and Ganguli of the National Research Council (NRC). The building received a lot of attention from building envelope researchers due to its unique precast rainscreen wall panels. Each panel (ref: Fig. 5) is 3.6 m x 2.9 m and consists of precast concrete elements 75 mm and 115 mm thick as rainscreen and air barrier, respectively. On the outside of the air barrier assembly, polystyrene insulation (64 mm) is provided, separated from the rainscreen by a 12.7 mm cavity. The cavities were well sealed laterally and vertically from adjoining wall panels and vented by a 15 mm slotting that spans the panel width above the window frame. Twelve panels at the 24th floor (about 80 m from ground level) were instrumented with exterior pressure taps and matching cavity pressure taps.

A typical time history for the pressure difference is shown in Fig. 6. This record shows the measured (400-500 Pa) pressure across a wall panel. During this 30 second period, the air-barrier experienced about the same amount of pressure difference that accrued across the wall panel. Additional experimental data were also collected to calculate the percentage of wind induced loads on the rainscreen and it was found that the rainscreen and its attachments (anchors, seals) had to withstand as much as 75% of the design wind pressure for the whole panel assembly. Recently, additional research results on Place Air Canada building are presented by Brown et al. (1991).
Figure 5  Open Rainscreen Pressure Equalized Wall Panels at Place Air Canada (Ganguli and Dalgliesh 1988)
Figure 6  Pressure across and Entire Panel and Corresponding Pressure across the Rainscreen (Ganguli and Dalgliesh 1988)
In continuation with the full-scale measurements, a wind tunnel investigation of the wall system was carried out by Irwin, Schuyler and Wawzonek (1984). This is the first of its kind, in which scale model rainscreen walls were fabricated and tested to the simulated wind environmental conditions in the wind tunnel. One of the objectives of this study was to compare the full scale data of the Place Air Canada building with the wind tunnel results.

Plexiglass was used to construct the models and a geometric scale of 1:200 was adapted to represent a full scale building of 100 m high with 36 m square cross-section. (Note that overall building dimensions are not representative of the Place Air Canada building). An important issue that emerged from this new attempt was the "Scale Effect" in modelling. This is one of the major existing drawbacks in wind tunnel studies, which often impose practical limitations in fabricating the details of building components. For example, the Place Air Canada panels were recessed at 76 mm, which corresponded to only 0.38 mm over a scale of 1:200, however, about 3 mm was actually provided in the model. Similarly, 13 mm full scale gaps between panels were modelled as 0.5 mm in contrast to its actual scale value of 0.065 mm. Pressure taps were also not placed to represent the full scale measurement locations. To avoid the scale effect, one can test complete wall specimens under simulated wind conditions such as on the Dynamic Loading Facility of IRC/NRC or undertake experiments in a long wind tunnel where the flow and the building can be modelled with the same scaling factor. On the other hand, efforts were made to simulate the wind speed and turbulence intensities corresponding to a suburban exposure (ref: Appendix 1). Extensive wind tunnel measurements were performed and the results are presented in the form of pressure coefficients such that they can be directly used for the wall design.

Figure 7 presents the load sharing pattern for a well compartmented panel of the Place Air Canada building. Due to symmetry only, half of the wall was instrumented and tested in the wind tunnel. Values are shown in form of ratios of the total wall loads at several locations for two levels on the building. Ratios equal to unity reveal that rainscreen cladding takes an equal amount of external loading. Ratios below unity imply a reduction in the rainscreen design load.
Figure 7  Peak Load Ratio on the Place Air Canada Building Panels from Wind-tunnel Study (Irwin et al 1984)
It is stipulated that even 20% reduction in design loads will save several million dollars in construction (Ganguli and Quirouette, 1987). The measurement indicated that both the positive and negative peak load ratios are reduced. As explained before, similar observations were noticed by Dalgliesh and Ganguli (1988) during the full scale measurements.

Irwin et al also performed a variety of wind tunnel experiments for a brick veneer wall model. The tested brick veneer has a continuous (uncompartmented) air space. Parameters such as vent area, air space thickness and leakage area were varied and pressures were measured.

The load sharing response of the brick veneer system is presented in Fig. 8. The ratios correspond to the worst (negative) peak loads for various leakage and venting configurations. In general, the ratios of the brick veneer are higher than the previous example due to its continuous air space. In Fig. 8(a) and (b), an airtight air-barrier is used and the venting area is increased from 0.05% to 0.16%. Increase in venting alone improves the pressure equalization and significantly reduces the rainscreen loading at the central portion of the wall. On the contrary, as shown in Fig. 8(c) and (d), an increase in leakage area on the air barrier increases the ratio. In both cases, the corner portion of the rainscreen has a load ratio of unity, indicating no load reduction from the external wind pressure. Similar patterns were noticed for the peak positive load ratios.

Extracted design information

For a rainscreen wall with an airtight air barrier system and well sealed small compartments (similar to the Place Air Canada type), it is recommended that the rainscreen panel be designed for 70% of the maximum negative wind load and the air barrier for 90%. 

Figure 8  Peak Load Ratio on the Brick Veneer Panels from Wind-tunnel Study (Irwin et al 1984)
For brick veneer walls with an airtight air barrier system it is reasonable to design for 90% of negative wind loads near corners and 80% in the central half of a flat wall.

A study on wood frame walls has been undertaken by Morrison and Hershfield Ltd. (1990). It consists of three parts:

(a) Evaluating the air leakage performance of wall systems with three cladding types (vinyl siding, stucco and brick veneer). These tests were performed by simulating the wind driven rain from a water spray rack with a simulated static wind pressure.
(b) Examining the pressure equalization performance of one of the cladding types by placing a scale model in the boundary layer wind tunnel of the University of Western Ontario.
(c) Developing a simplified mathematical model to simulate the pressure equalization performance of a rainscreen wall.

Air leakage tests were conducted in accordance with ASTM E - 330 and ASTM E - 331 and the experimental results indicate leakages less than 0.01 L/s/m². When the tests were repeated by introducing a 25 mm hole to act as a leakage area on the air barrier, a significant increase in leakage up to 0.58 L/s/m² was measured.

To evaluate the need for compartmentation inside the cavities of a pressure equalized rainscreen wall, wind tunnel experiments were undertaken with and without compartmentalization. Various combinations of compartmentation were obtained by sealing different corners, such as opposite corners, all four corners and so on. Pressure distributions on the model faces and in the cavity were examined for each configuration. Nevertheless, information regarding the adopted scale factors for modelling, parameters of the simulated velocity and turbulence intensity profiles, instrumentation of the pressure taps and methods used for data analysis were not reported.
Figure 9  Effect of Compartmentation for Normal Wind Flow Conditions (Morrison Hershfield 1990)
Figure 9 illustrates the effect of compartmentalization for the normal wind flow condition. Results are presented in the form of average pressure coefficients. When all four corners are sealed, the figure shows positive coefficients for the windward wall and negative coefficients for the other walls of the building. This was found to be true both for the external loading on the rainscreen, and for pressure in the cavity. This clearly indicates that there is no cross flow between the compartments, which may enhance the pressure equalization process in the cavity.

