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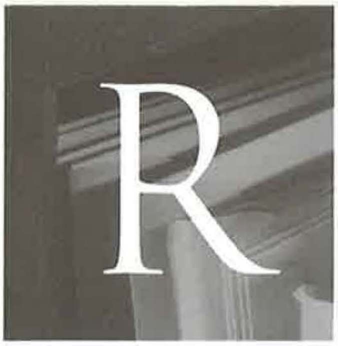

RESEARCH REPORT

MODELLING OF VENTILATION AND INFILTRATION ENERGY IMPACTS IN MID AND HIGH-RISE APARTMENT BUILDINGS

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Modelling of Ventilation and Infiltration Energy Impacts in Mid and High-Rise Apartment Buildings

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Abstract

A literature search was undertaken to assemble and interpret the best available data that can be used for performing multizone airflow modelling in mid and high rise apartment buildings. The best currently available data is presented and areas where further field testing research is required are identified.

A multizone airflow modelling software tool was used to provide an analysis of ventilation related energy issues in a newly constructed 10 story high-rise apartment building. The relative influences of infiltration and ventilation on energy consumption were compared, and other key energy related questions were looked at as they apply to one actual building modelled within a range of Canadian climates.

Executive Summary

The purpose of this project was to improve our understanding of the energy impacts of ventilation and infiltration in mid and high-rise apartment buildings in Canada, and improve the ability of building researchers and designers to use multizone airflow modelling tools to develop improved building designs.

First a literature search was undertaken to assemble and interpret the best available data that can be used for performing multizone airflow modelling in mid and high rise apartment buildings. Then a multizone airflow modelling software tool was used to provide an analysis of ventilation related energy issues in a newly constructed 10 story high-rise apartment building. The relative influences of infiltration and ventilation on energy consumption were compared, and other key energy related questions were looked at as they apply to one actual building modelled within a range of Canadian climates.

From the detailed literature review of multi-story apartment building airflow studies, conducted to assemble and interpret component leakage and other data required for airflow modelling, the following conclusions can be drawn:

1. A substantial quantity of good air leakage data for mid and high rise apartment buildings is available from the literature for the following components:
    - exterior envelope
    - exterior windows and doors
    - suite access doors

2. Good air leakage data for mid and high rise apartment buildings is very limited for the following components:
    - Floor to floor, inter-suite, and interior partition leakage exterior envelope
    - Stairway and elevator shaft leakage
    - Stairway and elevator door leakage
    - Plumbing and electrical penetration and riser leakage
    - Backdraft damper two way flow

3. Data is basically non existent for a number of additional parameters that are required for accurate airflow modelling including:
    - underground parking access door leakage
    - understanding of the prevalence of use of underground parking access doors
    - garbage chute door leakage
    - pressure flow characteristics of fans when not in operation
    - Window use and exhaust fan use diversity data

4. It would be beneficial to have more whole suite leakage area and distribution data to enable the correlation of estimated component leakage areas to typical values of whole suite leakage and distribution.

The following conclusions can be drawn from results of modelling of ventilation and infiltration airflow and energy consumption in the example 10 storey high-rise apartment building:

1. With corridor ventilation fans in the building operating as designed, infiltration contributed up to 72% of the total ventilation and infiltration heating load under static weather conditions modelling.

   Under outdoor conditions representative of typical January weather in the cities of Vancouver, Winnipeg, and Toronto, the average contribution of infiltration to total outdoor airflow heating load (with corridor ventilation fans on) was found to be 33%, 54% and 42% respectively with no suite exhaust fans operating. With the operation of all suite exhaust fans, these contributions increased to 50%, 62% and 55% respectively.

2. Operation of corridor ventilation fans reduced infiltration airflow by from 20%, when stack, wind, and exhaust fan depressurization effects are highest, to 83% when stack, wind, and exhaust fan depressurization effects are lowest.

3. Shutting off the corridor ventilation fan at -15°C, a common energy saving practice among some apartment building operators, reduces total ventilation and infiltration heating load by 5% to 24%.

4. Infiltration airflow rates into the building can produce high whole building airchange rates which are wasteful of energy, but not necessarily adequate indoor air quality in individual suites.

   At certain outdoor weather conditions, turning off corridor ventilation fans can result in reduced energy consumption while whole building air change rates remain above 0.35 ACH. However, even with high rates of air change on a whole building basis, and whether the corridor ventilation fan is operating or not, individual suites in the building may be inadequately ventilated.

   The conclusion that is drawn from this is that current designs for ventilation systems in mid and high rise apartment buildings do not work well for either ensuring adequate indoor air quality or reducing energy consumption attributable to infiltration airflow. Shutting off corridor ventilation systems at low outdoor air temperatures can save energy, but at the risk of reducing already hit and miss indoor air quality in individual suites.

5. Modelled results of the contribution of infiltration to heating loads compare favourably to measured results from previous energy audits of high rise apartment buildings.

6. This study, as well as previous apartment building airflow modelling studies, have shown that airflow modelling is a valuable tool for understanding how energy

performance and indoor air quality are related to ventilation and infiltration and for developing building designs that improve building performance. Airflow modelling is a valuable tool for improving apartment building ventilation and infiltration airflow performance.

To improve our understanding of both indoor air quality and energy performance as they relate to ventilation, both in existing mid and high rise apartment buildings and for developing design guidelines to improve performance in the future, we need to develop a much better understanding of ventilation and infiltration airflow through these buildings. Computer simulation methods are the most practical approach to developing this understanding, and future research efforts should be concentrated in this direction.

Résumé

La recherche avait pour objectif d'améliorer nos connaissances des répercussions énergétiques de la ventilation et des infiltrations d'air sur les immeubles à logements de faible et de grande hauteur au Canada. Elle visait également à aider les chercheurs en bâtiment et les concepteurs à utiliser des outils de modélisation à zones multiples des mouvements de l'air dans le but d'améliorer la conception des bâtiments.

On a d'abord effectué une recherche documentaire afin de recueillir et d'interpréter les meilleures données disponibles portant sur la modélisation à zones multiples des mouvements de l'air dans les immeubles à logements de faible et de grande hauteur. Un logiciel de modélisation à zones multiples des mouvements de l'air a ensuite été utilisé pour étudier la question de la consommation d'énergie des installations de ventilation dans une tour d'habitation de 10 étages nouvellement construite. On a comparé les incidences relatives des fuites d'air et de la ventilation sur la consommation d'énergie, et on a aussi examiné d'autres questions clés touchant l'énergie dans le cas d'un bâtiment réel modélisé à l'aide de différentes données climatiques canadiennes.

À partir des informations obtenues de la recherche documentaire sur les études de mouvements d'air dans les collectifs d'habitation, effectuées pour rassembler et analyser les données sur les fuites d'air des composants, et d'autres données requises pour la modélisation, on peut tirer les conclusions suivantes :

1. Pour les composants suivants, une grande quantité d'information de qualité est disponible dans la documentation sur les fuites d'air dans les immeubles à logements de faible et de grande hauteur :

- l'enveloppe du bâtiment
- les fenêtres et les portes extérieures
- les portes d'entrée des logements

1. Il existe peu de données fiables sur les mouvements de l'air dans les logements de faible et de grande hauteur pour les situations suivantes :

- d'un étage à l'autre, d'un logement à l'autre et à l'intersection des cloisons intérieures et de l'enveloppe
- dans les cages d'escalier et d'ascenseur
- à la hauteur des portes d'escalier et d'ascenseur
- à l'emplacement des ouvertures de plomberie et d'électricité ainsi qu'aux colonnes montantes
- l'écoulement bidirectionnel par les clapets anti-refoulement

1. Il n'existe pas, à vrai dire, de données sur une gamme de paramètres additionnels essentiels à l'élaboration d'une modélisation rigoureuse des mouvements d'air, notamment :

- les portes des garages de stationnement souterrains
- la caractérisation des habitudes d'utilisation des portes d'accès aux garages de stationnement souterrains
- les fuites d'air dans les chutes à déchets

- ◊ les caractéristiques d'écoulement d'air des ventilateurs en position d'arrêt
- ◊ les données sur l'utilisation des fenêtres et des ventilateurs d'extraction

1. Il serait avantageux d'obtenir des données supplémentaires sur les mouvements d'air globaux des logements et de leur distribution afin d'établir une corrélation entre les fuites d'air estimatives de chaque composant par rapport à celles de l'ensemble du logement.

On a tiré les conclusions suivantes à la suite de l'étude des résultats de la modélisation portant sur la ventilation et les infiltrations d'air et la consommation d'énergie dans une tour d'habitation modèle de 10 étages :

1. En supposant que les ventilateurs des corridors fonctionnaient selon les calculs, les infiltrations ont constitué jusqu'à 72 % de la charge totale de chauffage imputable à la ventilation et aux fuites d'air dans des conditions de modélisation climatiques statiques.

   Dans des conditions extérieures représentatives du mois de janvier, la quote-part moyenne attribuable aux infiltrations par rapport à la charge de chauffage due à l'écoulement total extérieur (les ventilateurs des corridors étant en marche) a été respectivement de 33, 54 et 42 % dans les villes de Vancouver, Winnipeg et Toronto, alors que tous les ventilateurs d'extraction des logements étaient arrêtés. Lorsque tous les ventilateurs d'extraction sont en marche, ces proportions passent à 50, 62 et 55 % respectivement.

2. La mise en marche du système de ventilation des corridors a réduit les infiltrations d'air de 20 %, lorsque les effets du vent, de la dépressurisation et du tirage étaient à leur niveau le plus fort, et de 83 % lorsque ces effets étaient à leur niveau le plus faible.

3. La pratique qui consiste à stopper la ventilation des corridors à une température de -15 °C (pratique courante d'économie d'énergie dans les tours d'habitation) diminue la charge du chauffage imputable à la ventilation et aux infiltrations dans une marge de 5 à 24 %.

4. Les infiltrations d'air dans un bâtiment peuvent produire des taux de renouvellement d'air élevés qui, tout en gaspillant l'énergie, ne fournissent pas nécessairement une qualité de l'air acceptable dans chacun des logements.

   Dans certaines conditions climatiques, l'arrêt des ventilateurs des corridors peut diminuer la consommation d'énergie tout en maintenant un taux de renouvellement d'air par heure supérieur à 0.35. Toutefois, même si le taux de renouvellement d'air pour le bâtiment dans son ensemble est élevé, la ventilation dans les logements pourrait être inadéquate, que l'installation de ventilation des corridors soit en marche ou non.

   Il faut en conclure que la conception actuelle des installation de ventilation dans les immeubles à logements de faible et de grande hauteur est déficiente et qu'elle n'assure ni une qualité de l'air acceptable ni une réduction de la consommation d'énergie imputable aux infiltrations d'air. L'arrêt des ventilateurs d'alimentation des corridors à de basses températures peut économiser l'énergie, mais risque de réduire la qualité de l'air, déjà aléatoire, dans les logements.

5. Les résultats de la modélisation de l'apport des infiltrations aux charges de chauffage se comparent avantageusement aux résultats mesurés antérieurement lors de vérifications du rendement énergétique de tours d'habitation.

6. La présente étude, tout comme les études antérieures de modélisation des mouvements de l'air dans les tours d'habitation, a montré que la modélisation constitue un outil important pour comprendre la relation entre le rendement énergétique et la qualité de l'air d'une part, et la ventilation et les infiltrations d'autre part, et pour l'élaboration de bâtiments à performance énergétique améliorée. La modélisation des mouvements de l'air est un outil précieux pour améliorer la ventilation dans les immeubles d'appartements et la performance du bâtiment en rapport avec les fuites d'air.

   Afin de mieux comprendre la qualité de l'air et le rendement énergétique par rapport à la ventilation, tant dans les logements de faible et de grande hauteur existants que dans l'élaboration de directives de conception visant l'amélioration de la performance future, nous devrons augmenter nos connaissances considérablement sur les phénomènes de ventilation et d'infiltration de l'air qui se produisent dans ces bâtiments. La modélisation par simulation informatique constitue l'approche la plus pratique pour acquérir ces connaissances, et c'est pourquoi les efforts de recherche devront être dirigés de ce côté.

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Contents

1.0 Introduction

Mid-rise and high-rise multi-unit residential buildings (MURBs) represent an important, yet poorly understood, segment of Canada's building stock. Together they represent a large proportion of all households in Canada but are not consistently included in studies of the residential building stock nor the commercial building stock and hence tend to fall between the cracks. Policy analysts, planners, and researchers are hampered in their ability to formulate and support federal policy for this important sector by the current lack of information.

While it should be expected that multiunit residential buildings consume much less energy than single detached houses on a per floor area basis because of reduced conductive losses resulting from lower exterior surface areas and shared walls , they are not generally built to high levels of energy efficiency. The Canadian stock of mid and high-rise multiunit residential buildings actually consume more energy than single detached houses on an energy per unit floor area basis. In new construction, annual energy consumption is roughly comparable between high-rise and single detached buildings.[1.]

Energy used to provide ventilation air and energy lost due to uncontrolled infiltration of outside air are major sources of energy consumption in these buildings. However, the impact of the relative influence of the two on the total building energy consumption is not well understood. Studies have shown that during peak winter conditions the air leakage component of high rise apartment buildings in Ontario contributes roughly 25% to 40% of peak heating demand. Therefore the control of air leakage in these buildings has become recognised as a key element in achieving energy conservation.

Designers of multi story apartment buildings do not currently have a good understanding of how both the air supply and air distribution in these buildings depends on weather, on building configuration and airflow paths, and on mechanical system operation. The complexity of the issue, and lack of research into airflow within these buildings, has resulted in little guidance for designers. Even if designers understood the airflow issues, the lack of data makes it difficult at the design stage to assess the implications of the many parameters that affect ventilation and infiltration performance.

The interaction between air infiltration, ventilation and energy consumption in MURBs is a complex interaction of factors including:

- indoor to outdoor temperature difference
- wind speed
- height of building
- building air tightness
- leakage between suites and floors
- mechanical ventilation systems, and

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[1] CMHC Research and Development Highlights, Energy Audits of High-Rise Residential Buildings, 97-100.

- occupancy patterns.

Stack and wind induced pressure differences can be significant driving forces for ventilation airflow. Mechanically induced pressure differences in MURBs range from approximately 2 Pa to a high of about 12 Pa. These do affect the resultant pressure drop across the building envelope, however they are relatively smaller than those caused by natural driving forces. In other high-rise buildings with elaborate ventilation systems such as office buildings, the mechanically induced pressure differences are designed to be greater than the pressure differences induced by natural forces.

It is common practice among many MURB building operators to turn off the corridor air systems when the outdoor temperature falls below a set point such as -15C. The assumption is that shutting off the corridor ventilation system will significantly reduce the overall ventilation rate, and thus energy consumption, and that the natural air change rate due to natural driving forces is significant enough to meet the ventilation requirements. Whether or not this practice leads to a significant reduction in energy consumption has not been verified. Also, a large portion of the MURB stock have corridor ventilation air systems which are heated with natural gas, and individual suite heating with electric baseboard heaters. At these lower temperatures, with the corridor air system shut off, space heating is provided solely by electric baseboard heaters. This may not be cost effective when compared to the partial displacement of heating load by a more cost efficient natural gas fuelled corridor air heating system.

There has been speculation that given the leakiness of MURBs, the operation or in-operation of mechanical ventilation systems has little impact on the overall energy consumption of the building, which would mean that the energy savings from this practice are minimal. On the other hand, it has been a general assumption of building designers that the operation of a ventilation system that pressurises the building would prevent some if not all of the infiltration air through the building envelope, thereby eliminating the need to consider infiltration in energy load calculations.

This incomplete understanding of the relative influences of air leakage and ventilation makes it difficult to determine the impact of energy efficiency retrofit measures for existing buildings such as variations in ventilation system flow rates, distribution patterns, ventilation system alternatives, air sealing, operating schedules, heat recovery opportunities, etc. As a result, in new buildings HVAC systems are often improperly sized, resulting in poor energy and ventilation performance.

To improve our understanding of both indoor air quality and energy performance as they relate to ventilation, both in existing MURBs and for developing design guidelines to improve performance in the future, we need to develop a much better understanding of ventilation and infiltration airflow through these buildings. Computer simulation methods are a practical approach to developing this understanding.

It is very difficult to assess MURB airflow patterns through field testing due to the complexity of the interaction between the many variables. Field-testing is complex and costly and results are very difficult to extrapolate over time or to other buildings because of our lack of understanding of the relative influence of key variables. However, building airflow modelling can relatively easily take into account the complex interaction of variables, and can be used to develop an understanding of the relative influence of each variable. Modelling of airflows by computer simulation can provide an understanding of variables that act randomly in actual buildings and provide insight into design approaches that could only be otherwise obtained (if at all) by studying actual buildings with very detailed and costly field-testing procedures.

While computer simulation airflow modelling is the ideal tool for answering our current questions and assessing the impact of possible design changes in the future, insufficient research on MURBs has been completed in this area.

The purpose of this project is first to complete a literature search to assemble and interpret MURB airflow modelling data. This will provide a significant advancement towards the goal of being able to use airflow modelling of MURBs to develop design guidelines.

