The Pressure Response of Buildings

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ABSTRACT

Airflow in buildings is one of the major factors that governs the interaction of the building structure with the mechanical system, climate, and occupants. If the airflow at any point within a building or building assembly can be determined or predicted, the temperature and moisture (hygrothermal or psychometric) conditions can also be determined or predicted. If the hygrothermal conditions of the building or building assembly are known, the performance of materials can also be determined or predicted.

This paper shows that airflow in buildings is complex, time dependent, and multidirectional. The understanding of airflow through and within buildings has been based on the requirement for continuity of mass and momentum caused by wind forces, thermal effects (stack action), and forces associated with the operation of mechanical cooling, heating, exhaust, and other ventilation systems.

Interstitial airflow and interstitial air pressure fields are not often considered. Building analysis typically develops the building pressure field from the airflow field. In doing so, exterior and interior walls, floors, and roof assemblies are either considered as monolithic or having openings resulting in flow across the specific assemblies.

This paper shows that many problems associated with pollutant transfer and the spread of smoke and fire cannot be explained by cross-assembly (one-dimensional) airflow as well as such moisture effects as microbial contamination, corrosion, and biological decay. Even the analysis of energy consumption and comfort within buildings needs to be considered in terms of multidirectional airflow.

This paper shows that buildings typically comprise multi-layer envelope assemblies with numerous air gaps or void spaces that are often connected to service chases. Complex three-dimensional flow paths and intricate air pressure relationships must be considered.

This paper also introduces an alternative pattern of analysis: developing the flow field, the leakage areas, and the flow relationships from the measured building pressure field—the air pressure regime within and surrounding the building. This approach accounts for interstitial air pressure fields and resulting interstitial airflows. It provides a powerful diagnostic tool for solving many of the problems related to direct and indirect effects of airflows.

INTRODUCTION

Airflow in buildings is complex, time dependent, and multidirectional. The understanding of airflow through and within buildings has assumed that wind forces, thermal effects (stack action), and air movements associated with mechanical cooling, heating, and exhaust and other ventilation systems are the dominant factors relating to air pressure relationships and air pressure related building performance.

In principle, this view is correct, though often too simplistic. Under this view, the wall assemblies, roof assemblies, interior floors, and demising walls/partitions are treated either as monolithic or having through-the-assembly openings. Airflow has been assumed to occur across these assemblies, from one side to the other based on the air pressure difference across them, typically through simple leakage areas, resulting in one-dimensional airflow.

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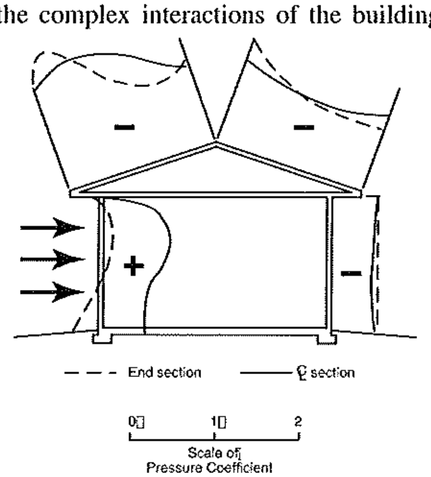
Actually, exterior wall, roof, interior floor, and interior wall/partition assemblies are often hollow or multi-layered with numerous air gaps or void spaces and can operate under air pressure regimes (fields) that are largely independent of the air pressures on either side of them. Typical buildings also contain numerous service chases that provide complex three-dimensional linkage among the exterior wall, roof, interior floor, and interior wall/partition assembly cavities and void spaces. These interstitial air pressure fields within building assemblies and their linkage to chases and service cavities can lead to lateral flow paths or more intricate three-dimensional flow paths that may or may not connect to the interior or exterior spaces that the building assemblies separate.

As a result of these interstitial air pressure fields, direct cross-assembly (one-dimensional) airflow does not always hold. To account for the presence of interstitial air pressure fields, airflow must be added or subtracted within an assembly, chase, or void space. In this manner, continuity of mass and momentum holds across the volume of the assembly or element.

The interstitial air pressure fields often vary with time, with complex daily, weekly, seasonal, and sometimes random cycles. They are often, but not always, driven by fan forces coupled with duct leakage. Thermal effects, moisture effects, and wind forces can also be interstitial air pressure field drivers depending on the linkages of interstitial flow paths. These time-variable interstitial air pressure fields help characterize the dynamic characteristics of the pressure response of buildings.

The presence of complex, time-dependent interstitial air pressure fields and associated lateral or three-dimensional flow paths can lead to complex interactions of the building structure with the mechanical system and climate. Understanding the complex interactions of the building pressure field—the air pressure regime within and surrounding the building—helps explain the increasingly common failures related to

- indoor air quality, sick building syndrome, and building-related illness;
- smoke and fire spread;
- condensation, corrosion, decay, and mold;
- comfort (temperature, humidity, and odors);
- operating costs (energy consumption, maintenance, and housekeeping).



Distribution of pressures (+) and suctions (-) on a house with a low-sloped roof with wind perpendicular to eave

Figure 1 *Exterior air pressure field (Hutcheson and Handegord 1983).*

One of the keys to understanding the complex interactions of the building structure with the mechanical system and climate is the pressure response of buildings. Building analysis typically focuses on flows and requires that all flow paths into and out of a control volume be defined. The flow path resistances need to be characterized. Determining all airflow paths and determining the flow path resistances directly is difficult. As such, estimates of these flow path resistances are typically used. These estimates are based on limited field data and laboratory measurements. The literature provides some component values that vary by orders of magnitude and their application is often unable to predict building flow fields (ASHRAE 1997).

This paper examines a different approach—determining the pressure response of buildings. Determining the pressure response of buildings, determining the characteristics of the building pressure field directly, is considerably easier. Pressures can be used to predict direction of flows. Knowing all the flow paths and their resistances may no longer be necessary. Pressures are relatively easy to measure; flows are not. It is typically easier to establish the pressure field rather than the flow field.

Standard building analysis typically develops the building pressure field from the flow field. This paper shows that analysis developing the flow field from the building pressure field is more powerful and permits accounting for interstitial air pressure fields and flows.

BUILDING AIR PRESSURE FIELD

The building air pressure field (static plus dynamic), the total air pressure regime within and surrounding the building, involves four contributing air pressure fields:

- exterior field
- interior field
- interstitial field
- air conveyance system field

The exterior field extends from infinity to the exterior skin of the building envelope. The remaining three component fields are inward of the exterior skin of the building envelope except in the special case of ductwork associated with the air conveyance system field that is located to the building exterior.

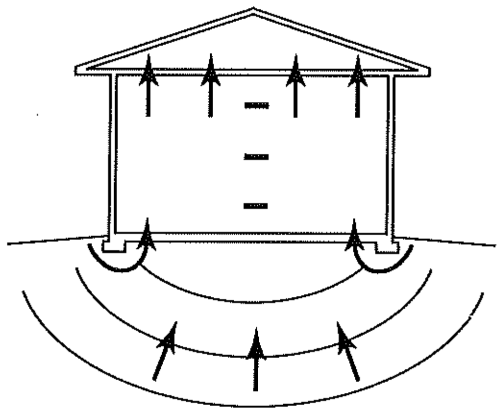


Figure 2 Exterior air pressure field extending below grade.

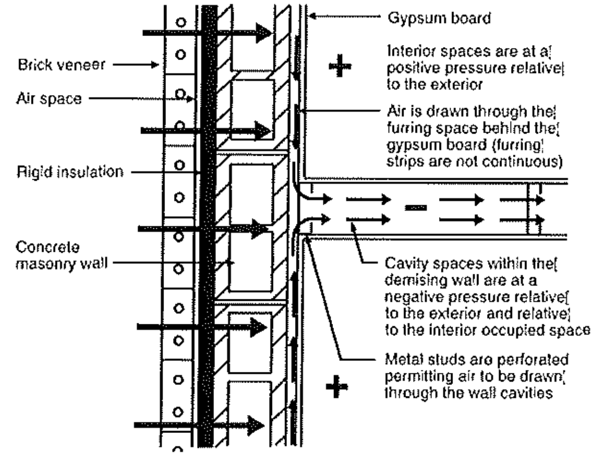


Figure 4 Interstitial air pressure field.

When considering the exterior field, the boundary layer at the building envelope surface is typically of primary significance in building analysis. The above-grade portion of the exterior field is typically dominated by wind-induced flows (Figure 1). The below-grade portion of the exterior field is a function of the soil characteristics (air porosity), the footprint of the building, the interaction with the building, and time-dependent atmospheric pressures in the vicinity of the building (Figure 2).