Results for the oblique wind direction were shown in Fig. 10. When the seals were removed, the positive pressures on the windward cavities changed into negative (suction) pressure, due to the pressure gradient across the faces. In addition, poor pressure equalization was noticed in the other cavities. This clearly demonstrates the need of compartmentalization in pressure equalized rainscreen walls. The effects of non-compartmentation are found to be more severe for the oblique wind than for normal wind conditions.

In addition to the wind tunnel experiments, a simplified model is developed by extending Latta's (1973) theory. Flow rate of the air entering the cavity was calculated by using the steady state incompressible orifice flow equation as:

\[ Q = C_d A \left( \frac{2 \Delta p}{\rho} \right)^a \]  

where:

- \( C_d \) is the discharge coefficient; 0.65,
- \( \rho \) is the density of air, 1.26 kg/m\(^3\),
- \( \Delta p \) is the pressure difference,
- \( a \) is the flow exponent, 0.5.
Figure 10  Effect of Compartmenation for Oblique Wind Direction (Morrison Hershfield 1990)
For calculating the volume change of the cavity, two new coefficients - flexibility constant of the rain screen, flexibility constant of the air barrier - having unit as m³/Pa were introduced.

If \( V_0 \) is the original cavity volume then volume change is calculated as:

\[
V_c = k_1 (P_e - P_c) + k_2 (P_c - P_i)
\]  \( \text{(10)} \)

where:

- \( k_1 \) is the flexibility coefficient of the rainscreen, in m³/Pa,
- \( k_2 \) is the flexibility coefficient of the air barrier, in m³/Pa,
- \( P_e, P_c \) and \( P_i \) are, respectively, the external, cavity, and internal pressure.

To calculate cavity pressure, the standard gas law equation is used:

\[
P_c = \frac{nRT}{V_c}
\]  \( \text{(11)} \)

where:

- \( R \) and \( T \) are the gas constant and standard temperature,
- \( V_c \) is the new volume of the cavity,
- \( n \) is the number of the air moles in the cavity.

A computer program was also developed to perform the above calculation; a decay function was used as the external driving force.

\[
P_e(t) = 1000e^{-5t}
\]  \( \text{(12)} \)

Figure 11 shows the computed cavity pressure and its difference from the external pressure. Parameters used in this particular calculation are also inserted. However, justifications were not given for selecting these parameters. The cavity pressure is always higher than the
Figure 11  Computed Cavity Pressure for an Exponential External Loading (Morrison Hershfield 1990)
external pressure which, in turn, provides a negative loading on the rainscreen cladding. The time taken for the external exponential pressure to equalize with the atmospheric pressure is about 1.19 seconds.

Extracted design information

*Compartments are necessary for faster and better pressure equalization in the cavity. The optimum condition occurs when all four corners are sealed.*

*Compartment seals were subject to loads two or three times higher than the external wind loading.*

Recently, Inculet (1990) performed a systematic study for the pressure equalization performance of rainscreen cladding. Her research work consists of three main parts: developing a theory for pressure equalization under unsteady wind loading, comparing the theoretical results with data obtained from turbulent boundary layer wind tunnel work and analysis of full scale experimental data on pressure equalized rainscreen walls. Most of her research results are presented in frequency domain.

Pressure drop across the rainscreen due to gusting wind will depend predominantly on venting area, cavity volume, discharge coefficient and both intensity and frequency of the wind gusts. Conventionally, a value of 0.65 is assumed for the discharge coefficient. Yamaguchi (1976) and Holmes (1979) observed significantly low values of \( C_d \) for fluctuating reverse flow and oscillating flow conditions. As shown in Fig. 12, Inculet also noticed differences in the transfer function when comparing calculated values with the measured results. (The calculations were performed by using the value of 0.65 for the discharge coefficient.) Moreover, the predicted (0.47 Pa) fluctuating component of the pressure drop across the rainscreen (r.m.s) also
Figure 12  Transfer Function for Pressure across Rainscreen with $C_d = 0.650$ and $C_d = 0.188$ (Inculet 1990)
differs significantly from the measured value of 3.86 Pa. On the other hand, a value of 0.188 for the discharge coefficient enables a close matching between the theoretical and experimental transfer functions. The discharge coefficient was also influenced by the leakage area; it ranged from 0.01 to 0.56 for different leakage areas.

A typical time history of the cavity pressure and pressure drop across the rainscreen is shown in Fig. 13. As explained before, different discharge coefficients are used in the calculations to represent flow from external to cavity (Cd = 0.27) and from cavity to the building interior (Cd = 0.16). Even using the new values, only the cavity pressures compare well with the experimental data and significant difference exist in the pressure difference across the rainscreen. Two causes were identified for the difference: unavoidable noise output during the experimentation at high frequencies and failure of the Runge-Kutta routine used in the modelling to calculate the system non-linearities.

Results of analyzing the full-scale data for the Place Air Canada building and the Lethbridge Courthouse were also reported. As mentioned earlier, measurements were taken at the Place Air Canada building in Montreal from June 1983 to October 1984 and at the Lethbridge Courthouse from April 1985 to November 1987. The rainscreen compartment design of the Lethbridge Courthouse is shown in Fig. 14 (see Fig. 5 for Place Air Canada rainscreen panel). The rainscreen is a 100 mm brick veneer wall with 4 venting holes per sublayer, 24 venting holes per compartment. The northern wall has 6 venting holes per sub-cavity. Each vent has an area of 54 x 10 mm. The wall is insulated with batt insulation and the air barrier is comprised of 12.7 mm gypsum board on either side of a steel stud. The compartment occurs only once in every six windows - within each group there are six sub-cavities of depth 330 mm, interconnected by a 30 mm gap, 190 mm wide, next to the air barrier.

A typical comparison for the performance of the two rainscreen walls is shown in Fig. 15. The figure represents data of from a high windy day, selected on the basis of wind speed and
Figure 13  Time History of Measured and Computed Pressure across the Rainscreen (Inculet 1990)
Figure 14  The Lethbridge Courthouse Rainscreen Design (Brown et al. 1991)
Figure 15  Pressure Equalization Performance of Place Air Canada and Lethbridge Courthouse Rainscreen Panels
direction. An attempt was made to select records having a constant mean and r.m.s for both, and low r.m.s for direction. Figure 15 shows the pressure difference across the wall assembly, cavity and rainscreen. They are presented in frequency domain and the vertical axis is normalized by using the respective square of the variance and thus the maximum value of the vertical axis is always equal to unity. Mean loads of the individual signals are given and they directly indicate the load sharing pattern of the wall assembly.

The rainscreen of the Courthouse carries a mean pressure of about 29, Pa representing 58 % of the total mean loads across the composite wall; the remaining 42 % (21 Pa) of the mean pressures were equalized by the cavity. About the same distribution was also noted in fluctuating components. Behavior of the Lethbridge Courthouse is largely dictated by a high leakage to venting ratio. Comparing the mean pressure drop across the rainscreen with the total pressure drop, suggests that the air barrier has approximately as much leakage area as the rainscreen venting area.

Place Air Canada records show an opposite trend, in which both the mean and fluctuating components of the external loadings are well equalized by the cavity and the pressure difference across the rainscreen is significantly revealed from the external loading. The Place Air Canada apparently behaved well due to its large venting area and its small compartment size. The first parameter assists in equalization of the fluctuating pressures, while the second limits both the mean and cross flows behind the rainscreen. These attributes are in addition to its well sealed air barrier system.

