Advanced Zonal Infiltration Measurement Method for Multifamily Buildings: A Novel Test Procedure to Determine Air Leakage Through External and Internal Surfaces

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ABSTRACT

Measuring air infiltration through the external building envelope as well as between adjacent zones within a building is important since air leakage is related to increased energy use and poor indoor air quality (IAQ). State of the art methods can determine both leakages, however it can be both time consuming and labor intensive as it requires running both guarded and compartmentalization tests. This paper presents our work on developing a simplified testing procedure to determine power law flow equation leakage parameters of both external and internal boundaries of tested zones. The proposed Zonal Multipoint Pressure Test (ZMPT) method modulates airflow in the zone using a variable airflow measurement panel (mounted in either a window or the door), and solving the mass balance equations for the leakage parameters. ZMPT results were compared to conventional test results and found to correlate to within +/-7%.

INTRODUCTION

Infiltration through the external envelope of a building as well as between adjacent zones within a building has implications on energy use as well as indoor air quality (IAQ). Our research focusses on developing a simplified testing procedure to simultaneously determine both internal and external leakage characteristics. This paper presents our work on development of the proposed Zonal Multipoint Pressure Test (ZMPT) method, including the numerical algorithm and related hardware to conduct the experiments, as well as the preliminary field testing to verify the ZMPT methodology and issues encountered.

The energy savings, thermal comfort, and indoor air quality benefits of controlling exterior air leakage is well established, and the practice of infiltration testing and modelling for residential low-rise buildings is now commonplace. Infiltration testing has been a mandatory requirement of the residential International Energy Conservation Code (IECC) since 2009 (ICC, 2009), and the 2021 IECC makes infiltration testing mandatory for the commercial code as well.

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Larger multi-family buildings are currently tested for different air tightness code requirements in 3 different ways a) whole building tests, b) compartmentalization tests and c) guarded tests. Whole building tests and guarded tests both measure air leakage through exterior pressure boundaries of the building. Compartmentalization testing measures the entire air leakage of a dwelling unit of a building without distinguishing between interior leakage and exterior leakage. These state of the art methods based on ASTM E779 (ASTM, 2019), can be used together to determine both external and internal surface leakages of a unit in a multifamily building, however this type of testing can be both time consuming and labor intensive as it requires running 2 versions of the ASTM test: a guarded test (with multiple zones simultaneously pressurized using multiple fans) and a compartmentalization test (using a single fan on a single zone), each performed for multiple pressure conditions. Commonly used Home Energy Rating System (HERS) based energy models use exterior infiltration of air as a heating and cooling load (and as an offset for ventilation requirements in single family homes) but these models do not have a way of accounting for variation in the interior leakage to surrounding conditioned areas.

Our research to develop a Zonal Multipoint Pressure Testing (ZMPT) method extends the work of many earlier researchers to further address diagnosis and quantification of air leakage through buildings. The pressurization device used for these tests is the blower door. Commercial production of blower doors in North America dates back to 1980s when they were primarily research devices, but quickly became a diagnostic tool used by weatherization programs for troubleshooting thermal bypasses in homes (Persily, 1982). The use of blower doors in multi-family and commercial buildings was slow to take hold, but in 1980s Modera et. al. was working on applying these new techniques to multi-family buildings and was looking at how blower doors could be used to measure interzonal air leakage (Modera et. al., 1986, Herrlin and Modera, 1988). Hult et. al. in their 2012 report, analyze the different techniques of both single fan and multiple fan methods, to measure internal leakages (Hult et.al. 2012, Hult et. al. 2014). By 1992 Michael Blasnik and Jim Fitzgerald developed Zone Pressure Diagnostics (ZPD) (Blasnik and Fitzgerald 1992, Fitzgerald 1994). ZPD is a quantitative method of determining air leakage through a boundary zone of a pressurized enclosure by measuring the change in the pressure through the zone and the change in the flow through the building when openings in the boundary zone were created to significantly change the pressure drop through the boundary zone. It measures whole building flow and interzonal pressure to determine series leakage in terms of leakages that pass an external boundary and then an internal boundary such as through the roof to ceiling cavity and then through the ceiling to the interior.