The second purpose of this project is to use an airflow modelling tool to provide an analysis of ventilation related energy issues in one of the new MURB buildings that was field-tested in a previous research project carried out by Sheltair Scientific for CMHC. The relative influences of infiltration and ventilation on energy consumption were compared, and other key energy related questions were looked at as they apply to one actual building modelled within a range of Canadian climates.

2.0 Apartment Building Airflow Modelling

2.1 Multizone Airflow Modelling Tools

The quantity of infiltration and exfiltration in a mid- or high-rise residential building depend on the size and location of leakage sites and on the magnitudes of the stack, wind, and mechanically induced pressure differences. Stack and wind induced pressure differences, which are created by external driving forces, cause uncontrolled infiltration and exfiltration of outdoor and indoor air. Pressure differences induced by operating mechanical ventilation systems can assist or counteract these airflows.

Empirically determining all of the time-varying pressure differences and airflows for in a mid- or high-rise residential building is difficult, time consuming, and expensive. Alternatively, a detailed analysis can be carried out to simulate the multi-compartment pressure differences and airflows in a calibrated computer model of the building.

Several software models have been developed for predicting airflow, contaminant dispersal, and fire induced smoke movement in multizone buildings. Feustel and Dieris (1992) report 50 different computer programs for multizone airflow analysis. Two multi zone airflow models that are validated, well supported, free to obtain, and commonly used in North America are "CONTAM96" developed by the US National Institute of Standards and Technology (NIST) and "COMIS" developed by ten scientists in nine countries and supported by the International Energy Agency's Annex 23.

These mathematical models calculate airflows based on mass balance calculations for individual zones that are connected together in a network.

2.2 Apartment Building Multizone Airflow Modelling Input Data Requirements

Multi story apartment buildings differ from other types of tall buildings and from single family houses in that they are divided into small units connected by a common corridor on each floor, resulting in a much more complex network of multizone airflow paths. Typically a common ventilation system provides fresh air into the corridors and individual suite fans exhaust air from individual units. Airflow paths connect apartments to one or more adjoining apartments as well as to common spaces such as hallways, stairways and other shafts. Hallways connect zones horizontally while stairwells, elevator shafts, garbage chutes etc, provide vertical airflow paths.

Due this unique layout of multi unit residential buildings, flow characteristics of the following components are critical for performing air movement calculations, and are required as inputs to multizone airflow models:

MURB Airflow Modelling Input Requirements

- ◊ Physical geometry and dimensions of the entire building and individual airflow zones.
- ◊ Airflow resistance of all airflow paths including:
  - Exterior envelope leakage (Exterior walls, windows, doors, roof, floor)
  - Suite to suite and other interior partition leakage
  - Floor to floor leakage
  - Suite/corridor door leakage
  - Stairway, elevator, and service door leakage
  - Stairway tread design (open/closed)
  - Elevator, stairway, garbage chute, and other shaft configuration and leakage to suites, corridors, and other zones
- ◊ Configuration of mechanical ventilation systems
- ◊ Ventilation system airflow rates
  - Rate of constant flow (for simplified modelling of air handling systems), or
  - Duct sizes, loss coefficients, roughness factors, leakage classes, and fan performance curves (for detailed modelling of air handling systems)
- ◊ Building Wind Pressure Coefficients for all facade locations and wind directions
- ◊ Ambient Weather Data

2.3 Units of Measurement of Air Leakage Characteristics

Several different methods exist for reporting the air leakage characteristics of whole buildings, individual suites, and specific building components. As a result the format of data found in the literature varies widely. Most building or component leakage data is derived from fan pressurisation measurements in which the flow is recorded as a function of differential pressure for several different pressures. However several different methods are commonly used to present this data in a simpler format. Generally, leakage data is reported in one of the following ways:

1. Constants for the fit of the data to pressure versus flow power law equations (flow coefficient C and flow exponent n)
2. Rate of flow at a given differential pressure across the component or between the interior and exterior of the building.
3. Equivalent leakage area of the opening, typically at a reference pressure of 10 Pa with a discharge coefficient (Cd) of 0.611 (ELA_{10}). ELA_{10} is most commonly used for reporting leakage characteristics in Canada and the Netherlands.

4. Effective leakage area of the component, typically at a reference pressure of 4 Pa with a discharge coefficient (Cd) of 1.0 (ELA_4). ELA_4 is most commonly used for reporting leakage characteristics in the United States.
5. Equivalent or effective leakage area normalised to:
    - ◊ the area of the component (for example leakage area of interior partitions per m2 of partition area),
    - ◊ the length of the component or crack between components (for example leakage area of windows per crack length, where crack length is defined in CSA Standard A440)
    - ◊ the floor area of the suite or whole building
6. Contribution of leakage of a particular component as a percentage of total leakage of the suite or whole building.

The airflow modelling programs CONTAM and COMIS both allow the user to enter leakage data in any of the first five of the above formats. The most commonly used format found in data reference sources is the effective leakage area (ELA_4) with a discharge coefficient of 1.0 (Cd=1.0) at 4 Pa pressure difference, normalised to any of a number of unit lengths or areas.

In this report all data was converted into effective leakage areas (ELA_4) to enable a comparison of data from different sources. Data has been converted to effective leakage areas using the conversion formulas from Chapter 25 of the 1997 ASHRAE Handbook - Fundamentals. A value of 0.65 was assumed for the flow exponent if an equation for the data was not provided. If sufficient information was available to do so, air leakage through individual components has been normalised to component areas. In other cases as noted, air leakage areas are presented as leakage areas on an individual component basis, or normalised to component length or crack length. Air leakage areas for whole suites have been normalised to the floor area of the suite if sufficient information was available in the literature to do so.

3.0 Literature Review of Apartment Building Airflow Modelling Input Data

Modelling of multi-compartment pressure differences and airflows in a calibrated computer model of a building is limited by the need for a detailed knowledge of the building and mechanical system flow characteristics. These characteristics are often unavailable and obtaining them through field measurements is also difficult, time consuming, and expensive. Instead, data from measurements of similar buildings and components can be used in airflow modelling.

While comprehensive databases of component leakage characteristics for low rise residential buildings are readily available in the literature, data specific to multi story apartment buildings is very scattered and not readily accessible to those interested in modelling airflow in these types of buildings.

The following discussion is an attempt to collect and present the best available data for specifying building and mechanical system airflow characteristics of multi story apartment buildings, in order to improve the ease of airflow modelling for researchers and designers, and help improve the accuracy of their input assumptions.

3.1 Apartment Suite Leakage and Distribution

A number of research studies have been completed that quantify air leakage and characterise the distribution of leakage within individual apartment building suites. While not directly providing input data for airflow modelling, this information is an essential starting point for comparing component leakage data and distribution to whole suite leakage rates found in specific buildings that have been studied.

Modera et al. measured air leakage in a six-unit building in Minneapolis (Modera et al., 1985). Using six blower doors simultaneously they showed that the average effective leakage area for each apartment was 1600 cm2. When normalised to floor area this results in 13 cm2 per m2 of floor area. They also showed that 40% of the air leakage was directly through the exterior envelope, with the remainder going either to the adjacent units or to interstitial spaces between apartments.

Two blower doors were used to measure air leakage in two three-story apartment buildings in Chicago (Diamond et al., 1986). Effective leakage areas of 2460 cm2 and 1880 cm2 were measured for the two apartments, which when normalised by floor area were both 19 cm2 per m2 floor area. Roughly 60% of the leakage was to other apartments.

Blower door measurements in a study of eleven multifamily buildings in upstate New York showed an average pre-retrofit leakage rate of 35.5 ACH @ 50 Pa, implying an effective leakage area of 24 cm2 per m2 of floor area. (Synertech, 1987).

Shaw and Magee (1991) carried out airtightness tests on ten suites in one mid-rise apartment building. The whole-suite leakage flow was in the range of 4.8 to 6.8 L/s per m^2 of exterior wall area for a 10 Pa pressure difference. Based on Shaw and Magee's data, the effective leakage area of the suites appear to be in the range of 198 to 216 cm^2 (average of 210 cm^2). Shaw and Magee also determined the component leakage distributions for six of the ten suites they tested. The following component leakage fractions are based on the total leakage flows for individual test suites (not including the suite access door from the corridor):

Corridor Walls	7 to 19%
Exterior Wall	34 to 64%
Ceiling and Floor	0 to 19%
Inter-Suite Partition Walls	12 to 36%

It appears from these data that the corridor wall, ceilings, and floors are minor leakage sites, whereas the exterior walls are major leakage sites. Partition walls are somewhere in the lower to middle leakage range. The contribution of suite access door leakage was not included in the leakage distribution.

Mark Kelley (Kelly et al. 1992) measured the air leakage pre-and post-retrofit in a high-rise apartment in Revere, Massachusetts. They found an average pre-retrofit leakage for 17 of the apartments of 532 CFM at 50 pascals (implying an effective leakage area of 190 cm2) and a post-retrofit leakage of 449 CFM at 50 Pascals (ELA_4 of 160 cm2), a reduction of 15%.

Five regional field investigation surveys were conducted across Canada to study airtightness, air movement, and indoor air quality in high-rise apartment buildings (Gulay et al. 1993) Suite, floor, and whole building fan depressurisation tests were performed on 11 high-rise apartment buildings built between 1960 and 1991. While suite leakage rates were not reported, the distribution of whole building air leakage and suite leakage was determined. On a whole building basis, the following distribution of leakage by component was found:

Windows	42%
Doors	26%
Building Envelope	6%
Vertical Shafts	14%
Miscellaneous	12%

On an individual suite basis the following distribution of leakage for four of the buildings studied was found:

Entry Door	42% (One building only)
Left, Right, and Corridor Walls	14 to 27%
Floor	2 to 18%
Ceiling	6 to 29%
Exterior Wall	25 to 62%

Researchers from LBL used a single-blower-door technique for measuring leakage in multifamily buildings in 1993 in two New York apartment buildings. One apartment was pressurised and depressurised to ±50 Pa, and the resulting pressures were measured in adjacent apartments. By incorporating the pressures measured in the adjacent apartments (1-15 Pa) into a mass balance equation, they were able to calculate that approximately 50% of each apartment's leakage was to outside in one building, and that a significantly larger fraction was to outside in the other (Dickerhoff et al., 1994).

Feustel and Diamond (1996) measured air leakage rates in three apartment buildings in California and Massachusetts. Air leakage was measured in nine apartments of a 150 unit high rise apartment building, built in 1974 and located in Chelsea, Massachussetts. They found average total effective leakage areas of 225 cm2 and 256 cm2 for one and two bedroom apartments respectively. Following window retrofits effective leakage areas were found to be an average of 230 cm2 and 248 cm2 for one and two bedroom suites. The second building, an 11 storey building built in 1968 and located in California, was found to have suite leakage rates of 445 and 416 m3/hr for two suites measured, implying effective leakage areas of 93 and 87 cm2 or 1.9 and 2.6 cm2 per m2 of floor area respectively. The third building, a 13 storey building built in 1977 and located in California, was found to have suite leakage rates of 1089 and 1038 m3/hr for two suites tested, implying effective leakage areas of 229 and 218 cm2 or 4.4 and 4.2 cm2 per m2 of floor area.

What emerges from a review of these studies is that there is a wide variance in the airtightness between buildings, between suites within a single building, and between similar leakage components within suites. The variance is likely due to different building ages, location, types of construction, and inconsistent construction quality or building maintenance, which causes non-uniformity in the size and distribution of leaks from building to building and suite to suite.

Another conclusion is that it is unclear whether on not suite access door leakage is included in many of the suite leakage areas or distributions reported. In most studies a fan is used to pressurise or depressurise the suite that is installed in a blower door that is sealed into the door frame of the suite access door, automatically eliminating the effect if suite access door leakage. While many studies report that a large fraction of suite leakage (25 to 64%) is due to leakage through exterior walls, these fractions can be misleading because the leakage of suite access doors can strongly effect the leakage distribution. It is also clear that the format used to report leakage areas and their distribution is not consistent between studies, making it difficult to compare results.

3.2 Component Leakage Data

Multizone airflow modelling in apartment buildings requires the specification of pressure induced air leakage characteristics (flow versus pressure relationship or leakage areas that represent this relationship) for all significant leakage paths in the building. The establishment of appropriate leakage characteristics for each component is not an easy task. Determining these air leakage values is difficult since the air leakage of an individual building element depends on its design, installation, and deterioration over time. The only way to know the air leakage characteristics of an element is to measure it. However, it is impractical to measure all the leakage characteristics of all openings in a building. Instead, air leakage values from field test measurements of similar components can be used in airflow modelling.

Exterior Wall, Window, and Door Leakage Areas

In 1978 the Division of Building Research at the National Research Council of Canada initiated a study to collect air leakage data for high rise apartment buildings in Canada (Shaw 1980). Exterior wall, window, and balcony door component leakage data was collected on five apartment buildings that varied in height from 5 to 20 stories and year of construction from 1965 to 1978. Ranges of component leakage data that was collected are shown below in Table 3.1 with results converted to effective leakage areas at 4 Pa pressure difference with a discharge coefficient of 1.0.

Extensive component leakage data was collected on a five-story apartment building that was built in Ottawa in 1981 (Shaw, Magee, and Rouseau, 1991). In this study component leakage data was collected for complete exterior wall assemblies (including leakage through windows and balcony doors) on three stories of the building. Ranges of component leakage data that was collected are shown in Table 3.1.

Exterior wall air leakage rates were measured in two high rise apartment buildings in Canada in another study (Shaw, Gasparetto, Reardon, 1990). The two buildings were 14 and 17 stories in height, built in 1977 and 1982 respectively. Both were constructed with masonry panel exterior walls. Effective leakage area results for exterior wall assemblies (including windows and doors) are shown in Table 3.1.

Exterior wall, floor to floor, and suite to suite air leakage rates were measured in another study of eleven high rise apartment buildings in five separate regions of Canada (Gulay, Stewart, Foley, 1993). Buildings that were tested ranged in year of construction from 1960 to 1991 and in height from 4 to 21 stories. Exterior wall effective leakage areas, including the effect of walls and windows in the exterior walls, are shown in Table 3.1 for those buildings for which data was reported.

Table 3.1 Effective Leakage Areas of Exterior Wall Assemblies in High Rise Apartment Buildings

				Effective Leakage Area (ELA$_4$)			
Study	**# Stories**	**Year of Construction**	**Component**	**Units***	**Min**	**Max**	**Reference**
1	5 to 20	1965 to 1978	Exterior Walls - brick	cm2/m2	0.39	2.0	Shaw (1980)
			Exterior Walls - concrete spandrel panel	cm2/m2	0.16	0.16	"
			Windows - fixed and openable sealed double glazing, including window frame-wall joints	cm2/lmc	0.22	1.1	"
			Doors - Balcony Sliding	cm2/m2	0.74	1.7	"
2	5	1981	Exterior Walls - brick veneer, concrete masonry backup, including leakage through windows and balcony doors	cm2/m2	2.7	4.5	Shaw (1991)
3	14	1977	Exterior Walls - Masonry panel, including leakage through exterior windows and doors	cm2/m2	2.6	3.2	Shaw (1990)
	17	1982	Exterior Walls - Masonry panel, including leakage through exterior windows and doors	cm2/m2	1.7	2.9	"
4	7	1982	Brick veneer/ steel stud	cm2/m2	4.2	8.2	Gulay (1993)
	6	1983	Brick veneer/ steel stud	cm2/m2	1.4	5.2	"
	15	1991	Brick veneer/ steel stud	cm2/m2	1.7	1.7	"
	4	1960	Double wyth brick/ steel stud	cm2/m2	3.5	3.5	"
	10	N/a	Brick veneer/ steel stud	cm2/m2	0.67	2.03	"
	13	1973	Double wyth brick/ steel stud	cm2/m2	1.9	1.9	"
	13	1973	Double wyth brick/ steel stud	cm2/m2	1.6	2.4	"
	11	1984	Precast Concrete/steel stud	cm2/m2	1.43	1.43	"
	8	1991	Stucco/steel stud	cm2/m2	0.51	0.52	"
	10	1991	Stucco/steel stud	cm2/m2	0.52	1.32	"

***Effective leakage areas normalized to exterior wall area**

While not specific to apartment buildings, a comprehensive source of residential building component air leakage data compiled from studies of buildings in North America is that produced by Colliver, Murphy, and Sun (1994). This compilation of data was conducted under an ASHRAE research project in order to update the component leakage data tables for the 1993 ASHRAE Handbook - Fundamentals. An extensive search for sources of component leakage data was carried out, with the scope of the literature search narrowed to include only data that was collected after 1970 and from structures in North America.

Exterior wall, window, door and wall penetration leakage data from their literature search that is useful to airflow modelling in apartment buildings is presented below in Table 3.2.

The majority of data contained in this table has been compiled from studies of single detached and low rise residential buildings. However, much of it is also relevant to multi story apartment buildings. Some of the exterior wall leakage data is applicable to multi-story apartment buildings, depending on the type of construction of the building of interest. Data provided for leakage areas of doors is applicable to many MURB exterior doors, and much of the window data is also useful.