**Extracted design information**

*Ratio of the area of venting on the rainscreen to the total area of the wall may not be less than 2 % for high rise buildings.*
Peak pressure difference across the rainscreen can be expressed as:

\[ \Delta P_{rs} = 3.6 \ C_{prs} \hat{P}_{e} \quad (13) \]

where:

\( \hat{P}_{e} \) is the peak external pressure, and
\( C_{prs} \) is the rainscreen pressure coefficient.

Depth of the cavity can be calculated as:

\[ d_c \leq \frac{10\sqrt{A_v}}{A_w} \quad (14) \]

where:

\( d_c \) is the depth of the cavity in m,
\( A_v \) is the venting area of the rainscreen in m\(^2\), and
\( A_w \) is the total wall area in m\(^2\).
2.2 CURRENT RESEARCH EFFORTS

Studies on the PER walls were reinstated (1990) at the IRC/NRC. A reinforced brick wall assembly was selected for analysis of the pressure equalization performance. It is shown in Fig. 16. The wall (1.5 x 2.1 m) consists of reinforced brick-veneer (100 mm), a cavity (100 mm) and an air barrier system (15 mm). The cavity is covered with mineral fibre insulation whereas an aluminum foil is used on the outside of the gypsum board to prevent leakage. Venting conditions were achieved by opening/closing the vent holes which are provided at the wall assembly bottom.

2.2.1 Experimental Studies

Experiments have been carried out at IRC/NRC to evaluate three main performance factors of the assembled wall system: structural performance of wall components, air leakage characteristics, and pressure equalization performance to control rain penetration. Tests were carried out under simulated cyclic wind loading, using the Dynamic Loading Facility (DLF).

For the structural performance, the specimen was exposed to simulated cyclic negative and positive loading. In addition, a continuous ramp loading was applied. Magnitudes of these loads typically represent wind action on a high rise building located in a downtown area. The wall system, in particular, the components of air barrier system; gypsum board, fasteners and exterior aluminum foil, showed no signs of structural failure under the above loading pattern. The wall system was also tested for air leakage. An air leakage rate of only 0.03 L/s/m² at 75 Pa was measured with an airtight air barrier system. Provisions of about 36 cm² (5 holes of 9 mm diameter) as leakage area, increased the air flow rate to 0.342 L/s/m² at 75 Pa.
Figure 16 Components of a Brick-Veneer Pressure Equalized Wall Assembly Tested in the DLF
To evaluate the pressure equalization performance, differential pressures were measured at two locations on the cavity and one location at the external side of the wall assembly. They represent the cavity pressure and external loading on the wall system. The external cyclic pressure can be expressed as:

$$ P_e(t) = P_e + A_e \sin(2\pi ft) $$

where:
- $P_e$ is the mean component of the cyclic loading,
- $A_e$ is the amplitude of the cyclic loading,
- $f$ is the frequency of the cycle, and
- $t$ is the time.

The mean component is kept constant around 2 kPa whereas frequency of the sinusoidal loading is varied from 0.1 Hz to 2 Hz along with its amplitude, $A_e$. Typical pressure equalization performance of the wall, for a 2:1 venting/leakage ratio, is shown in Fig. 17. Measured times are shown on the x-axis and pressure differences are given on the Y-axis. The DLF machine was operated at 0.5 Hz with amplitude of 1 kpa for the cyclic pressure. This can be seen clearly from the figure. The pressure difference across the air barrier (cavity pressure) and across the brick veneer (rain screen) behave in tune with the external loading. The cavity pressure not only has a time lag in response but its amplitude also reduced. Difference between the external and the cavity is shown as the pressure on the rain screen cladding. For this wall assembly, having a venting/leakage ratio of 2:1, the rainscreen undergoes only about 40 - 50% of the fluctuating external wind pressure.

Additional experiments were performed along with commencement of a computer model to predict the pressure equalization performance of the wall. The experimental procedure remains essentially as before, however, venting holes on the brick veneer are closed and instead
Figure 17  Pressure Equalization Performance of a Brick-Veneer Wall Assembly Tested in the DLF
head joints are opened. It is believed that the opening of head joints for venting will improve
the pressure equalization performance. Moreover, flow through the head joints can be
reasonably assumed as sharp edged orifice flow in the mathematical modelling.

2.2.2. Computer Modelling

Steady state conditions were assumed for the development of the mathematical model. Consider a
simplified wall segment similar to the one shown in Fig. 2. The wall parameters are: external
rainscreen with area $A_W$, cavity with depth $d_C$ and an air barrier system having the same
area as the rain screen. A venting area of $A_V$ is provided on the rainscreen for pressure
equalization and an uncontrolled leakage area of $A_L$ is found on the air barrier system. Mean
pressures on the external wall, cavity and internal wall are denoted respectively as $P_e$, $P_c$ and
$P_i$.

The flow rate through venting area can be calculated as:

$$Q_1 = C_d A_V \sqrt{\frac{2}{\rho} (P_e - P_c)}$$  \hspace{1cm} (16)

where:

$C_d$ is the discharge coefficient, assumed as 0.65, and

$\rho$ is the density of air, equal to 1.26 kg/m$^3$.

Since the area, $A_V$, is intentionally provided to promote pressure equalization, the flow
discharge is termed "direct discharge through venting." Unavoidably, there are cracks and
porosity holes in the rainscreen through which there will be a discharge and called the
"secondary discharge on the rainscreen." It is calculated from Shaw (1981), Tamura and Shaw
(1976) and Etheridge (1977) as:
\[ Q_1 = C_d A_w (P_e - P_c)^{0.65} \] (17)

where:

\[ C_d \] is the leakage coefficient given as:

- \(2.0 \times 10^{-4} \pm 1.1 \times 10^{-4} \text{ m/s Pa}^{-0.65}\) : for high-rise buildings
- \(4.8 \times 10^{-4} \pm 2.0 \times 10^{-4} \text{ m/s Pa}^{-0.65}\) : for schools
- \(8.1 \times 10^{-5} \pm 5.6 \times 10^{-5} \text{ m/s Pa}^{-0.65}\) : for supermarkets

Similarly, flows through the air barrier system are termed "direct discharge due to leakage" and "secondary discharge due to leakage." They are denoted by \(Q_2\) and \(Q_1^1\) respectively, and calculated as:

\[ Q_2 = C_d A_L \sqrt{\frac{2}{\rho}} (P_c - P_i) \]

\[ Q_1^1 = C_d A_w (P_c - P_i)^{0.65} \] (18) (19)

Using the equations (16) to (19) in the condition of continuity:

\[ Q_1 + Q_1^1 = Q_2 + Q_2^1 \] (20)

For a given wall system, equation (20) takes the following form:

\[ C_1 (P_e - P_c)^{0.5} + C_3 \left[ (P_e - P_c)^{0.65} - (P_c - P_i)^{0.65} \right] = C_2 (P_c - P_i)^{0.5} \] (21)

where \(C_1, C_2\) and \(C_3\) are wall constants, calculated as follows:
Another factor is the time lag of the cavity response. This has been obtained by calculating 'Helmholtz resonator frequency', a theory developed by Rayleigh (1945). A Helmholtz resonator is a jar-like acoustic device used in medieval churches and amphitheaters in Europe. Recently this theory has been applied to calculate the wind induced internal pressures on buildings by (Saathoff and Liu 1983). For the present study, the oscillating cavity flow may behave similar to a Helmholtz resonator as shown below:

\[
C_1 = C_d A_v \left( \frac{2}{\rho} \right)^{0.5}
\]

(22)

\[
C_2 = C_d A_L \left( \frac{2}{\rho} \right)^{0.5}
\]

(23)

\[
C_3 = C_d A_W.
\]

(24)

The frequency response of the Helmholtz resonator can be predicted as (Saathoff and Liu, 1983):

\[
f_H = \frac{A_p}{\pi^{1.25}} \sqrt{\frac{n_p P_a}{2\rho V_R}}
\]

(25)
where:
n_p is the polytropic exponent;
Pa is the atmospheric pressure;
Ap is the area of air plug; and
VR is the volume of the resonator.