The proposed Zonal Multipoint Pressure Test is an expansion of ZPD with the goal of applying it to parallel leakages such as leakages through ceiling/external walls to outside and through internal walls to adjacent interior spaces. It expands the original ZPD approach to calculate the normalized leakage coefficient ($\tilde{C}$) and the leakage exponent (*n*) in the power law flow equation (Eq. 1) where Q_i is the leakage flowrate, A_i is the boundary area and ΔP is the pressure drop across the boundary Like the original ZPD method, it is used to determine the leakage rates through both interior boundaries and exterior boundaries of a tested zone but in ZMPT this is done simultaneously.

$$Q_i = \widetilde{C}_\iota A_i (\Delta P)^{n_i} \tag{1}$$

The power law flow equation can be used to take flows measured at high pressures and extrapolate the expected flow at natural pressures in a building. These high pressures (typically 50 or 75 Pa), are used because they easily achieve repeatable testing conditions using blower doors; whereas natural pressures (typically up to 10 Pa) result in variations depending on wind, temperature and mechanical pressures on a building. With improved standards for measurement of interzonal leakage and improved predictions of energy savings and IAQ impacts, effective goals for air sealing of zones of buildings can be better established and incentivized.

Current Residential Infiltration Testing Standards

The latest residential air tightness testing standard is RESNET/ANSI 380-2019 (RESNET, 2019) and the accompanying modelling standard is RESNET/ANSI 301-2019 (RESNET, 2019). These standards encourage multipoint air leakage testing, the results of which can be used to determine $\tilde{C}$ and n factors in the Power Law flow equation (Eq. 1). RESNET/ANSI 380-2019 does allow single pressure point testing, but the results of a single point test are assigned a 10% penalty when used in residential energy modelling or for compliance programs. RESNET/ANSI 380-2019 describes only one type of test methodology, which is a compartmentalization test of a single dwelling unit. However, it doesn't require adjacent dwelling units to be consistently open or closed to the interior or to the exterior. RESNET/ANSI 301-2019 requires the RESNET/ANSI 380-2019 compartmentalization test of a dwelling unit as an input for the energy model of a dwelling unit. If the normalized air leakage is less than 0.30 cfm_{50}/ft^2 (1.52 L/s-m^2) of the enclosure, this standard allows the results of the test to be multiplied by a reduction factor which is the ratio of the exterior enclosure area to the total enclosure area.

The resulting input to the residential energy model has three significant concerns for the compartmentalization test standard. The first is the lack of consistent treatment of surrounding spaces from RESNET/ANSI 380, the second is the discontinuity of the input to the model for air tightness results above and below the threshold of 0.30 cfm_{50}/ft^2 (1.52 L/s-m^2) of enclosure from RESNET/ANSI 301, and the third is that there appears to be poor correlation between results of a compartmentalization test and exterior infiltration (Bohac et. al., 2020.)

When the 2012 IECC was applied to residential buildings of up to 3 stories, only a small percentage of multi-family homes could pass the mandatory air tightness test limit of 3 ACH50 (air changes per hour conducted at 50 Pa) using compartmentalization tests. Where individual units had to be tested, the easier path to passing this limit was to perform guarded testing in which adjacent conditioned spaces are all held at the same pressure as the dwelling unit being tested in a type of multi-zone test which eliminated measured leakage to conditioned spaces and measured only leakage to the exterior or to unconditioned space. As a result, guarded testing became common in states where these requirements were in place, however there was no ASTM or ANSI standard that thoroughly described the practice. Guarded testing was not included in the RESNET/ANSI 380 standard because it does not quantify the interior leakage and therefore doesn't encourage the good practice of air sealing of interior boundaries of dwelling units. It was also thought to be relatively rare, a complicated test to run, and difficult to repeat for quality assurance.