The interior field occurs within spaces such as rooms, corridors, stairwells, and elevator shafts (Figure 3) and is dominated by the operation of air conveyance systems, the stack effect, and wind. The interior field is typically bounded by the interstitial air pressure field except in the special case of monolithic, solid, nonporous walls, floors, and roofs.

The interstitial field occurs within a building cavity, such as an exterior or interior wall assembly, roof assembly, or floor assembly (Figure 4). The interstitial field is bounded by the exterior and interior fields and is often dominated by the leakage of air conveyance systems and building leakage pathways.

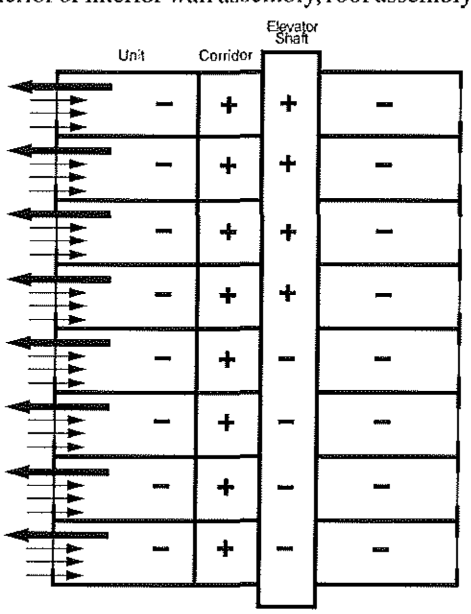


Figure 3 Interior air pressure field.

The air conveyance system field occurs within the ductwork of forced-air thermal distribution systems, chimneys, air exhaust, and air supply systems (Figure 5) and is dominated by the size and capacity of ductwork, fans, and blowers and temperature differentials. It is bounded by the other three pressure fields.

These air pressure fields are coupled and interact dynamically. The interstitial field provides linkage between the exterior field, the interior field, and the air conveyance system field.

DYNAMIC INTERACTION OF COMPONENT FIELDS

A hotel room/bathroom suite with an exhaust grille, a fan coil unit, corridor makeup air, and steel stud partition walls provides a good example of the dynamic interaction of the component fields and the limitations of traditional analysis (Figure 6).

As is common in hotel construction, a fan coil unit is suspended from the ceiling and enclosed in a gypsum board dropped ceiling enclosure. The dropped ceiling enclosure is designed as a return air plenum. The fan coil unit provides heating and cooling to the hotel room by pulling air from the room through a return grille located at the underside of the dropped ceiling enclosure, conditioning the air, and returning the air through a supply register located in the face of the dropped ceiling enclosure. These units typically supply 1.75 to 2.5 kilowatts of heating and cooling and typically move approximately 100 to 150 L/s of air. Under conventional thinking, this fan coil unit only recirculates air and, therefore, does not affect the air pressure relationships in the room (Figure 7).

Additionally, an exhaust grille is located in the bathroom of each hotel room suite. This exhaust grille is typically

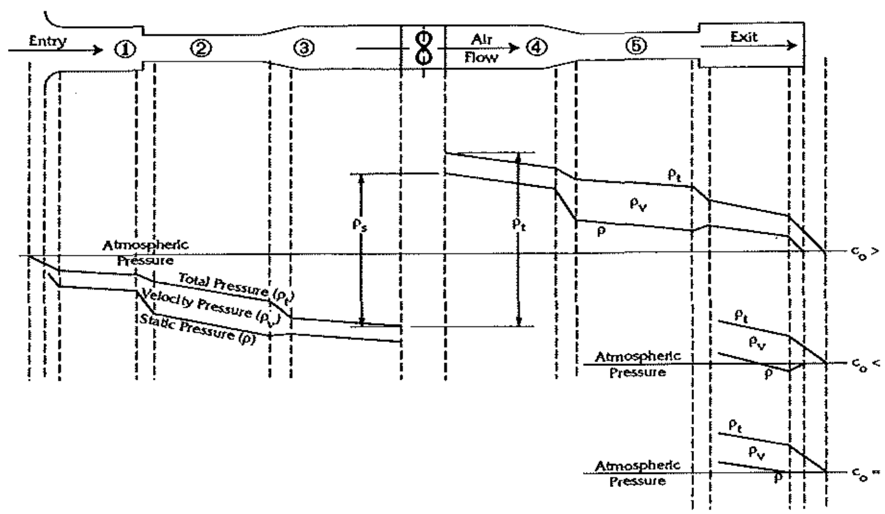


Figure 5 *Air conveyance system air pressure field (Sauer and Howell 1990).*

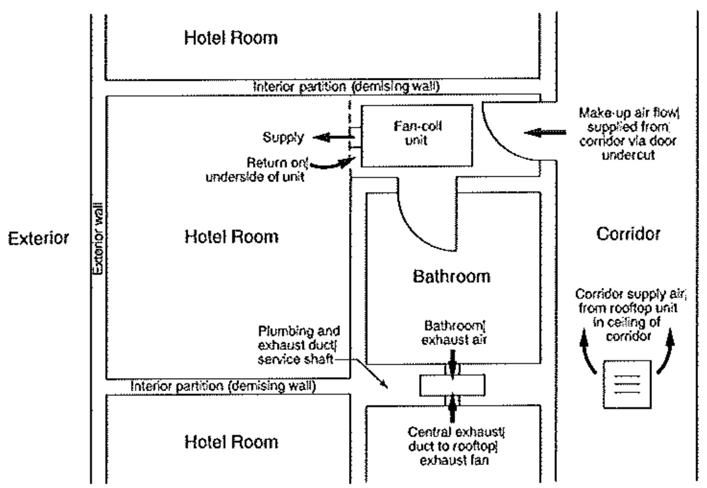


Figure 6 *Hotel room/bath suite plan view.*

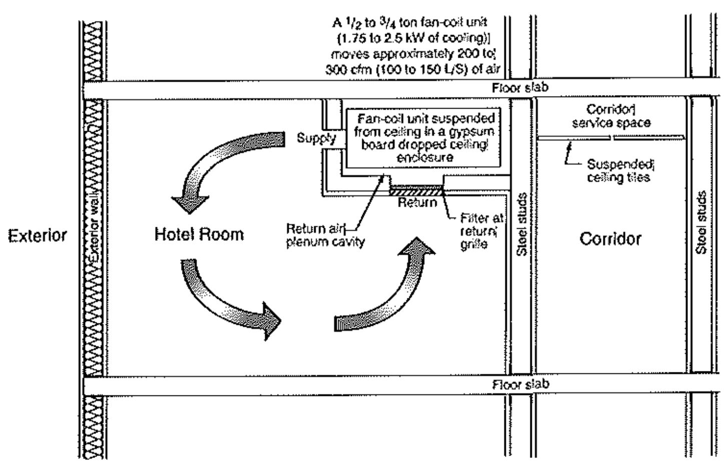
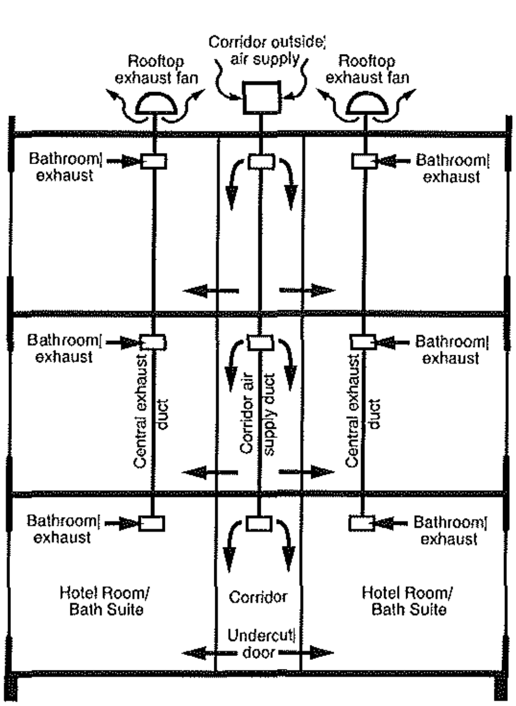


Figure 7 *Hotel room/bath suite section view.*



· Air exhausted from bathrooms via central rooftop exhaust fans
· Air supplied from corridors via undercut doors

Figure 8 Hotel HVAC system.

connected to a central exhaust duct extending to a rooftop exhaust fan. The rooftop exhaust fan often serves several hotel room suites via the central exhaust duct. This exhaust fan typically runs continuously, although in some facilities, timer-controlled operation occurs. Air that is exhausted from the hotel room/bathroom suite by this exhaust fan is intended to be replaced with makeup air supplied from the corridor. The main HVAC system typically supplies sufficient conditioned makeup air to the corridor to supply all of the hotel room suites served by the corridor. Makeup air from the corridor is intended to enter the hotel rooms by passing under the door between the room and the corridor. This door is undercut to provide passage of air from the corridor to the room (Figure 8).