Another useful source for air leakage data is from Fang and Persily (1995) who conducted a literature search for leakage data from studies of large public and commercial buildings. Their search was also restricted to literature published after 1970, and to studies on buildings in North America only. They compiled data on leakage areas of a large number of exterior wall types from office buildings, school buildings, and supermarkets and shopping malls which are shown in Table 3.3. Although this data is not specific to apartment buildings, the presented leakage data may be useful to multi story apartment buildings constructed with exterior wall types common with office building wall types such as curtain walls.

Table 3.2 Residential Building Exterior Component Leakage Area Data - Colliver, Murphy, and Sun (1994)

	Effective Leakage Area (ELA_4)			
Component	**Units***	**Best Estimate**	**Min**	**Max**
Ceiling - General	cm2/m2	1.8	0.79	2.8
Ceiling - Drop	cm2/m2	0.19	0.046	0.19
Ceiling Penetrations - whole house fans	cm2/ea	20	1.6	21
Ceiling Penetrations - recessed lights	cm2/ea	10	1.5	21
Ceiling Penetrations - ceiling/flue vent	cm2/ea	31	28	31
Ceiling Penetrations - surface mounted lights	cm2/ea	0.82		
Door Frame - General	cm2/ea	12	2.4	25
Door Frame - Masonry - Not Caulked	cm2/m2	5	1.7	5
Door Frame - Masonry - Caulked	cm2/m2	1	0.3	1
Door Frame - Wood - Not Caulked	cm2/m2	1.7	0.6	1.7
Door Frame - Wood - Caulked	cm2/m2	0.3	0.1	0.3
Door Frame - trim	cm2/m	1		
Door Frame - jamb	cm2/m	8	7	10
Door Frame - threshold	cm2/m	2	1.2	24
Doors - Double - Not Weather-stripped	cm2/m2	11	7	22
Doors - Double - Weather-stripped	cm2/m2	8	3	23
Doors - General - average	cm2/lmc	0.31	0.23	0.45
Doors - Mail Slot	cm21m	4		
Doors - Sliding Exterior Glass Patio	cm2/ea	22	3	60
Doors - Sliding Exterior Glass Patio	cm2/m2	5.5	0.6	15
Doors - Storm (diff. between with/without)	cm2/ea	6	3	6.2
Doors - Single - Not Weather-stripped	cm2/ea	21	12	53
Doors - Single - Weather-stripped	cm2/ea	12	4	27
Doors - Vestibule (subtract per each location)	cm2/ea	10		
Electrical Outlets/ S witches (No gaskets)	cm2/ea	2.5	0.5	6.2
Electrical Outlets/ S witches (with gaskets)	cm2/ea	0.15	0.08	3.5
Joints: Ceiling-Wall	cm2/m	1.5	0.16	2.5
Joints: Sole Plate, floor/wall - uncaulked	cm2/m	4	0.38	5.6
Joints: Sole Plate, floor/wall - caulked	cm2/m	0.8	0.075	1.2
Joints: Top Plate - Band Joist	cm2/m	0.1	0.075	0.38
Piping/ Plumbing /Wiring ring Penetrations uncaulked	cm2/ea	6	2	24
Piping/Plumbing/Wiring Penetrations caulked	cm2/ea	2	1	2
Wall: Exterior				
Cast in Place Concrete	cm2/m2	0.5	0.049	1.8
L W Concrete Block - unfinished	cm2/m2	3.5	1.3	4
L W Concrete Block - painted or stucco	cm2/m2	1.1	0.52	1.1
H W Concrete Block - unfinished	cm2/m2	0.25		
Continuous Air Infiltration Barrier	cm2/m2	0.15	0.055	0.21
Rigid Sheathing	cm2/m2	0.35	0.29	0.41
Clay Brick cavity wall - finished	cm2/m2	0.68	0.05	2.3
Precast Concrete Panel	cm2/m2	1.2	0.28	1.65

Component	Effective Leakage Area (ELA_4) Units*	Best Estimate	Min	Max
Windows: Framing - Masonary - uncaulked	cm2/m2	6.5	5.7	10.3
Windows: Framing - Masonary - caulked	cm2/m2	1.3	1.1	2.1
Windows: Framing - Wood - uncaulked	cm2/m2	1.7	1.5	2.7
Windows: Framing - Wood - caulked	cm2/m2	0.3	0.3	0.5
Window: Awning - Not Weather-stripped	cm2/m2	1.6	0.8	2.4
Window: Awning - Weather-stripped	cm2/m2	0.8	0.4	1.2
Windows: Casement - Weather-stripped	cm2/lmc	0.24	0.1	3
Windows: Casement - Not Weather-stripped	cm2/lmc	0.28		
Windows: Double Horizontal Slider -Not Weather-stripped	cm2/lmc	1.1	0.019	3.4
Windows: Dbl Nor Sldr - wood - Weather-stripped	cm2/lmc	0.55	0.15	1.72
Windows: Dbl Nor Sldr - aluminum - Weather-stripped	cm2/lmc	0.72	0.58	0.8
Windows: Double Hung - Not Weather-stripped	cm2/lmc	2.5	0.86	6.1
Windows: Double Hung - Weather-stripped	cm2/lmc	0.65	0.2	1.9
Windows: Double Hung - Not Weather-stripped, w storm	cm2/lmc	0.97	0.48	1.7
Windows: Dbl Hung - Weather-stripped, with storm	cm2/lmc	0.79	0.44	1
Windows: Dbl Hung - Weather-stripped, w press trackstm	cm2/lmc	0.48	0.39	0.56
Windows: Jalousie	cm2/louvre	3.38		
Windows: Lumped	cm2/lms	0.471	0.009	2.06
Windows: Single Horizontal Slider	cm2/lms	0.67	0.2	2.06
Windows: Single Horizontal Slider- Not Weather-stripped				
Windows: Single Nor Slider - aluminum	cm2/lms	0.8	0.27	2.06
Windows: Single Nor Slider - wood	cm2/lms	0.44	0.27	0.99
Windows: Single Nor Slider - wood clad	cm2/lms	0.64	0.54	0.81
Windows: Single Hung - Weather-stripped	cm2/lms	0.87	0.62	1.24
Windows: Single Hung - Not Weather-stripped				
Windows: Storm Inside - heat shrink	cm2/lms	0.018	0.009	0.018
Windows: Storm Inside - rigid w magnetic seals	cm2/lms	0.12	0.018	0.24
Windows: Storm Inside - flex sheets w mechanical seals	cm2/lms	0. 154	0.018	0.833
Windows: Storm Inside - rigid w mechanical seals	cm2/lms	0.4	0.045	0.833
Windows - Storm Outside (Storm only)			1.8	
Windows - Storm Outside - pressurized track	cm2/lmc	0.528	4	
Windows - Storm Outside 2 track	cm2/lmc	1.23	1.1	
Windows - Storm Outside - 3 track	cm2/lmc	2.46		
Windows: Sill	cm2/lmc	0.21	0.139	0.212

***Units are cm2 of effective leakage area per:**

m2 = square meters of component surface area
lmc = lineal meter of crack
lms = lineal meter of sash
m = lineal meter
ea = each

Table 3.3 Large Building Component Leakage Area Data (Fang and Persily, 1995)

ELA @ 4 Pa (cm2/m2*)	Component
	Exterior Walls - Office Buildings
3.64	Precast concrete panel
2.74	Precast concrete panel walls retrofitted with rigid insulation after about 20 years WB
1.63	Precast concrete panel
1.02	Precast concrete panel walls retrofitted with all windows and vertical columns recaulked after about 20 years
0.55	Precast concrete panel
1.91	Metal panel
1.08	Metal panel walls retrofitted by replacing metal panel with a curtain wall after about 20 years
1.36	Metal panel
1.36	Metal panel walls retrofitted with all joints in the curtain wall recaulked after 20 yrs
1.3	Precast concrete panel
1.6	Precast concrete panel walls after about 20 years
1.87	Precast concrete panel
1.35	Precast concrete panel walls retrofitted
0.5	Metal panel
2.1	Precast concrete panel
1.3	Tile veneer, concrete masonry backup
1.9	Stone panel
0.6	Brick veneer, concrete masonry backup
2.3	Brick veneer, steel stud backup
1.1	Brick veneer, brick backup
2.9	Precast concrete panel
5.2	Glass and metal curtain wall
4.97	Glass and metal curtain wall
2.53	Precast concrete panel
1.6	PEAC panel
1	Glass and metal curtain wall
0.53	Precast concrete panel
	Exterior Walls - School Buildings
6.7	Brick veneer, concrete masonry backup
4.8	Brick veneer, concrete masonry backup
2.9	Brick veneer, concrete masonry backup
	Exterior Walls - Supermarkets and Shopping Malls
15.7	Concrete block
9.2	Brick veneer, concrete masonry backup
2.6	Concrete block, steel stud backup
	Floors - Office Buildings
0.39	Reinforced concrete.
0.26	Reinforced concrete
0.22	Reinforced concrete

***Effective leakage areas normalized to component area**

Floor to Floor and Inter-Suite Leakage Areas

Leakage data for floor to floor separations and interior partitions between units was collected on a five-story apartment building located in Ottawa and built in 1981(Shaw, Magee, and Rouseau, 1991). Floor to floor leakage was measured between four stories of the building. Leakage through partitions was measured between 10 apartment units. Interior partitions between units were constructed of metal studs, insulation blanket, and gypsum wallboard on each side. Results from their data, converted to effective leakage areas at 4Pa with a discharge coefficient of 1.0, are shown in Table 3.4.

Table 3.4 Floor to Floor, and Suite to Suite Component Leakage for Apartment Buildings

Study	# Stories	Year of Construction	Component	Effective Leakage Area (ELA_4) Units*	 Min	 Max	Reference
1	5	1981	Floor to Floor Separations	cm2/m2	0.12	0.32	Shaw (1991)
			Interior Partition Walls Between Units - Gypsum board on stud wall	cm2/m2	0.4	4.1	Shaw (1991

***Effective leakage areas normalized to component area**

Fang and Persily (1995) report floor to floor leakage areas for reinforced concrete floors in office buildings from their literature search. Effective leakage areas of 0.22 to 0.30 cm2/m2 of floor area are reported (see Table 3.3), which lie within the upper range of leakage areas measured for apartment buildings by Shaw, Magee, and Rouseau, (1991).

Floor to floor, and suite to suite air leakage rates were measured in another study of eleven high rise apartment buildings in five separate regions of Canada (Gulay, Stewart, Foley, 1993). Buildings that were tested ranged in year of construction from 1960 to 1991 and in height from 4 to 21 stories. While leakage rates were not reported on a rate per unit floor or wall area, for four of the buildings tested the proportional distribution of leakage from results of a six sided air leakage test on individual suites are reported. Total suite air leakage is broken into the percentage of leakage due to contributions of leakage from suite entry doors, corridor walls, floors, ceilings, and exterior walls. The results are shown in Table 3.5.

Table 3.5 Distribution of Leakage in Six Sided Air Testing of Four Apartment Suites

	% Distribution of Leakage Prairies 1	 Prairies 2	 Quebec 1	 Quebec 2
Corridor/Suite Access Door	42%	-	-	-
Left, Right, and Corridor Walls	25%	27%	14%	20%
Floor	2%	16%	18%	18%
Ceiling	6%	14%	29%	-
Exterior Wall	25%	43%	39%	62%

Suite Access Door Leakage

Leakage areas through corridor to suite access doors were tested in ten new high rise apartment buildings across Canada (Wray, Theaker, 1998). Effective leakage areas were found to range between 83 and 467 cm2. The ten buildings ranged in height from 6 to 32 stories, were all built between 1990 and 1995, and were located in Vancouver (4), Winnipeg (3) and Toronto (3). One suite access door was tested in each building. Of the ten doors tested, three doors were completely weather stripped, two doors were partially weather stripped, and the remaining five doors were not weather stripped. The test results converted to effective leakage areas using a flow exponent of 0.55 are shown below in Table 3.6. Measurements of the gap between the door and frame of each door tested are shown in Table 3.7.

Table 3.6 Corridor to Suite Access Door Leakage Areas in Ten High Rise Apartment Buildings (Wray et al 1998)

Building Number	Component	Units	Effectve Leakage Area (ELA_4)
1	Suite Access Door - Weather Stripped	cm2	83
2	Suite Access Door - Non Weather Stripped	cm2	216
3	Suite Access Door - Weather Stripped	cm2	146
4	Suite Access Door -Part Weather Stripped	cm2	117
5	Suite Access Door - Non Weather Stripped	cm2	193
6	Suite Access Door - Non Weather Stripped	cm2	155
7	Suite Access Door -Part Weather Stripped	cm2	197
8	Suite Access Door - Weather Stripped	cm2	117
9	Suite Access Door - Non Weather Stripped	cm2	467
10	Suite Access Door - Non Weather Stripped	cm2	147

***Effective leakage areas per door**

Table 3.7 Suite Access Door Gap Data

	Door		Door to Frame Gaps			
Building Number	Width [mm]	Height [mm]	Top	Bottom	Hinge Side	Latch Side
1	900	2060	<----- *No gap data collected* -----			
2	860	2030	<----- *No gap data collected* -----			
3	860	2010	10	5	3	6
4	910	2010	6	7	1	4
5	850	2060	2	6	3	4
6	850	2060	6	5	3	3
7	910	2010	4	18	3	2
8	890	2210	6	10	2	6
9	890	2000	5	19	2	6
10	910	2010	5	16	2	5

Wray et al combined their suite access door leakage data with the suite leakage distribution data reported by Shaw and Magee (1991) for the 5 story Ottawa apartment building constructed in 1981. They showed that using the leakage data for the tightest access door measured results in an average contribution of suite access door leakage of roughly 20% of total suite leakage in the suites tested by Shaw and Magee. Using data for the leakiest door measured results in a suite access door leakage contribution of approximately 55%.

These leakage distributions indicate that the leakage between the suite and corridor is significant, that half to almost all of this leakage can be attributed to the suite access door, and that this leakage can be greater than the exterior wall leakage.

In the Colliver, Murphy, and Sun (1994) database of effective leakage areas are a number of leakage rates for doors of low-rise residential buildings. Data that is useful for estimating apartment building interior door leakage areas is presented in Table 3.8. Their database provides a range of leakage areas for single doors without weather-stripping of 12 to 53 cm2 per door, which appears to be too low for typical suite access doors that do not have weather-stripping.

Colliver et al's database also indicates that the leakage between a door and its frame can be larger than the range of values described above for the single door. They reported effective leakage areas of 8 to 10 cm^2/m of door jamb perimeter and 2 to 24 cm^2/m of door threshold length. Assuming a typical suite access door size of 0.9 m wide and 2.0 m high results in an effective leakage area range of 41 to 71 cm2 per door. Combining single door leakage areas with door frame leakage areas results in a range of 53 to 124 cm2 per door, which is still lower than the leakage areas found by Wray et al.

Table 3.8 Interior Door Leakage Area Data - Colliver, Murphy, and Sun (1994)

		Effective Leakage Area (ELA_4)		
Component	**Units***	**Best Estimate**	**Min**	**Max**
Door Frame - General	cm2/ea	12	2.4	25
Door Frame - Masonry - Not Caulked	cm2/m2	5	1.7	5
Door Frame - Masonry - Caulked	cm2/m2	1	0.3	1
Door Frame - Wood - Not Caulked	cm2/m2	1.7	0.6	1.7
Door Frame - Wood - Caulked	cm2/m2	0.3	0.1	0.3
Door Frame - trim	cm2/m	1		
Door Frame - jamb	cm2/m	8	7	10
Door Frame - threshold	cm2/m	2	1.2	24
Doors - General - average	cm2/lmc	0.31	0.23	0.45
Doors - Interior (Pocket) (on top floor)	cm2/ea	14		
Doors - Interior (Stairs)	cm2/m	0.9	0.25	1.5
Doors - Single - Not Weatherstripped	cm2/ea	21	12	53
Doors - Single - Weatherstripped	cm2/ea	12	4	27

***Units are cm2 of effective leakage area per:**
m2= square meters of component area
lmc = lineal meter of crack
m = lineal meter
ea = each

Stairway and Elevator Shaft Leakage

Several studies have examined the leakage size of vertical shafts within buildings, such as Tamura and Shaw (1976) and Achakji and Tamura (1989). These studies have shown that leakage areas within shafts along their length are extremely large compared to the leakage areas of most other openings in buildings (including the leakage areas of walls and closed doors located between the shafts and the remainder of the building).

For example, Achakji and Tamura carried out tests of a ten-storey conventional stair shaft. Their results indicated that the inter-storey leakage area per storey of an unoccupied stair shaft is in the range of 21% to 24% of shaft cross-sectional area. Based on their data, the equivalent leakage area (ELA_{10}) within the stair shaft they tested is in the range of 26,000 to 30,000 cm^2 per storey. The large variation in leakage areas is due to differences in stair type (open versus closed treads).