We propose our Zonal Multipoint Pressure Test to overcome the shortcomings of the 3 current test methodologies and can quantify both interior and exterior leakage of a dwelling unit. While a combination of results from a multi-point Guarded test and a multi-point Compartmentalization test can also quantify the interior and exterior leakage of a dwelling unit, performing these tests for many units in a multi-zone building would take much more testing time and effort than is feasible for common practice. The 3 types of tests are 1) whole building infiltration test, 2) Compartmentalization test of a unit/room and 3) Guarded test of a unit/room. Whole building infiltration testing is performed to characterize the infiltration through the total external envelope of a building. Compartmentalization testing is performed to measure the infiltration through the total boundary of a dwelling unit in a multifamily building. In this, a fan is mounted on the door of the unit in concern and the unit is either pressurized or depressurized to achieve a series of unit pressures with respect to atmospheric pressure. In order to make sure that all the neighboring spaces of the unit are at atmospheric pressure, windows and doors of the neighboring units and other parts of the building should be opened to outside as shown in Figure 1a. In this type of testing there is no differentiation of leakage through external (shared with outside) and internal walls (shared with other conditioned spaces in the same building) boundaries.

Guarded testing (Figure 1b) is performed to directly identify leakage through only the external surfaces. In this test, all internal neighboring spaces are equally pressurized using a fan at the building main door so that there is no pressure drop across any internal surfaces, and hence no internal leakage airflow (Q_{int}). From a mass balance, airflow measured through the fan mounted on the dwelling unit is equal to the airflow through the external boundary.

Conventional testing used in this study includes both compartmentalization and guarded tests for multiple unit pressures (P_{Rm}) ranging from 10 to 60 Pa and the data were fitted for a standard power law model using the least square method to determine leakage characteristics of 1) total unit envelope from compartmentalization test data and 2) external boundaries ($\widetilde{C_{ext}}, n_{ext}$) from guarded test data. Equation 2 below was used to determine the leakage flowrate through the internal boundaries (Q_{int_calc}) for the same room pressures used in the compartmentalization test using compartmentalization flowrate ($Q_{compart.}$) and external flowrate (Q_{ext}). These pressure and flowrate data were then fitted with the power law fit using the least square method to calculate the leakage characteristics ($\widetilde{C_{int}}, n_{int}$) of the internal boundaries.

$$Q_{int\_calc} = Q_{compart.} - Q_{ext} = \widetilde{C_{int}} A_{int} (\Delta P_{int})^{n_{int}} \tag{2}$$

One concern, is that when $Q_{compart.} >> Q_{ext}$, there might be errors and large uncertainties introduced since internal flowrate is a calculated as the difference between a very large number and a small number.

