VENTILATION IN 2 OR 3 UNIT MULTI-FAMILY BUILDINGS BEFORE AND AFTER WEATHERIZATION

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Final Report

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ABSTRACT

This study investigates the fresh air distribution in 2 or 3-unit multifamily buildings before and after weatherization and evaluates the effectiveness of exhaust-only ventilation in providing the minimum recommended fresh air flows to dwellings in such buildings. Low-rise multifamily buildings often have no mechanical ventilation system and rely on the air leakage through the exterior envelope to provide outdoor air to occupants. Weatherization of the roof space, a common energy conservation measure applied to 2 or 3-unit multifamily buildings (also known as Duplex or Triplex) in Quebec can greatly reduce the equivalent leakage area of the exterior shell and change the location of the neutral pressure plane. Consequently, this has a major impact on the outdoor air supply to the building and how it is distributed on a unit-per-unit basis. Field test data characterizing the shell leakage and inter-zonal leakage of a case study building was used to define various pre- and post-weatherization airflow models. Airflow models were introduced in CONTAM, a software developed by the National Institute of Standards and Technology (NIST), to determine the air change profiles (fresh air change & total air change) for the individual dwellings. The results of simulations presented herein shed light on the most popular mechanical ventilation strategy used in weatherized low-rise multifamily buildings.

EXECUTIVE SUMMARY

Older multifamily buildings offer a great opportunity for energy savings because they are poorly insulated and are not airtight. These buildings often have no mechanical ventilation system and rely on the air leakage through the exterior envelope to provide an adequate supply of outdoor air. Sealing measures can greatly reduce the equivalent leakage area of the exterior shell and change the location of the neutral pressure plane. This has a major impact on the outdoor air supply and how it is distributed on a unit-per-unit basis.

This study investigates the outdoor air supply of a 2-unit multifamily building before and after weatherization and evaluates the effectiveness of exhaust only ventilation in weatherized buildings. Air flow was simulated with CONTAM, a software developed by the National Institute of Standards and Technology (NIST) and the case study building is typical of the buildings targeted by recent weatherization programs performed in Quebec.

The results show that outdoor air supply due to infiltration depends on the location of the unit and its degree of connectivity with the adjacent unit. For buildings whose units are relatively well connected to each other, the results show that the fresh air change rate of the top unit due to infiltration is negligible prior to weatherization and that weatherization of the roof space significantly reduces inter-zonal leakage. The results also showed that exhaust fans are ineffective in increasing outdoor air supply to the top unit of such buildings. Possible solutions include the installation of a balanced mechanical ventilation system or performing sealing works to increase the airtightness between the units. For buildings whose units are relatively isolated from one another, the results showed that exhaust-only ventilation is an effective means of providing outdoor air, especially during mild outdoor temperatures.

The findings presented herein contribute to our knowledge of ventilation issues with respect to a segment of the existing building stock which is most likely to be targeted for energy retrofits and weatherization programs in the near future. The results also shed light on the effectiveness of exhaust only ventilation as a means to increase fresh air supply to occupants.

Determining the ventilation needs of multifamily buildings, regardless of weatherization, is a complex task. Within the scope of a weatherization program, it is important to establish an airtightness testing method which quantifies both the shell and inter-zonal leakage and to adopt a computer program which can simulate the fresh air distribution for a given design day or hourly weather profile.

RÉSUMÉ

Les collectifs d'habitation âgés offrent d'excellentes occasions d'économiser l'énergie parce qu'ils sont mal isolés et peu étanches à l'air. Ces collectifs sont souvent dépourvus de ventilation mécanique et doivent compter sur les infiltrations d'air à travers leur enveloppe pour fournir aux logements un volume approprié d'air extérieur. Les mesures d'étanchéisation peuvent réduire considérablement la surface de fuite équivalente de l'enveloppe et déplacer la zone de pression neutre. Cette opération a un effet important sur l'apport d'air extérieur et sur sa diffusion d'un logement à l'autre.

Cette étude porte sur l'apport d'air extérieur mesuré dans un duplex avant et après son intempérisation. On y évalue également l'efficacité de la ventilation dans les bâtiments intempérisés uniquement dotés de dispositifs d'extraction. Les mouvements d'air ont été simulés avec CONTAM, un logiciel mis au point par le National Institute of Standards and Technology (NIST), le bâtiment étudié étant représentatif des collectifs ciblés par les récents programmes d'intempérisation mis sur pied au Québec.

Les résultats obtenus révèlent que l'apport d'air extérieur par infiltration est tributaire de l'emplacement du logement et de son degré de liaison avec le logement voisin. Pour les bâtiments dont les logements sont étroitement liés, l'étude montre que le taux de renouvellement de l'air frais du logement supérieur causé par les infiltrations d'air est négligeable avant l'intempérisation et que l'intempérisation du vide sous toit réduit considérablement les fuites interzones. Les résultats permettent également de conclure que les ventilateurs d'extraction n'arrivent pas à augmenter l'apport d'air extérieur au logement supérieur de ces bâtiments. Parmi les solutions envisagées, on mentionne la pose d'un dispositif de ventilation mécanique équilibrée ou la réalisation de travaux de scellement visant à prévenir la circulation d'air entre les logements. Dans le cas des bâtiments dont les logements sont relativement isolés l'un de l'autre, les résultats montrent que la ventilation réalisée uniquement par extraction d'air est un moyen efficace de fournir de l'air extérieur, surtout lorsque le temps est clément.

Les résultats présentés dans ce rapport améliorent nos connaissances sur la ventilation de bâtiments qui feront fort probablement l'objet de rénovations éconergétiques dans un proche avenir. Ces résultats mettent aussi en lumière l'efficacité des installations d'extraction d'air comme moyen d'accroître l'apport d'air frais pour les occupants.

Il est difficile de déterminer les besoins de ventilation des collectifs d'habitation, quel que soit leur état d'intempérisation. Dans le contexte d'un programme d'intempérisation, il importe d'établir une méthode de détermination de l'étanchéité à l'air qui puisse quantifier à la fois les fuites qui surviennent dans l'enveloppe et les fuites interzones, et de recourir à un logiciel capable de simuler la diffusion d'air extérieur pour une journée standard donnée ou un profil climatique horaire.

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1. INTRODUCTION

Low-rise, 2 or 3 unit multi-family buildings built prior to 1970 typically have no mechanical ventilation system. These buildings are leaky and fresh air requirements are usually satisfied through infiltration across the building envelope. In many buildings, the leakage area is concentrated at the ceiling/roof junction which causes the neutral pressure plane to be at or near the top of the building. For this reason, even the top units are usually under negative pressure and receive a substantial quantity of fresh air. Insulating and sealing these buildings has a dramatic impact on natural air change and on how the fresh air is distributed to the individual units. A popular energy retrofit for these buildings consists of insulating and sealing the roof cavities. As a result, the neutral pressure plane is lowered and this leads to a decrease in fresh air for the top units giving rise to potential indoor air quality problems.

These multi-family buildings offer a great potential for energy savings since they are usually less insulated and less airtight than single family dwellings. In Montreal, a substantial portion of the building stock consists of this type of building and this tremendous opportunity for energy savings was the focus of Hydro-Québec's ISOLACTION weatherization program in 1995 which treated approximately 1000 of these buildings. In addition, several leading Montreal renovation contractors are targeting these buildings for their energy renovation services and the Quebec Energy Efficiency Agency is preparing a new weatherization program which will also target this building stock. Therefore, there is a need to study how the weatherization of these buildings influences the fresh air change of the individual dwellings and the benefits of practical ventilation measures such as strategically located exhaust fans.

Weatherization programs often rely on exhaust-only mechanical ventilation to compensate for the reduction in fresh air flows caused by sealing and insulating works, and to provide the minimum ASHRAE-recommended fresh air flows in dwellings. Although exhaust-only mechanical ventilation may be suitable for single family houses which have no risk of combustion spillage or back-drafting, there is speculation as to whether it is suitable for multifamily buildings.

Although ventilation requirements are specified for new construction in the National Building Code of Canada and in standards such as CAN/CSA F326, there are no codes or standards which address ventilation requirements for retrofitted multi-family buildings. Numerous studies have already addressed issues relating to the ventilation requirements and the effectiveness of ventilation systems. For example, a CMHC study entitled "The effectiveness of Low-Cost Continuous Ventilation Systems" in 1990 investigated low cost alternatives to heat recovery ventilators for single family detached houses. A study which appeared in ASHRAE transactions in 1994, by A. TenWolde, dealt with ventilation and humidity in manufactured houses. However, prior to large scale weatherization programs in Canada such as the ISOLACTION program, little information was available specific to 2 or 3 unit multi-family buildings, typical of the Montreal building stock.

Apart from the fact that is difficult to determine minimum recommended fresh air flow rates which ensure adequate indoor air quality, quantifying fresh air flows in multifamily buildings is a complex phenomenon. Due largely in part to the advent of micro computing, pressure diagnostics and new software such as CONTAM and COMIS, we can now study the impact of sealing and mechanical ventilation in these types of buildings.

The focus of this study is to evaluate the impact of weatherization works and exhaust-only mechanical ventilation on 2 or 3 unit residential buildings (typically built between 1946-71) in Montreal. Simplified building models were defined to represent these types of buildings. CONTAM, a software developed by the National Institute of Standards and Technology (NIST), was used to determine the fresh air flows in individual dwellings. Several simulations were performed in order to evaluate the impact of sealing works, and the effectiveness of exhaust-only mechanical ventilation. On-site airtightness results were used to best represent the air leakage pathways occurring in the buildings at their pre and post weatherization stages.

Section 2 presents the objectives of the study and section 3 presents a review of past studies which deal with airtightness testing in multifamily buildings. Section 4 describes the different building models, the airtightness values used in the models, and the parameters introduced into CONTAM. The analysis of results in Section 5 evaluates the impact of weatherization works on fresh air distribution in multifamily buildings and assesses the effectiveness of exhaust-only ventilation. Finally, Section 6 draws conclusions from the results and makes recommendations with regards to the use of exhaust-only mechanical ventilation in 2 or 3 unit multifamily buildings.