CONTAM contains a stairway shaft model that uses the Tamara and Shaw data to create an equivalent orifice based on whether or not the stairs have open or closed treads and the number of people on the stairs. Measured flow resistance of elevator shafts has not yet been identified. As a result they are usually modelled either as a conduit or duct using the Darcy/Colebrook flow resistance model or as a single tall zone similar to an atria.

Tamara and Shaw (1976) measured the leakage of 7 elevator shafts and 8 stair shafts serving from 6 to 28 stories in high rise buildings. Their leakage rates converted to effective leakage areas as presented in Fang and Persily (1995) are shown in Table 3.9.

Table 3.9 Elevator and Stairwell Shaft Leakage

	Effective Leakage Area (ELA_4)		
Component	**Units***	**Min**	**Max**
Elevator Shaft Walls			
Hollow clay tile block or concrete block	cm2/m2	7.5	
Cast-in-place concrete	cm2/m2	0.75	3.5
Stairway Shaft Walls			
Cast in place concrete	cm2/m2	0.06	1.5

***Effective leakage areas normalized to component area**

In the same study Tamara and Shaw measured leakage openings between the top of the elevator shafts and the sub floor of elevator machine rooms. Using a measuring tape, they found leakage openings for vents, cables, and other accessories that varied from 0.046 to 0.97 m2 in area.

Stairway and Elevator Door Leakage

Tamura and Shaw (1976) tested the airtightness of elevator and stair shaft doors in eight mid- and high-rise buildings. The stairwell doors they tested were similar in size to suite access doors. Conversion of the test data to effective leakage areas indicates leakage areas in the range of 81 to 217 cm² (See Table 3.10). The corresponding average gap between these doors and their frames was reported to be in the range of 2 to 5 mm. These leakage areas are roughly in the same range as found for suite access doors measured by Wray et al. (1998).

In the same study they tested the leakage of elevator doors with average crack width varying between approximately 5.3 and 6.8 mm. Conversion of the test data to effective leakage areas indicates leakage areas in the range of 236 to 354 cm² (See Table 3.10).

Table 3.10 Office Building Stairway and Elevator Door Leakage

	Effective Leakage Area (ELA_4)		
Component	**Units**	**Min**	**Max**
Stairway Doors - Office Buildings			
0.9mx2.1m Stairway Doors, average crack width from 2 to 5 mm	cm2/ea	81	217
Elevator Doors - Office Buildings			
1.1 m x 2.1m elevator door, average crack with from 5.3 to 6.8 mm	cm2/ea	236	354

Electrical and Plumbing Penetration Leakage

The Colliver, Murphy, and Sun (1994) database contains effective leakage areas for a number of electrical and plumbing penetrations in low-rise residential buildings, which are presented below in Table 3.12.

Table 3.11 Effective Leakage Areas of Bathroom, Kitchen, and Dryer Vents

	Effective Leakage Area (ELA_4)			
Component	**Units**	**Best Estimate**	**Min**	**Max**
Electrical Outlets/ S witches (No gaskets)	cm2/ea	2.5	0.5	6.2
Electrical Outlets/ S witches (with gaskets)	cm2/ea	0.15	0.08	3.5
Piping/ Plumbing /Wiring ring Penetrations uncaulked	cm2/ea	6	2	24
Piping/Plumbing/Wiring Penetrations caulked	cm2/ea	2	1	2
Ceiling Penetrations - whole house fans	cm2/ea	20	1.6	21
Ceiling Penetrations - recessed lights	cm2/ea	10	1.5	21
Ceiling Penetrations - ceiling/flue vent	cm2/ea	31	28	31
Ceiling Penetrations - surface mounted lights	cm2/ea	0.82		

3.3 Mechanical Ventilation Airflow

Multizone airflow modelling requires the definition of airflow rates from mechanical ventilation supply and exhaust systems. Mechanical ventilation systems can be represented by models ranging from single fans that force air from one zone to another at constant flow, to elaborate systems of air distribution ductwork that require the definition of loss coefficients, duct leakage, and fan performance curves. Ventilation system data required for airflow modelling is essentially no different than that required for ventilation system design. Fan performance curves are available from fan manufacturers, and duct roughness, leakage classes, and loss coefficients can be used following standard duct and fan design principals. For existing buildings and those under design this information can be obtained from analysis of mechanical drawings. The design intention of mechanical ventilation systems in mid and high rise apartments, and typical design and measured flowrates of systems in new Canadian apartment buildings is discussed below.

Air Supply Systems

In mid- and high-rise residential buildings, one mechanical ventilation system typically supplies 100% outdoor air continuously to the corridors. Sometimes a time clock is used to shutdown this system in an attempt to conserve energy. One or more central "constant volume" fans provide the driving force in these systems. The central fans supply outdoor air through vertical ducts connected to corridors. They sometimes also supply air to service rooms, elevator lobbies, and entrance lobbies and vestibules. As air flows through the ducts, the static pressure within the duct decreases due to friction and turbulence effects.

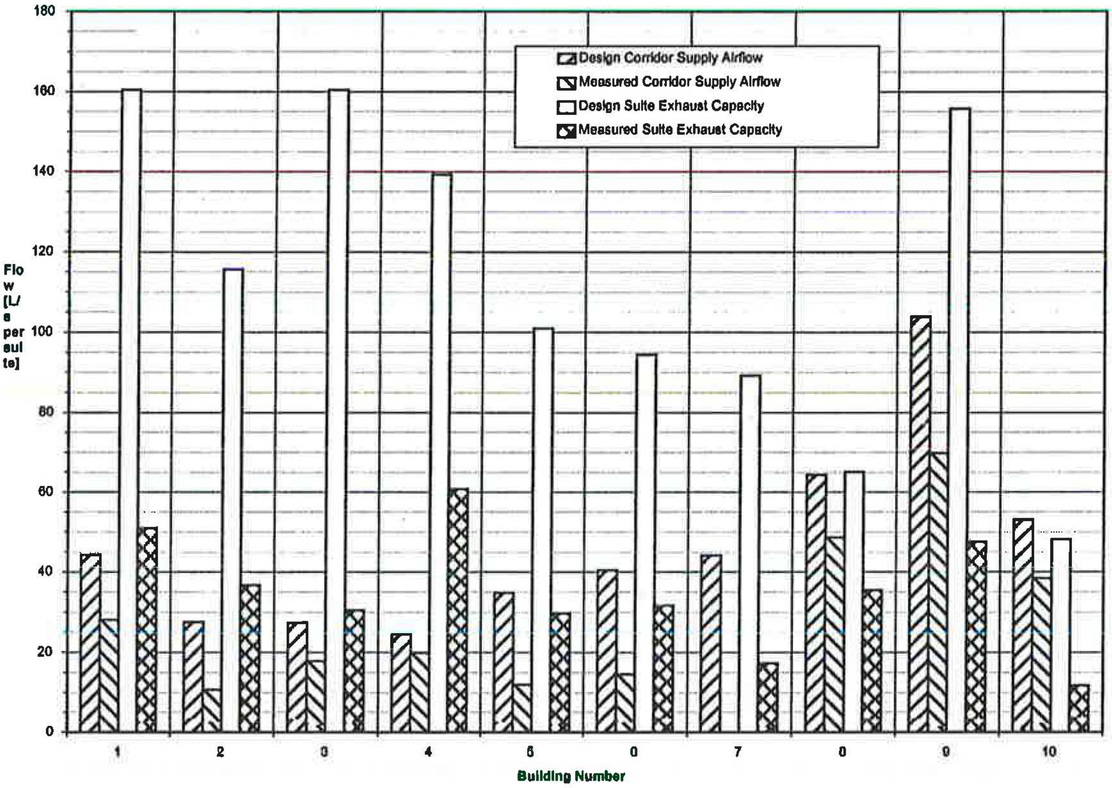
In a survey of designers of mechanical ventilation systems for mid and high rise residential buildings in Canada performed by Wray et al (1998), it was found that corridor supply air systems are generally designed to pressurise the corridors relative to suites with the intent of limiting the migration of contaminants between suites.

However, when designing the supply system, they typically do not specify and have little or no information regarding the actual airtightness of the combined corridor wall and suite access door assemblies or of the airtightness of the building envelope or other components effecting corridor pressurisation. Furthermore, they seldom take into account the effects of stack- and wind-induced pressure differences. They do typically use safety factors of 25 to 125 Pa to take some of these uncertainties into account.

Rarely are corridor ventilation systems designed specifically to provide ventilation for the suites. However, in the absence of other driving forces and when in-suite exhaust equipment is not operating, the corridor supply air system will also pressurise the suites relative to outdoors and will provide some suite ventilation, because the suites are not completely isolated from the corridor or outdoors. Consequently, the pressure in the corridor relative to the suites is unknown, the amount of air leaking from the corridor into the suites is unknown, and suite ventilation occurs more through accident than design.

In the same study Wray et al. (1998) measured the flowrates of corridor ventilation systems in 10 mid and high rise apartment buildings across Canada and compared the results to design flowrates and minimum outdoor air requirements. The ten buildings ranged in height from 6 to 32 stories and were all built between 1990 and 1995. The results are shown in Figure 3.1.

Figure 3.1 Design and Measured Corridor Supply Airflows and Suite Exhaust Capacities in Canadian Mid and High Rise Apartment Buildings



They found a wide variation in the design specification of corridor supply airflows, with specified design airflows ranging from 25 to 109 L/s per suite, or 40 L/s per suite on average. This corresponds to 154 to 461% of the minimum outdoor air capacity requirements of ASHRAE Standard 62, with an average of 264% (minimum ventilation rates based on 7.5 L/s per person and occupancy assumption from ASHRAE 62). Measured corridor supply airflows were found to be significantly lower than design airflows, ranging from 34% to 81% of design flows, with an average of 59%. This corresponds to flowrates of 53% to 310% of ASHRAE 62 Standard minimum outdoor air requirements, with an average of 160%.

Feustel and Diamond (1996) also measured corridor ventilation system supply airflows in a number of mid and high rise apartment buildings in the US. For one building for which sufficient data was provided to calculate airflows on a per suite basis, a 13 story apartment building in California, corridor supply airflow rates were measured at 6 to 15

L/s per suite, with an average of 10 L/s per suite. This compares to ASHRAE 62 ventilation requirements of 14L/s per suite.

Another study on ventilation in multifamily buildings was conducted by the New York State Energy Research and Development Authority (Shapiro-Baruch, 1993). They developed and tested a ventilation audit in 10 multifamily buildings, finding measured airflow rates to be on average 32% less than the design values. Energy use for mechanical ventilation varied widely from building to building, from less than 2% to more than 20%. They identified poorly designed and poorly operated supply air systems as the source of many indoor air quality problems.

Air Exhaust Systems

In mid and high rise apartment buildings the complexity of mechanical exhaust systems can vary from minimal (separate in-suite systems) to elaborate (central systems that connect to several or all suites). The in-suite systems usually run intermittently whereas the central systems usually run continuously. Some buildings also use time-clocks to switch off the central systems at night in attempts to conserve energy.

Intermittent exhaust systems such as in-suite kitchen or bathroom exhausts are usually occupant-controlled by a manual or humidistat -activated switch located within the suite. With the manual switch, the exhaust system only runs when the occupants feel there is need for increased ventilation. With the humidistat-activated system, the system runs whenever the humidity in the suite exceeds an occupant controlled set-point. Intermittent exhaust systems within a suite can also include other devices such as clothes dryers vented to outdoors.

Intermittent exhaust systems tend to use small low-pressure fans to exhaust indoor air from the suites through ducts connected to outdoors. Most of these fans are typically rated at a static pressure difference of about 25 to 60 Pa. Stall pressures for some of these devices can be in the range of 30 to 50 Pa (Caneta 1992). The ducts connected to these fans often include several elbows and are long, because the kitchens and washrooms are not usually located near exterior walls. As air flows through these ducts, the static pressure within the duct decreases due to friction and turbulence effects. Designers usually oversize the fans in an attempt to compensate for these pressure losses. However, designers rarely specify static pressure requirements for these systems.

Continuous exhaust systems typically have one or more central "constant volume" fans that are connected by vertical ducts to several or all of the suites within the building. Various other areas of the building such as common kitchens, equipment and service rooms, garbage chutes, and parkades are sometimes also connected to these systems. Often in these systems, branch ducts and exhaust grilles are installed without balancing devices, such as dampers.

All of the suite exhaust systems are intended to provide supplemental ventilation for a suite. As a result, these exhaust systems require that makeup air (primarily outdoor air) enter the suite to replace the exhausted air. The corridor supply air systems are intended to provide some of this makeup air. Designers expect that the remainder of the makeup air will be provided by outdoor air infiltration through exterior walls. Only in exceptional buildings are transfer ducts provided between the corridor and suite or between outdoors and the suite for makeup air. Consequently, makeup airflows are typically dependent on the uncontrolled leakage areas of the corridor wall, suite access door, and exterior walls. They are also dependent to a lesser extent on ceiling, floor, and inter-suite partition wall leakage.

The amount of air exhausted from any particular suite is also dependent on the suite leakage area and on the static pressure regime within and around the suite. By continuity, air can only flow out of the suite if the same amount of air flows into the suite. Small leakage areas will reduce the amount of air that can flow into the suite. This results in a decreased suite static pressure that reduces the exhaust flow from the suite. Suite leakage is not currently specified in the design of exhaust systems and is not controlled once the building is occupied. As a result, there is no control of exhaust flows from suites or of in-suite pressures.

Wray et al. (1998) measured the total exhaust capacity with all exhaust devices operating in the suite in 10 mid and high rise apartment buildings across Canada, and compared the results to design exhaust capacities. Flowrates were measured while each suite was depressurised to 20 Pa. The results are shown in Figure 3.1. They found design specifications for total suite exhaust capacities of the test suites ranged from 48 to 160 L/s per suite with an average of 113 L/s per suite. Based on the total volume of the test suites, these exhaust capacities correspond to suite air exchange rates in the range of 1.22 to 4.91 ach, with an average of 2.88 ach. Typically, the total design exhaust capacities are in the range of 120 to 400% of the total suite exhaust capacities required by ASHRAE Standard 62 and CSA Standard F326.

Measured exhaust capacities were always considerably lower than the design exhaust capacities. The installed capacities of suite exhaust devices were only a small fraction of the exhaust capacities specified by the designers. Measured total exhaust capacities for the test suites ranged from 19 to 54% of the design capacities with an average of 32%.

3.4 Backdraft Dampers

Many air supply and exhaust systems used in mid and high rise residential buildings contain backdraft dampers that different pressure drop characteristics depending on the direction of flow. Individual bathroom, kitchen, dryer, and parkade exhaust systems typically contain backdraft dampers. Other systems that may contain backdraft dampers include elevator and stairway pressurisation fans, and central exhaust and air supply systems.

The Colliver, Murphy, and Sun (1994) database contains two direction effective leakage areas for bathroom, kitchen, and dryer backdraft dampers in low-rise residential buildings, which is shown below in Table 3.12.

Table 3.12 Effective Leakage Areas of Bathroom, Kitchen, and Dryer Vents

	Effective Leakage Area (ELA_4)			
Component	**Units**	**Best Estimate**	**Min**	**Max**
Vents: Bathroom with Damper Closed	cm2/ea	10	2.5	20
Vents: Bathroom with Damper Open	cm2/ea	20	6.1	22
Vents: Dryer With Damper	cm2/ea	3	2.9	7
Vents: Dryer Without Damper	cm2/ea	15	12	34
Vents: Kitchen With Damper Open	cm2/ea	40	14	72
Vents: Kitchen With Damper Closed	cm2/ea	5	1	7
Vents: Kitchen With Tight Gasket	cm2/ea	1		

3.5 Window and Exhaust Fan Use Schedules

Window and exhaust fan use can each have large impacts on airflow in mid and high rise apartment buildings. With increasing air tightness of new and existing buildings, the influence of wind and stack effect on air change are reduced, and user controlled parameters gain a greater influence.

In airflow modelling schedules can be set to open and close windows and turn ventilation fans on and off under predefined schedules. Unfortunately, the diversity of use of occupant controlled windows and exhaust fans can very widely depending on occupant preferences, ventilation and indoor air temperature characteristics of the suite (which depend on the design of the building), sources of indoor moisture, and outside climate conditions - temperature, humidity, and wind speed. Humidity controlled exhaust fan use also varies widely due to the same variables plus the fact that the control set-point is adjustable by the user.

A few studies have looked at user effects on air change in residential buildings. Shapiro-Baruch (1993) investigated bathroom and kitchen exhaust use in multifamily apartment buildings and concluded that when apartment occupants have local control over bathroom and kitchen exhaust, they use them less than one hour per day, if at all.

Kvisgaard and Collet (1990) looked at user influence on air change in 28 residential dwellings and houses in Denmark over a one week time period during which the outdoor air temperature varied between approximately 2.5 to 12.5°C. They concluded that for the 16 naturally ventilated dwellings measured, 67% of total air change was provided by user operation of windows, doors, and exhaust fans. For the remaining 12 mechanically ventilated dwellings, they concluded that 65% of total air change was provided by user operation of windows, doors, and exhaust fans.