Design Intent

The design intent typically calls for the hotel room to be pressurized relative to the exterior. The reason for pressurization to be called for in the design intent is the control of infiltrating hot, humid air during cooling periods, the exclusion of exterior pollutants, and the minimization of drafts during heating periods. Standard practice calls for supplying approximately 15% more air to a room than is exhausted to accomplish this. For example, if the exhaust flow out of the bathroom is 25 L/s, the design makeup air to be supplied to the hotel room/bathroom suite through the door undercut is approximately 30 L/s.

TYPICAL PROBLEM AND TRADITIONAL ANALYSIS

Mold contamination under vinyl wall coverings is an increasingly common problem in interior partition wall assemblies associated with buildings constructed as described in Figures 6, 7, and 8. The investigation of such a problem is typically instigated by one or a combination of the following symptoms:

- the room smells;
- the humidity levels within the room are excessive;
- the vinyl wall covering becomes discolored with pink or maroon stains; or
- the gypsum board is soft and water logged.

Using traditional analysis, an investigation of the moisture damage in an unoccupied hotel room as described proceeds along the following path.

- The capacity of the fan-coil unit is checked to ensure that it is not oversized. Oversized fan coils are known to have short duty-cycles. Short duty-cycles are incapable of removing significant quantities of airborne moisture. The fan-coil units are typically required to have sufficient latent capacity to remove moisture generated by occupants within the hotel rooms due to respiration and to remove moisture entering by vapor diffusion through the building envelope. In this particular example, let us assume that the fan-coil unit has been sized correctly.
- The capacity and operation of the central exhaust system is checked against the capacity and operation of the rooftop makeup air unit. Exhaust flow rates are measured with a flow hood and compared to the supply airflow rate (makeup air) provided by the rooftop unit to the corridors. A pitot tube or hot wire anemometer is used to measure supply flow at the rooftop unit. Exhaust fan operation is typically interlocked with the rooftop makeup air unit. This interlock is checked. The intent is to ensure that more air is supplied by the rooftop unit to the corridors than is exhausted out of the rooms by the central exhaust fans in order to avoid negative air pressures within the hotel rooms with respect to the exterior. This is desirable to control infiltration of exterior humid air and the associated latent load. In this particular example, let us assume that positive pressurization is achieved within the hotel room by the operation of the rooftop unit while the central exhaust system is operating. This is verified with a smoke pencil at the exterior window and by summing the measured exhaust flows from the bathroom/suites served by the corridor and comparing this flow to the measured supply airflow to the corridor.
- The intent of the bathroom exhaust flow is to handle odors and moisture generated within the bathroom due

to showers and bathing. A smoke pencil shows that air is pulled into the bathroom under the bathroom door. The quantity of air extracted from the bathroom via the central exhaust system (as measured by a flow hood) is approximately 25 L/s. This matches the design intent and is known by experience to be able to handle typical bathroom moisture loads and odors.

- The relative humidity and temperature in the corridor are measured and recorded as follows: 55% relative humidity and 23°C or a dew point temperature of approximately 14°C This matches the design intent for the rooftop unit to supply "neutral temperature air at a neutral relative humidity."
- The exterior relative humidity and temperature are measured and recorded as follows: 60% relative humidity and 32°C or a dew point temperature of approximately 24° C. This is an expected condition for August in the location where the hotel is constructed.
- The relative humidity within the hotel room is measured as fluctuating between 65% and 75% relative humidity. The interior hotel room temperature varies between 23°C and 27°C. This corresponds to dew point temperatures of between 16°C and 20°C. The interior room air moisture levels are unexpectedly high and not explainable. The interior room airborne moisture levels should match the corridor moisture levels, especially if rooms are unoccupied. Recall that the rooms are at a positive air pressure with respect to the exterior so that infiltration of exterior moisture-laden air is eliminated as a moisture source using traditional analysis and that vapor diffusion from the exterior through the exterior wall is negligible.
- The possibility of rainwater leakage through the building envelope is examined. The possibility of roof leakage is examined. Let us assume that no rainwater leakage through wall or roof assemblies is occurring.

At this point, the investigation and analysis typically break down. More often than not moisture of construction is assumed to be the culprit and the contractor is blamed for not covering the work during construction and preventing rain wetting of the materials. This argument is typically eroded if the hotel is more than a few years old and no explanation whatsoever is provided.

NONTRADITIONAL ANALYSIS

Hotel building envelope and interior wall construction is typically steel studs with gypsum board (Figure 9). Steel studs are perforated with punched openings to facilitate installation of services. These perforations create a connected wall cavity in both interior and exterior walls. In exterior walls, fiberglass batt insulation is installed. As fiberglass batt insulation provides very small resistance to airflow, the connected wall cavity construction in both interior and exterior walls permits considering these walls as acting as air ducts.

Using nontraditional analysis, the investigation of the moisture damage in an unoccupied hotel room as previously presented proceeds along the following path.

- The air pressures within the partition walls relative to the exterior are measured with a manometer. Additionally, the air pressure within the room relative to the exterior is measured. The partition wall on one side of the room is measured to be operating under a varying negative air pressure with respect to the exterior between 1 Pa and 2 Pa. This pressure fluctuates based on the opening and closing of the bathroom door. The partition wall on the opposite side of the room varies between a positive air pressure of 1 Pa and a negative air pressure of 1 Pa to the exterior. This pressure fluctuates based on the duty cycle of the fan coil. The room is measured to have a positive air pressure with respect to the exterior that varies between 1 Pa and 2 Pa based on the duty cycle of the fan coil.

At this point, the investigation is essentially complete. Interpretation of the results follows.

AIR PRESSURE DRIVER 1: FAN COIL

In the example described in Figures 6 and 7, the fan-coil unit extracts air out of the dropped ceiling assembly because the dropped ceiling enclosure is designed to act as a return plenum. Resistance to airflow is provided by a filter in the return grille, creating a negative pressure within the dropped ceiling enclosure relative to its surroundings. However, dropped ceiling enclosures are seldom airtight due to numerous penetrations for controls, power supply, and piping. Additionally, joints and seams in the materials forming the dropped ceiling enclosure are difficult to make airtight.

The dropped ceiling enclosure is connected to the partition wall via the penetrations for controls, power supply, and piping and through openings reflective of the prevailing construction practice. The partition wall is further connected

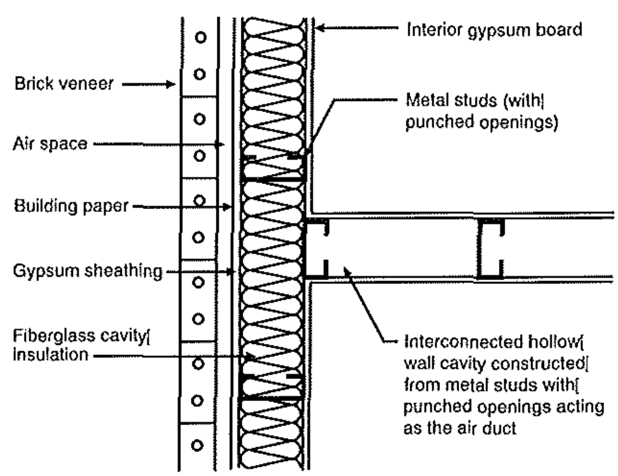


Figure 9 *Wall construction plan view.*

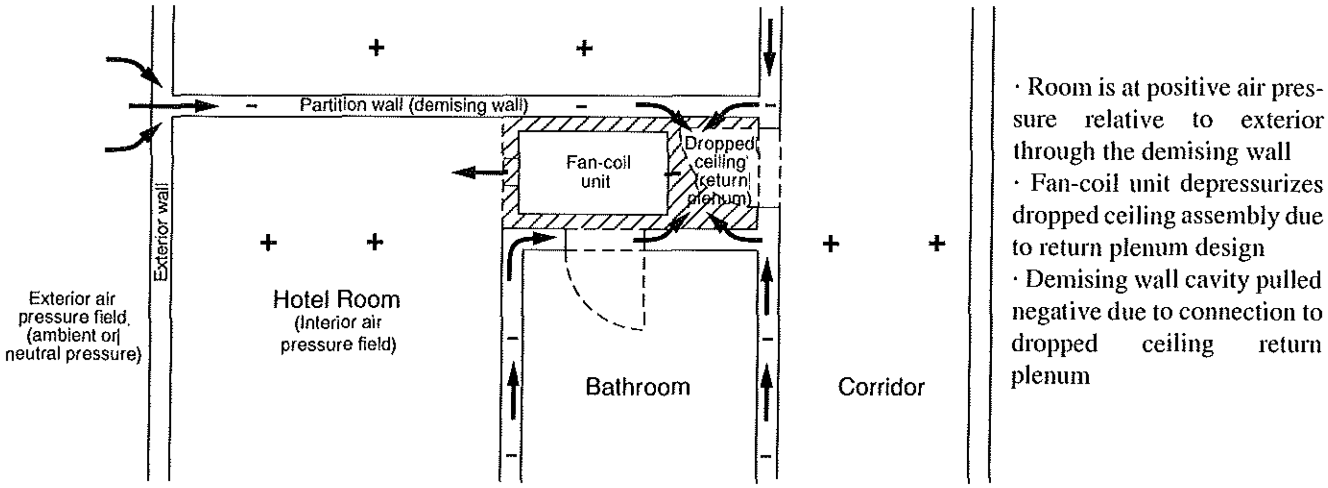


Figure 10 Pressure field due to fan-coil unit plan view.

to the exterior wall. A negative air pressure field is created in the partition wall relative to the rooms on both sides due to its connection to the dropped ceiling plenum. This negative air pressure field extends to the exterior wall and may or may not be negative with respect to the exterior.