The research presented herein addresses two of CMHC's research priority areas, housing renovation and building performance and housing technology. In Canada, the renovation market represents a $21.6 billion dollar industry and its growth is outpacing the new construction market. Leading renovation contractors, utilities and government agencies are taking advantage of this growth to promote energy efficiency and are implementing an increasing number of energy retrofits and programs. This project is also consistent with CMHC's mandate to investigate the scope of performance problems and to evaluate health and safety issues in the renovation industry.

2. OBJECTIVES

The scope of this study is to evaluate the impact of weatherization works on fresh air distribution in 2 or 3 unit multifamily buildings which are typical to Montreal's building stock and to assess the effectiveness of exhaust-only mechanical ventilation in providing adequate fresh air to the individual dwellings in these buildings.

The objectives of the study are to:

(i) study the impact of sealing/insulation measures performed at the ceiling/roof junction;

(ii) evaluate the effectiveness of exhaust-only mechanical ventilation;

(iii) make recommendations for ensuring adequate ventilation in retrofitted 2 or 3 unit multifamily buildings.

3. REVIEW OF PAST STUDIES

Most of the research reviewed did not address directly the building stock or the ventilation issues dealt with in this study. However, it provided valuable information and data about airtightness testing methods, modelling and analysis strategies, and air leakage characteristics of multifamily buildings. This information was used to define the air flow patterns and characteristics of the different building models which were simulated on computer.

The information was obtained through a scan of various bibliographical indexes (including CMHC, Concordia University), research compendiums, and other sources such as the Internet, the ASHRAE journal, and other publications.

The lack of information concerning the ventilation needs of 2 or 3 unit multifamily buildings may be attributed to the following reasons:

- A proportionately small number of such buildings exist outside of Québec (get number of buildings in Quebec, Canada and N. America, if possible) and thus many researchers are not aware of the particular demands of this building stock;
- A decline in the construction of this type of building since the 1970's;
- New buildings of this type are built in compliance to the NBCC 1995

which stipulates the installation of a central ventilation systems which can provide adequate ventilation to each dwelling;
- Up until the advent of cost effective micro-computing and new instruments, obtaining air leakage characteristics, and modelling air flow patterns in multifamily buildings was practically unheard of;

Despite the downward trend in popularity of this type of construction and the lack of research performed in this area, many of these buildings are still in use and will be undergoing weatherization works as many of their components (roof, walls, windows, etc.) near the end of their useful life, i.e. major capital renewal and renovation.

The information reviewed and retained for discussion is presented under the following headings:

- Ventilation requirements
- Determining Mechanical Ventilation Requirements
- Airtightness Testing Methods
- Airtightness data

3.1 Ventilation Requirements

Although indoor air quality (IAQ) is a function of the materials contained in a dwelling, the occupants' activities, the outdoor air, and other factors, it is generally recommended or stipulated in standards and codes that each dwelling should be equipped with some means of providing a minimum amount of ventilation. Canadian codes and other recognized standards which are applicable to the target building stock will be the premise in establishing a reference. The review presented below is a brief synopsis of the ventilation requirements contained in these standards.

The established minimum rate will be used as a reference point from which we will benchmark the current state of ventilation in the target building type and from which we will evaluate post-retrofit ventilation solutions.

ASHRAE - 1989-62 Ventilation for Acceptable Indoor Air Quality

- For living spaces, this ASHRAE standard recommends 0.35 air changes per hour (ACH) but not less than 7.5 l/s per person of outdoor air for each dwelling unit. Occupant load is based on two occupants for the master bedroom and one occupant for each additional bedroom.

- For kitchens, ASHRAE requires either a 50 l/s intermittent fan or a 12 l/s continuous fan or openable windows.
- For bathrooms, ASHRAE requires either a 25 l/s intermittent fan or a 10 l/s continuous fan or openable windows.

The standard states that the outdoor air requirements can be satisfied through infiltration and natural ventilation but recognises that dwellings with tight enclosures may require supplemental ventilation in certain cases.

National Building Code of Canada (NBCC) 1990 Article 9.32.3.1

Many municipalities in the greater Montreal area require compliance to the mechanical ventilation and roof venting requirements of the 1990 NBCC for weatherized 2 or 3 unit multifamily buildings. The NBCC 1990 states that each dwelling unit shall be provided with a mechanical ventilation system which can exhaust inside air or introduce outside air at a rate of not less than 0.3 ACH averaged over a 24 hr period. The NBCC 1990 emphasizes the point that the required air change rate refers to the installed capacity of the system, not the rate of ventilation that is actually used in the house. Mechanical ventilation systems can be as simple as bathroom and kitchen exhaust fans.

Unlike ASHRAE 1989-62, the NBCC 1990 does not specify outdoor air requirements per se. For example, a dwelling unit equipped with an exhaust fan which inadvertently draws most of its air from adjacent units rather than from the outside can still satisfy the requirements of the NBCC 1990. The installation of exhaust fans in multi-family buildings does not ensure adequate outdoor air supply to individual dwellings. Thus, if outdoor air requirements are to be met with exhaust-only fans we must determine how the fan affects air movement in the building in order to calculate how much fresh air is actually supplied to individual dwellings.

CAN/CSA Standard F-326 Residential Mechanical Ventilation Systems

Standard F-326 states that each dwelling unit must have a mechanical ventilation system which can supply outdoor air at a rate of the greater of either 0.3 ACH or the sum of individual room requirements. The ventilation system must be capable of running on a continuous basis and must supply a minimum amount of outside air to each of the main rooms of the dwelling. The NBCC 1995 requirements for ventilation are based on this standard.

Meeting the requirements of this standard would ensure a continuous and controlled supply of fresh air to each dwelling. Each unit would be supplied with fresh air directly, therefore ensuring fresh air distribution.

This approach is the least cost effective and practical for the type of building targeted by this study because of the requirement for the installation of a central air distribution system. However, for the purpose of this study, the individual room requirements recommended by this standard will be retained.

Minimum recommended ventilation rate

Based on a review of recent weatherization programs, the minimum ventilation rate of 0.35 ACH recommended by ASHRAE 1989-62 (regardless of the number of occupants) was the most frequently adopted. Based on data obtained for the target building stock, dwellings in 2 or 3 unit multifamily buildings generally have a higher occupant density (people/m^3) than a single family detached dwelling. Therefore, it is best to define the minimum ventilation rates based on occupant load or individual room requirements rather than conditioned volume. For the purpose of this study, the occupant requirements of ASHRAE 1989-62 and the individual room requirements of CSA-F326 will be retained as the basis for establishing the minimum recommended ventilation rate for post-retrofit dwellings.

If we consider the ventilation requirements of a typical dwelling (with the characteristics shown below, the above mentioned standards would recommend the following minimum ventilation rates:

Data for a typical dwelling: $280m^3$, 4 occupants, 2 bedrooms, kitchen, living room, bathroom

ASHRAE 1989-62: 0.35ACH = 0.35ACH x 280m3/AC x H/3600s x 1000l/m3 = **28 l/s**

but not less than

4 occupants (2 for master bedroom, 1 for each add'l room) x 7.5 l/s = **30 l/s**

NBCC 1990: 0.3ACH = **24 l/s** (not based on room requirements or occupants)

F326: 10 l/s (master bedroom)+ 5 l/s (bedroom) + 5 l/s (living room) + 5l/s (kitchen) + 5 l/s (bathroom) = **30 l/s**

3.2 Determining Mechanical Ventilation Requirements

Recent weatherization programs in Canada and the US have used a simple approach to determine the mechanical ventilation requirements of small weatherized multifamily buildings and row houses. The required mechanical ventilation rate was generally calculated as being the difference between the minimum ventilation rate of 0.35 ACH recommended by ASHRAE 1989-62, and the average annual natural infiltration rate calculated by dividing the building's airtightness value in ACH50 by an N factor (N is a factor defined by Lawrence Berkeley Laboratory which is used to convert whole building airtightness to an average annual air change rate), as described by the equation below:

Mechanical Ventilation = [0.35 ACH - (ACH50 / N)] where ACH50 is the air change per hour measured during an airtightness test with the building under 50 Pa depressurization.

There are 3 things which are lacking in this approach:

1. ASHRAE requirements are recommended for individual dwellings, and should not be applied to whole buildings which contain multiple dwellings. Although a building may satisfy the fresh air requirements of ASHRAE (ie the building is treated as one dwelling), the fresh air distribution within the building may be such that some units are under ventilated and others are over ventilated;

2. Mechanical ventilation requirements should be based on design day or annual hourly calculations whereby the recommended minimum ventilation rate is satisfied during the periods of the year when ventilation is most needed. For example, using a late march day as a design day when stack effect is low but outdoor temperature is low enough that occupants keep their windows

closed would be appropriate. Using an average annual infiltration rate results in an underestimation of the ventilation needs during spring and autumn and an overestimation of the ventilation needs in winter;

3. This approach does not consider the fresh air distribution to each dwelling within the building. The fresh air change rate of individual dwellings often depends on its location within the building, its degree of connectivity to the other units, and other factors;

An alternative approach would be to determine the shell leakage on a unit basis and associate individual N factors for each unit based on its connectivity to adjacent units, position within the building, level of the neutral pressure plane (NPP), etc. This would reflect the fact that outdoor air supply due to natural infiltration in multifamily buildings is not uniform. However, determining the N factor for individual units before and after retrofit works would complicate the process and oversimplify the problem, thus introducing more potential for error.

Recommended Approach for Determining Mechanical Ventilation Requirements

In order to assess the mechanical ventilation requirements of individual dwellings and to recommend appropriate mechanical ventilation systems and controls for these dwellings, two important elements are required:

1. An effective **airtightness testing method** which quantifies both shell leakage and inter-zonal leakage. Although a multiple blower door method would give accurate results, a single blower door technique would be more suitable in the context of a weatherization program because of the time, effort and resources required;

2. A **computer program** which can be used on site by technicians to simulate the fresh air distribution in individual dwellings based on a design day or annual hourly calculation, under post-retrofit conditions. This program should also recommend the most appropriate ventilation system type, capacity and controls for individual dwellings.