3.6 Building Surface Wind Pressure Coefficients

Surface wind pressure coefficients depend on the building height, surrounding terrain and obstacles, location on the building, building geometry and orientation, and on wind direction. Surface pressure coefficients are usually in the range of -0.8 to +0.8 (ASHRAE 1992, 1997). They are generally positive for windward walls and negative on other surfaces. Negative pressures are caused by areas of flow separation. Roofs of slopes less than 30° are usually in a low pressure region, irrespective of wind direction. In airflow modelling, for each leakage opening of interest, wind pressure coefficients must be specified for all wind directions.

Actual surface pressure coefficients for an existing building can be determined by full-scale testing. However, these tests are costly and time-consuming. The coefficients can be more conveniently determined by well-controlled boundary layer studies using a model of the building and its surroundings in a laboratory wind tunnel. For a building that is still in the design stage, the full-scale approach cannot be used. The laboratory modelling approach is also often impractical or uneconomical during design.

As an alternative to full-scale or laboratory testing, surface pressure coefficients can be estimated using results of previous wind tunnel testing research. While the coefficients calculated using equations developed from experiment are not exact, they are useful as an approximation to demonstrate the impact of wind effects on ventilation and infiltration in mid- and high-rise residential buildings.

Numerous articles on wind pressure distribution as input data for infiltration models have been published, as reviewed by Kula and Feustel (1988). Swami and Chandra (1988) have developed a set of equations for calculating wind pressure coefficients based on non-linear regressions of surface pressure coefficient data from various experimental sources. They have presented two equations: one for "low-rise" buildings and one for "high-rise" buildings. Their building type definitions are not conventional and are based on geometry rather than on the number of stories. Specifically, they defined "low-rise" buildings as those with a long- to short-wall ratio (LW/SW) between 1 and 8 and an eave-height to short-wall ratio (EH/SW) between 0.1 and 0.4. "High-rise" buildings have a narrower LW/SW range (between 1 and 4) and a considerably larger EH/SW ratio (between 1 and 8). Many buildings that are conventionally defined by their number of stories as mid-rise or even as high-rise can be represented using Swami and Chandra's "low-rise" equation due to their geometric proportions.

It is important to note that the published coefficients for Swami and Chandra's "high rise" equation are incorrect. The published coefficients did not produce surface pressure coefficients that were symmetrical about the vertical centreline of windward walls for winds that are perpendicular to the wall. The original 14 coefficients have been replaced with 12 new coefficients (Swami 1996). These new coefficients resolved this lack of symmetry problem.

Grosso (1994) carried out a similar regression analysis of wind pressure coefficient data and developed an easy to use software program called CPCALC. Wind pressure coefficients are easily produced for locations on the facade of a building following specification of wind angle, building height, aspect ratio, terrain roughness, plan area density, and roof geometry. While not applicable to all building geometry's, the program applies to rectangular plan buildings with boundary conditions that fall within ranges relating to the Cp data on which the parametrical analysis was based.

3.7 Discussion and Conclusions

A detailed literature review of multi-story apartment building airflow studies was conducted to assemble and interpret component leakage and other data required for airflow modelling. The following conclusions can be drawn from this literature review:

5. The only way to know the air leakage characteristics of an element is to measure it. However, it is impractical to measure all the leakage characteristics of all openings in a building. Instead, air leakage values from measurements of similar components can be used in airflow modelling.

6. A substantial quantity of exterior envelope leakage data is available from the literature. Leakage data is available from measurements from a number of Canadian apartment buildings, high-rise office buildings, and low rise residential buildings. Most of the data is specified for a specific wall construction design. Unfortunately, since most wall construction consists of an air barrier and painted drywall on the inside surface, the airtightness of the wall assembly is dependent on how well the air barrier and interior components are installed. Therefore, the materials used to construct the exterior portion of a wall assembly would not likely have a significant influence on its air leakage characteristics (Shaw, Magee, Rouseau, 1991).

   Good leakage data is available for windows and doors since installed components are commonly tested for air leakage and air leakage rates are specified by building code referral to CSA A440 or ASTM Standards.

7. Good suite access door leakage data is available. Leakage data measured for suite access doors in 10 Canadian mid and high rise apartment buildings is presented along with data for door gap widths. This data provides an excellent basis for estimating suite access door leakage from measured gaps in existing doors, or providing averages if no other data is available.

8. Floor to floor, inter-suite, and interior partition leakage data is very limited. Measured data for leakage areas of these components was found in the literature for only one Canadian apartment building. In another study these leakage areas appear to have been measured for four other Canadian apartment buildings but were not reported. Airflow modelling would greatly benefit from a larger database of leakage data for these components. Better floor to floor leakage data is required to specify leakage between suites, but also between corridors on different floors, and for areas that contain plumbing and electrical risers or other penetrations. Improved inter-suite leakage data that is based on wall construction type is also required.

9. Stairway and elevator shaft leakage data is very limited. The only data available from the literature for stairway and elevator shaft leakage is from a 23 year old study of office buildings. While the shaft wall leakage areas are likely applicable to current apartment construction, the penetrations though these walls (and top of shafts) likely have the greatest effect on leakage could be different in new MURB construction.

10. Stairway and elevator door leakage data is very limited. The only data available from the literature is also from a 23 year old study of office buildings. Leakage areas could be substantially different in new MURB construction.

11. Plumbing and electrical penetration and riser data is very limited. While there is data available in the literature on leakage areas for single plumbing and electrical penetrations, no data is available on the magnitude and distribution of leakage areas caused by multiples of these penetrations in apartment buildings. It would be very useful to have improved data on service penetration leakage areas and their distribution through floors and interior partitions, either for the leakage caused by the penetrations on their own or in combination with average leakage of floors and interior partitions.

12. Backdraft damper data is very limited. A small quantity of data is available for two way leakage though individual suite bathroom, kitchen, and dryer exhaust backdraft dampers. However, large leakage paths exist through other air handling systems that may contain backdraft dampers such as elevator and stairway pressurisation fans, and central exhaust and air supply systems. Measured two direction flow data would be useful for these components.

13. Data is basically non existent for a number of additional parameters that are required for accurate airflow modelling. No underground parking access door leakage data was found in the literature. But of even greater importance is the need for an improved understanding of the prevalence of use of underground parking access

doors. For example, in Vancouver most apartment building underground parking garages have no automobile entry doors, only security gates with very wide airflow openings.

While a large number of apartment buildings have garbage chutes, no data is available on the leakage of garbage chute doors.

Another important flow characteristic that requires improved data is the pressure flow characteristics of fans when not in operation. Corridor ventilation fans and central and local exhaust fans can generally be modelled as equivalent orifice area flow models to represent pressure flow characteristics when not in operation, however the equivalent orifice area must be specified.

Window use and exhaust fan use diversity data is also practically non existent.

14. It would be beneficial to have more whole suite leakage area and distribution data to enable the correlation of estimated component leakage areas to typical values of whole suite leakage and distribution.

4.0 Airflow Modelling of a Canadian High-Rise Apartment Building

4.1 Selection of Test Building

In a previous study carried out by Sheltair Scientific Ltd. for CMHC (Wray et al 1998), detailed suite ventilation field-testing was performed on ten mid and high-rise residential buildings across Canada. The ten buildings ranged in height from 6 to 32 stories, were all built between 1990 and 1995, and were located in Vancouver (4), Winnipeg (3) and Toronto (3).

One of the ten buildings previously studied was chosen for detailed modelling of ventilation and infiltration airflow. The following criteria were used in the selection of the test building:

- ◊ Building use and geometry being representative of the Canadian average,
- ◊ Ventilation system configuration being representative of the Canadian average,
- ◊ Quality of as built architectural and mechanical drawings and specifications for providing airflow modelling input data
- ◊ Quality of field test data for providing airflow modelling input data and correlation of the model.

Using these criteria, several buildings were eliminated because they contained more than one use, such as one or two floors of commercial floor space, were very complicated in geometric design, or were at the upper or lower height boundaries of the buildings studied. While most mid and high rise residential buildings in Canada contain underground parking levels, none of the Manitoba buildings contained underground parking and so were eliminated from selection. All of the ten buildings field tested contained roof mounted corridor supply air systems, however one building had more than one supply shaft and so was eliminated. Seven out of ten test buildings (and 18 out of 25 buildings for which drawings were reviewed in the study) contained separate in-suite intermittent bathroom and kitchen exhaust systems as opposed to common vertical continuous exhaust systems. As a result, a building with separate intermittent in-suite exhaust was chosen.

The end result was the selection of a 10 story apartment building located in Mississauga, Ontario that contains 112 suites, one level of underground parking, and occupied in 1991.

4.2 Description of Test Building

The building selected to be modelled is a public rental housing project, located in Mississauga, Ontario. Plans were issued for construction in November 1989, and the building was occupied in early 1991. The building is a residential high-rise, with ten above-grade floors entirely occupied by suites (with a medium-sized amenity room on the ground floor), and one underground parking level. Suite plans include one, two, and three bedrooms, for a total of 112 suites and a total floor area of 9,170 m². Total building height is 27 m to the top of the 10th floor roof. The building floor plan is essentially square from grade to the roof. Typical floors each have 12 suites, and a total floor area of ~970 m².

The physical geometry, dimensions, and specifications required for airflow modelling were taken from as-built architectural and mechanical drawings that were obtained from the building owner.

Envelope

Exterior walls are primarily brick veneer construction, with 100 mm (4") bricks outside a 25 mm (1") airspace over 25 mm (1") Styrofoam SM insulation over 89 mm (3-1/2") steel studs at 400 mm (16") o.c. with RSI 2.5 (R14) fibreglass batts and a gypsum wall board interior. Wall construction was unusual in that there was a flexible connection to the ceiling above, using a double top channel.

Polyethylene vapour barriers were specified behind exterior drywall, but were not wrapped about floor slab edges; the lower channels were noted to be laid over a continuous bed of caulking. No caulking was called for at the top plate connection. No detailing of utility penetrations was provided, but the vapour barrier was noted to "...extend around all electrical boxes."

Roof construction is a modified inverted type: 38 mm (1.5") precast pavers or gravel ballasts over 102 mm (4") RSI 3.5 (R20) exterior insulation, on a membrane over up to 102 mm (4") of concrete topping over the high density concrete slab. Stipple ceiling finish was applied directly to the underside of the slabs. Concrete floors above the unheated parking garage have a suspended ceiling of a large airspace over 203 mm (8") fibreglass batt insulation on GWB on 13 mm (1/2") metal channels.

Windows are standard residential double-glazed with a thermal spacer and aluminum frames; operable sections were typically 0.30 m x 0.60 m (1 ft x 2 ft) sliders. All suites have double-glazed enclosed balconies accessed through double-glazed aluminum sliding glass doors. Continuous caulking was called for inside and outside, with foam rope as required, in window and door details. No special details or specifications regarding air sealing measures were found to isolate suites from each other. All ground floor entries and exits are through vestibules.

Shafts
Two elevators were installed in a single elevator shaft, with one continuing to a pressurised vestibule in the parking level. The elevator equipment room was at the roof. The building has a garbage shaft running from ground level, with access to every floor and vented at the top. Elevator and garbage shaft walls were of two constructions: one or more walls of concrete, or 200 mm concrete block and one layer of GWB with one layer of GWB facing finished areas. The corridor supply shaft was of 140 mm concrete block with one layer of 13 mm (1/2") GWB; stairwell shaft walls were concrete. Plumbing and the corridor supply shaft also had at least one wall of the latter construction, and other walls of 13 mm (1/2") GWB on steel studs with a 2 hour fire rating. Stairwell shaft walls were concrete. No caulking was called for at floor and ceiling joints of any of the shafts.

An unusual feature of this building was a dedicated exhaust shaft serving electrical closets at every second floor. Wall construction was 200 mm lightweight concrete blocks with 13 mm (1/2") GWB facing finished areas.

Ventilation & Mechanical
The building has one heating-only, gas-fired corridor supply unit (an EEnmar model RB-13-1080) mounted outside on the roof and equipped with a 24 hour timer. The unit provides a total of 4,250 L/s at 298 Pa static pressure, or ~35 L/s per suite. The corridor ventilation the shaft also pressurises the elevator and stair vestibules in the parking level. On the corridor ventilation ducts no balancing dampers are shown, only opposed blade dampers integral with the diffuser. Fire dampers are also shown at the corridor ventilation outlet on each floor. The duct shaft size varies from 800 mm x 500 mm from the roof to the fifth floor, and 500 mm x 300 mm or 200 mm below. It is unknown if there were specific requirements for leakage of ducts or dampers.

Each suite has one bathroom and a kitchen fan rated at 47 L/s and 54 L/s respectively, ducted laterally in ceiling chases to the outdoor walls. The kitchen exhaust duct runs are typically long, reaching up to 12.8 m with four elbows. Neither undercut hallway doors nor transfer grilles into suites are shown on the plans.

The dedicated exhaust shaft from the electrical closets located on alternate floors terminates in an exhaust fan with a rated capacity of 472 L/s at 125 Pa.

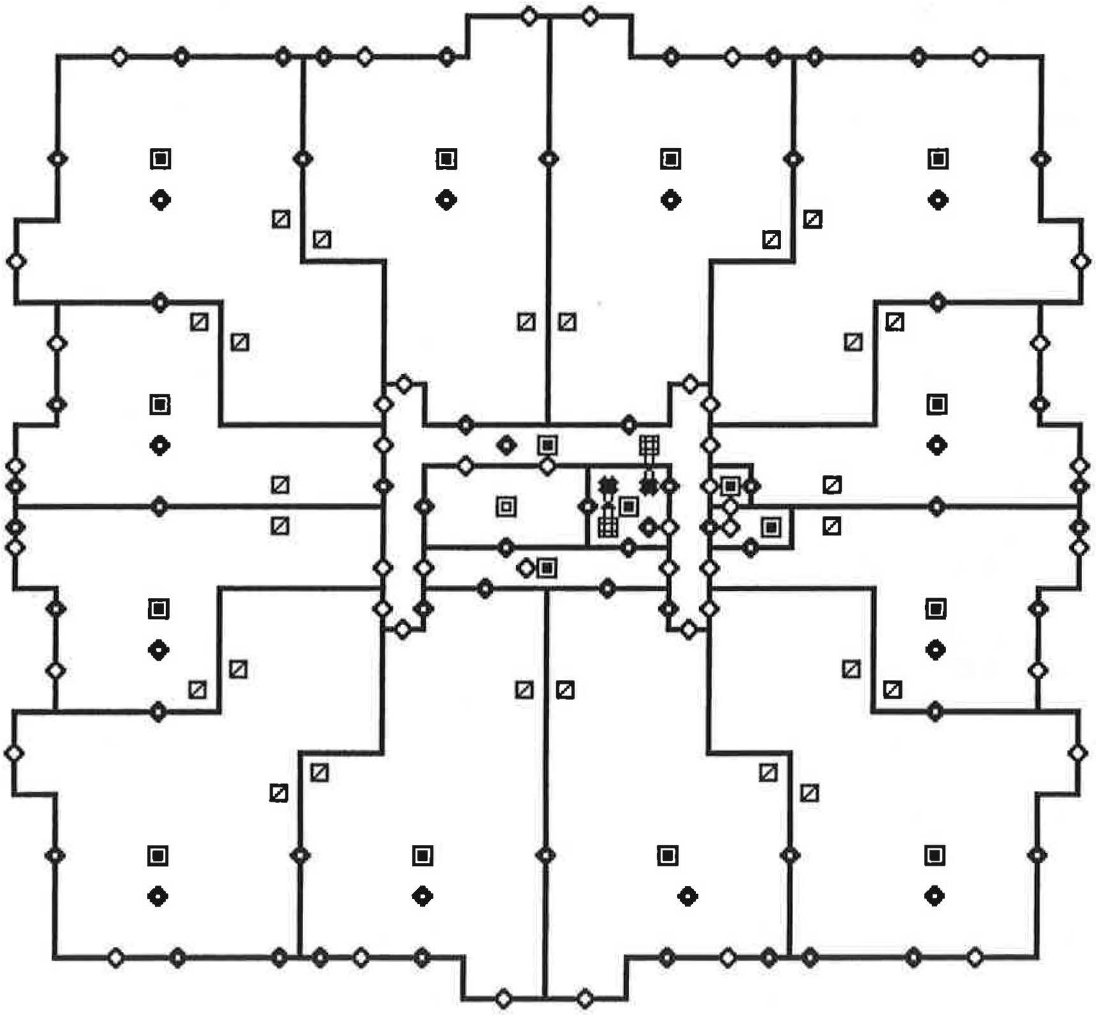
All suites are heated with electric baseboard units. Two atmospherically-vented, gas-fired boilers located in a roof mechanical room provide domestic hot water.

Laundry facilities are located on the second floor, with dedicated exhausts laterally through the wall.