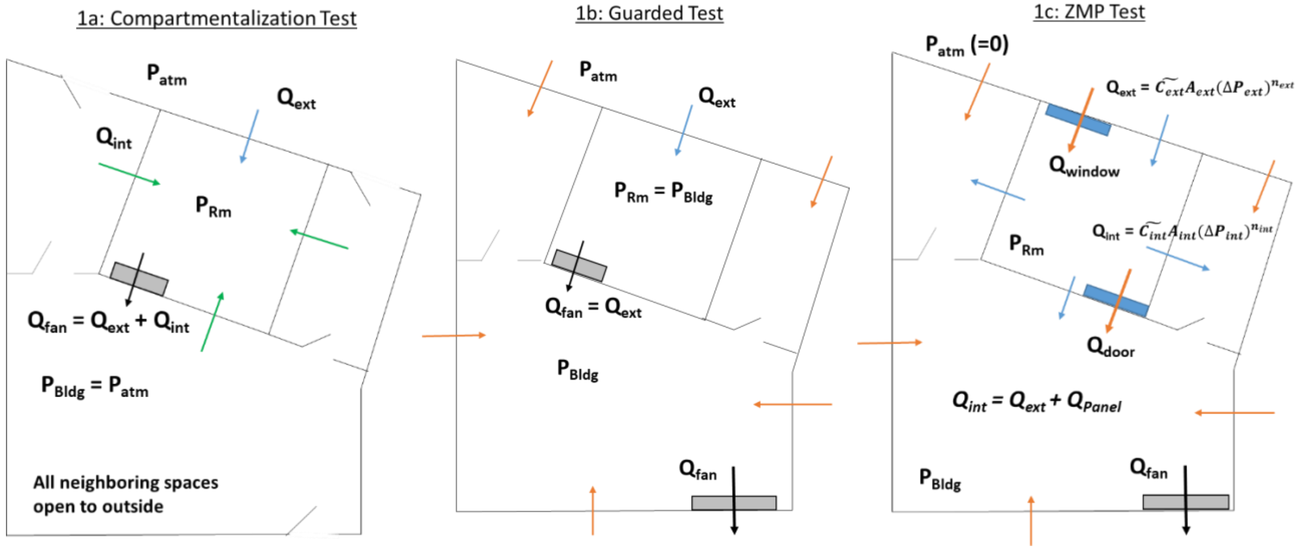

Figure 1 a) Compartmentalization, b) Guarded and c) ZMP test setups for 2-lump system showing air flow paths for unit/building depressurization.

ZMPT Development

To develop and evaluate the performance of the ZMPT method, we have taken an integrated effort involving analysis/modelling/algorithm development, equipment design and experimental evaluation, and testing in a number of real buildings. To develop a solution methodology for the system of equations reflecting the pressure and flowrate relationships of a building, an algorithm was developed to solve the system of nonlinear equations. The simple case of one dwelling unit of a building is focused on, treating the rest of the rooms/apartment units/common spaces as a single combined body (2-lumped system). To develop the related ZMPT hardware, we have built and experimentally tested a series of door/window panels, and to evaluate the viability of this method, we have conducted a number of real-world tests in buildings.

A truth model was developed to find the expected building conditions in terms of the pressure in different spaces (P_i) and flowrate through walls and panels (Q_i). Conditions for the truth model include: dwelling unit volumes (V_i), areas (A_i) of each type of boundary, boundary leakage parameters, i.e. normalized leakage flow coefficient ($\tilde{C}_i$) and leakage pressure exponent (n_i). For the model and results presented in this paper, a 2- lump system of one dwelling unit and the rest of the building is considered where all boundaries that are shared between the unit in concern and other spaces of the same building (other rooms, units or common spaces) are collectively treated as internal boundaries whereas all other walls/celling/floor are collectively treated as external boundaries. The standard power law relationship between pressure and airflow (Eq. 1) (Walker et. al., 1997) was used. In this representation $\widetilde{C_i}$ is the normalized (per ft^2) leakage coefficient and n_i is the leakage exponent which is expected to be between 0.5 and 1 (Lstiburek, 2000). From crack flow analysis, turbulent flows in large holes are expected to have exponents close to 0.5 while laminar flows in small holes are expected to have exponents close to 1 (Sherman, 1980). A mass balance yields a dynamic differential pressure relationship (Eq. 3) which can be solved in terms of flow rates based on the measured pressures of spaces and wall/panel flowrates. Here V_{Rm} is the room volume, $\dot{P}_{Rm}$ is the time variation of room pressure and Q_{ext}, Q_{int} and Q_{panel} are external, internal and panel flowrates.

$$V_{Rm}\dot{P}_{Rm} = Q_{ext} - Q_{int} + Q_{panel} \tag{3}$$

ZMPT Approach and Algorithm Development

ZMPT requires development of an algorithm to solve the nonlinear system of equations that can determine the characteristics of walls in the building (leakage coefficient and exponent of walls) using the measured pressure of spaces and the airflow rate through door/window panels. Figure 1c shows a simplified model of a typical 2-lump system where the room and rest of the building are considered to be the two systems. A calibrated ZMPT panel that can modulate and measure door ($Q_{p,door}$) and window ($Q_{p,window}$) panel flowrates and a blower door is used to depressurize the rest of the building. In practice, to make sure that all neighboring spaces of the room are at the same pressure, all internal doors of the building are opened, and a whole building envelope leakage test fan pressurization method is used (ASTM, 2019). In steady state, Equation 3 yields the mass balance relationship shown in Equation 4. Based on Equation 4 and using the pressure-flow relationship in Eq. 1, the system relationship given by Equation 5 is derived where f_i denotes the particular pressure and flow test conditions.

$$Q_{ext} + Q_{p,window} = Q_{int} + Q_{p,door} \tag{4}$$

$$f_i(\vec{x}) = \widetilde{C_{ext}} A_{ext} (\Delta P_{ext,i})^{n_{ext}} + Q_{p,window,i} - \widetilde{C_{int}} A_{int} (\Delta P_{ext,i})^{n_{int}} - Q_{p,door,i} = 0 \tag{5}$$