If this air pressure field within the partition wall is also negative with respect to the exterior, it leads to the infiltration of hot, humid air during cooling periods and contaminants during other periods through the exterior wall assembly, down the demising wall to the dropped ceiling assembly (Figure 10). During cooling periods, when this air is cooled due to the cooling of the hotel rooms on both sides of the partition wall, moisture is deposited in the wall cavities, leading to mold and microbial contamination.

This negative air pressure field in the interstitial spaces exists only when the fan coil unit is operating and exists despite the positive air pressure in the hotel room created by the airflow from the corridor. This interstitial negative air pressure field is time-dependent and is related to the duty cycle of the fan-coil unit.

The partition wall acts as an outside air duct supplying outside air to the fan coil. This outside air supply tends to increase the positive air pressure in the room with respect to the exterior. This causes fluctuation in the positive pressure (with respect to the exterior) in the room in synchronization with the duty cycle of the fan coil. It also leads to elevated levels of airborne moisture within the room.

AIR PRESSURE DRIVER 2: CENTRAL EXHAUST

In a similar manner to the fan-coil unit-induced interstitial partition wall depressurization, leakage of the central exhaust duct located within the plumbing service shaft also leads to the creation of a negative air pressure field relative to the rooms in the opposite demising wall that also extends to the exterior wall. This negative air pressure field exists only when the rooftop exhaust fan operates and again exists despite the positive

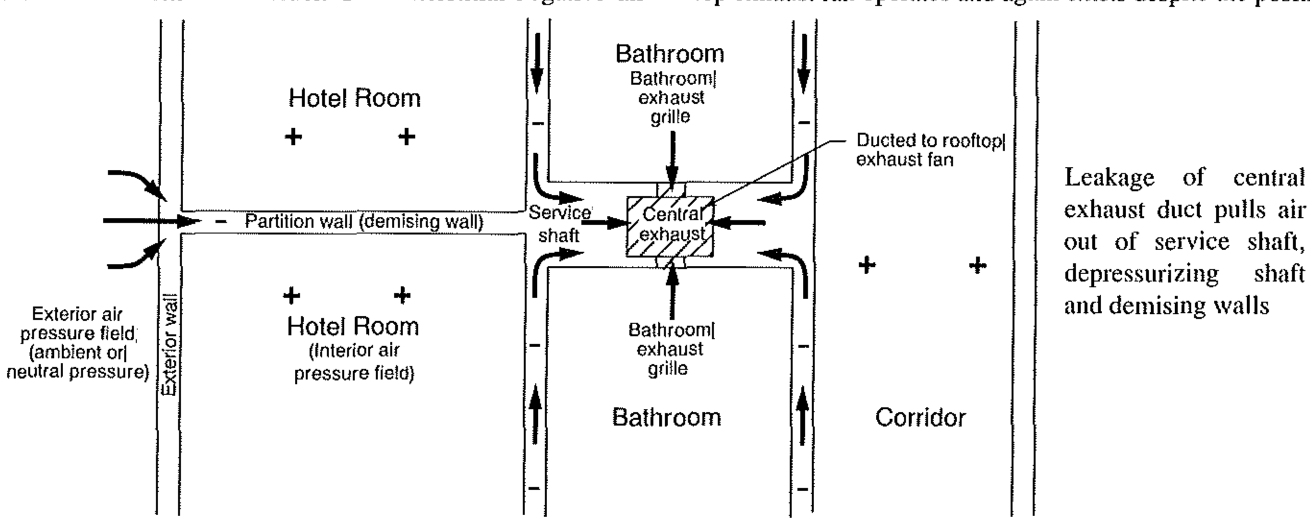


Figure 11 Pressure field due to central exhaust plan view.

air pressure in the hotel room (Figure 11). When the bathroom door is closed, the flow path from the suite to the exhaust grille in the bathroom is interrupted, creating a flow resistance resulting in more air to be extracted from the partition wall. This results in increased depressurization within the partition wall on a cycle matched to the opening and closing of the bathroom door.

The negative air pressure field due to the rooftop exhaust fan (as modified by bathroom door closure) may or may not be negative with respect to the exterior. If it is negative with respect to the exterior, it will result in the infiltration of exterior air into the partition wall, similarly to the fan-coil unit example. However, it will not lead to an increase in the levels of airborne moisture within the room since the flow path of this infiltrating air is to the plumbing service shaft and subsequently out of the building via the rooftop exhaust fan. This infiltrating air does not enter the rooms on either side of the partition wall.

However, moisture in the infiltrating air is deposited on the gypsum board surfaces enclosing the partition wall interstitial cavity. The deposited moisture migrates by diffusion to the vinyl wall covering/gypsum board interface. Little moisture diffuses through the vinyl wall covering, therefore not affecting the room airborne moisture levels. Unfortunately, the gypsum board and the vinyl wall covering both deteriorate due to the accumulated moisture.

COUPLING OF AIR PRESSURE FIELDS

Figures 10 and 11 illustrate the coupling of the air conveyance system field with the interstitial field and the coupling of the interstitial field to both the exterior and the interior fields. Traditional analysis recognizes the coupling of the air conveyance system field to the exterior and interior fields. A typical example is that of exhaust fans pulling air from bathrooms and discharging it to the exterior. Traditional analysis, however, does not recognize the interaction of the air conveyance system field with the interstitial field.

Traditional analysis assumes a "flow-through" mass balance and an assumption that the air pressure profile and flows are dependent only on the total pressure difference between the exterior and interior air pressure field. This is clearly not the case in the examples in Figures 10 and 11 where airflow is extracted at an intermediate location (the partition wall cavity) due to leakage of the dropped ceiling plenum containing the fan coil and due to central exhaust duct leakage. The air extraction from the partition wall cavities leads to replacement air (makeup air) for the partition wall cavities drawn from the exterior as well as from the rooms on both sides of the partition walls.

Traditional analysis would assume a positive air pressure with respect to the exterior exists within the partition walls of magnitude somewhere between the interior positive air pressure and the boundary layer air pressure. Time-dependent negative air pressures within the partition walls relative to both the boundary layer air pressure and the interior air pressure are completely unexpected and unaccountable with traditional analysis.

The significance of these complex, time-dependent interstitial air pressure fields has not been appreciated or identified for several reasons:

- materials, methods, and means of construction have changed;
- the system model is incomplete; and
- the process of construction is fragmented.

In the past, buildings were leaky and not well insulated and the effect of HVAC systems and other air conveyance systems on building pressures was small. The key air pressure relationships defining interstitial air pressures are also small and have until recently been difficult to measure and quantify. Older building structures were more massive with exterior wall assemblies and interior partitions constructed from masonry, masonry backup, and plaster, resulting in few or no interstitial connected cavities. More recent construction relies on metal framing, steel studs, gypsum board interior, and exterior sheathing, resulting in more numerous and larger void spaces, chases, and interstitial cavities.

Building design and construction have also become fragmented as a consequence of the increasing specialization and complexity of the technology of construction. Specialization has lead to an abundance of specialists who have tended to focus principally on their own disciplines. In doing so, the system view is often missed. Under these conditions, the significance of interstitial airflows and the need for a complete air pressure field system model is not readily apparent.