4.3 *Modelling of Test Building Using CONTAM*

A geometric model of the building and its airflow paths was created using the airflow modelling software program CONTAM. Architectural and mechanical drawings were used to create the geometric model of the building and air handling systems. A total of 177 zones were created to represent independent control volumes linked by airflow paths. The layout of zones and airflow path for a typical floor is shown in Figure 4.1.

Figure 4.1 CONTAM Model Zones and Aiflow Paths for Floors 2,4,6,8,10



Each suite is represented by a single control volume zone, as well as the corridor, electrical room (on even floors only), and garbage chute room on each floor. Other single zones consisted of the parking garage, parking level elevator and stair vestibules, first floor common and utility rooms, and roof level mechanical and elevator rooms. The elevator shaft was modelled as a single zone running the height of the building. The stairway shaft was modelled using the Achakji and Tamura (1989) stairway model contained in CONTAM. The garbage shaft was modelled as a shaft with friction losses and garbage chute doors on each floor. Corridor ventilation and electrical room exhaust systems were modelled as duct systems with friction losses, loss coefficients for changes in area, Y's, dampers, and fan pressure flow performance curves. Flow rates were correlated to field measured flow rates (see 3.4) and balanced for equal flow on each floor plus specified flowrates for parking level vestibules and first floor common areas. Suite bathroom and kitchen exhaust systems were modelled as constant flow systems based on the measured flowrates from field tests. Backdraft dampers were modelled for bathroom and kitchen exhaust systems, parking level exhaust fans, and elevator shaft smoke control fans.

The starting point for setting component leakage areas were based on measured leakage areas for the suite access doors, and best estimates of other leakage areas from a comparison of architectural drawing details to data contained in the literature review. Some leakage areas were then modified based on correlation to field test data as discussed in Section 4.4

4.4 Use of Test Building Field Data to Correlate Airflow Model

A number of building airflow characteristics were measured in the field testing of each building in the Wray et al (1998) study. For the airflow modelling test building, airflow and pressure difference measurements were taken within one eighth floor test suite and corridor, and in corridors on other levels of the building. These measurements were used to define the CONTAM airflow model input parameters, to correlate the model against measured performance of air supply and exhaust systems, and to correlate the model against measured pressure difference data taken at specific outdoor weather conditions. The following measurements were utilised from the test data.

1. ***Weather Measurements During Field Testing***
   Continuous wind speed, wind direction, and outdoor temperature measurements were taken from the roof of the building throughout the time of the field testing. These weather conditions were used to model the building at the same static weather conditions as measured during field testing, and allow correlation of the model to field test data.

2. ***Flow versus pressure leakage characteristics of the test suite's access door.***
   The measured equivalent leakage area of the suite to corridor access door in the test suite was found to be 330 cm2. This suite door leakage area was used for all suite access doors in the CONTAM model of the building. Conversion to an effective leakage area was made using a flow exponent of 0.55, resulting in an effective leakage area of 192.6 cm2.

3. ***Corridor supply system airflow rates.***
   Corridor supply system airflow rates were measured on the eighth floor for three different corridor leakage and winter weather combinations - normal night time

operation, normal daytime operation, and with increased leakage between the corridor and outdoors caused by the opening a large airflow path. Measured airflow rates for the floor varied between 144 and 216 L/s. The building was modelled at static weather conditions measured during testing of corridor supply airflow rates. The modelled supply airflow rates were then correlated to measured airflow rates by adjusting loss coefficients of air supply dampers on each floor.

4. ***Airflow rate through test suite exhaust devices.***
   A flow rate of 30 L/s was measured for both exhaust devices running simultaneously against a fixed indoor-outdoor pressure difference of 20 Pa. Combined bathroom and kitchen exhaust systems were modelled as a single constant flow device for each suite using these airflow rates.

5. ***Pressure difference measurements across suite and building leakage components.***
   The following field measurement of pressure differences across components were made with the simultaneous measurement of outdoor weather conditions.

   Pressure difference between:
   - ◊ Interior of test suite and outdoors
   - ◊ Corridor and interior of test suite
   - ◊ Stairway shaft and corridor on four floors
   - ◊ Elevator shaft and corridor on four floors
   - ◊ Garbage shaft and corridor on test suite floor

   These measured pressure differences were then used to correlate leakage areas used in the CONTAM airflow model. The building was modelled under static weather conditions as measured at the time of field tests. Then component leakage areas were adjusted to obtain as close as possible the pressure differences measured in the test suite and corridors. Minor changes were made to a number of leakage areas to improve the correlation between modelled and measured pressure differences. The main modification that had to be made to component leakage areas was an increase in exterior envelope leakage in each suite, to a leakage level that remained below the upper limits of exterior envelope leakage measured by Shaw (1991).

5.0 Ventilation and Infiltration Airflow Modelling and Energy Implication Results

5.1 Ventilation and Infiltration Airflow

Airflow rates through airflow paths in the apartment building were modelled with the corridor ventilation system on and off under varying static and dynamic weather conditions, and with exhaust fans either turned on or off. Windows and doors to the exterior and suite access doors, stairway doors, and other doors between zones were kept closed. Ventilation and infiltration airflow rates between ambient and all zones within the building were examined in order to explore the relationship between ventilation and infiltration outdoor air airflow rates and heating energy consumption. Modelled airflow rates are presented in mass flow units converted to sL/s, which is a volumetric flow of dry air at standard conditions, 1 atmosphere and 20°C.

5.1.1 Ventilation and Infiltration Airflow Under Static Weather Conditions

The quantity of outdoor air entering the building was modelled under a variety of static weather, corridor ventilation fan, and exhaust fan operation conditions. Outdoor air entering the building includes outside air supplied through the corridor ventilation system (in the case of the corridor ventilation fan operating) plus the infiltration of outside air into heated areas of the building. The outside air temperature was varied between 23°C (the constant indoor air temperature assumed for occupied indoor areas) and -40°C. Wind speeds were varied between 0 m/s and 10 m/s (36km/hr). Exhaust fans were either all turned on or all turned off. These exhaust fans included one kitchen and one bathroom exhaust fan in each of the 112 suites plus the exhaust fan for the electrical room ventilation system that exhausts air from the electrical room on every second floor through a vertical ventilation shaft to the roof. Although it is unlikely that all exhaust fans from all units would ever be operating simultaneously, this operating condition shows the boundary of the effect of exhaust fan operation.

Corridor Ventilation Fan On

With the corridor ventilation fan operating, the rate of outdoor air entering the building from both ventilation and infiltration is shown in Figure 5.1. The rate of outdoor air from infiltration alone is shown in Figure 5.2.

As can be seen from Figure 5.1 the quantity of ventilation and infiltration outdoor air entering the building increases with decreasing outdoor air temperature, higher wind speeds, and operation of exhaust fans due to the indoor to outdoor pressure differences caused by stack, wind, and exhaust fan depressurisation effects respectively.

Figure 5.1 Total Ventilation and Infiltration Airflow from Outdoors- Corridor Ventilation Fan On

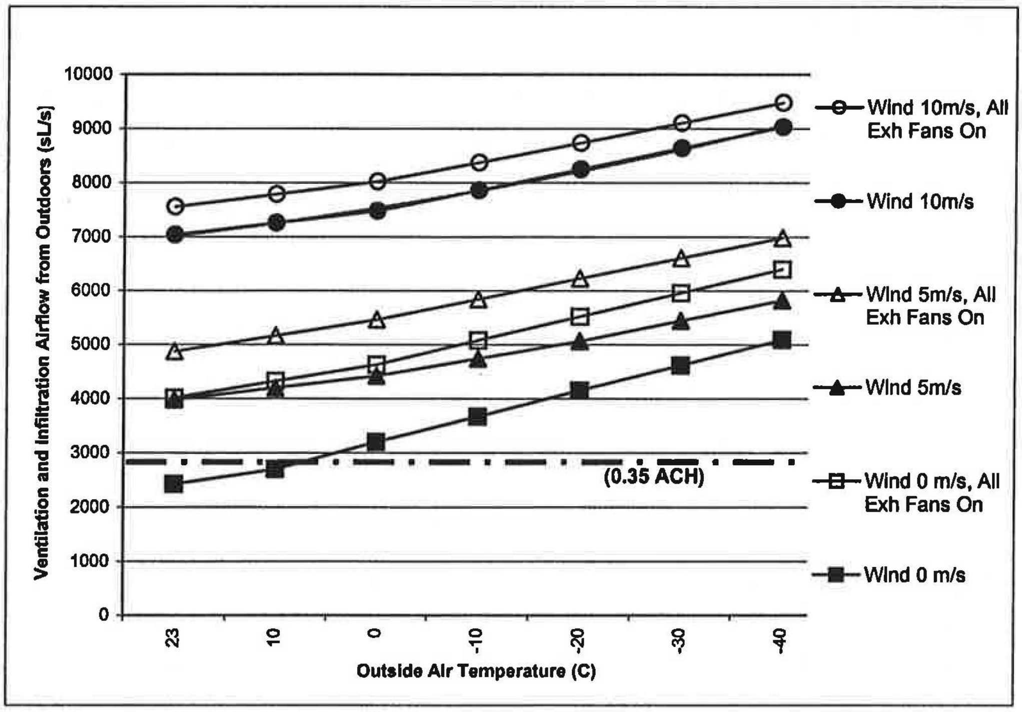
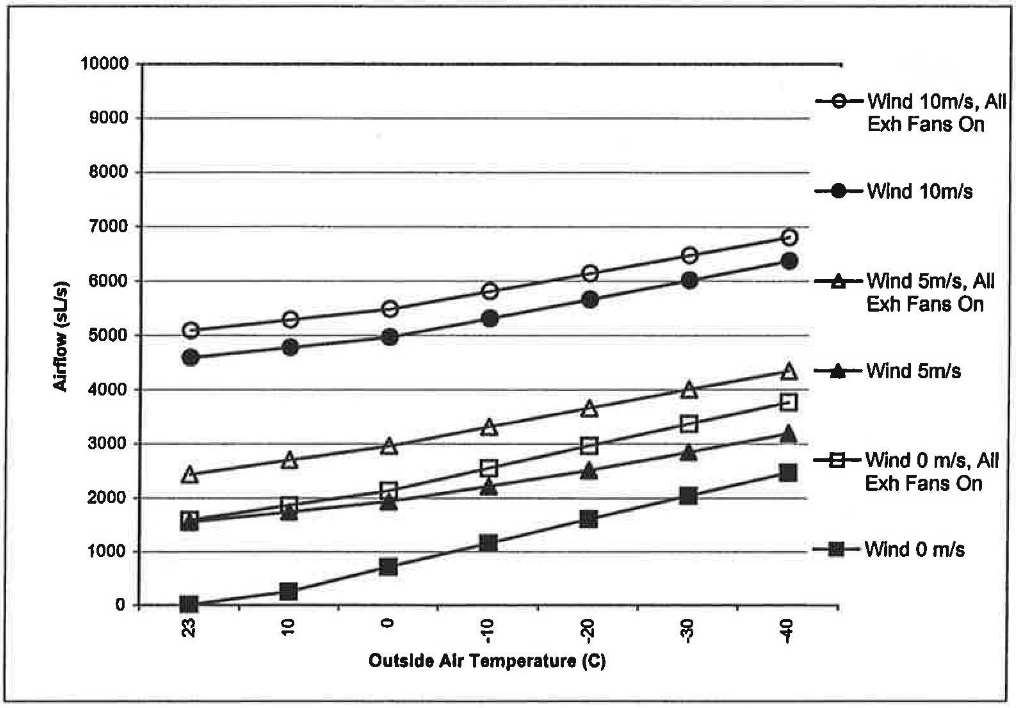


Figure 5.2 Outside Air Infiltration - Corridor Ventilation Fan On



Stack induced pressure differences in isolation, caused by a decrease in the outdoor air temperature from 23°C to -40°C with no wind and no exhaust fans operating, increases the total outdoor airflow into the building by a factor of 2. At higher wind speeds and/or with exhaust fans operating the proportional stack induced effect is reduced.

Wind induced pressure differences in isolation, caused by an increase in wind speed from 0m/s to 10 m/s (36 km/hr) at an outdoor air temperature of 23°C with no exhaust fan operation, increases the total outdoor airflow into the building by a factor of 2.9. The proportion effect of wind induced pressure differences is less for lower air temperatures and other exhaust fan operating conditions.

Depressurisation of the building caused by the operation of all exhaust fans operating simultaneously has the effect of increasing outdoor airflow into the building by a factor of 1.7 at an outdoor air temperature of 23°C with no wind, and less for lower air temperatures and higher wind conditions.

As can also be seen from Figure 5.1, the total quantity of outdoor air entering the building on a whole building basis is less than the 0.35 air changes per hour (ACH) minimum outdoor air requirements of ASHRAE Standard 62 when no stack or wind pressure induced pressure differences exist (23°C and no wind) and no exhaust fans are operating. Once the outside air temperature falls below about 10°C, or with any of the modelled wind speed and/or exhaust fan operation conditions, this minimum outdoor air requirement is exceeded.

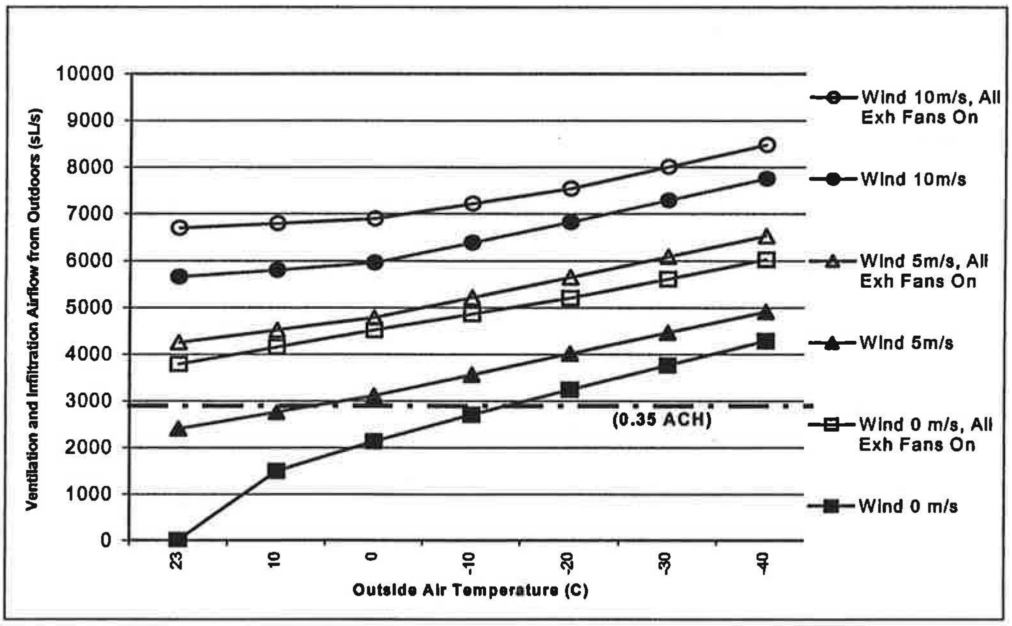
A comparison to the whole building air change rate of 0.35 ACH is made to provide a basis for comparison of the relative magnitude of outside air entering the building under a variety of operating conditions, in order to illustrate the effect of ventilation and infiltration airflow on energy consumption. However, a whole building air change rate of 0.35 ACH does not suggest that all individual suites are adequately ventilated. Depending on stack and wind induced pressure differences and the side of the building and the height above ground, the suite may be under ventilated or over ventilated.

Corridor Ventilation Fan Off

With the corridor ventilation fan turned off, the quantity of infiltration outdoor air entering the building is shown in Figure 5.3.

The rate of outdoor air entering the building on a whole building basis is now less than 0.35 ACH under a wider range of operating conditions than with the corridor ventilation fan on. The rate of outside air entering the building is less than 0.35 ACH for outdoor air temperatures above approximately -10°C with no wind and no exhaust fans operating, and for outdoor air temperatures above approximately 10°C with a 5m/s wind.