3.3 Airtightness Testing Methods

In Canada, the CAN/CGSB-149.10 standard entitled "A Method for Testing the Airtightness of Buildings by the Fan Depressurization Method" is the industry recognized standard for determining the airtightness of the building envelope of single zone detached buildings.

Although a lot of literature exists on the use of the blower door as an instrument to quantify whole building airtightness and to estimate natural infiltration, very little research has been done on the use of this instrument in combination with pressurization techniques to quantify inter-zonal air leakage in multifamily buildings.

The need to establish mechanical ventilation requirements in multifamily buildings has resulted in the emergence of several innovative airtightness testing methods in recent years. Such methods have been developed as part of research projects or have been developed within weatherization programs. Several innovative blower door techniques which quantify inter-zonal leakage were introduced in 1995 in a report entitled «Simplified Multizone Blower Door Techniques for Multifamily Buildings» by Steven Winter Associates and LBL for the New York state Energy Research and Development Authority.

More recently, in September 1999, a thesis by Mr. Sebastiano DePani of Concordia University, evaluated the accuracy of three single blower door techniques to determine the shell leakage and inter-zonal leakage in low-rise multifamily buildings. The results obtained using these three methods were compared to those obtained using a Multiple-door method which is regarded as the most accurate method to determine air leakage characteristics of multifamily buildings.

In his thesis, Mr. DePani concludes that of the three single-door methods evaluated, the Unit Method is most suitable for quantifying shell leakage and inter-zonal leakage in small multifamily buildings in the context of a weatherization program. The unit method consists of measuring the total leakage of individual units, one unit at a time, and measuring the pressure drops to adjacent units. A data set based on the power law equation ($Q=C\Delta P^n$) is defined and solved to obtain the airtightness characteristics of interior partitions and the external envelope of each unit.

3.4 Airtightness Data

Mr. DePani's thesis was the principle source of inter-zonal leakage data for modelling the target building stock. Of the four multifamily buildings tested by Mr. DePani, the Multiple Door method results of one of these buildings (Building #4) will be used to develop one of the building models which will be simulated for air movement. A description and the air leakage characteristics of this multifamily building are presented below.

Case Study Building: 5465 Coolbrook, Montreal

This detached building was built in 1950 and is located in the NDG district of Montreal. The building has a total heated floor area of 345 m^2 and a conditioned volume of 840 m^3. The principle unit occupies the ground floor and the basement (230 m^2). A second unit occupies the second floor (115 m^2). Each unit has a separate exterior entrance (side entrance for top unit is not visible in figure 1). Space heating is provided by electric baseboards.

Figure 1: Case Study Building

Table 1: Building Takeoffs

	Unit 1	Unit 2	Total
Floor Area (m^2):	230	115	345
Envelope Area (m^2):	220	225	445
Volume (m^3):	560	280	840

Table 2: Airtightness Characteristics

Leakage Path	*Airtightness Characteristics (ELA in cm^2 / CFM50)*
Exterior to Unit 1	1194 / 1801
Exterior to Unit 2	715 / 1078
Unit 1 to Unit 2	930 / 1403
Exterior to Building	1909 / 2879

- The case study building has an overall airtightness of 5.8 ACH50 and an exterior ELA of 1909 cm^2. These results are typical of pre-1970 buildings and are consistent with results of a Hydro-Québec report published in July 1994 entitled «ÉVAL-ISO». The ÉVAL-ISO report which is based on airtightness tests performed on over 1000 buildings (single family, 2 unit, and 3 unit multifamily buildings) states that the average whole building airtightness of 2 and 3 unit multifamily buildings built in Quebec from 1946 to 1985 is 4.61 ACH50.
- The top unit of the case study building has an airtightness of 6.5 ACH50 and the

bottom unit has an airtightness of 5.5 ACH50. The inter-zonal leakage is 1403 CFM50. Based on the author's experience, the units can be qualified as well connected.

4.0 MODELLING

4.1 Description of Airflow Models

This section describes the two air flow models which were defined with CONTAM, a multi-zone air flow software developed by NIST, to determine the fresh air flows in a typical 2-unit, 2-floor multifamily building.

The first airflow model is based on the airtightness data of the case study building presented in the preceding section. This model will represent buildings with high inter-zonal leakage and will be referred to as the «well connected units» scenario. The second airflow model will represent a hypothetical building which is identical in configuration, size, and shell leakage to the case study building, except that the inter-zonal leakage will be reduced to simulate the fresh air distribution in buildings whereby the dwellings are relatively isolated from one another. The amount of inter-zonal leakage defined in the second model is consistent with values obtained from field tests. The airtightness characteristics for the airflow models are presented below.

Table 3: Airtightness Characteristics of the Airflow Models

	Airtightness Characteristics (ELA in cm^2 / CFM50)	
Leakage Path	**Well Connected Units Scenario**	**Isolated Units Scenario**
Exterior to Unit 1	1194 / 1801	same
Exterior to Unit 2	715 / 1078	same
Unit 1 to Unit 2	930 / 1403	166 / 250
Exterior to Building	1909 / 2879	same

The shell leakage results of the case study building are consistent with results obtained by the author through another project whereby the multiple door method was used to validate the whole building airtightness results of a single door technique (Open/Closed Method). Based on a sample size of ten 2 and 3 unit multifamily buildings which were similar in size to the case study building, the average measured whole building airtightness (or shell leakage) was 3115 CFM50.

The configuration of the airflow models are based on the configuration of the case study building and consist of a 2-story building with 2 zones, one unit per floor with the ground floor unit open to the basement.

Although the airtightness testing method used to obtain the leakage data provides the flow coefficients and ELAs of the exterior walls and interior partitions, it does not give an indication of how the leakage area is distributed within the units. The leakage distribution affects natural and mechanical ventilation because the pressure gradients along the walls vary with stack and wind induced pressures. The assumptions made with regards to leakage distribution are as follows:

- In unit 1 (ground floor and basement), the exterior leakage area is split evenly between eight exterior leakage paths to the outside. Four are located at one quarter of the floor height (one on each exterior wall) and four are located at three quarters of the floor height;
- In unit 2 (2nd floor), half the exterior leakage area is located at the ceiling, and the remaining leakage area is split evenly between eight leakage paths on the exterior walls (similar to unit 1);
- It is assumed that the units do not connect to a shaft, and the inter-zonal leakage is represented by a direct path through the floor which separates the two units.

Through pressure diagnostic tests performed by the author in a recent weatherization program for low rise multifamily buildings in Quebec, it was found that there may exist a leakage pathway which connects dwellings to each other and to the attic and crawlspace/basement. Referred to as shafts, these pathways may take different forms such as:

- thin pathways (<25mm) formed by the furring space on the interior part of exterior walls;
- the partition which contains the building's principal plumbing stack;
- common staircases (common entrances);
- central air distribution systems; and
- interconnected skylights and chimneys.

Air leakage through shafts are very difficult to quantify because the common pressure boundary of such pathways are difficult to identify. Shaft leakage was not evaluated for the case study building and was not introduced into the airflow models.

Other CONTAM parameters

The airtightness characteristics of building components (walls, ceilings, and floors) were entered into CONTAM using the «one point test data» option. Indoor temperature was defined as 21°C for each unit. Simulations were carried out for outdoor temperatures of -10, -5, 0, 5 and 10°C and for three wind conditions, namely calm (no wind), light wind (5 km/h) and moderate wind (10 km/h).

4.2 Performance Issues

In order to evaluate the impact of weatherization on fresh air distribution and to assess the effectiveness of exhaust-only ventilation, the following questions should be addressed:

1. What is the fresh air change rate in dwellings at the pre-retrofit stage (benchmark results) as a function of outdoor temperature and wind?
2. What would be the resulting fresh air change rate in dwellings which have undergone weatherization works (insulating and sealing) in the roof space (post-retrofit results)?
3. Can exhaust-only fans produce the minimum recommended ventilation rates in «well connected» dwellings and in«isolated» dwellings at the post-retrofit stage?
4. If so, what fan capacity is required to draw enough outside air through the building envelope of the dwelling? Is this fan capacity realistic?
5. Would exhaust only ventilation draw more air from the adjacent unit when compared to the leakage between dwellings at the pre-retrofit stage?

6. For which dwellings does a central ventilation system become the only option?

The following performance criteria (applied to each dwelling) will assist us in addressing these questions:

• Total Air Change (TACH):	The total air change rate is proportional to the sum of air flows which enter the dwelling either from the exterior or from adjacent units.
• Fresh Air Change (FACH):	The fresh air change rate is proportional to the sum of air flows which enter the dwelling directly from the exterior envelope.
• Inter-zonal Leakage (l/s):	The inter-zonal leakage is equivalent to the sum of air flows which enter the dwelling from adjacent units

5.0 SIMULATION RESULTS

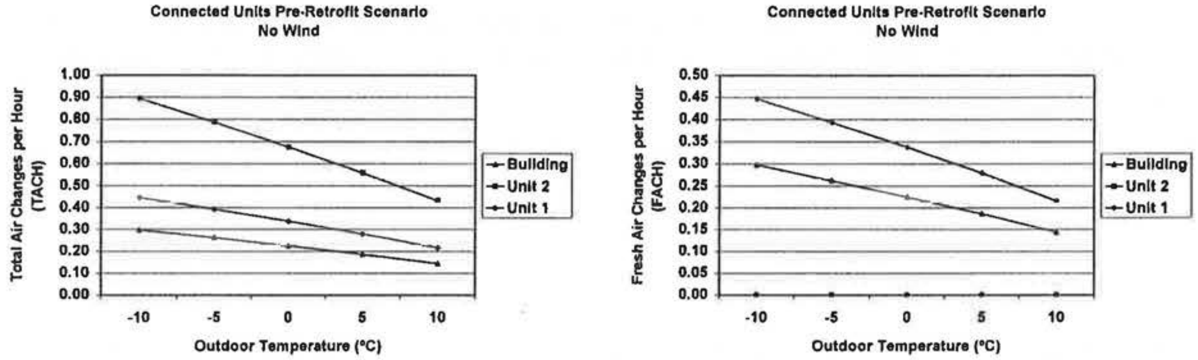
Sections 5.1 to 5.6 present the Total and Fresh Air Change profiles for the Connected and Isolated Units scenarios under various temperature and wind conditions. For each scenario, profiles at the following weatherization stages are presented:

- ***Pre-Retrofit***
- ***Post-Retrofit***
- ***Post-Retrofit + 70 CFM Fan***

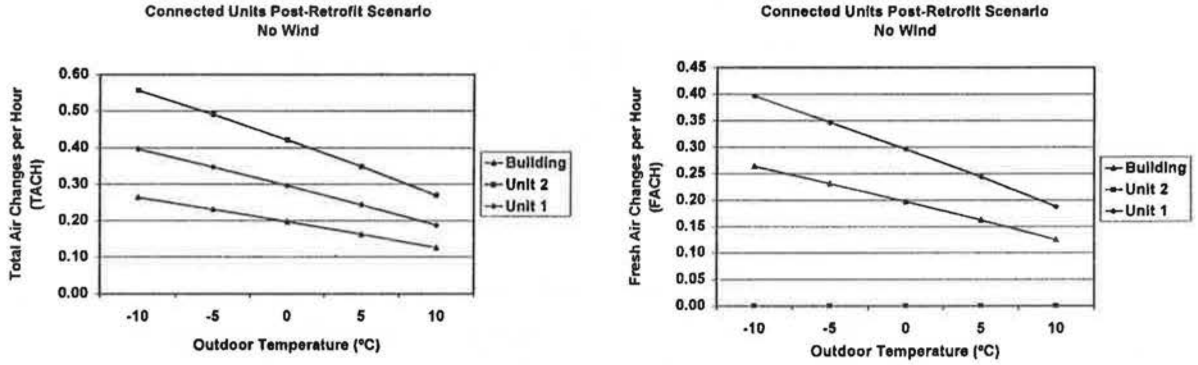
Pre-Retrofit -	Airflow models (Connected and Isolated Units Scenarios) are simulated as described in section 4.1. and represent typical buildings prior to weatherization.
Post -Retrofit -	Airflow models represent typical buildings which have undergone weatherization of the roof space. This scenario is based on the ISOLACTION program whereby the principle energy conservation measure consisted of insulating and sealing the roof space with high-density cellulose fibre insulation and polyurethane spray applied insulation. In most cases, this technique reduced air-leakage through the roof space by 85-95%. For the purposes of this study, it was assumed that the ELA through the roof space was reduced by 90%. Thus, the air leakage pathway from the top unit to the outdoors was reduced from 539 CFM50 to 53.9 CFM50.
Post-Retrofit -	Simulations represent weatherized buildings whereby the top unit is equipped with an exhaust fan whose capacity complies to the minimum recommended ventilation rate of 30 l/s determined in section 3.1. A continuous exhaust rate of 70 CFM (33 l/s) was introduced into the airflow models to simulate the typical mechanical ventilation strategy adopted by weatherization programs.

The results presented in this chapter are also presented in tabular form in the appendix.

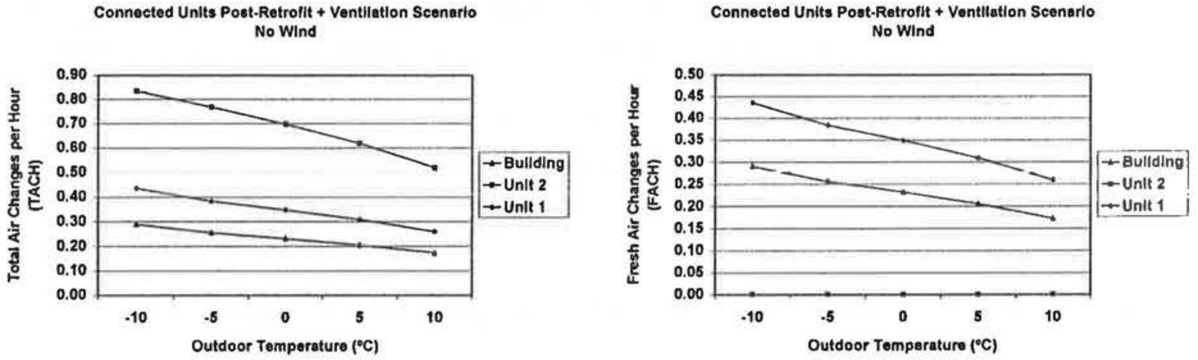
5.1 Connected Units - No Wind - Total & Fresh Air Change Profiles



Pre-Retrofit

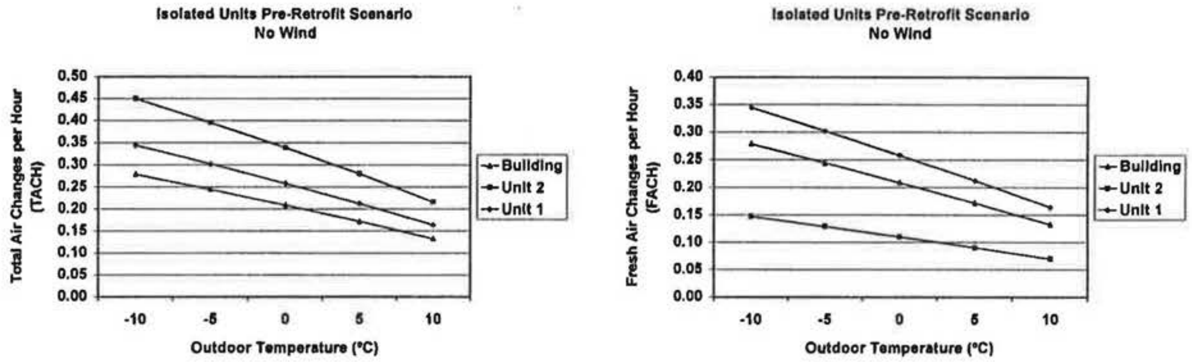


Post-Retrofit

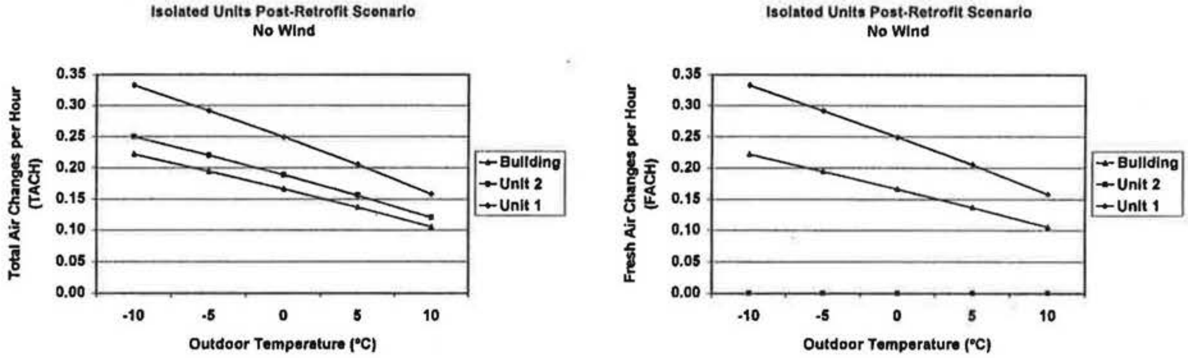


Post-Retrofit + 70 CFM Fan

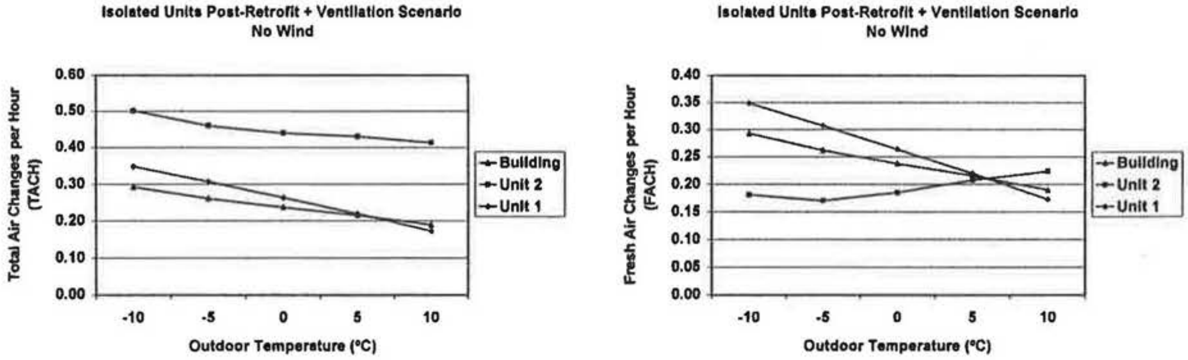
5.2 Isolated Units - No Wind - Total & Fresh Air Change Profiles