By equating the air plug area (Ap) to the cavity venting area (Av) and resonator volume (VR) to the volume of the cavity (V_c = A_w d_c) one can show the Helmholtz response frequency for the cavity flow, R_f, in Hz, as:

\[ R_f = \frac{A_v^{0.25} \sqrt{n_p P_a}}{\pi^{1.25}} \sqrt{2p V_c} \]  \hspace{1cm} (26)

or

\[ R_f = \frac{A_v^{0.25}}{\pi^{1.25}} \frac{V_s}{\sqrt{2V_c}} \]

where \[ V_s = \sqrt{\frac{n_p P_a}{p}} \]

the velocity of sound.

Using the velocity of sound as 340 m/s at S.T.P and simplifying, equation (26) can be written as:

\[ R_f = 57.48 \sqrt{\frac{(A_v)^{0.5}}{A_w d_c}} \]  \hspace{1cm} (27)

It is clear from equation (27) that the frequency or time lag (1/R_f) is also a constant for a given wall assembly and can be calculated as:
In the past, the pressure equalization performance was analyzed based on load sharing factors (see Fig. 8) or time history (see Fig. 13). These methods depend on the magnitude or duration of the external loading. Overall performance of a wall system may not be reflected in these analyses and performance comparisons between wall configurations are rather difficult. Attempts were made to evaluate the pressure equalization performance of a wall assembly, for a given driving force, by calculating an index termed "Pressure Equalization Index" (hereafter abbreviated as PEI):

\[
PEI (\%) = \left[ 1 - \frac{\sum_{t=1}^{nt} P_e(t) - \sum_{t=1}^{nt} P_c(t)}{\sum_{t=1}^{nt} P_e(t)} \right] \times 100
\]

The calculated PEI directly indicates the overall pressure equalization performance. For example, a value of 100% indicates that the cavity pressure of the wall system is well equalized with the external loading conditions. Similarly, a value of 10% indicates a poor equalization process. For given wall parameters \(C_1, C_2, C_3\) and \(t_1\), the following classification is proposed to evaluate the pressure equalization performance:

\[
\begin{align*}
PEI > 75 : & \text{ Good} \\
75 < PEI < 50 : & \text{ Acceptable} \\
50 < PEI < 25 : & \text{ Poor} \\
PEI < 25 : & \text{ Not Acceptable}
\end{align*}
\]

The cavity pressure (unknown) appears on both sides of equation (21) and thus the equation becomes implicit in nature. One way to obtain a solution of the implicit equation is by iterating methods. To perform the iterating process and other modelling procedures, a computer program
has been developed. Typical input parameters are shown in Table. 1 and the program flow chart is presented in Fig. 18. The program consists of five parts: inputting wall parameters, calculating wall constants, computing cavity pressures, evaluating PEI and plotting the computed results. The following assumptions are used in the development of the program:
1) Only incompressible flow conditions prevail in the process,
2) External loading is periodic,
3) The cavity is continuous, and
4) Both rainscreen and air barrier are rigid.

2.2.3 Results and Discussion

This subsection presents and discusses the simulated results. Computed results are validated by comparing them to the experimental results. Simulated results with three types (ramp, pulse and cyclic) of external forcing functions are presented to demonstrate the flexibility of the model. To identify the effect of venting, two ratios of venting area to total wall area of 0.3% and 1.1% were used for all cases. Similarly, leakage ratios of 0.07% and 0.11% were used. These parameters were kept constant for all three external driving function. By doing this one can identify the role of different external forces on the pressure equalization performance and, experimental data for validating the model were available for these venting/leakage conditions.

In Fig. 19, computed results are displayed for ramp-type external loading. Computations were performed for two venting and leakage conditions, as discussed before. A linear ramp function is used as external driving force. As shown, an increase of the venting area improves the pressure equalization process. Results from pulse loading are shown in figure 20. The National Building Code of Canada (NBCC,1990) recommends designing structures for 3 to 5 second wind gust conditions. However, monitoring in the field [Ganguli and Dalgliesh, 1988] revealed wind gusts lasting for 0.1 to 1.0 second with 4000 Pa/s rate. In the current model pulses were generated with a magnitude of 4000 Pa (approximately equal to 80 m/s wind velocity), over a period of 1 second. From the calculated cavity pressure, it is clear that the venting ratio of 0.03% transfers only about 2.75 kPa of pressure to the cavity, whereas the cavity pressure equalizes well with the external pressure when the venting ratio is increased to 1.1%.
Wall Parameters

a) Area of the wall \([A_W \text{ in } \text{m}^2]\)  
   \(3.15\)

b) Size of the air space \([d_c \text{ in } \text{m}]\)  
   \(0.1\)

c) Area of venting \([A_V \text{ in } \text{m}^2]\)  
   \(800\times10^{-6}\)

d) Area of leakage \([A_l \text{ in } \text{m}^2]\)  
   \(510\times10^{-6}\)

Driving Function

a) Mean pressure \((P_e \text{ in Pa})\)  
   \(2139\)

b) Dynamic amplitude \((A_e \text{ in Pa})\)  
   \(1007\)

c) Frequency \((f \text{ in Hz})\)  
   \(0.5\)

Table 1 Typical Input Parameters for the Computer Program
Figure 18  Flow Chart for Computer Modelling of a Pressure Equalized Wall under Steady Wind Loading
Figure 19  Computed Cavity Pressure with Ramp Loading for Different Leakage Ratios
Figure 20  Computed Cavity Pressure with Pulse
Loading for Different Leakage Ratios
With cyclic external loading, experiments and computations have been made for a variety of conditions. They can be grouped under three sets depending on the venting area: areas of 800 \( \text{mm}^2 \), 1600 \( \text{mm}^2 \) and 3200 \( \text{mm}^2 \) were provided by opening one, two, and four head joints on the brick veneer. For each set, four leakage conditions were considered by providing 0, 3, 5 and 8 holes of 9 mm diameter on the air barrier. Also for each set, the frequency (ref: Eq.14) of external loading is changed as 0.1, 0.2, 0.5, 1.0, 1.5 and 2.0 Hz. These frequency ranges were selected to represent the majority portion of a typical wind speed spectrum (ref: Fig. A.1.4). Combination of these \((\#A_y \times \#A_L \times \#f : 3 \times 4 \times 6)\) provide a total of 72 experiments. For each case, the pressure difference across the wall assembly and air barrier was monitored to represent the external and cavity pressures, respectively. Computations were also performed for all these cases and the comparisons are discussed below.