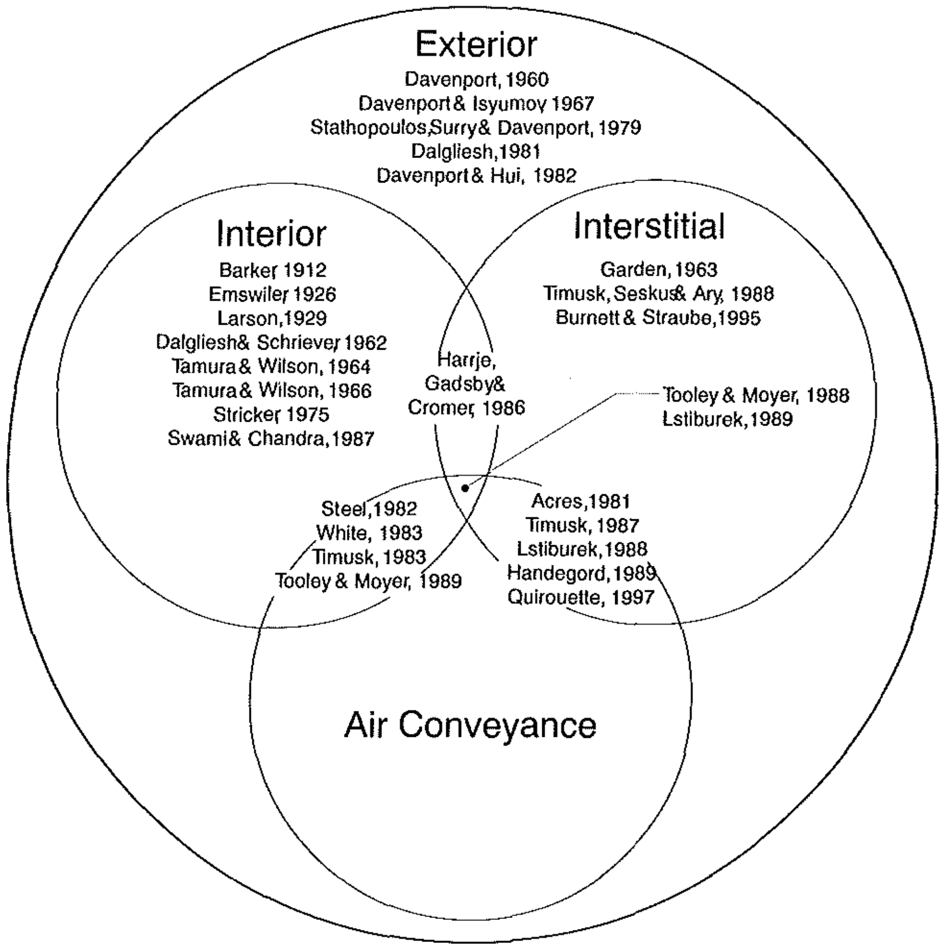
AIR PRESSURE FIELD MODEL FOR BUILDINGS

Considering interstitial air pressure fields and airflows and the coupling of mechanical systems to the building envelope and building cavities leads to the development of an air pressure field (APF) model for buildings. The APF model can be used to predict and understand the pressure response of buildings.

An APF model is presented in Figure 12, which shows the relationships among the four component fields comprising the building air pressure field. The proposed APF model involves research on airflows and pressures in buildings that spans this century. The key papers of the component fields are referred to while illustrating their contribution to enhanced understanding (Figure 12).

Historical Basis for Model

Coupling of the exterior field and the interior field is a key factor typically utilized in the design of buildings and cladding systems. Loads for the design of cladding can be found from the algebraic difference between the boundary layer and inte-



A schematic representation of the APF model for buildings with reference to the key papers and their contribution

Figure 12 Air pressure field (APF) model.

rior pressures (Davenport 1960; Dalgliesh and Schriever 1962; Davenport and Isyumov 1967; Stathopoulos et al. 1979; Dalgliesh 1981; Davenport and Hui 1982).

Coupling of the interior and exterior fields due to air density differences between the interior and exterior (stack effect) has long been utilized in the ventilation design of process buildings (Barker 1912; Emswiler 1926) and in establishing air and smoke flow patterns in high-rise buildings (Tamura and Wilson 1966).

Coupling of the exterior and the interior fields has also been extensively studied with respect to wind-induced natural infiltration (Swami and Chandra 1987).

Understanding of the coupling of the exterior and the interstitial fields within exterior wall assemblies forms the basis of pressure-equalized rain screen (PER) design for the control of rain entry into walls (Garden 1963).

The study of wind washing of cavity insulation in exterior wall assemblies further established the link between the exterior field and the interstitial field (Timusk, Seskus & Ary, 1988). The study of ventilation in cladding expanded knowledge about the link between the exterior field and the interstitial field and identified thermal and moisture convection as air pressure drivers (Burnett and Straube 1995).

Coupling of the interior field, the air conveyance system field, and the exterior field was studied extensively because of concerns arising from carbon monoxide poisoning and negative pressures in airtight houses (Steel 1982). Relationships between building envelope tightness (leakage) and air requirements for chimneys were developed (White 1983) along with test protocols establishing negative air pressure limits for interior air pressure fields. The pressure limits were related to flow reversals in chimney air conveyance system fields using calibrated fans to alter interior fields in a controlled manner (Timusk 1983).

Building envelope leakage characteristics using calibrated fans to alter interior air pressure in a controlled manner have been extensively studied (Tamura and Wilson 1964; Stricker 1975) leading to the development of leakage-pressure relationships for building envelopes. The work on building envelopes is an extension of leakage-pressure relationships developed for wall assemblies that date to the early part of this century (Larson 1929).

Door closure and the distribution of supply registers and return grilles were determined to be air pressure drivers in the spillage and backdrafting of combustion appliances (Timusk 1983), thereby identifying the three-way linkage of the interior field, the air conveyance system field, and the exterior field. This work was significantly expanded to include duct leakage of ducts in both conditioned and unconditioned spaces (Tooley and Moyer 1988).

Duct leakage into interstitial spaces was identified as an energy (operating cost) factor (Harrje et al. 1986; Nelson et al. 1986; Tooley and Moyer 1988) thereby identifying the link between the interior and exterior fields, the air conveyance system field, and the interstitial air pressure field.

The linkage between different interstitial fields was subsequently identified as a moisture transport path (Tooley and Moyer 1989; Lstiburek 1989) where the air pressure driver for the interstitial field was an HVAC system.

Active control of air pressures within interstitial spaces as a design strategy has been proposed as a viable method of moisture and pollutant control (Handegord 1989) and forms the basis of strategies for thermal comfort and ventilation (Timusk 1987).

Rehabilitation techniques using active control of air pressures within building envelope interstitial air spaces are common. Pressurization of roof assembly cavities with exterior air has been successfully used to control the exfiltration of interior moisture-laden air in heating climates (Lstiburek and Lee 1988; Quirouette 1997) as well as active depressurization of sub-slab granular pads to control the infiltration of radon and other soil gases into occupied spaces (Scott 1979; Acres 1981). These examples highlight the linkage between interstitial fields, air conveyance system fields, and interior and exterior fields that are used in the design process.

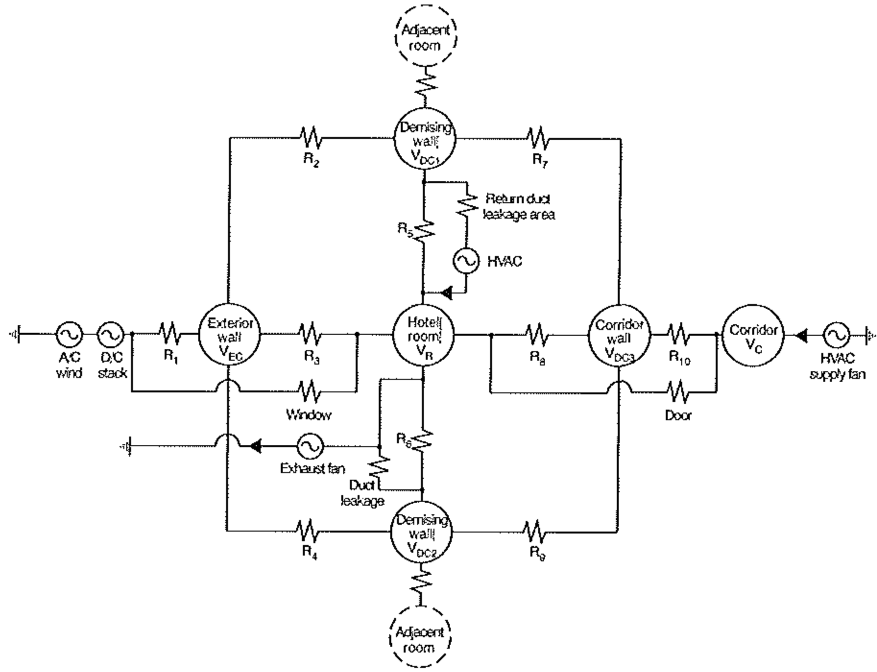
Designing the linkage of exterior and interstitial air pressure fields is also typical where the use of powered attic ventilation exhaust fans provides attic air change. This same strategy has also been found to provide incidental linkage to the interior field and subsequent chimney flow reversal. Specifically, the operation of powered attic ventilation exhaust fans has been shown to depressurize conditioned spaces, leading to the backdrafting of chimneys and flame roll-out in combustion water heaters (Tooley and Davis 1994).