Equation 5 has 4 unknowns, $\widetilde{C_{ext}}$, n_{ext}, $\widetilde{C_{int}}$ and n_{int}, and can be expressed as a vector ($\vec{x}$). To solve for all unknowns, at least 4 pressure and flow rate test conditions are required. Each of these need to result in "independent" conditions, i.e. so that the system of equations is well posed, and the Jacobian of the system is non-singular. This is done by modulating P_{Bldg}, Q_{door}, and/or Q_{window} to get independent internal and external pressure differences.

Thus, a system of equations is developed (Eq. 5) using four different operating conditions of pressure and flowrates (based on the truth model). This system of equations is then linearized and numerically solved using an iterative Newton's method utilizing the inverse of the Jacobian matrix (J) as expressed in Equations 6 and 7 and the unknowns (perturbations of unknowns) are iteratively solved. Equation 7 is iteratively solved until the solution converges within a certain tolerance level.

$$f_i(\vec{x_j})_k + \left[\frac{\partial f_i}{\partial x_j}\right]_k \overrightarrow{\delta x_j} = \vec{b} + J\overrightarrow{\delta x} = 0 \tag{6}$$

$$\overrightarrow{\delta x_j} = -J^{-1}\vec{b} = -J^{-1}\,[f_i]_k \tag{7}$$

Algorithm Verification and Error Analysis

Selection of test conditions is based on 2 goals; a) convergence of the algorithm to obtain an estimate for the four unknowns and b) those that will minimize errors in converged values in the presence of measurement error. An example set of conditions generated using the truth model is shown in Table 1. Input leakage parameters of external and internal surfaces to the truth model were based on experiments conducted in a Boston University brownstone dormitory building. Building leakage parameter values were $\widetilde{C_{ext}} = 0.09$, $n_{ext} = 0.83$, $A_{ext} = 120$ ft² (11 m²), $\widetilde{C_{int}} = 0.29$, $n_{int} = 0.6$

and A_{int}=340 ft^2 (32 m^2). **The algorithm was able to successfully recover the same leakage parameters using the iterative method in Eq. 7 within 6 iterations.** This was done by the use of measured values for panel flowrates that are based directly on the truth model.

Table 1. Truth Model Generated Data for 4 ZMPT Conditions Used to Iteratively Solve and Recover Leakage Parameters (*Algorithm Uses the Values in Bold Face)

n	P_{Rm} (Pa)	P_{Bldg} (Pa)	ΔP_{ext} (Pa)*	ΔP_{int} (Pa)*	$Q_{window,panel}$*CFM(L/s)	$Q_{door,panel}$* CFM(L/s)
1	-15.8	-50	**15.8**	**34.2**	**715** (337)	**0**
2	-9.1	-30	**9.1**	**20.9**	**543** (256)	**0**
3	-46.9	-50	**46.9**	**3.1**	**0**	**70** (33)
4	-28.5	-30	**28.5**	**1.5**	**0**	**49** (23)

To test the sensitivity of solving the system of equations when there is a pressure measurement error, 1) a +5% error to column 4 of Table 1 (ΔP_{ext}) and corresponding error to column 6 (Q_{window}), 2) a -5% error to column 4 of Table 1 (ΔP_{ext}) and corresponding error to column 6 (Q_{window}), 3) a +5% error to column 5 (ΔP_{int}) and corresponding error to column 7 (Q_{door}) and, 4) a -5% error to column 5 (ΔP_{int}) and corresponding error to column 7 (Q_{door}) were introduced. Table 2 shows the values of the parameters that the algorithm converged to when pressure measurement error is introduced and the actual values of the parameters used in the truth model, showing that a 5% pressure measurement error can lead to up to 3.1% error in the values of the parameters and up to 3% error in the calculated modelled flow rate.