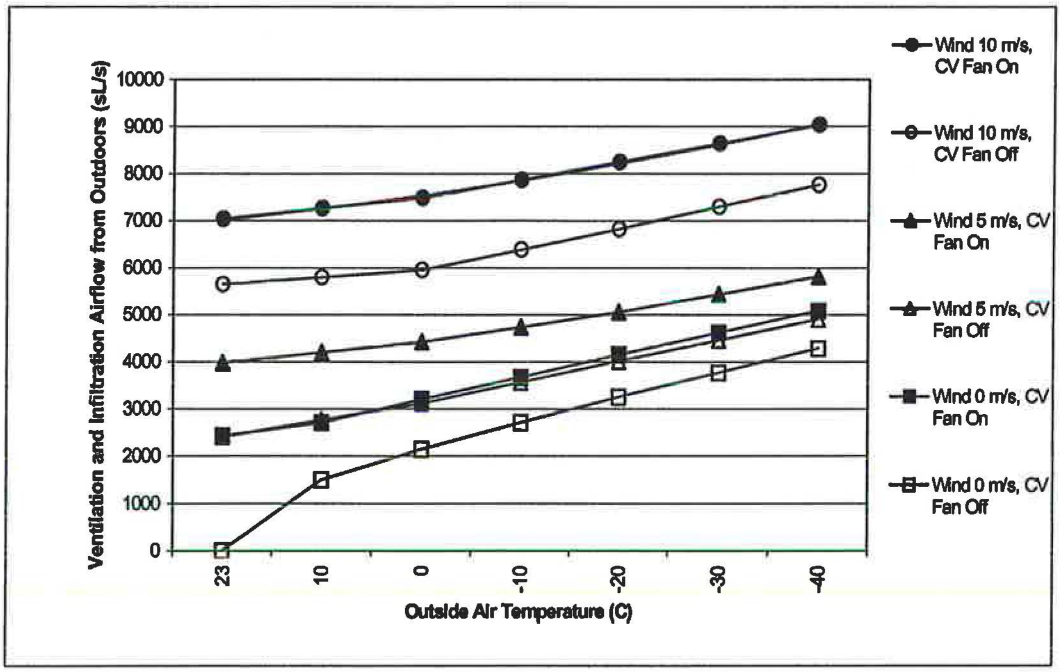
Figure 5.3 Infiltration Airflow from Outdoors- Corridor Ventilation Fan Off



A comparison of infiltration airflow with the corridor ventilation fan on (Figure 5.2) and off (Figure 5.3) shows that the operation of the corridor ventilation fans reduces infiltration airflow by from 20% to 83%. Operation of corridor ventilation fan pressurizes the building and reduces the quantity of infiltration airflow and resulting infiltration heating load. The greatest effect on reducing infiltration heating load occurs when stack, wind, and exhaust depressurization effects are lowest. At an outdoor air temperature of 10°C with no wind or exhaust fans, operation of the corridor ventilation fan reduces infiltration airflow by 83%. As stack, wind, and exhaust depressurization effects increase, infiltration airflow increases, and the percentage reduction in infiltration caused by corridor supply air pressurization correspondingly decreases. At an outdoor air temperature of -40°C with a 10 m/s wind and all exhaust fans on, operation of the corridor ventilation fan only reduces infiltration airflow by 20%.

However, under all conditions modelled the total quantity of ventilation and infiltration outdoor air entering the building is much lower with the corridor ventilation fan off than when turned on. A comparison of total outdoor airflow into the building with the corridor ventilation fan on and off under a variety of weather conditions is shown in Figure 5.4 (with no exhaust fans operating).

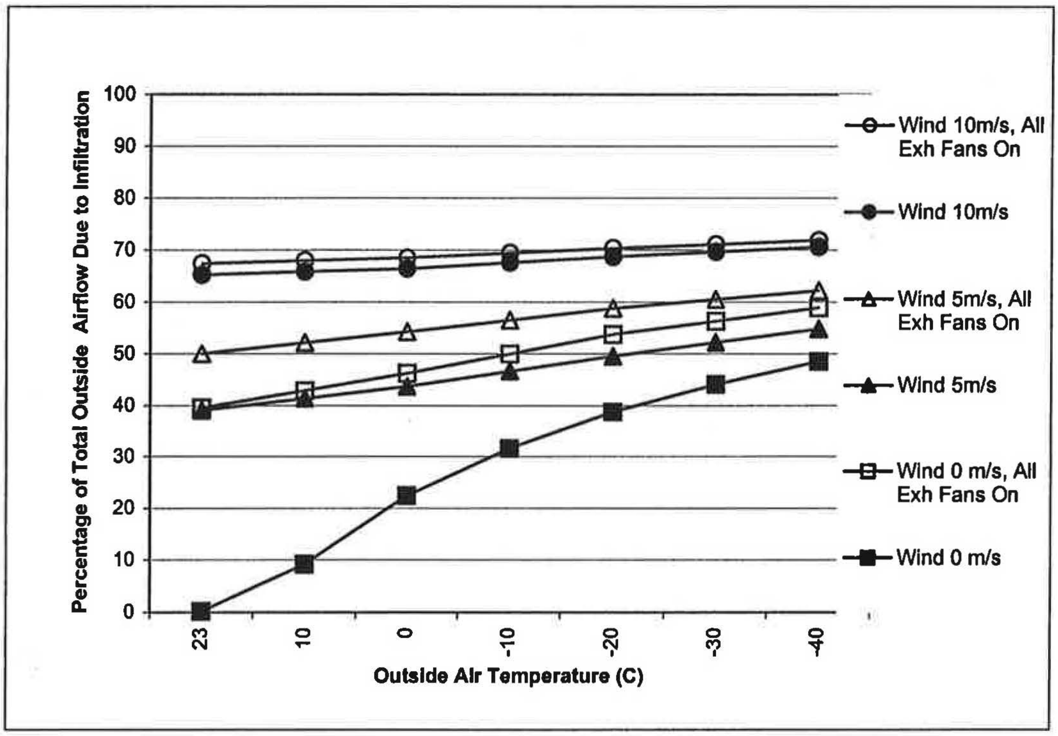
Figure 5.4 Total Outside Airflow Into Building - Corridor Ventilation Fan On Versus Off



Comparison of Infiltration Airflow to Ventilation Airflow

With the corridor ventilation fan turned on, the contribution of infiltration to the total of outside air entering the building is shown in Figure 5.5. As shown, the contribution of infiltration to total outdoor air entering the building varies between 0% (@ 23°C, no wind, and no exhaust fans) and 72% (@-40°C, 10m/s wind, and exhaust fans on).

Figure 5.5 - Percentage of Outside Air Due To Infiltration - Corridor Ventilation Fan On



Stack induced pressure differences in isolation of wind and exhaust fan effects increase the contribution of infiltration to 50% of total outdoor airflow with an outdoor air temperature of minus 40°C. Wind induced pressure differences alone increase the contribution of infiltration to 65% of total outside airflow at wind speeds of 10m/s. Operation of exhaust fans with no wind or stack induced effects increases the contribution of infiltration to 40% of total outside airflow.

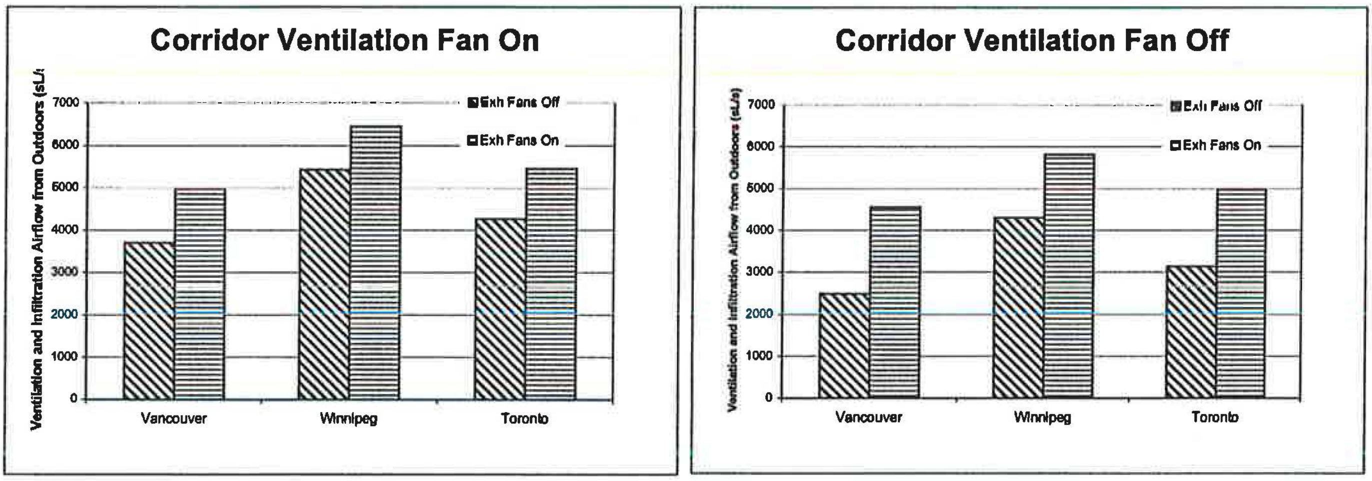
When the corridor ventilation fan is turned off, infiltration obviously contributes 100% of outdoor airflow.

5.1.2 Ventilation and Infiltration Airflow Under Dynamic Weather Conditions

Multizone airflow modelling for the same apartment building was also performed to illustrate the effect of ventilation and infiltration on energy consumption during a month of typical winter weather in the cities of Vancouver, Winnipeg, and Toronto. Weather data used for each city was typical weather for the month of January in Canadian Weather for Energy Calculations (CWEC) format, which is based on the ASHRAE defined WYEC2 format and has been adopted by the National Research Institute of Canada for the creation of Canadian weather files for energy calculations.

Figure 5.6 below shows the January average rate of total airflow from outdoors into the building for the three cities, with the corridor ventilation fan on and off, and with all exhaust fans on or off.

Figure 5.6 January Average Ventilation and Infiltration Airflow From Outdoors - Corridor Vent Fan On and Off

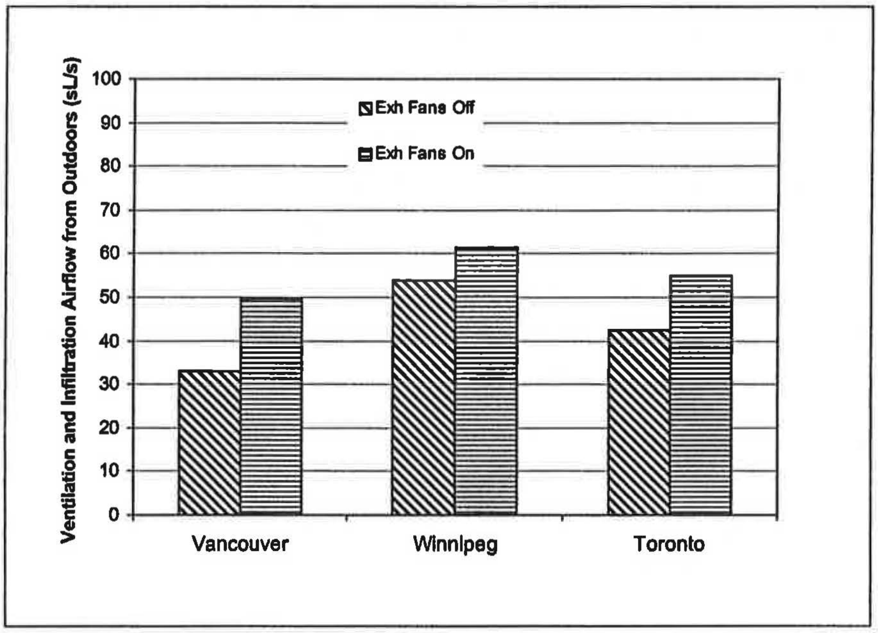


The contribution of infiltration to the January average flowrate of outdoor air into the building with the corridor ventilation fan on is shown in Figure 5.7.

As shown, the contribution of infiltration varies greatly between cities due to differences in outdoor air temperatures and wind speeds. Infiltration airflows account for the following percentages of average total outdoor airflow during the month of January for each city:

	Average January Contribution of Infiltration to Total Outdoor Airflow Into Building	
City	**All Exhaust Fans Off**	**All Exhaust Fans On**
Vancouver	33%	50%
Winnipeg	54%	62%
Toronto	42%	55%

Figure 5.7 January Average Percentage of Outside Air Due To Infiltration - Corridor Ventilation Fan On



5.2 *Ventilation and Infiltration Energy*

Outside air entering the building must be heated or cooled to the indoor air temperature (sensible heating or cooling load), and humidification or dehumidification of outside air may also be required (latent heating or cooling load). In mid and high rise apartment buildings in Canada, heating of ventilation and infiltration air contributes a significant portion of annual energy usage.

As an example, a study of high rise apartment buildings in Ontario identified the magnitude of ventilation and infiltration heating load in four buildings (Scanada, 1991). Based on energy audits of four electrically heated high rise apartment buildings they found that:

- Ventilation and infiltration together contributed an average of 23% to total annual energy use and 33% to total peak energy (electrical) load.
- Considering space heating energy alone, ventilation and infiltration together contributed an average of 45% to annual space heating energy consumption and 54% to peak space heating load (where peak load was based on ambient temperatures below -18°C and wind speed greater than 5 m/s).
- Air leakage due to infiltration contributed 71% of total ventilation and infiltration energy on an annual consumption basis.
- Air leakage due to infiltration contributed 67% of total ventilation and infiltration energy load on a peak consumption basis. The peak infiltration heating demand in the four buildings ranged from 12 to 25 W/m2.

5.2.1 *Ventilation and Infiltration Energy Under Static Weather Conditions*

For the apartment building modelled in this study, the heating load due to outdoor ventilation and infiltration airflow into the apartment building was calculated for a range of weather and exhaust fan operating conditions. The resulting ventilation and infiltration heating load with the corridor ventilation fan either on or off is shown in Figures 5.1 and 5.2 respectively. Heating loads shown are sensible heating loads only, assuming no humidification of outdoor air.

Considering an outdoor temperature of -18°C and with a wind speed of 5 m/s, the heating demand due to ventilation and infiltration is as follows:

	Heating Demand (W/m2)		
	Ventilation	Infiltration	Total
All Exhaust Fans On	13	19	32
All Exhaust Fans Off	13	13	26

The range of infiltration peak heating energy load for the modelled building (13 to 19 /m2) falls within the range of results from the four buildings audited in the Scanada (1991) study.

Assuming the same peak space heating load (41 W/m2) as the average of the four audited buildings in the Scanada study results in a contribution of ventilation and infiltration of 63 to 78% of peak space heating load.

As can be seen from a comparison of Figure 5.8 and Figure 5.9, the energy used to heat ventilation and infiltration outdoor air entering the building is lower with the corridor ventilation fan turned off under all conditions. The magnitude of the energy reduction under example extreme weather and building operation conditions is illustrated below.

With stack induced pressure differences caused by an outdoor air temperature of minus 40°C, in isolation of wind and exhaust fan operation effects, the energy required to heat outdoor air is 16% lower with the corridor ventilation fan off.

With wind and stack induced pressure differences caused by a wind speed of 10 m/s (36 km/hr) and an outdoor air temperature of minus 40, the energy required to heat outdoor air is 14% lower with the corridor ventilation fan off.

With depressurisation of the building caused by the operation of all exhaust fans operating simultaneously, plus wind and stack induced pressure differences (10 m/s wind and minus 40°C), the energy required to heat outdoor air is 6% lower with the corridor ventilation fan off.

Figure 5.8 Ventilation and Infiltration Heating Load - Corridor Ventilation Fan On

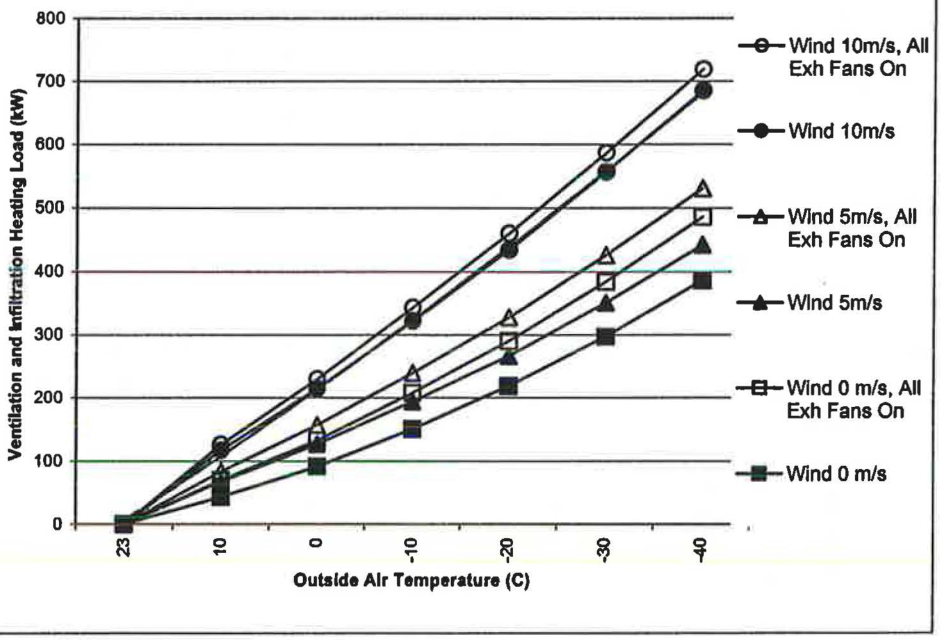
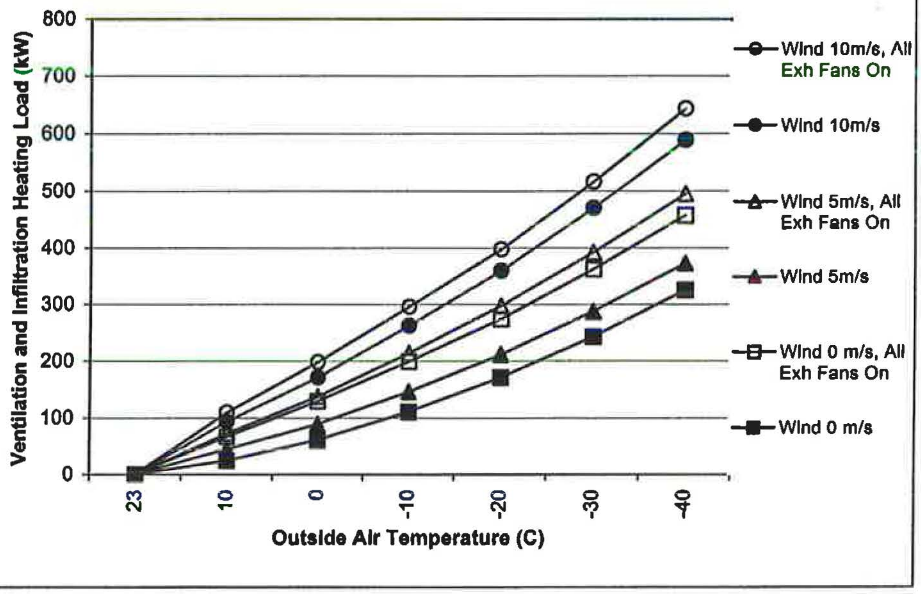