Figures 21 to 23 present the comparisons of the cavity pressure for two venting conditions. The external loading rate was changed by changing the operating frequency of DLF to 0.1, 0.5 and 1.0 Hz. The corresponding comparisons are grouped in Figs 21, 22 and 23, respectively. In terms of pressure equalization performance, the figure shows:

1. Venting area ratio of 1.1 % is sufficient for acceptable pressure equalization under cyclic loading. This has been found true for all three loading rates.

2. By increasing the frequency of the external loading, the time lag is increased. Since the venting area and other parameters are kept constant, the cavity pressure is not responding to the rapid changes of the external pressure and thus increases the time lag.

3. Amplitude of the external pressure is reduced when its frequency is increased. This was one of the limitations of DLF which fails to keep high mean pressure values at higher frequencies. However, this will rectified under the current refurbishing of DLF.

If one compares the computed cavity pressure with the experimental data, in general, the agreement is good. However, an increase in the operating frequency of the external pressure does not affect the time lag of the computed cavity response. This may be due to the steady flow assumption used in the model for flows inside the cavity.

To investigate the effect of leakage on the pressure equalization and to compare it with that of the venting effect, results are assembled in the same fashion as before for
Figure 21  Computed and Measured Cavity Pressure for Different Venting Ratios ($f = 0.1$ Hz)
Figure 22  Computed and Measured Cavity Pressure for Different Venting Ratios (f = 0.5 Hz)
Figure 23  Computed and Measured Cavity Pressure for Different Venting Ratios (f = 1.0 Hz)
different leakage ratios. One basic requirement for successful performance of a PER wall is an airtight air barrier system. However, due to imperfections in construction, poor design of joint seals, and quality of material used as air barrier, there will be leakage in the system. Airtight air barriers not only improve the pressure equalization performance but also play a major role in the energy saving by avoiding exfiltration problems.

As shown in Figs. 24 to 26, increasing the leakage ratio reduces the pressure equalization performance of the wall system. This was found true for all loading rates. Another observation from the figure is the overestimation of cavity pressure by the model. In other words, the model shows better pressure equalization than the experimental data for all leakage ratios and loading rates. The model does not predict as much phase shift as that of the measurement. The optimistic behavior of the model can be explained as follows. Equation (17) is used to compute the time lag of the pressure equalization process and it is independent of the leakage area and loading rate. Due to this assumption, the model is insensitive in the phase shift prediction. Air leakage experiments on the specimen show exponent values of 0.87 and 0.60 for the airtight and leaky air barrier systems, respectively. Brown and Poirier (1988) also performed several experiments on wood stud walls and found an exponent value of 1.0 for most of the tested cases. However, the model uses an exponent value of 0.5 and this may cause overestimation of the cavity pressure.

Overall performance of the wall system is evaluated by calculating the PEI of the individual cases. Results obtained from measurements and computations are displayed in Fig. 27. In general, the PEI is above 50 % for all venting/leakage conditions considered. Irrespective of the leakage ratios, the PEI was found to improve with an increase in the venting ratios. This is valid both for measurements and simulations. If one uses the classifications listed in equation (30), then the pressure equalization performance of the wall assembly is "Good", even with the minimum venting ratio of 0.3% and leakage ratio of 0.10%. Increasing the leakage ratio, as shown, clearly reduces the PEI value. Figure 27 also reveals that the PEI of the simulated results is higher than that of the measured ones. This trend has been noted for all leakage and
Figure 24  Computed and Measured Cavity Pressure for Different Leakage Ratios (f = 0.1 Hz)
Figure 25  Computed and Measured Cavity Pressure for Different Leakage Ratios \(f = 0.5\) Hz
Figure 26  Computed and Measured Cavity Pressure for Different Leakage Ratios ($f = 1.0$ Hz)
Figure 27  Computed and Measured PEI for a Wall Assembly under Various Leakage/Venting Conditions
venting conditions and this may be due to the idealized conditions considered in the modelling process.

**Extracted design information**

Venting area in the neighborhood of 1.0-1.5% of the wall area may be necessary to equalize the cavity pressure with the external wind-induced pressure difference.

For better pressure equalization, an airtight air-barrier is an ideal choice. Increasing the leakage area will reduce the pressure equalization performance of the wall system and hence the pressure equalization index.
CHAPTER 3

EXTRACTED DESIGN INFORMATION

3.1 GENERAL

PER wall design is admittedly complex. Its fundamental concepts are illustrated in Chapter 1. Chapter 2 undertook a systematic approach in reviewing the existing studies on PER walls and also presented results from the current research efforts. This chapter presents the extraction of design guidelines from all the studies. In Canada, no formal document is available for the design guidelines of a PER wall, so the following design information will not only be timely but also identifies the need for further research.

Recognizing that different situation may require different design specifications, recommendations for the three common components (rainscreen, cavity and air-barrier system) of a PER wall are presented. As the data came from many sources, complete accuracy can not be guaranteed and possibilities are open for differences in geometrical dimensions. Nevertheless, the existing research results can be generalized and, the following recommendations can serve as preliminary design guidelines (at least for similar constructions), of PER walls. For a completely new situation, as opposed to the types that are discussed in Chapter 2, designers are strongly urged to carry out experiments for their particular wall assembly or consult with the experts in this field.

3.2 DEVELOPED DESIGN GUIDELINES

3.2.1 RAINDSCREEN

Total venting area
An optimum venting area of 1 to 2% of the wall area is necessary to obtain around 75% pressure equalization.

Venting location*
Venting should be placed at the bottom of a wall and all venting should be at the same height.

Venting size*
A minimum diameter or slotting of 10 mm is necessary for venting.

Protective measure
Remove "construction spills" and provide wire mesh or vent deflector.

Design loads for rainscreen*
For a well compartmented PER wall, the rainscreen cladding may be designed for 70% of maximum negative design wind load.

Stiffness of the rainscreen cladding
No information available.

3.2.2 CAVITY

The cavity depth of a PER wall can be calculated using the following formula:

Depth of the Cavity

\[ d_c \leq \frac{10\sqrt{A_v}}{A_w} \]  \hspace{1cm} (14)
where:

c_c  is the depth of the cavity in m,

A_V  is the venting area of the rainscreen in m^2, and

A_W  is the total wall area in m^2

Compartmentation*

No more than 1.2 m on center in a 6 m wide zone around the wall perimeter. Compartments should be 3 to 6 m on center in both directions over the central portion. Horizontal and vertical closures are necessary for all corners of a compartment.

Design Loads on the Cavity Seals

Compartment seals and their attachments must be designed for a load of 2 or 3 times higher than the maximum external wind loading.

3.2.3 AIR BARRIER SYSTEM

Leakage Area

An airtight air barrier system is recommended; a maximum leakage area of 0.5% of total wall area may be tolerated.

Design Loads on the Air Barrier*

Air-barrier system have to be designed to withstand the total external wind loading.

Fasteners on the Air Barrier*

Care has to be taken to minimize the leakage due to fixing of fasteners or attachments.