Unifying these excellent, though disjoined, research papers under the APF model as developed in this thesis enhances prediction and understanding of the pressure response of buildings and of each component field as they interact during the operation of the building.

ELECTRICAL ANALOGUE

The relationships shown in Figure 12 can be used to develop tools for analysis, such as modified multi-cell models. Figure 13 represents an electrical analogue of the hotel room described in Figure 6. Currents represent the rate of airflows, voltages represent air pressures, and resistances represent air leakage paths. Ambient air pressure under no wind conditions at ground level is considered "ground."

Although this approach has a long history (Nylund 1966, 1980; Kronval 1980; Walton 1989), it is adapted here to consider interstitial spaces and the leakage effects of HVAC systems. In an extension of typical analysis, the nodes represent either rooms or interstitial spaces. In this manner, connected compartments such as rooms, exterior wall cavities, and interior wall cavities are all considered in the APF model. Additionally, compartments can also have generators associated with them. The generators represent mechanical system leakage from either ducts, equipment housing, or exhaust system service ductwork and chases.



R_1 = Leakage area between ambient and exterior wall cavity
R_2 = Leakage area between exterior wall cavity and demising (partition) wall cavity
R_3 = Leakage area between exterior wall cavity and hotel room
R_4 = Leakage area between exterior wall cavity and demising (partition) wall cavity
R_5 = Leakage area between demising (partition) wall cavity and hotel room
R_6 = Leakage area between demising (partition) wall cavity and hotel room
R_7 = Leakage area between demising (partition) wall cavity and corridor demising wall cavity
R_8 = Leakage area between hotel room and corridor demising wall cavity
R_9 = Leakage area between demising (partition) wall cavity and corridor demising wall cavity
R_{10} = Leakage area between corridor wall demising cavity and corridor
R_{EC} = Pressure in exterior wall
V_R = Pressure in hotel room
V_C = Pressure in corridor
V_{DC1} = Pressure in demising (partition) wall cavity
V_{DC2} = Pressure in demising (partition) wall cavity
V_{DC3} = Pressure in corridor demising wall cavity

Figure 13 *Electrical analogue of hotel room.*

In this manner a mass balance at each node can occur while allowing the introduction or removal of flows at intermediate "nodes." Generators are also used to represent the other drivers, such as wind, stack, and other effects of mechanical systems. Alternating current (AC) generators are used to represent the dynamic effect of wind, whereas direct current (DC) generators are used to represent stack effects (temperature differences) and exhaust and supply flows from fans and HVAC systems. The DC generators are used in two different forms; in one form they provide a constant voltage, and in the other form they provide a constant current. This is analogous to representing the stack effect (constant voltage) and an HVAC system flow (constant current).

In using the electrical analogue discussed above, the model boundary conditions, specifically the resistances representing air leakage paths, can be determined by "pressure mapping" a building or portion of a building under imposed known airflows. Under this approach, the pressure response of the building (or portion of building) is measured as a result of the imposed known airflows. These pressures and imposed flows are input into the model, and air leakage path resistances are calculated, meeting the convergence criterion. The calculated air leakage path resistances are then "fixed" and the subsequent effect of variable airflows and wind and stack effects modeled.

This differs from typical multi-cell model analysis, where the inputs are wind and stack pressures, flow rates relating to the air conveyance systems (currents), and air leakage characteristics (resistances) of the building components. Outputs are component airflows (currents) and component air pressures (voltages).

The discussed approach avoids the difficulties of predicting component air leakage characteristics since component leakage areas are calculated from air pressures and airflows measured directly. Additionally, the nonlinearity typically introduced in multi-cell numerical analysis in dealing with calculating pressures from flows is also avoided since the pressures are measured directly.

Accuracy of the discussed electrical analog can be further increased by a taking series of pressure measurements across exterior and interior wall assemblies, thereby determining the ratios of leakage areas across nodes representing exterior and interior wall cavities.

Accuracy of the approach can be validated by conducting air leakage tests of the building envelope and room compartments to determine combined leakage areas of the surfaces bounding the nodes representing rooms and comparing the results to calculated values using a multi-cell model.

MEASURING AIR PRESSURE FIELDS

The prevailing air pressure differences in the interstitial and the interior fields are small. Until recently they have been difficult to measure and quantify. Most investigators have relied on smoke tubes to detect airflows. Smoke tubes are extremely sensitive even for small air pressure differences (the author has found them useful with air pressure differences of less than a pascal) and can establish the direction of airflow.

Timusk (1983) found that air pressure measurement resolution on the order of 1 pascal was necessary in conducting research on chimney backdrafting and air pressure drivers within houses. Timusk (1987) found that measuring even lower air pressure differences was necessary when testing airflow through wall insulation. Inclined fluid manometers and diaphragm-type magnetic linkage pressure gauges were not sufficiently sensitive for these research needs.

While digital electronic micromanometers with resolution of 0.1 pascal provided the necessary resolution (see Timusk [1983]), they were expensive and difficult to obtain. It was not until recently that low-cost (less than $1,000) portable digital electronic micromanometers became widely available. With availability came opportunity for field use unimaginable only years before. Differential air pressure measurements can now be conducted easily, quickly, and inexpensively. These breakthroughs in measurement technology set the stage for the enhanced understanding of air pressure drivers in buildings (Tooley and Moyer 1988; Lstiburek 1989; Blasnik and Fitzerald 1992).

AIR PRESSURE DIFFERENTIAL MEASUREMENTS

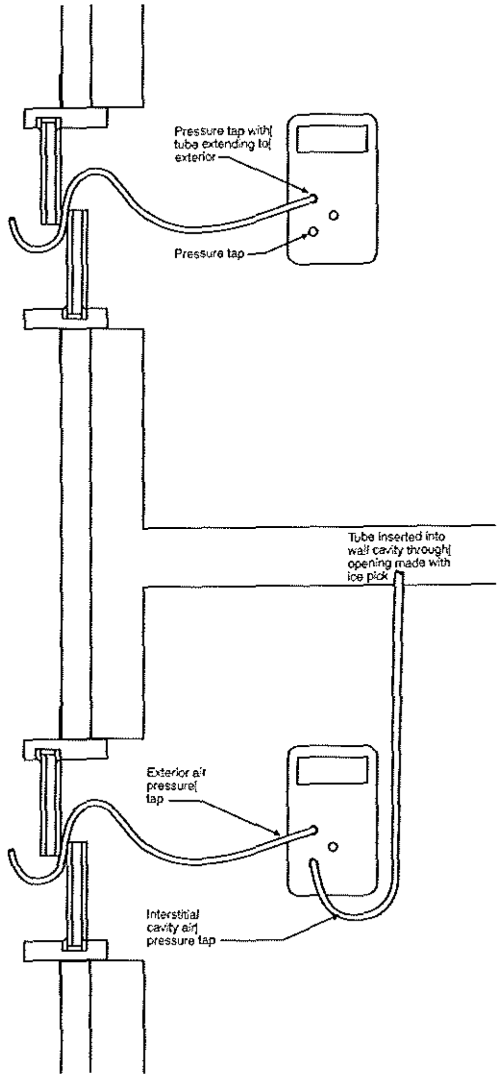
Figures 14a and 14b illustrate the use of a digital electronic micromanometer to measure the air pressure difference between the exterior and interior and between the exterior and an interstitial cavity in a demising wall, respectively.

As it became clear that the linkage between different component air pressure fields is critical for the understanding of building performance, a need for specialized measurement technology became apparent. Moyer developed a six-channel digital electronic micromanometer to establish a "pressure map" of a nursing home facility (Lstiburek and Moyer 1991). The pressure map records the magnitude and direction of the pressure relationships within the facility under a set of specific operating conditions, such as the operation of the facility HVAC system, or under a given interior to exterior temperature difference. Figure 15 illustrates the six-channel digital electronic micromanometer set up to pressure map the hotel room described in Figure 6. The multi-channel manometer is connected to a laptop computer that simultaneously records and graphically displays the air pressure differentials.

Air pressure measurements are typically taken relative to the exterior ambient pressure. During initial field research, calm wind conditions (less than 10 kph) were necessary in order to develop an understanding of the building air pressure relationships. Calm wind conditions allow accurate determination of the exterior air pressure field, which can act as a reference for all other pressure measurements.