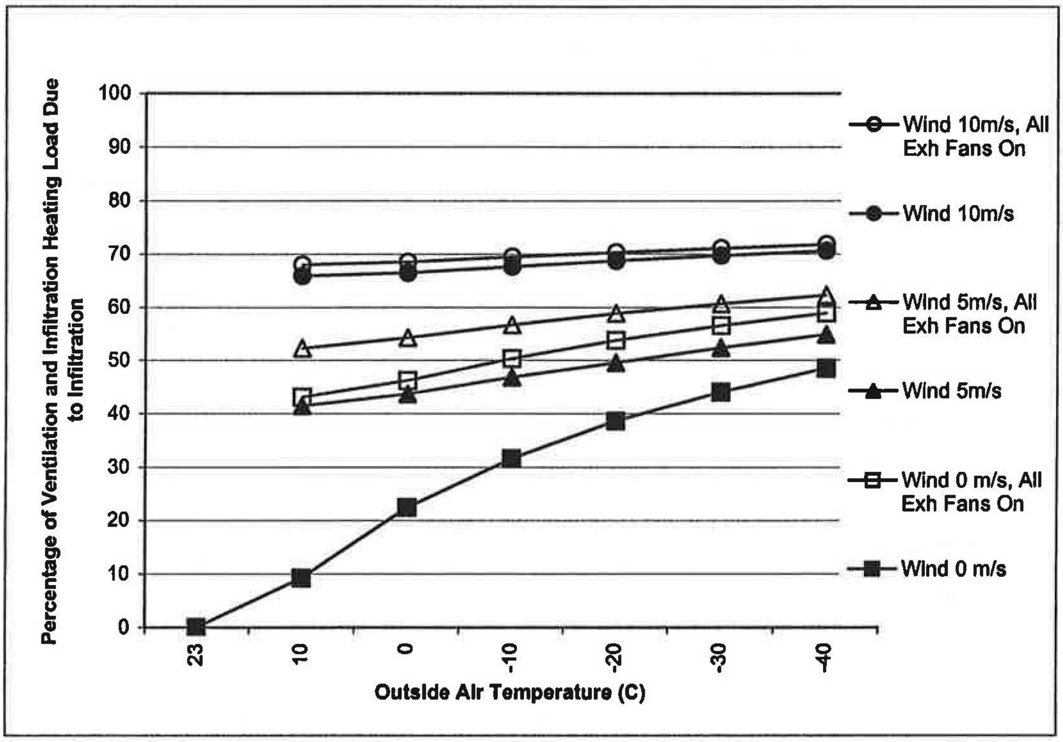
Figure 5.9 Infiltration Heating Load - Corridor Ventilation Fan Off



Comparison of Infiltration Energy to Ventilation Energy

During normal operation of the building with the corridor ventilation fan turned on, the contribution of infiltration to the total ventilation and infiltration heating load is shown in Figure 5.10. The contribution of infiltration to total ventilation and infiltration heating load varies between 0% (@ 23°C, no wind, and no exhaust fans) and 72% (@-40°C, 10m/s wind, and exhaust fans on). During the winter heating season it can be seen that infiltration contributes anywhere from approximately 20% to 70% of ventilation and infiltration heating demand.

Figure 5.10 Contribution of Infiltration to Total Ventilation and Infiltration Heating Load - Corridor Ventilation Fan On



Stack induced pressure differences alone increase the contribution of infiltration to as much as 50% of total outdoor airflow heating load at an outdoor air temperature of minus 40°C. Wind induced pressure differences in combination with stack induced pressure differences increase the contribution of infiltration to 70% of total outside airflow heating load (at wind speeds of 10m/s and an outdoor air temperature of minus 40°C). Operation of exhaust fans in addition to stack and wind effects increases the contribution of infiltration to 72% of total outside airflow heating load.

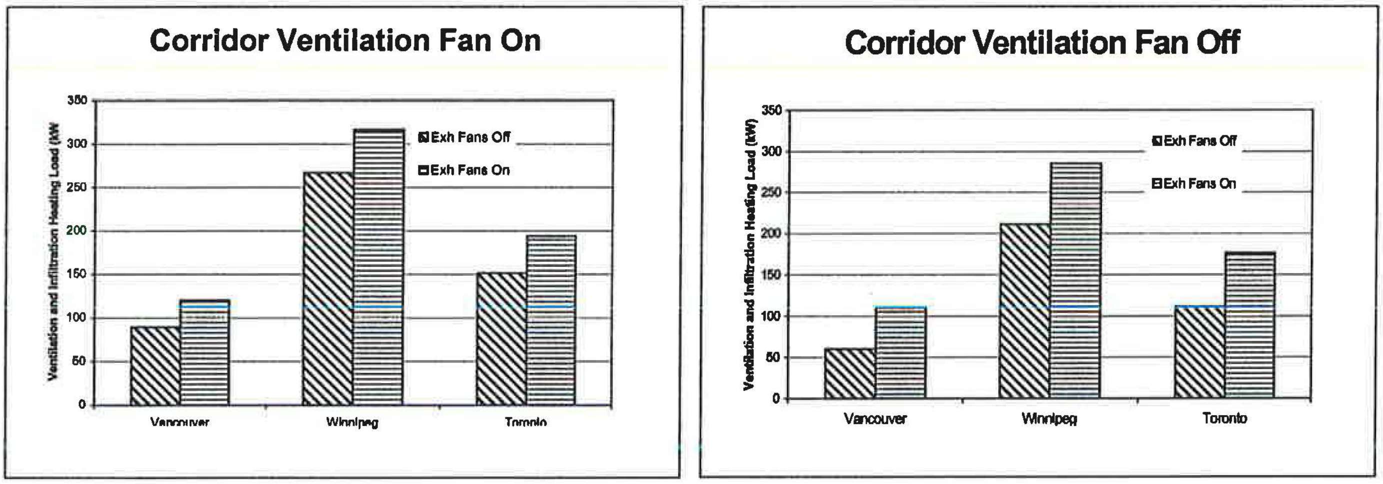
The modelled results compare favourably to those of the Scanada (1991) study mentioned previously. At outdoor air temperatures of below -18°C and with wind speeds of 5 m/s or greater, the modelled building shows a the contribution of infiltration to the total of ventilation and infiltration heating demand of between 50% and 72% depending on modelled weather conditions and operation of exhaust fans. This compares to an average of 67% for the four buildings audited in the Scanada study.

5.2.2 Ventilation and Infiltration Energy Under Dynamic Weather Conditions

The energy consumption required for heating outdoor ventilation and infiltration airflow was calculated for the base case building simulated using typical January weather data for the cities of Vancouver, Winnipeg, and Toronto.

Figure 5.11 below shows the January average outdoor air heating load for the cities of Vancouver, Winnipeg, and Toronto with the corridor ventilation fan either on or off, and with all exhaust fans on or off.

Figure 5.11January Average Ventilation and Infiltration Heating Load - Corridor Vent Fan On

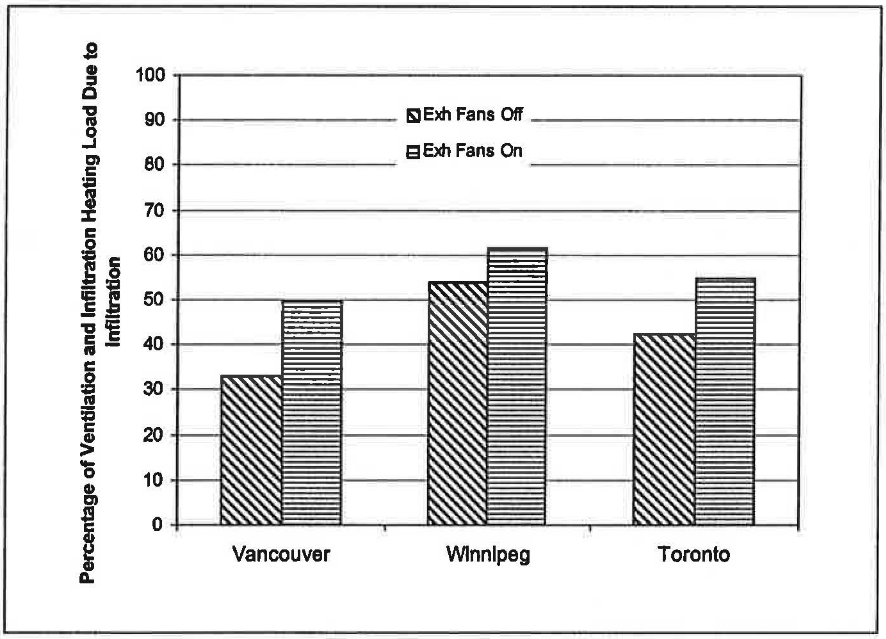


The average contribution of infiltration to the total outdoor air heating load during the month of January with the corridor ventilation fan on is shown in Figure 5.12.

As shown, the infiltration energy contribution varies greatly between cities due to differences in outdoor air temperatures and wind speeds. Infiltration accounts for the following average percentages of total outdoor air heating load for each city during the month of January:

	Average January Contribution of Infiltration to Total Outdoor Airflow Heating Load	
City	**All Exhaust Fans Off**	**All Exhaust Fans On**
Vancouver	33%	50%
Winnipeg	54%	62%
Toronto	42%	55%

Figure 5.12 January Average Contribution of Infiltration to Total Outdoor Airflow Heating Load - Corridor Ventilation Fan On



5.3 Discussion and Conclusions

The following conclusions can be drawn from results of modelling of ventilation and infiltration airlfow and energy consumption in the Mississauga 10 storey high-rise apartment building:

1. **With corridor ventilation fans on, the infiltration contribution to total ventilation and infiltration heating load varied between 0 and 72%.**
   With no wind, stack, or exhaust fan depressurization effects on the building, all outside air entering the building is provided through the corridor ventilation system. As wind, stack, and exhaust fan depressurization effects are increased, the contribution of infiltration increases to as much as 72% of the building's total ventilation and infiltration heating load under the static conditions modelled in this study.

   Under outdoor conditions representative of typical January weather in the cities of Vancouver, Winnipeg, and Toronto, the average contribution of infiltration to total outdoor airflow heating load (with corridor ventilation fans on) was found to be 33%, 54% and 42% respectively with no suite exhaust fans operating. With the operation of all exhaust fans, these contributions increased to 50%, 62% and 55% respectively.

2. **Operation of corridor ventilation fans reduces infiltration airflow by from 20% to 83%.**
   Operation of corridor ventilation fans pressurizes the building and reduces the quantity of infiltration airflow and resulting infiltration heating load. The greatest effect on reducing infiltration heating load (83%) occurs when stack, wind, and exhaust depressurization effects are lowest. As stack, wind, and exhaust depressurization effects increase, infiltration airflow increases, and the percentage reduction in infiltration caused by corridor supply air pressurization correspondingly decreases (20% reduction at -40°C, 10m/s wind and all exhaust fans on).

3. **Shutting off the corridor ventilation fan at -15°C reduces total ventilation and infiltration heating load by 5% to 24%.**
   It is common practice among some MURB building operators to turn off the corridor air systems when the outdoor temperature falls below a set point such as -15C. If the corridor ventilation fan was shut off once the outdoor air temperature reached -15°C in the building modelled, total outdoor air heating load energy savings of between 5% and 24% could be achieved. The greater end of the range of savings would be achieved with no wind and no exhaust fans operating, the lower end with higher wind speeds and exhaust fan operation. At decreasing outdoor air temperatures the savings decrease as a percentage of total ventilation and infiltration heating load due to increasing infiltration airflow rates. However, the absolute energy savings from turning off the corridor ventilation system increase with decreasing temp.

4. **Infiltration airflow rates into the building can produce very high whole building airchange rates, but not necessarily adequate indoor air quality in individual suites.**
With the corridor ventilation fan on and no stack, wind, or exhaust fans (no infiltration) the whole building air change rate is approximately 0.3 ACH which is less than the ASHRAE 62 Standard minimum of 0.35 ACH. At the extreme end of stack, wind, and exhaust fan operation conditions modelled the whole building air change rate increases to 0.93 ACH.

In comparison, with the corridor ventilation fan off the whole building air change rate varies between 0 ACH with no wind, stack, and exhaust fan effects and 0.83 ACH at the extreme end. At temperatures below approximately -10°C, stack effect alone produces a whole building air change rate greater than 0.35 ACH.

What these results indicate is that during winter weather conditions with all windows closed, much higher rates of infiltration are being induced by stack, wind, and exhaust fan operation effects than are required to meet minimum outdoor air requirements for adequate indoor air quality. These higher than necessary infiltration rates are wasteful of energy.

These results also indicate that, at certain conditions, turning off corridor ventilation fans can result in reduced energy consumption while whole building air change rates remain above 0.35 ACH. However, even with high rates of air change on a whole building basis, and whether the corridor ventilation fan is operating or not, individual suites in the building may be inadequately ventilated.

Previous studies have shown that ventilation to individual mid and high rise apartment building suites varies widely, with inadequate ventilation rates commonly found.

Diamond, Feustal, and Dickerhoff (1996) performed airflow measurements and carried out airflow modelling simulations on a 13 story apartment building located in Massachusetts. They found that without the corridor air supply system operating and with no wind, suites at the lower level of the building receive adequate ventilation only on days with high indoor to outdoor temperature differences, while units on higher floors receive no outdoor air ventilation under all indoor to outdoor temperature differences. Units facing the windward side were found to be over-ventilated when the building experiences wind induced pressure effects. At the same time, leeward apartments do not receive any outdoor air because outdoor air enters suites from the corridor and exits through exhaust shafts and leakage paths in the building facade.

With the mechanical ventilation system operating, they found slightly higher rates of outdoor airflow into apartments, but similar effects of inadequate outdoor air supply to individual suites. While the corridor ventilation system is designed to provide outdoor air to suites, they found the direction of airflow between suites and the corridor to vary widely depending on location and outdoor conditions.

The conclusion that is drawn from this is that current designs for ventilation systems in mid and high rise apartment buildings do not work well for either ensuring adequate indoor air quality or reducing energy consumption attributable to infiltration airflow. Shutting off corridor ventilation systems at low outdoor air temperatures can save energy, but at the risk of reducing already hit and miss indoor air quality in individual suites.

5. **Modelled results of the contribution of infiltration to heating loads compare favourably to measured results from energy audits of high rise apartment buildings.**
   The peak infiltration heating demand (based on winter conditions of -18°C and 5 m/s wind velocity) of the modelled building was found to be 13 W/m2 and 19 W/m2 with all exhaust fans off and on respectively. This compares to a range of peak infiltration heating demand (under similar outdoor conditions) of 12 to 25 W/m2 found in four audited Ontario high-rise apartment buildings (Scanada 1991).

   In the modelled building, the contribution of infiltration to peak ventilation and infiltration heating loads was found to vary between 50% and 72% depending on modelled weather conditions and operation of exhaust fans. This compares to an average of 67% for the four buildings audited in the same Scanada study.

6. **Airflow modelling is a valuable tool for improving apartment building performance.**
   This study, as well as previous apartment building airflow modelling studies, have shown that airflow modelling is a valuable tool for understanding how energy performance and indoor air quality are related to ventilation and infiltration and for developing building designs that improve building performance.

   It has been suggested in previous studies that to improve indoor air quality within individual suites in mid and high-rise apartment buildings, ventilation air should be supplied directly to each apartment at a high enough pressure to overcome natural driving forces, and suites should be uncoupled from the rest of the building by tight corridor to suite doors. This design would also significantly reduce infiltration energy. However, air leakage through the building envelope would have to be reduced to avoid moisture problems, and improved continuous exhaust ventilation systems would be required to avoid the unnecessary use of energy. Airflow modelling is an excellent tool for investigating this or other types of improved design for these buildings by allowing the balance between improved indoor air quality and improved energy performance to be fine tuned, and then for developing improved building design concepts and specifications.

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