Stiffness of the Air Barrier system*

No information available.
3.3 REMARKS

The system features listed above have to be carefully considered and suitably implemented during design of a PER wall. Some of the sub-components are differentiated by an asterisk (*) to indicate caution for designers that the particular guideline needs further research work. In other words, they should not be taken as the final version of the design specification. Nevertheless, in providing a rule of thumb, they may stand on their own. Also, for some of the sub-components no design information is available. The following Chapter will address the need for further research in obtaining the design guidelines of those components.
A systematic attempt has been made to extract the design information from the literature; it is presented in the previous chapter. Two features are evident from this attempt. First, the design information is available only for a few features of a PER wall assembly. Secondly, to generalize the existing design information, further research is necessary. The review attempt also showed research transitions in the pressure equalized rainscreen wall and they are summarized in figure 28. In reality, some overlap in the classification order is possible. However, for simplicity and clear understanding, the state-of-the-art is grouped under four different stages as:

1. Laboratory experiment
2. Wind tunnel measurement,
3. Full scale monitoring,
4. Model development.

Figure 28 also highlights a few advantages and disadvantages of each stage. Laboratory experiments applying steady external loading started soon after Garden introduced the "open rainscreen principle" and they helped in understanding the basic behavior of the pressure equalized walls such as the need for venting, effect of leakage and so on. Some of these results were used to develop rules of thumb for constructing PER walls. On the other hand, experimental simplifications introduced in these studies are so significant that the results do not represent actual wall behavior.
Figure 28  Research Transitions in Pressure Equalized Rainscreen Walls
To measure directly the effect of wind on PER walls and to understand its actual behavior, full scale measurements were undertaken on existing buildings. Wind-induced pressures on the facade and inside the cavity were monitored. Wind speeds and directions were also recorded to normalize the pressure values as well as to correlate the results with metrological data (ref: Appendix 1). Full scale measurements on existing buildings are not only time-consuming but they are also considerably expensive. Nevertheless, the limited data obtained from these tests are very useful to validate the wind tunnel, as well as the simulated, results.

Full scale experiments are nature-dependent. To control uncertainties and to maximize experimental options, wind tunnel studies on pressure equalized walls were started in the mid-1980's. Scale models were fabricated and tested under turbulent wind conditions. Different combinations of the venting/leakage ratios were formulated and the date collected were then used in developing design guidelines. The wind tunnel results of a particular building can be used during the design stage of that building and repetitive experiments can also be performed for modifications, if necessary. This is one of the main advantages of wind tunnel testing over full scale measurements. However, problems like "scaling" in wind tunnel experiments impose limitations on the model details and increasing costs for fabricating the models make designers seek other alternatives.

Results of the recent experimental studies at IRC/NRC by using the DLF are promising. Walls up to 2.5 x 2.5 m can be tested under various operating frequencies. These frequency ranges (0.1 to 2 Hz) represent the major portion of a typical wind spectrum and help in simulating dynamic wind components. Moreover, the scaling problems that one may encounter in wind tunnels are suitably eliminated. Conducting experiments for various influencing parameters (venting area, leakage area, compartment size etc.) may identify the critical design parameters of PER walls.
An advancement in computer hardware and software provides a new tool for understanding the performance of PER walls. Reviews made in the second chapter clearly reveal only an early stage in model development. Lack of research in formulating mathematical expressions for the cavity response and difficulties involved in expressing the unsteady wind loading, are the main obstacles in the modelling approach. Validating the computed results is an integral part of the model development. No doubt, this approach will be faster and more economical if one can make use of a systematically developed and validated computer code.

In the view of the author, experiments using the DLF and computer modelling performed in parallel would complement each other in identifying the critical parameters of a PER wall. In fact initially, the computer modelling approach can be used to get a wider range of design alternatives at reduced cost. Laboratory experiments can follow up, based on the finalized/reduced options. Knowledge gathered from these experiences can then be well utilized in developing design guidelines for pressure equalized rainscreen walls.
CHAPTER 5

BIBLIOGRAPHY


APPENDIX 1

WIND EFFECTS ON PRESSURE EQUALIZED RAINSCREEN WALLS

BASIC CONCEPTS

Since the performance of a pressure equalized rainscreen wall mainly depends on the external wind loading, successful design demands a clear understanding of local wind conditions. This appendix provides a basic understanding of the wind flow conditions and wind induced effects on a building envelope. The parameters considered include wind climate, wind profile, wind spectra and wind induced pressures. Attempts have also been made to correlate these parameters with the design concept of pressure equalized rainscreen walls.

A.1 Properties of Wind

a) Wind Climate

Wind climate parameters (speed, direction, number of occurrences, etc.) are usually monitored at major city airports. Since airports have large open land area, with few buildings and other obstructions, the local or surrounding effects will be minimum during the measurements. Such measured time history is shown in Fig. A.1.1, which clearly demonstrates that the wind speed:

(1) varies randomly with time;
(2) increases in magnitude with increases of height from the ground level; and
(3) decreases its randomness (fluctuation) with increases of height from the ground level.

On the other hand, figures of this type provide neither the prevailing wind direction nor the number of occurrences of a particular wind speed. They are usually presented in the form of
Figure A 1.1  
Record of Wind Speed at Different Heights  
(Aynsley et al 1977)
a polar plot, as shown in Fig. A.1.2. This particular example gives the probability distribution of hourly mean wind speed at 300 m over Montreal for daylight hours (07:00 to 19:00) during the winter period. To calculate probability distribution, mean wind speeds and directions are obtained, usually from records of one-hour intervals. Such mean values are grouped for a sufficiently longer period, in this case 10 years, and the probability of occurrence for different intervals of speed and directions are calculated. For this example, intervals of 20 km/h and 22.5 degrees are taken for the speed and direction, respectively. It is apparent from the figure that south-westerly winds are the strongest, followed by north-easterly winds. Also, the probability of mean wind speed exceeding 80 km/h is relatively small.

b) Wind Profile

The above discussion presents the wind climatology of a location. However, the wind at a building site will be different from records measured at the airport, mainly due to roughness of the upstream surface and effects of the surrounding building configurations. In such a case, it is necessary to make correction for the observed wind speeds. A reasonably good representation of the mean wind speed variation with height can be obtained from a power law equation. It is formulated based on the concept of gradient wind speed, $V_g$, at the gradient height, $Z_g$, above the ground level, at which ground roughness no longer has an effect, and it is written as:

$$\frac{V_g}{V_z} = \left(\frac{Z_g}{Z}\right)^{\alpha}$$

**(A.1.1)**

where:

- $V_z$ is the mean wind speed at height $Z$;
- $Z_g$ is the gradient height above ground level;
- $V_g$ is the mean gradient velocity; and
- $\alpha$ is the power law exponent.
Figure A.1.2  Probability Distribution of Hourly Mean Wind Speeds at 300 m over Montreal for Daylight hours (07:00-19:00)
Earth surface can be classified under three major types of terrains, as open country, suburban and urban exposures and they respectively represent areas with water or scattered trees, small towns and city centres with concentrated buildings and other structures. Parameters of the power law equation for different terrains are tabulated in Table A.1.1.