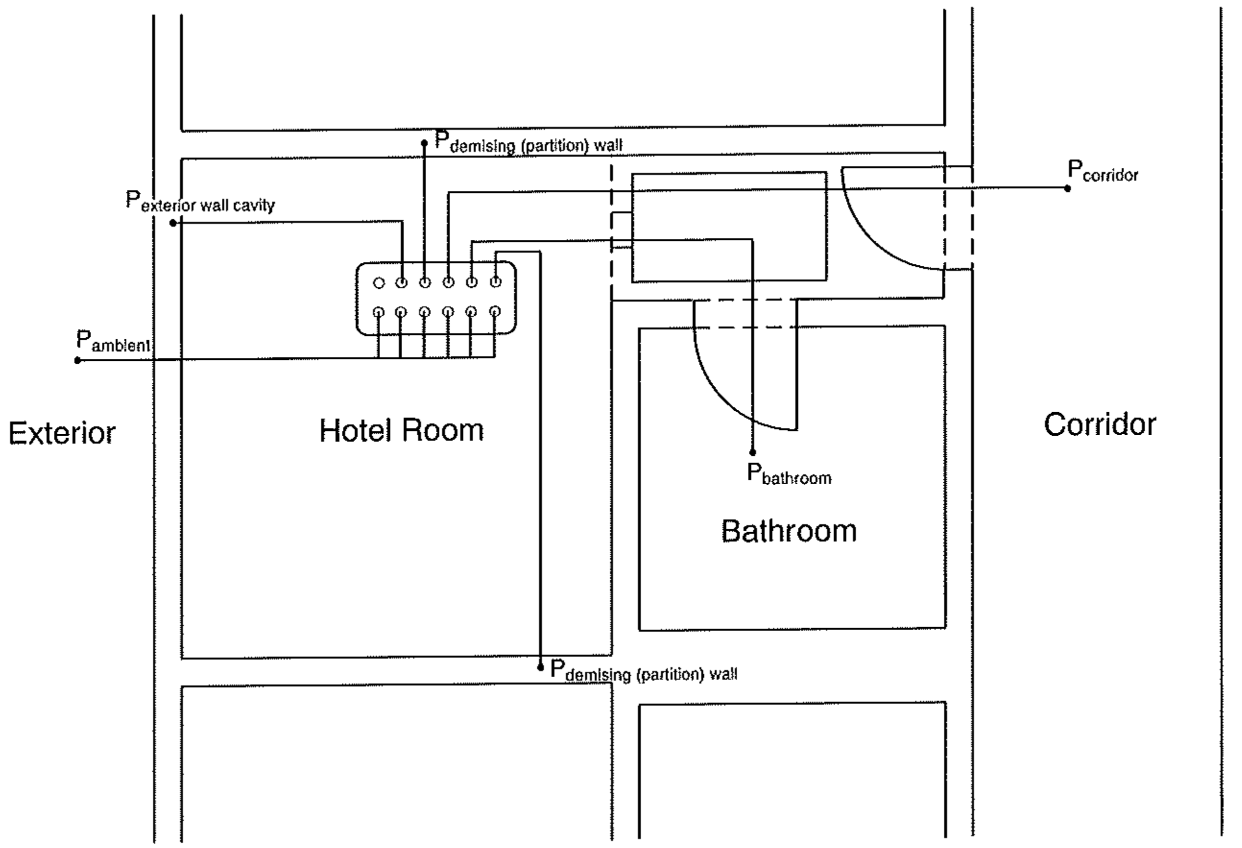
Measurement protocols evolved with field experience. Manometers with time-averaging capabilities allow accurate determination of the exterior air pressure field even under

(a) Air pressure difference between exterior and interior measured across a window sash with a digital electronic micromanometer (± 0.1 pascal)



(b) Measurement of air pressure difference between exterior and interstitial cavity in demising (partition) wall

Figure 14 *(a) Air pressure difference plan view.* (b) *Measurement of air pressure difference plan view.*



Six-channel micromanometer set up to pressure map hotel room described in Hotel Room/Bath Suite Plan View figure.
All measurements are measured relative to exterior air pressure (ambient) in the configuration shown above.
Manometer connected to laptop computer to simultaneously track pressure response.

- Corridor door opened and closed
- Bathroom door opened and closed
- Room fan coil cycled on/off
- Rooftop exhaust fan cycled on/off
- Corridor makeup air supply cycled on/off

***Figure 15** Measurement protocol plan view.*

moderate wind conditions (10 kph to 25 kph). Although it is still desirable to use the exterior ambient as the reference air pressure, in many cases building common areas such as atria, crawl spaces, or attics were found to act as reasonable reference air pressures. Wind effects were found to alter the interior to exterior air pressures in accordance with the conventional view. However, in most cases, wind effects did not alter the relationships occurring as a result of the coupling of the building envelope and the mechanical systems. Specifically, many of the air pressure relationships occurring among the interstitial field, the interior field, and the air conveyance system field were able to be determined under moderate wind effects.

The standard measurement protocol used when testing the hotel room illustrated in Figure 6 involves instrumentation shown in Figure 16. This protocol involves measurement of air pressures under many possible combinations of building HVAC system operation and building envelope leakage pathways. For example, the operation of building air conveyance systems includes various combinations of open and closed interior doorways. The effect of these changes on the building air pressure field is recorded.

Typically, air pressure measurements represent a "snapshot" of the air pressure field. Snapshot air pressure measurements may or may not be representative of the air pressure field of the building. Skill and insight by the investigator conducting measurements are necessary to interpret the snapshot air pressure measurements. Snapshot mapping of building air pressure fields is made more effective if the building HVAC system can be cycled through the various operational conditions (including the effects of door closure), especially when this is combined with knowledge of the building operational conditions over a daily, weekly, and seasonal basis. However, such cycling is not always possible nor under the control of the investigator. Long-term air pressure monitoring is sometimes necessary and desirable to establish air pressure relationships through the normal building operating range.

Typically, building air pressure fields have daily, weekly, and seasonal patterns. For example, most buildings do not operate their HVAC systems at full capacity or at night or over weekends. Additionally, building exhaust fans are often operated on timers. Specialized exhaust fans, such as kitchen range hood exhausts, dryers, and spot ventilators, operate only as needed. Large differences in airflow induced by HVAC systems also occur between maximum heating and maximum cooling conditions. During swing seasonal conditions, economizer operation typically provides the largest airflow rates and the largest air pressure extremes. Additionally, stack effect pressures vary with indoor to outdoor temperature differences further complicating matters.

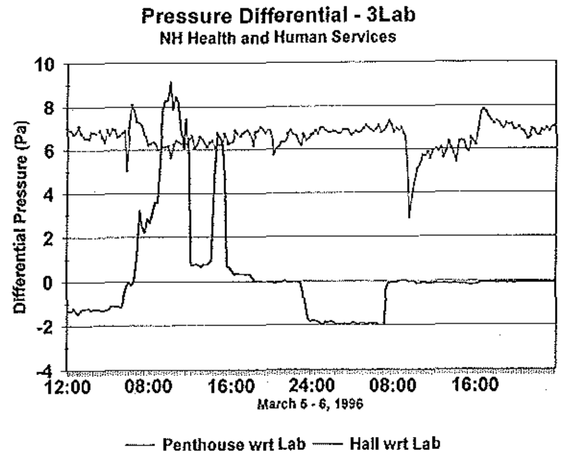


Figure 16 Long-term pressure differential monitoring.

Figure 16 shows the monitoring of air pressure relationships between a hallway and work area in a laboratory facility in New Hampshire over a two-day period. The measurements were taken by connecting a digital micromanometer with an analog output to a stand-alone electronic data storage microprocessor. The data storage capacities of the data storage microprocessor allow measurements to be taken over several weeks. Data are downloaded into a laptop computer where data manipulation and analysis can occur.

SERIES PRESSURE DIFFERENTIAL

Figure 17 illustrates the use of digital electronic micromanometers to measure the air pressure distribution across the elements of a wall assembly.

The general relationship between airflow and pressure is given by Currie (1974):

$$Q = C(\Delta p)^{\eta}$$

where

Q = volume flow rate,

C = leakage coefficient,

Δp = pressure difference,

η = exponent varying between 0.5 and 1.0.

Let

$$C = C_1 A$$

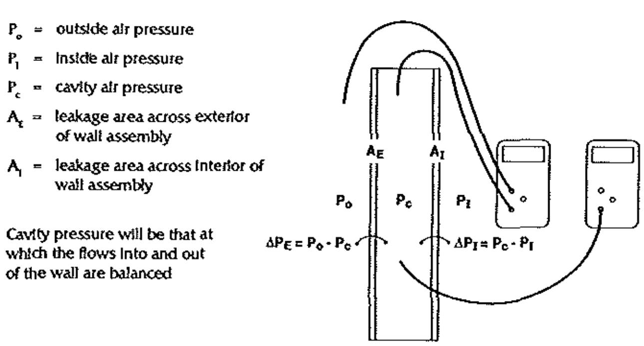


Figure 17 Series pressure differential.

where

C_1 = discharge coefficient,

A = area.