Our primary interest of developing the ZMPT system is not in obtaining the leakage parameters, but rather the actual leakage airflow rates that will be calculated using these parameters. To this end, Table 2 gives the area normalized external ($\tilde{Q}_{ext}$) and internal leakage ($\tilde{Q}_{int}$) flowrates shown in CFM/ft^2 / L/s-m^2 at a pressure of 50 Pa.

Table 2. Comparison of Actual Values of Variables and Modelled Flowrates Used in the Truth Model to Recovered Variable Values and Flowrates from the Algorithm

	Actual modelled variables	**Identified values with +5% measured Δ(P_{ext}) error**	**Identified values with -5% measured Δ(P_{ext}) error**	**Identified value with +5% measured Δ(P_{int}) error**	**Identified value with -5% measured Δ(P_{int}) error**
$\widetilde{C_{ext}}$	0.09	0.088 (-2.4%)	0.092 (2.6%)	0.091 (0.9%)	0.089 (-0.9%)
n_{ext}	0.83	0.830 (0.1%)	0.830 (-0.1%)	0.830 (-0.1%)	0.830 (0.1%)
$\widetilde{C_{int}}$	0.29	0.297 (2.5%)	0.283 (-2.5%)	0.282 (-2.9%)	0.299 (3.1%)
n_{int}	0.60	0.600 (0%)	0.600 (0%)	0.600 (0%)	0.600 (0%)
$\tilde{Q}_{ext}$ at 50Pa	2.31 /11.7	2.26/11.5 **(-2.3%)**	2.37/12.0 **(2.4%)**	2.33/11.8 **(0.7%)**	2.30/11.7 **(-0.7%)**
$\tilde{Q}_{int}$ at 50Pa	3.03 /15.4	3.10/15.7 **(2.4%)**	2.96/15.0 **(-2.4%)**	2.95/15.0 **(-2.8%)**	3.12/15.8 **(3.0%)**

ZMP FIELD TESTING

To conduct the ZMP tests in real buildings (Figure 1c), all internal neighboring spaces were depressurized to the same pressure using a fan at the building main door by opening all internal doors. Unit main door was closed and a ZMPT panel device was mounted with adjustable holes. Flowrate through the panel was calibrated and measured using a powered flow hood. Combinations of 2 to 3 building pressures and 2 to 3 panel hole sizes (panel flowrates) were used to generate 4 to 9 independent pressure-flowrate relationships. These conditions were then used with the algorithm (Equations 6-7) to iteratively determine external and internal leakage parameters ($\boldsymbol{\widetilde{C_{ext}}}$, $\boldsymbol{n_{ext}}$, $\boldsymbol{\widetilde{C_{int}}}$ and $\boldsymbol{n_{int}}$).

The ZMPT panel device was constructed with different hole sizes ranging from 6 in. to 12 in. in diameter. The panel was calibrated in a laboratory using two available commercial devices; 1) A calibrated fan was used to modulate and measure airflow and 2) a powered flow hood was used to measure airflow downstream. When run against each other or used to measure the same flow, they read up to 10% different flowrates, raising questions of the accuracy of the measurement procedure, which requires further investigation. This also raises a question as to the accuracy of conventional results which is the basis for comparison of ZMPT results.

Field tests have been performed in 10 buildings with a range of conditions, construction styles, sizes and ages including two brownstone style dormitory buildings constructed about a century ago and newly constructed/ recently renovated residential buildings in Massachusetts. Both the conventional style guarded and compartmentalization testing under the current standards, as well as ZMP testing were conducted to calculate leakage parameters for external and internal surfaces of a dwelling unit using the 2-lump model. Figure 2 compares the results from conventional and ZMP testing for the residential buildings including the normalized external ($\tilde{Q}_{ext}$) and internal ($\tilde{Q}_{int}$) leakage flowrates shown in CFM/ft^2 / L/s-m^2 at 50 Pa.