Mean wind speed profile for all the exposure conditions are displayed in Fig. A.1.3. Influence of the surface roughness is clearly illustrated and gradient heights are established by assuming a mean wind speed of 100 km/h. Roughness effect is significant in the case of city centres for which the gradient height is about 500 m above the ground level. Moreover, buildings with height less than 200 m undergoes strong velocity gradients, as shown in the figure.

Turbulence intensity variation is also an important property of wind. It indicates relative gustiness or random characteristic of the wind. As before, turbulence intensity profiles are plotted for different terrain in Fig. A.1.3. Gust values are smaller for the open country than the urban exposure. This is due to the reduction in the surface roughness which causes most of the turbulence. Maximum intensity is found near ground level and it is about 18, 32 and 58 % for the open, suburban and urban exposure, respectively.

The combined effect of the mean wind speed and turbulence intensity can be represented by means of gust speed or peak speed defined as follows:

$$\frac{G_g}{G_z} = \left(\frac{Z_g}{Z}\right)^\beta$$

where

- $G_g$ = peak or gust speed at gradient height $Z_g$; and
- $G_z$ = peak or gust speed at height $Z$;
- $\beta$ = an exponent related to terrain roughness, with a value of about 0.6 $\alpha$. 
Figure A.1.3  Mean Velocity and Turbulence Intensity Profiles
(Dalgliesh et al 1962)
<table>
<thead>
<tr>
<th>Terrain Category and description</th>
<th>Gradient Height $Z_g$(m)</th>
<th>Mean Speed Exp. $\alpha$</th>
<th>Gust Speed Exp. $\beta$</th>
<th>Turbulence Intensity $I_v$(%)</th>
<th>Surface Drag Coef. $k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open country: Low scrub or scattered trees</td>
<td>300</td>
<td>0.15</td>
<td>0.09</td>
<td>18</td>
<td>0.005</td>
</tr>
<tr>
<td>Suburban areas: Small towns or well wooded areas</td>
<td>400</td>
<td>0.25</td>
<td>0.14</td>
<td>32</td>
<td>0.015</td>
</tr>
<tr>
<td>Urban exposure: Numerous tall buildings or city centres or well developed industrial areas</td>
<td>500</td>
<td>0.36</td>
<td>0.20</td>
<td>58</td>
<td>0.040</td>
</tr>
</tbody>
</table>

Table A.1.1: Parameters of Power Law Equation (Dalgliesh et al 1962)
An approximate relationship between mean wind speed and gust speed has also been proposed by Aynsley et al. (1977), in which

\[ G_g = 1.35 V_g \]  

(A.1.3)

A numerical example will illustrate the above concepts. Following is the step-by-step procedure to calculate the gust speed for the evaluation of wind effects on the building envelope.

**Problem:**

"Calculate the mean wind speed and the peak gust speed to be expected at the top of a building 55 m high located in downtown Ottawa, when the mean speed recorded at the anemometer at 10 m above ground level at the city airport is 30 m/s."

Data: Mean wind speed at anemometer height, \( V_a = 30 \) m/s

- Anemometer height, \( Z_a = 10 \) m
- Building height, \( Z_b = 55 \) m

**Step 1:**

*Identify terrain parameters using table A.1.1.*

<table>
<thead>
<tr>
<th>Measured Location (Airport)</th>
<th>Building Location (Downtown Ottawa)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Terrain</strong></td>
<td>Open Country</td>
</tr>
<tr>
<td>Exponent</td>
<td>0.15</td>
</tr>
<tr>
<td>Gradient</td>
<td>300 m</td>
</tr>
<tr>
<td>Height</td>
<td></td>
</tr>
</tbody>
</table>
Step 2:

*Calculate the gradient wind speed at the airport.*

\[
V_g = V_a \left(\frac{Z_g}{Z_a}\right)^\alpha
\]

\[
= 30 \left(\frac{300}{10}\right)^{0.15}
\]

\[
= 50 \text{ m/s}
\]

Step 3:

*Calculate the mean wind speed at the building top.*

\[
V_{55} = V_g \left(\frac{Z_b}{Z_g}\right)^\alpha
\]

\[
= 50 \left(\frac{55}{500}\right)^{0.36}
\]

\[
= 22.6 \text{ m/s}
\]

Step 4:

*Calculate the gradient gust speed at the airport.*

\[
G_g = 1.35 V_g
\]

\[
= 1.35 \times 50
\]

\[
= 67.5 \text{ m/s}
\]

Step 5:

*Calculate the gust speed at the building top.*

\[
G_{55} = G_g \left(\frac{Z_b}{Z_g}\right)^\beta
\]

\[
= 67.5 \left(\frac{55}{500}\right)^{0.20}
\]

\[
= 43.4 \text{ m/s}
\]
c) Wind Spectra

Wind climate and wind speed profiles discussed in the previous subsection; will be useful in representing the random characteristic of the wind in a deterministic fashion by averaging the properties with respect to time. Note that Figures A.1.2 and A.1.3 are independent of the time scale. In other words, the properties are useful to calculate static wind effects on the building envelope. Studies report that the majority of building or building component failures are due to the "instantaneous wind effect." Thus, it is vitally important to study how quickly or slowly the process will vary with time. In order to define the process in time domain, another function is required. The function which fulfills this requirement is the spectral density function, or spectrum of the turbulent process.

Van der Hoven (1957) and Davenport (1961) indicated that the mean wind speed spectrum could be expressed as:

\[
\frac{fS(f)}{kV_{10}^2} = \frac{4 \left( \frac{fL}{V_{10}} \right)^2}{\left[ 1 + \left( \frac{fL}{V_{10}} \right)^2 \right]^3} \tag{A.1.4}
\]

where:
- \( f \) is the frequency;
- \( S(f) \) is the power spectral density;
- \( L \) is the length scale of the turbulence; 1200 m;
- \( k \) is the drag coefficient based on the terrain roughness (ref: Table. A.1.1); and
- \( V_{10} \) is the mean wind speed at 10 m height.
The spectrum defined by equation A.1.4 is plotted in Fig. A.1.4, together with a number of field observations. The vertical axis represents the energy content of the turbulent process in a non-dimensional parameter. Conventionally, the x-axis is also represented by a non-dimensional parameter known as wavelength. This will help in a universal representing of the spectrum which is independent of the local wind speed. As shown in the previous example, a design mean wind speed of 30 m/s is selected and the wavelength is correlated with time and frequency of the random process. By assuming 30 m/s (70 MPH) as the design wind speed for Canadian conditions, the parameters are calculated and displayed in the same figure.