Pre-Retrofit

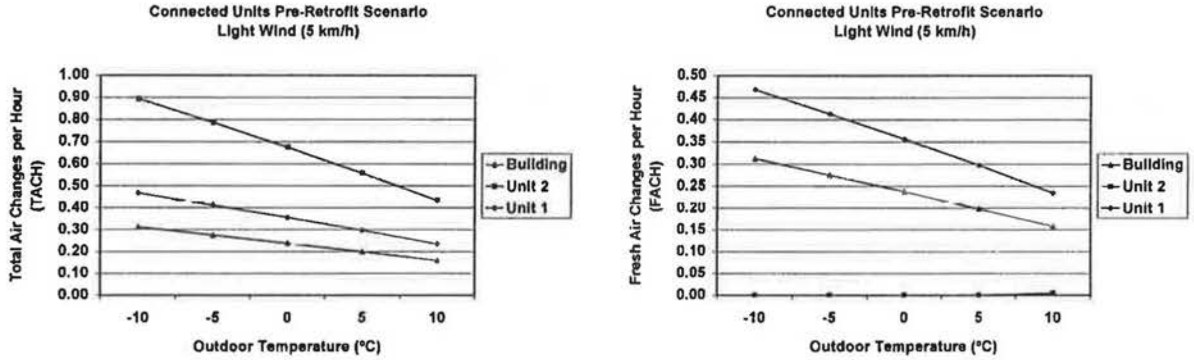


Post-Retrofit

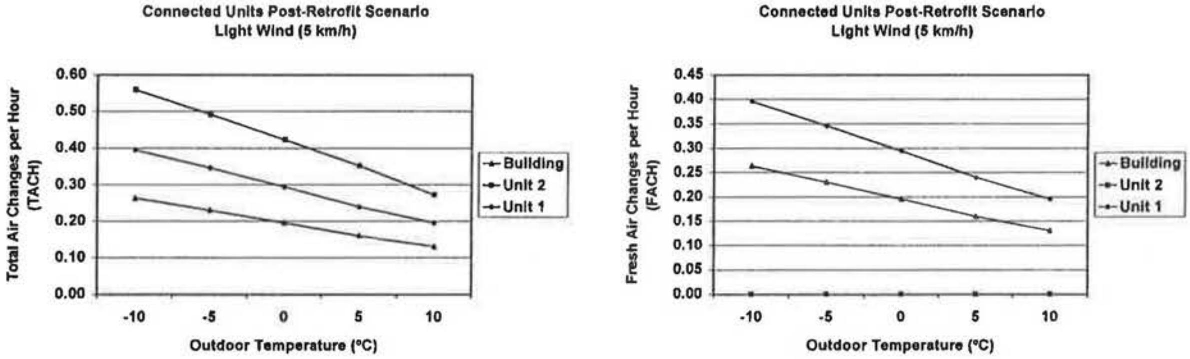


Post-Retrofit + 70 CFM Fan

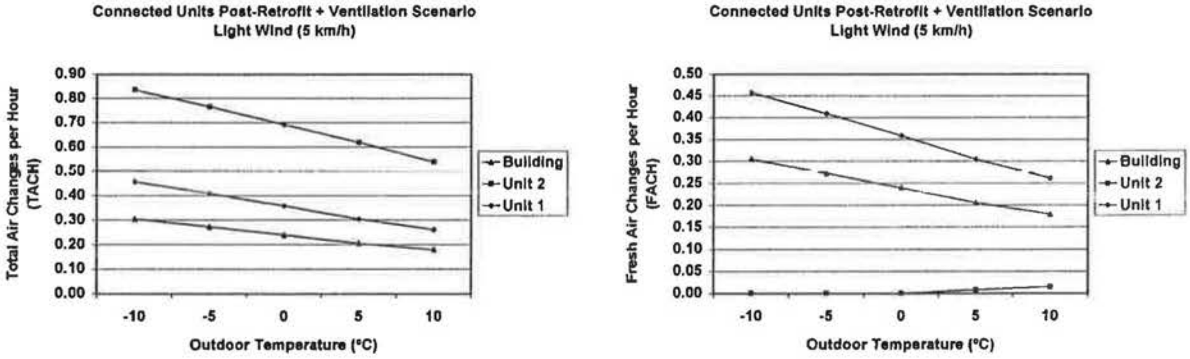
5.3 Connected Units - Light Wind - Total & Fresh Air Change Profiles



Pre-Retrofit

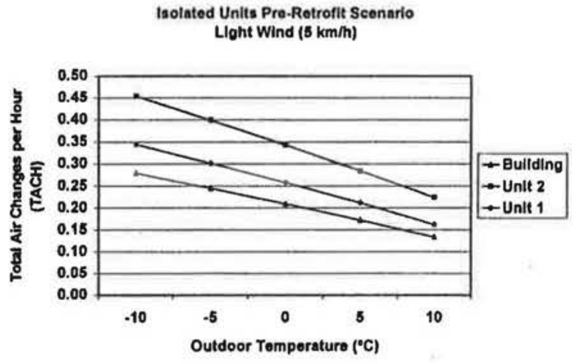


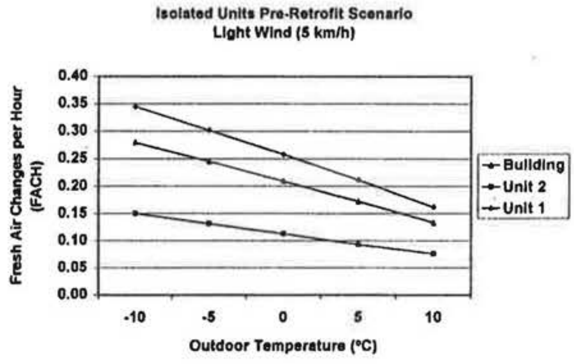
Post-Retrofit



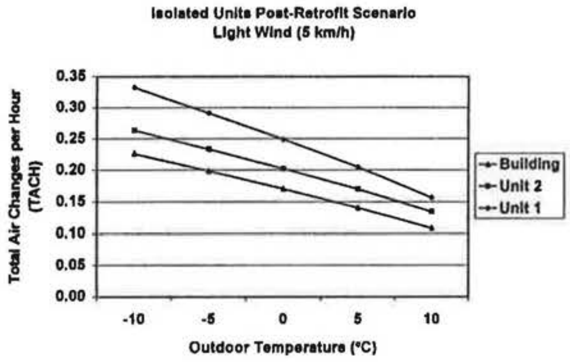
Post-Retrofit + 70 CFM Fan

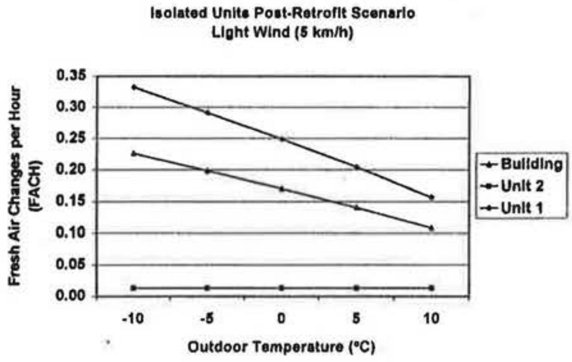
5.4 Isolated Units - Light Wind - Total & Fresh Air Change Profiles



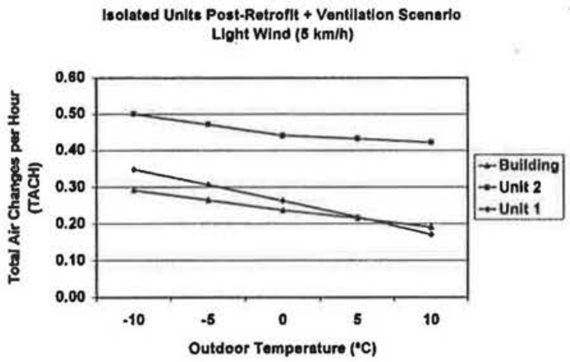


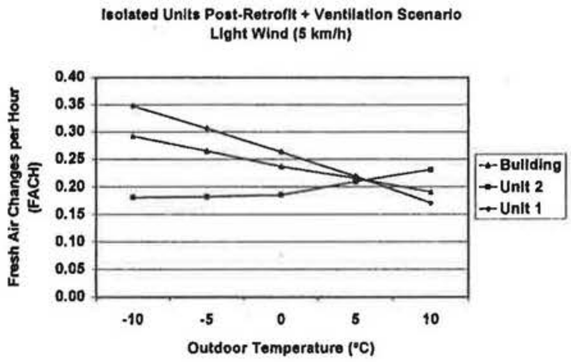
Pre-Retrofit





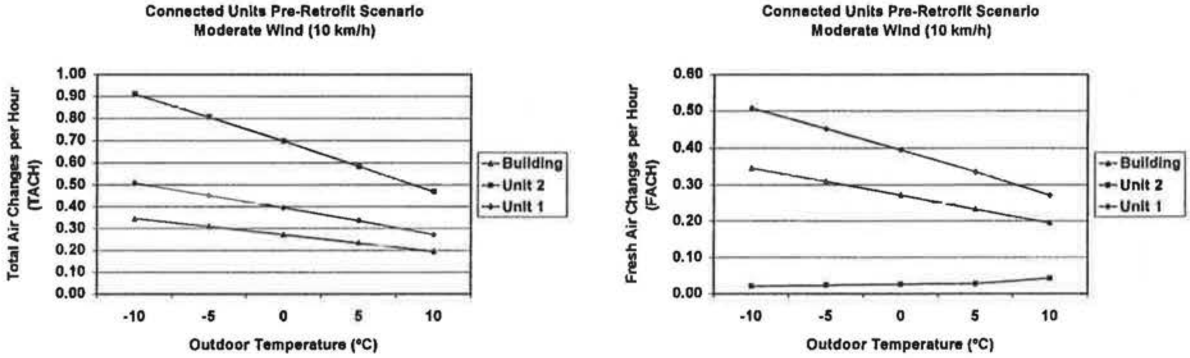
Post-Retrofit



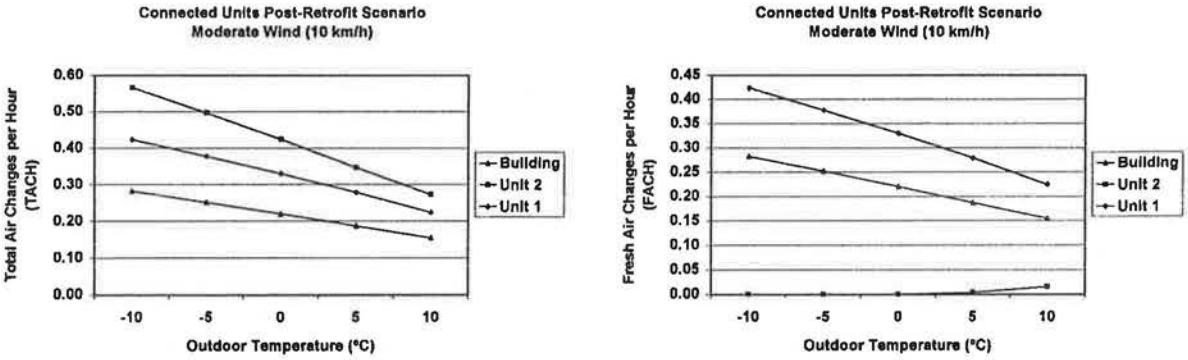


Post-Retrofit + 70 CFM Fan

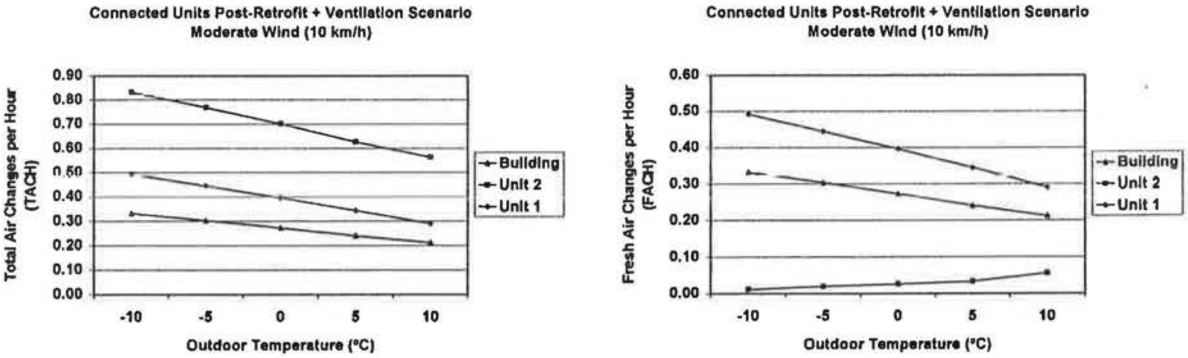
5.5 Connected Units - Moderate Wind - Total & Fresh Air Change Profiles