Q = $C_1 A (\Delta p)^{\eta}$ (1)

from Hutcheon and Handegord (1983).

As illustrated in Figure 17, the cavity air pressure will be that at which the airflows into and out of the wall cavity are balanced. Assuming no leakage out of the top and bottom of the wall cavity, the following holds:

$$Q = C_E A_E \Delta P_E^{\eta} = C_1 A_1 \Delta P_1^{\eta}$$

$$\frac{C_E A_E}{C_I A_I} = \frac{\Delta P_I^{\eta}}{\Delta P_E^{\eta}}$$

$$\approx \frac{A_E}{A_I} = \left(\frac{\Delta P_I}{\Delta P_E}\right)^{\eta}$$

$$\left(\frac{A_E}{A_I}\right)^{1/n} = \frac{\Delta P_I}{\Delta P_E}$$

from Hutcheon and Handegord (1983) where

C_E = discharge coefficient for exterior of wall assembly,

C_I = discharge coefficient for interior of wall assembly,

ΔP_E = pressure difference across exterior of wall assembly,

P_I = pressure difference across interior of wall assembly,

A_E = leakage area across exterior of wall assembly,

A_I = leakage area across interior of wall assembly,

η = exponent varying between 0.5 and 1.0.

This concept was further developed by Blasnik (1988). The air pressure differences across the wall assembly elements are measured under a given pressure difference. An opening of known size (A_k) is added and the air pressure differences across the wall assembly elements remeasured. Equation 2 is then used as follows to yield the individual leakage areas (Blasnik 1988):

$$A_E = A_I\left(\frac{\Delta P_{I_1}}{\Delta P_{E_1}}\right)^{\eta}$$

$$A_E + A_k = A_I\left(\frac{\Delta P_{I_2}}{\Delta P_{E_2}}\right)^{\eta}$$

Let

$$\left(\frac{\Delta P_{I_1}}{\Delta P_{E_1}}\right)^{\eta} = R_1^{\eta}$$

Let

$$\left(\frac{\Delta P_{I_2}}{\Delta P_{E_2}}\right)^{\eta} = R_2^{\eta}$$

$$A_E = A_I R_1^{\eta}$$

$$A_E + A_k = A_I R_2^{\eta}$$

$$A_E = A_I R_2^{\eta} - A_k = A_I R_1^{\eta}$$

$$A_I = \frac{A_k}{(R_2^{\eta} - R_1^{\eta})}$$

Similarly,

$$A_E = \frac{A_k R_1^{\eta}}{(R_2^{\eta} - R_1^{\eta})}$$

where

ΔP_{I_1} = initial air pressure difference across interior of wall assembly,

ΔP_{E_1} = initial air pressure difference across exterior of wall assembly,

ΔP_{I_2} = subsequent air pressure difference across interior of wall assembly,

ΔP_{E_2} = subsequent air pressure difference across exterior of wall assembly,

A_K = an opening of known size.

Although Blasnik used this approach in determining leakage areas across flat roof attic ceiling assemblies, the approach can be adapted to determine room leakage areas. Consider the following case of a series of rooms served by a corridor (Figure 18). Room A is located between Room B and Room C. Each room has an operable window opening to the exterior and a connecting door to the corridor. To simplify matters, let us assume that the floor and ceiling are of slab construction or negligible leakage area.

Initially, the door in Room A is closed and the doors in Room B and Room C are open. The windows in all three rooms are closed. A positive pressure relative to the exterior is induced in the corridor creating a two-zone pressure boundary. The pressure differences P_{I_1} and P_{E_1} are recorded (Figure 19). An opening of known size, A_k, is introduced by partially opening the window in Room A. The new pressure differences P_{I_2} and P_{E_2} are recorded (Figure 20). Equation 2 is used as before to determine A_E and A_I.

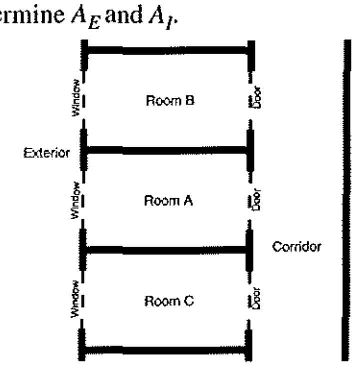
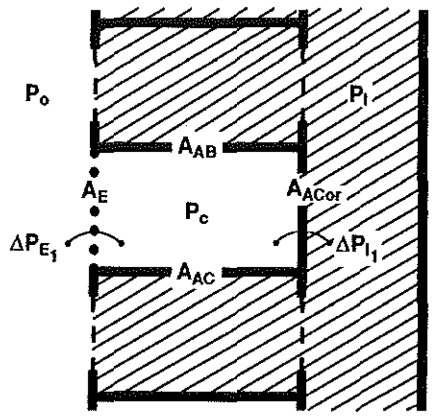


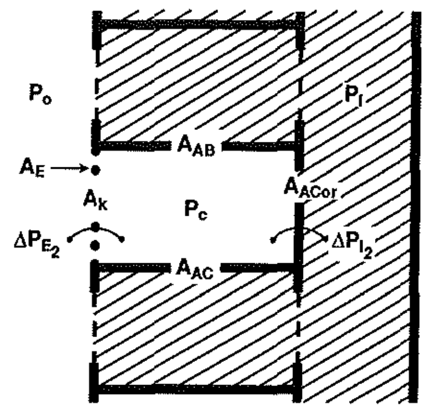
***Figure 18** Series of rooms connected to corridor.*



$A_t = A_{AB} + A_{AC} + A_{ACor}$

- Door to corridor in Room A closed
- Doors to corridor for Rooms B and C are open
- Windows in all rooms closed

Figure 19 *Initial pressure measurements.*



$A_t = A_{AB} + A_{AC} + A_{ACor}$

An opening of known size, A_k, is added to Room A (i.e., window in Room A is opened)

Figure 20 *Subsequent pressure measurements.*

The process is repeated with a negative pressure relative to the exterior induced in the corridor. In this case, the doors to the corridor for Room B and Room C are closed and the windows in Room B and Room C are wide open, creating a different two-zone pressure boundary (Figure 21). In this case, an opening of known size is introduced in A_{AC} by partially opening the door in Room A. This yields the leakage area of A_{AC}.

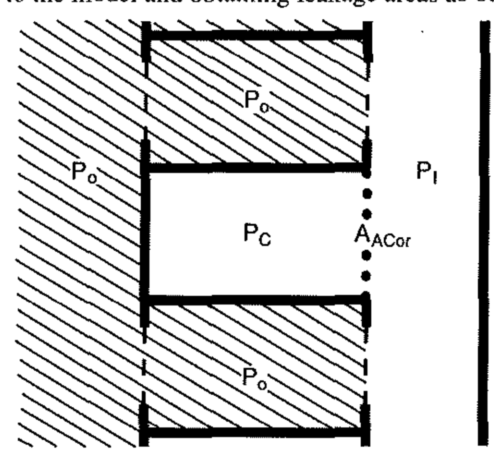
INDUCING PRESSURE DIFFERENTIALS AND DETERMINING THE PRESSURE RESPONSE

The method exemplifies an alternative approach of measuring pressures and using them as inputs to determine leakage areas. It was used in a three pressure zone, two boundary area case. A more general case for *n* pressure zones occurs when the building pressure field is measured and used to determine building leakage areas.

This approach is particularly suitable for buildings with forced air distribution systems that provide heating, cooling, and ventilation. In most of these buildings, the supply system extends to each room and is typically more extensive than the return system. By shutting down the return system and blocking the return air paths at the return grilles, the supply system can be used to induce a positive pressure field within the building that is readily measured using the techniques previously described. Additionally, test and balance information (or techniques) can be used to yield the flow rates to individual rooms. In this manner, individual supply airflows can be matched to individual room pressures throughout the building, yielding a combined pressure and flow map. The pressure and flow map can be used to determine the leakage areas or boundary conditions of the interconnected zones using a multi-cell network model.

Where forced air systems are not present, calibrated fans (e.g., blower door fans) can be used to supply a known airflow, inducing a measurable pressure field. This technique can be extended with multiple fans used to simulate the effect of a supply system where corridors and stairwells are used as ducts and risers.

In the general case described, the matrix equations of the multi-cell network model are not altered. However, the model has been turned upside down by using pressures as measured inputs to the model and obtaining leakage areas as outputs.



- Windows in Rooms B and C are opened
- Windows in Room A are closed
- Doors to corridor for all rooms are initially closed: door in Room A subsequently opened

Figure 21 *Determining leakage area* A_{ACor}

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