A number of features are evident from the figure:

(1) data of the various field observations compares well with the results predicted by the theoretical equation A.1.4. Thus one can determine the energy content of the spectrum for any desired mean wind speed by using equation A.1.4;

(2) peak value of the spectrum lies in the neighborhood of 0.04 Hz (1/25 th second of the gust);

(3) most of the turbulent energy lies in the range of about 0.01 to 1.0 Hz;

(4) gusts less than 0.006 Hz and more than 3 Hz have little energy and can be neglected in the analysis;

(5) the wavelength for most of the field observations is less than 1000 m.
Figure A.1.4  Spectrum for Mean Wind Speed (Aynsley et al. 1977)
A.2 Wind Pressure Coefficients

Wind induced pressure on the building envelope largely depends on the following parameters:

1) wind speed and turbulence conditions,
2) wind direction and flow stability,
3) building geometry,
4) architectural features such as exposed mullions and parapets, and
5) shielding from the surrounding buildings.

a) Definition of Pressure Coefficient

Building codes and wind standards provide the value of wind pressures in terms of "pressure coefficients." These coefficients are obtained by normalizing the measured pressure at a location with respect to the dynamic pressure at roof height of the building. One of the main advantages of this representation is that the non-dimensional pressure coefficients obtained are independent of the wind speed and thus they can be directly used during the envelope design. The coefficients are defined as follows (Baskaran, 1986):

\[
\begin{align*}
\nu C_P &= \frac{v}{q_H} \\
\bar{C}_P &= \frac{\bar{p}}{q_H} \\
\hat{C}_P &= \frac{\hat{p}}{q_H} \\
\tilde{C}_P &= \frac{\tilde{p}}{q_H}
\end{align*}
\]

(A.1.5)

where:
\(\nu C_P\) = the maximum instantaneous pressure coefficient measured over the sampling period;
\(\hat{C}_P\) = the minimum instantaneous pressure coefficient measured over the sampling period;
\[ C_p = \text{the time-averaged mean pressure coefficient;} \]
\[ \bar{C}_p = \text{the root mean square pressure coefficient; and} \]
\[ q_H = \frac{1}{2} \rho V_H^2, \text{the dynamic pressure associated with the mean velocity at roof height.} \]

A pictorial representation of the all pressure coefficients is shown in Fig. A.1.5. The mean value gives an indication of the static wind load that can be expected. The \( \bar{C}_p \) or \( \hat{C}_p \) is the measure of storm pressure or maximum suction on the envelope, which is mostly needed for the design of cladding elements. The rms value is a measure of fluctuation in the pressure signal. Large deviations from the mean value will give a higher rms value.

b) Mean Pressure Coefficient

Fig. A.1.6 shows the mean pressure coefficients on a 55 m high building. These data are obtained from wind tunnel model studies. Contours of equal intervals are shown. Positive value (pressure) for the windward side and negative value (suction) of other walls are displayed. The contours are closer together near the wall edges and corners, implying that the compartments of the rainscreen cavity should be small. Where the contours are further apart, such as the central portion of a face, the compartments may be larger. Wind directionality effects are also noticed from the figure. In the absence of the predominant wind direction, it would be safe to design the rainscreen and its components for the worst wind direction. Usually, the wind coming at an angle of 135\(^\circ\) (oblique wind) is considered the critical wind direction.

c) Gust Pressure Coefficient

Gust factors of wind-induced pressures can be calculated by using the following formula; they will be incorporated in the design of window panels and rainscreen cladding elements:
Figure A.1.5  Statistics of Pressure Coefficients (Baskaran 1986)
Figure A.1.6  Mean Pressure Coefficients on a Building (H = 55 m)
where:

\[ \hat{g} = \frac{1}{N} \sum_{1}^{N} (\hat{C}_P - \bar{C}_P) \]
\[ \hat{g} = \frac{1}{N} \sum_{1}^{N} (\hat{C}_P - \bar{C}_P) \]

\[ \gamma = \text{maximum peak pressure factor}, \]
\[ \hat{g} = \text{minimum peak pressure factor}, \]
\[ N = \text{number of measurements}, \]
\[ C_P = \text{maximum peak pressure coefficient}, \]
\[ C_P = \text{minimum peak pressure coefficient}, \]
\[ \bar{C}_P = \text{mean pressure coefficient}, \]
\[ \bar{C}_P = \text{rms. pressure coefficient}. \]

To illustrate the complexity of wind induced pressures on a building, the wind tunnel data of the tallest building in North America (Sears Tower, Chicago) are shown in Fig. A.1.7. Both the mean and dynamic pressures on the envelope at different levels are displayed. Such figures are extremely useful in deciding the compartment size of Pressure Equalized Rainscreen Walls. The building shape is changed from level 2 to level 6, and so is the pressure distribution. In other words, the compartment size of level 6 will be smaller than on level 2 due to pressure distribution changes. Another feature that is evident from the figure is the high dynamic pressure component near the corners of each level. For the design of pressure equalized walls, this means the compartment seals or closures have to be designed to withstand these high dynamic pressures.
Figure A.1.7  Variation of External Pressure on Different Levels of a Building
(H = 485 m) (Davenport et al 1971)
APPENDIX 2

NOMENCLATURE

\( a \) = Flow exponent; 0.5
\( A_e \) = Mean amplitude of cyclic loading
\( A_p \) = Area of air plug
\( A_L \) = Effective area of leakage
\( A_w \) = Area of the wall or rainscreen
\( A_v \) = Effective area of venting
\( C_1, C_2, C_3 \) = Wall constants
\( C_d \) = Discharge coefficient; 0.6.
\( C_d \) = Leakage coefficient
\( C_p \) = Mean pressure coefficient
\( C_p \) = rms. pressure coefficient
\( C_p \) = Negative peak pressure coefficient
\( C_p \) = Positive peak pressure coefficient
\( C_{prs} \) = Rainscreen pressure coefficient
\( d_c \) = Depth of cavity
\( D \) = Chark dimension
\( f \) = Frequency
\( f_H \) = Helmholtz resonator frequency
\( g \) = Gust factor for wind loading
\( v \) = Minimum peak factor (-ve)
\begin{align*}
g & = \text{Maximum peak factor (+ve)} \\
G_g & = \text{Gust wind speed at gradient height} \\
G_Z & = \text{Gust wind speed at height } Z \\
l_v & = \text{Turbulence intensity} \\
k & = \text{Surface drag coefficient} \\
k_1 & = \text{Flexibility coefficient of cladding} \\
k_2 & = \text{Flexibility coefficient of air barrier} \\
L & = \text{Length scale of turbulence: 1200 m} \\
N & = \text{Number of samples} \\
n & = \text{Number of moles} \\
nt & = \text{Number of time intervals} \\
n_p & = \text{Polytropic exponent} \\
P & = \text{Pressure} \\
P_a & = \text{Atmospheric pressure} \\
P_c & = \text{Cavity pressure} \\
P_e & = \text{External pressure or wind pressure} \\
P_i & = \text{Internal pressure} \\
Q_1 & = \text{Direct discharge through rainscreen} \\
Q_1^1 & = \text{Secondary discharge through rainscreen} \\
Q_2 & = \text{Direct discharge through air barrier}
\end{align*}
Secondary discharge through air barrier

Dynamic pressure at roof height

Flow rate through leakage

Flow rate through venting

Gas constant

Resonance frequency

Power spectral density

Temperature

Time

Time lag

Volume

Gradient wind speed

Volume of the resonator

Velocity of sound; 340 m/s

Mean wind speed at height Z

Height from ground level

Gradient height

Rainscreen gust factor

Power law gust exponent
\[ \Delta P_i = \text{Pressure difference between cavity and building interior} \]
\[ \Delta P_o = \text{Pressure difference between building exterior and cavity} \]
\[ \rho = \text{Density of air; } 1.26 \text{ kg/m}^3 \]
\[ \Gamma = \text{Wave length} \]

Abbreviations

DLF = Dynamic Loading Facility
PER = Pressure Equalized Rainscreen
PEI = Pressure Equalization Index