Pre-Retrofit

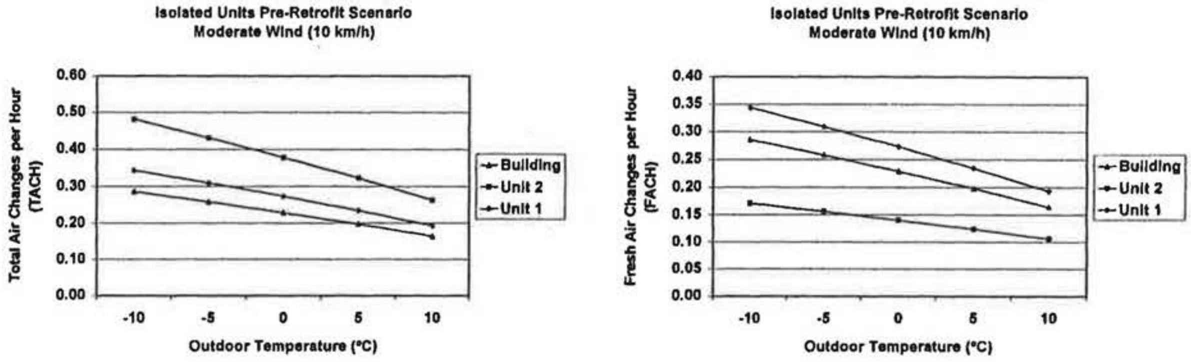


Post-Retrofit

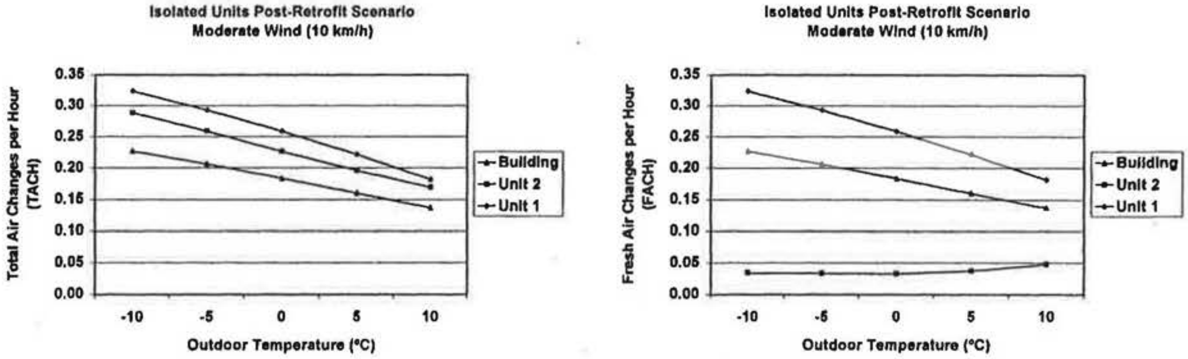


Post-Retrofit + 70 CFM Fan

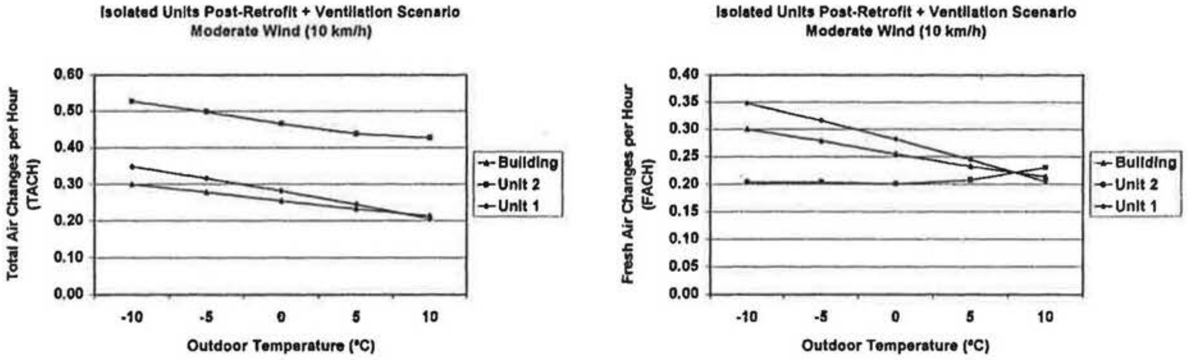
5.6 Isolated Units - Moderate Wind - Total & Fresh Air Change Profiles



Pre-Retrofit



Post-Retrofit



Post-Retrofit + 70 CFM Fan

5.7 Discussion of Results

Pre-Retrofit Results

- Outdoor air supply on a unit-per-unit basis depends on the location of the unit.
  - Due to stack effect and the absence of a central mechanical ventilation system, the top unit receives less outdoor air than the bottom unit. The fresh air change rate of the top unit depends on its degree of connectivity with the bottom unit (next point).

- Outdoor air supply on a unit-per-unit basis depends on the degree of connectivity of the units.
  - The fresh air change rate of the top unit depends on its degree of connectivity with the bottom unit. In the absence of wind, the top unit of a relatively well connected building receives **no fresh air** when the outside temperature is above -10°C. Thus, the top unit may be susceptible to IAQ problems which arise from a lack of fresh air and the transport of contaminants which emanate from the bottom unit.
  - For a building with relatively isolated units, the fresh air change rate in the top unit is directly proportional to the decrease in outdoor temperature. Some pre-retrofit results are shown below:

	Bottom Unit	Top Unit
at -10°C and no wind, the FACH =	0.34	0.15
at 10°C and no wind, the FACH=	0.16	0.07

- The effect of wind on the fresh air change rate in individual units depends on the location and degree of connectivity of the units.
  - Low to moderate winds (0 to 10 km/h) have little effect on the fresh air change rate of the top unit of a well connected building. The fresh air change rate varies from:

	Top Unit
at -10°C and no wind, the FACH =	0.00
at -10°C and 10 km/h winds, the FACH =	0.02

at 10°C and no wind, the FACH = 0.00
at 10°C and 10 km/h winds, the FACH= 0.04

- For the bottom unit of a well connected building, an increase in wind speed adds to the fresh air driven by stack effect. Some pre-retrofit simulation results are shown below:

	Bottom Unit
at -10°C and no wind, the FACH =	0.45
at -10°C and 10 km/h winds, the FACH=	0.51

- Low and moderate winds have little effect on the outdoor air supply to the units of a building with relatively isolated units.

  At low temperatures, an increase in wind speed, has a marginal impact on the fresh air change rate in both units of a building with relatively isolated units as shown by the results presented in sections 5.1 to 5.6. For example:

	Bottom Unit	Top Unit
at -10°C and no wind, the FACH =	0.34	0.15
at -10°C and 10 km/h winds, the FACH=	0.34	0.17

  The outdoor air supply to both units converge as the outdoor temperature approaches the indoor temperature (see charts in sections 5.1 to 5.6) and the incremental increase in outdoor air due to wind at high outdoor temperatures is marginal:

	Bottom Unit	Top Unit
at 10°C and no wind, the FACH =	0.16	0.07
at 10°C and 10 km/h winds, the FACH=	0.19	0.11

- The maximum natural infiltration rate for the top unit falls short of the minimum recommended ventilation rate of 0.35 FACH.

  - Although the combined fresh air change rate of the top and bottom units meets or exceeds the minimum recommended ventilation rate of 0.35 FACH, in 63% of the pre-retrofit simulations performed, the top unit attains a maximum natural infiltration rate of only 0.17 FACH (Isolated unit, -10°C, 10km/h wind) in the case of an isolated unit scenario and only 0.02 FACH (Connected Unit, -10°C, 10 km/h) in the case of a well connected unit scenario.

Post-Retrofit Results

- Weatherization of the roof space has the biggest impact on the outdoor air supply to the bottom unit of a building with well connected units.
    - Sealing work performed in the roof space lowers the neutral pressure plane and consequently increases the proportion of envelope surface area under exfiltration in the top unit.
    - For the top unit of a well connected building, the fresh air change rate remains at 0.0 FACH at the post-retrofit stage (for all simulated conditions). However, the total air change is reduced significantly. This is beneficial in the sense that it reduces the potential transport of contaminants from the bottom unit. The total air change rate in the top unit at the pre-retrofit and post-retrofit stages is shown below for two sets of outdoor temperature and wind conditions:

	Top Unit	
	Pre-Retrofit	Post-Retrofit
at -10°C and no wind, the TACH =	0.89	0.56
at -10°C and 10 km/h winds, the TACH=	0.91	0.57

Weatherization of the roof space reduces the fresh air change rate in the bottom unit of a well connected building:

	Bottom Unit	
	Pre-Retrofit	Post-Retrofit
at -10°C and no wind, the FACH =	0.45	0.40
at -10°C and 10 km/h winds, the FACH=	0.51	0.42

- Weatherization of the roof space of buildings with relatively isolated units reduces the outdoor air supply to the top unit significantly.
    - The weatherization of the roof space has a marginal impact on the fresh air change rate of the bottom unit of a building with relatively isolated units as shown below:

	Bottom Unit	
	Pre-Retrofit	Post-Retrofit
at -10°C and no wind, the TACH =	0.34	0.33
at -10°C and 10 km/h winds, the TACH=	0.34	0.32

- The largest reduction in fresh air change rate occurs for the top unit of a building with relatively isolated units. For example:

	Top Unit	
	Pre-Retrofit	Post-Retrofit
at -10°C and no wind, the TACH =	0.15	0.0
at -10°C and 10 km/h winds, the TACH=	0.17	0.0

Post-Retrofit + Fan Results

- The use of exhaust-only ventilation in the top unit of a building with well connected units is ineffective in providing an adequate supply of outdoor air to the top unit.
  - Exhaust fans are a simple and inexpensive approach to adding mechanical ventilation in existing buildings. However, a common misconception is that an exhaust fan with capacity "A" l/s will draw the same "A" l/s through the envelope. The actual amount of outdoor air drawn through the envelope will be less than the fan capacity and will depend on the following factors:
    - airtightness of the envelope;
    - inter-zonal airtightness;
    - indoor/outdoor temperature difference;
    - wind speeds; and
    - location of the exhaust fan.
  - The 70 CFM exhaust fan restores the initial conditions to the top unit in terms of total air change rate, which is not desirable since it increases the potential transport of contaminants from the ground floor unit via air leakage. At an outdoor temperature of -10°C and in the absence of wind, a 70 CFM exhaust fan (33 l/s) installed in the top unit will draw only 6 l/s of new outdoor air into the entire building and no outdoor air (0 l/s) for the top unit. As the outdoor temperature approaches the indoor temperature, the exhaust fan draws more outdoor air into the building. When the outdoor temperature is 10°C,

the exhaust fan draws an additional 11 l/s of outdoor air through the envelope of the building but still no impact on the fresh air change rate of the top unit.

- The use of exhaust-only ventilation in the top unit of a building with relatively isolated units is more effective in providing outdoor air to the top unit.
    - At an outdoor temperature of -10°C and in the absence of wind, a 70 CFM (33 l/s) will draw 17 l/s of new outdoor air into the entire building and 14 l/s of outdoor air for the top unit. It is worth mentioning that the incremental ventilation provided by the exhaust fan is similar to the natural infiltration rate at the pre-retrofit stage. At an outdoor temperature of 10°C, the exhaust fan draws an additional 20 l/s of out door air through the envelope of the building and 17 l/s for the top unit.
    - For a building with relatively isolated units, the fresh air change rate curve of the top unit converges with the decreasing fresh air change rate curve of the bottom unit as the outdoor temperature rises (see sections, 5.2,5.4, & 5.6), illustrating the reduction in stack effect. Exhaust-only ventilation is effective in providing outdoor air during mild outdoor temperatures:

	Top Unit	
	Pre-Retrofit	Post-Retrofit
at 10°C and 10 km/h winds, the FACH =	0.11	0.23

- In order to provide the minimum recommended ventilation rate of 0.35 FACH in the top unit, additional simulations were performed to determine the required exhaust fan capacity. The results indicate that a 100 CFM (52 l/s) exhaust fan would be required to provide the minimum recommended ventilation rate. However, this would also increase the total air change rate of the top unit, hence drawing more air from the bottom unit than at pre-retrofit conditions.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Connected Units

The occupant(s) of the top unit of a building whose units are relatively well connected, receive little outdoor air from infiltration and fall short of the minimum recommended ventilation rate of 0.35 FACH prior to weatherization. Although weatherization of such buildings decreases the fresh air change rate of the bottom unit, the fresh air change rate of the bottom unit complies to the minimum recommended ventilation rate for most of the simulated conditions, and the interzonal leakage is reduced significantly. The reduction in interzonal leakage has a beneficial impact on the top unit as is reduces the potential transport of contaminants which may emanate from the bottom unit via air leakage. The simulation results also show that exhaust-only ventilation is ineffective in providing adequate outdoor air to the top unit of a weatherized building whose units are relatively well connected. The use of exhaust-only ventilation benefits the lower units of the building only and restores initial conditions to the top unit in terms of total air change rate, which is not desirable. Albeit very difficult to install in an existing building, a balanced ventilation system is the most effective means of ventilating the top unit of a building with well connected units. Another alternative would be to seal the floors and bypasses between the units in order to render them relatively isolated from one another. Based on the authour's experience, both alternatives are seldom implemented.

Isolated Units

Although the outdoor air supply to the top unit of a building increases as its degree of connectivity to the bottom unit decreases, the fresh air change rate of the top unit did not attain the minimum recommended ventilation rate for the pre-retrofit conditions simulated. Weatherization of such buildings reduces significantly the outdoor air supply to the top unit. The results show that exhaust-only ventilation is recommended for the top unit of such buildings subsequent to weatherization of the roof space. The results also show that exhaust-only ventilation more than doubles the outdoor air supply (vs. pre-retrofit conditions) at mild outdoor temperatures.

Closing Remarks

Addressing ventilation in multifamily buildings is much more complex than for detached single-family houses. The general guidelines used to evaluate natural ventilation and the need for mechanical ventilation in detached houses cannot be used for multifamily buildings.

Ventilation in multifamily buildings depends greatly on both the exterior leakage area and the airtightness between dwellings. The amount of fresh air drawn through the envelope by exhaust fans can only be estimated using a multi-zone airflow model such as CONTAM (with pre-defined templates and an interface for presentation of results and recommendations) and a practical airtightness testing method such as the Unit Method as described in Chapter 3.

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APPENDIX

No Wind

	Outdoor Temp = -10oC				Outdoor Temp = -5oC				Outdoor Temp = 0oC				Outdoor Temp = 5oC				Outdoor Temp = 10oC		
Scenario & Unit	Total ACH		Fresh ACH		Total ACH		Fresh ACH		Total ACH		Fresh ACH		Total ACH		Fresh ACH		Total ACH		Fresh ACH
Connected Pre-retrofit	-10	CFM	-10,00	CFM	-5,00	CFM	-5,00	CFM	0,00	CFM	0,00	CFM	5,00	CFM	5,00	CFM	10,00	CFM	10,00
Unit 1	0,45	147,25	0,45	147,25	0,39	129,64	0,39	129,64	0,34	111,40	0,34	111,40	0,28	92,17	0,28	92,17	0,22	71,35	0,22
Unit 2	0,89	147,25	0,00	0,00	0,79	129,64	0,00	0,00	0,68	111,40	0,00	0,00	0,56	92,17	0,00	0,00	0,43	71,35	0,00
Building	0,30	147,25	0,30	147,25	0,26	129,64	0,26	129,64	0,23	111,40	0,23	111,40	0,19	92,17	0,19	92,17	0,14	71,35	0,14
Isolated Pre-retrofit	-10,00		-10,00		-5,00		-5,00		0,00		0,00		5,00		5,00		10,00		10,00
Unit 1	0,34	113,60	0,34	113,60	0,30	99,56	0,30	99,56	0,26	85,16	0,26	85,16	0,21	70,16	0,21	70,16	0,16	54,08	0,16
Unit 2	0,45	74,13	0,15	24,28	0,40	65,16	0,13	21,28	0,34	55,86	0,11	18,16	0,28	46,15	0,09	14,96	0,22	35,67	0,07
Building	0,28	137,88	0,28	137,88	0,24	120,84	0,24	120,84	0,21	103,32	0,21	103,32	0,17	85,12	0,17	85,12	0,13	65,60	0,13
Connected Post-retrofit	-10,00		-10,00		-5,00		-5,00		0,00		0,00		5,00		5,00		10,00		10,00
Unit 1	0,40	130,64	0,40	130,64	0,35	114,36	0,35	114,36	0,30	97,72	0,30	97,72	0,24	80,44	0,24	80,44	0,19	61,92	0,19
Unit 2	0,56	91,69	0,00	0,00	0,49	80,87	0,00	0,00	0,42	69,42	0,00	0,00	0,35	57,38	0,00	0,00	0,27	44,38	0,00
Building	0,26	130,64	0,26	130,64	0,23	114,36	0,23	114,36	0,20	97,72	0,20	97,72	0,16	80,44	0,16	80,44	0,13	61,92	0,13
Isolated Post-retrofit	-10,00		10,00		-5,00		5,00		0,00		0,00		5,00		5,00		10,00		10,00
Unit 1	0,33	109,72	0,33	109,72	0,29	96,16	0,29	96,16	0,25	82,24	0,25	82,24	0,21	67,76	0,21	67,76	0,16	52,20	0,16
Unit 2	0,25	41,26	0,00	0,00	0,22	36,29	0,00	0,00	0,19	31,14	0,00	0,00	0,16	25,74	0,00	0,00	0,12	19,91	0,00
Building	0,22	109,72	0,22	109,72	0,19	96,16	0,19	96,16	0,17	82,24	0,17	82,24	0,14	67,76	0,14	67,76	0,11	52,20	0,11
onnected Post-retrofit + Vent.	-10,00		-10,00		-5,00		-5,00		0,00		0,00		5,00		5,00		10,00		10,00
Unit 1	0,44	143,68	0,44	143,68	0,38	126,58	0,38	126,58	0,35	114,98	0,35	114,98	0,31	102,00	0,31	102,00	0,26	85,67	0,26
Unit 2	0,83	137,52	0,00	0,00	0,77	126,58	0,00	0,00	0,70	114,98	0,00	0,00	0,62	102,00	0,00	0,00	0,52	85,67	0,00
Building	0,29	143,68	0,29	143,68	0,26	126,58	0,26	126,58	0,23	114,98	0,23	114,98	0,21	102,00	0,21	102,00	0,17	85,67	0,17
Isolated Post-retrofit + Vent.	-10,00		10,00		-5,00		-5,00		0,00		0,00		5,00		5,00		10,00		10,00
Unit 1	0,35	114,92	0,35	114,92	0,31	101,20	0,31	101,20	0,26	86,96	0,26	86,96	0,22	72,44	0,22	72,44	0,17	57,00	0,17
Unit 2	0,50	82,65	0,18	29,84	0,46	75,75	0,17	28,12	0,44	72,41	0,19	30,52	0,43	70,90	0,21	34,28	0,41	68,10	0,22
Building	0,29	144,76	0,29	144,76	0,26	129,32	0,26	129,32	0,24	117,48	0,24	117,48	0,22	106,72	0,22	106,72	0,19	93,88	0,19

Light Wind (5 km/h)

	Outdoor Temp = -10oC				Outdoor Temp = -5oC				Outdoor Temp = 0oC				Outdoor Temp = 5oC				Outdoor Temp = 10oC		
Scenario & Unit	Total ACH		Fresh ACH		Total ACH		Fresh ACH		Total ACH		Fresh ACH		Total ACH		Fresh ACH		Total ACH		Fresh ACH
Connected Pre-retrofit	-10	CFM	-10,00	CFM	-5,00	CFM	-5,00	CFM	0,00	CFM	0,00	CFM	5,00	CFM	5,00	CFM	10,00	CFM	10,00
Unit 1	0,47	154,30	0,47	154,30	0,41	136,05	0,41	136,05	0,36	117,42	0,36	117,42	0,30	98,04	0,30	98,04	0,23	77,30	0,23
Unit 2	0,89	147,22	0,00	0,00	0,79	129,54	0,00	0,00	0,67	111,23	0,00	0,00	0,56	91,89	0,00	0,00	0,43	71,57	0,01
Building	0,31	154,30	0,31	154,30	0,28	136,05	0,28	136,05	0,24	117,42	0,24	117,42	0,20	98,04	0,20	98,04	0,16	78,13	0,16
Isolated Pre-retrofit	-10,00		-10,00		-5,00		-5,00		0,00		0,00		5,00		5,00		10,00		10,00
Unit 1	0,34	113,55	0,34	113,55	0,30	99,48	0,30	99,48	0,26	85,02	0,26	85,02	0,21	69,86	0,21	69,86	0,16	53,41	0,16
Unit 2	0,45	74,82	0,15	24,72	0,40	65,84	0,13	21,69	0,34	56,57	0,11	18,59	0,28	46,84	0,09	15,35	0,22	36,97	0,08
Building	0,28	138,27	0,28	138,27	0,25	121,17	0,25	121,17	0,21	103,61	0,21	103,61	0,17	85,21	0,17	85,21	0,13	65,93	0,13
Connected Post-retrofit	-10,00		-10,00		-5,00		-5,00		0,00		0,00		5,00		5,00		10,00		10,00
Unit 1	0,40	130,39	0,40	130,39	0,35	113,99	0,35	113,99	0,29	97,06	0,29	97,06	0,24	79,16	0,24	79,16	0,20	64,66	0,20
Unit 2	0,56	92,14	0,00	0,00	0,49	81,10	0,00	0,00	0,42	69,77	0,00	0,00	0,35	58,00	0,00	0,00	0,27	44,96	0,00
Building	0,26	130,39	0,26	130,39	0,23	113,99	0,23	113,99	0,20	97,06	0,20	97,06	0,16	79,16	0,16	79,16	0,13	64,66	0,13
Isolated Post-retrofit	-10,00		-10,00		-5,00		-5,00		0,00		0,00		5,00		5,00		10,00		10,00
Unit 1	0,33	109,58	0,33	109,58	0,29	95,99	0,29	95,99	0,25	82,02	0,25	82,02	0,20	67,44	0,20	67,44	0,15	51,61	0,16
Unit 2	0,26	43,42	0,01	2,16	0,23	38,46	0,01	2,16	0,20	33,35	0,01	2,18	0,17	27,98	0,01	2,15	0,13	22,19	0,01
Building	0,23	111,74	0,23	111,74	0,20	98,15	0,20	98,15	0,17	84,18	0,17	84,18	0,14	69,59	0,14	69,59	0,11	53,74	0,11
onnected Post-retrofit + Vent.	-10,00		-10,00		-5,00		-5,00		0,00		0,00		5,00		5,00		10,00		10,00
Unit 1	0,46	150,62	0,46	150,62	0,41	134,84	0,41	134,84	0,36	118,29	0,36	118,29	0,30	100,39	0,30	100,39	0,26	86,19	0,26
Unit 2	0,84	137,66	0,00	0,00	0,77	126,14	0,00	0,00	0,69	114,01	0,00	0,00	0,62	102,02	0,01	1,37	0,54	88,67	0,01
Building	0,30	150,62	0,30	150,62	0,27	134,84	0,27	134,84	0,24	118,29	0,24	118,29	0,21	101,76	0,21	101,76	0,18	88,66	0,18
Isolated Post-retrofit + Vent.	-10,00		-10,00		-5,00		-5,00		0,00		0,00		5,00		5,00		10,00		10,00
Unit 1	0,35	114,70	0,35	114,70	0,31	100,98	0,31	100,98	0,26	86,75	0,26	86,75	0,22	72,06	0,22	72,06	0,17	56,36	0,17
Unit 2	0,50	82,49	0,18	29,78	0,47	77,68	0,18	30,06	0,44	72,64	0,19	30,57	0,43	71,30	0,21	34,52	0,42	69,58	0,23
Building	0,29	144,48	0,29	144,48	0,27	131,04	0,27	131,04	0,24	117,32	0,24	117,32	0,22	106,58	0,22	106,58	0,19	94,44	0,19

Moderate Wind (10 km/h)

	Outdoor Temp = -10oC				Outdoor Temp = -5oC				Outdoor Temp = 0oC				Outdoor Temp = 5oC				Outdoor Temp = 10oC		
	Total ACH		Fresh ACH		Total ACH		Fresh ACH		Total ACH		Fresh ACH		Total ACH		Fresh ACH		Total ACH		Fresh ACH
Connected Pre-retrofit	-10	CFM	-10,00	CFM	-5,00	CFM	-5,00	CFM	0,00	CFM	0,00	CFM	5,00	CFM	5,00	CFM	10,00	CFM	10,00
Unit 1	0,51	167,52	0,51	167,52	0,45	149,13	0,45	149,13	0,40	130,34	0,40	130,34	0,34	110,77	0,34	110,77	0,27	89,56	0,27
Unit 2	0,91	150,01	0,02	3,45	0,81	132,81	0,02	3,87	0,70	115,00	0,03	4,24	0,58	96,11	0,03	4,56	0,47	77,33	0,04
Building	0,35	170,97	0,35	170,97	0,31	153,00	0,31	153,00	0,27	134,58	0,27	134,58	0,23	115,33	0,23	115,33	0,20	96,54	0,20
Isolated Pre-retrofit	-10,00		-10,00		-5,00		-5,00		0,00		0,00		5,00		5,00		10,00		10,00
Unit 1	0,34	113,26	0,34	113,26	0,31	102,00	0,31	102,00	0,27	90,10	0,27	90,10	0,23	77,45	0,23	77,45	0,19	63,66	0,19
Unit 2	0,48	79,35	0,17	28,22	0,43	71,01	0,16	25,72	0,38	62,34	0,14	23,14	0,32	53,22	0,12	20,45	0,26	43,29	0,11
Building	0,29	141,48	0,29	141,48	0,26	127,72	0,26	127,72	0,23	113,24	0,23	113,24	0,20	97,90	0,20	97,90	0,16	81,16	0,16
Connected Post-retrofit	-10,00		-10,00		-5,00		-5,00		0,00		0,00		5,00		5,00		10,00		10,00
Unit 1	0,42	139,68	0,42	139,68	0,38	124,55	0,38	124,55	0,33	108,90	0,33	108,90	0,28	91,99	0,28	91,99	0,22	74,06	0,22
Unit 2	0,57	93,24	0,00	0,00	0,50	81,85	0,00	0,00	0,42	69,92	0,00	0,00	0,35	57,10	0,00	0,63	0,27	45,00	0,02
Building	0,28	139,68	0,28	139,68	0,25	124,55	0,25	124,55	0,22	108,90	0,22	108,90	0,19	92,62	0,19	92,62	0,16	76,65	0,16
Isolated Post-retrofit	-10,00		-10,00		-5,00		-5,00		0,00		0,00		5,00		5,00		10,00		10,00
Unit 1	0,32	106,69	0,32	106,69	0,29	96,54	0,29	96,54	0,26	85,38	0,26	85,38	0,22	73,16	0,22	73,16	0,18	59,90	0,18
Unit 2	0,29	47,57	0,03	5,65	0,26	42,65	0,03	5,54	0,23	37,37	0,03	5,43	0,20	32,30	0,04	6,16	0,17	27,93	0,05
Building	0,23	112,34	0,23	112,34	0,21	102,08	0,21	102,08	0,18	90,81	0,18	90,81	0,16	79,32	0,16	79,32	0,14	67,77	0,14
onnected Post-retrofit + Vent	-10,00		-10,00		-5,00		-5,00		0,00		0,00		5,00		5,00		10,00		10,00
Unit 1	0,49	162,31	0,49	162,31	0,44	146,62	0,44	146,62	0,40	130,61	0,40	130,61	0,34	113,59	0,34	113,59	0,29	95,73	0,29
Unit 2	0,83	137,22	0,01	1,86	0,77	128,77	0,02	3,26	0,70	115,64	0,03	4,30	0,63	103,18	0,03	5,46	0,56	92,73	0,06
Building	0,33	164,17	0,33	164,17	0,30	149,88	0,30	149,88	0,27	134,91	0,27	134,91	0,24	119,05	0,24	119,05	0,21	104,90	0,21
Isolated Post-retrofit + Vent	-10,00		-10,00		-5,00		-5,00		0,00		0,00		5,00		5,00		10,00		10,00
Unit 1	0,35	114,70	0,35	114,70	0,32	104,12	0,32	104,12	0,28	92,85	0,28	92,85	0,24	80,65	0,24	80,65	0,21	67,78	0,21
Unit 2	0,53	88,90	0,20	33,65	0,50	82,14	0,20	33,60	0,47	76,65	0,20	33,12	0,44	72,05	0,21	34,25	0,43	70,25	0,23
Building	0,30	148,35	0,30	148,35	0,28	137,72	0,28	137,72	0,25	125,97	0,25	125,97	0,23	114,90	0,23	114,90	0,21	105,80	0,21