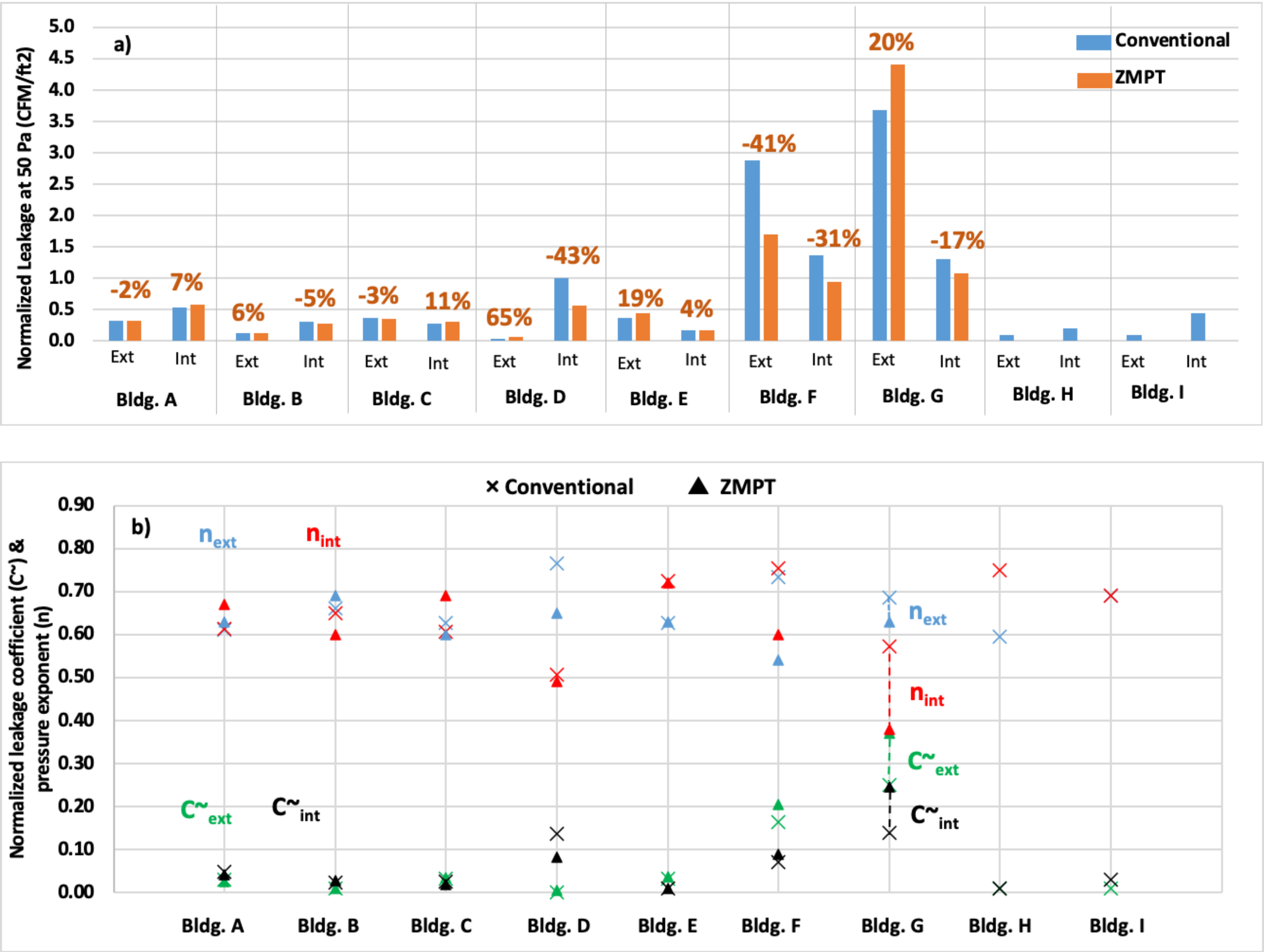

Figure 2 a) Comparison of conventional and ZMP normalized leakage at 50 Pa. **b)** Comparison of conventional and ZMP leakage parameters for tested residential buildings. Buildings A to C shows good agreement, Buildings D to G shows larger errors and for Buildings H and I, ZMPT algorithm did not converge to a solution.

Buildings A, B and C shows leak flow agreement within 10% for the ZMPT compared to conventional guarded and compartmentalization test results. However, results from buildings D to G showed up to 40% difference. In Building D, the wind effect varied on exterior boundaries with different orientations, making the pressure across the external boundary non-uniform. In building E, outside pressure was measured with respect to a common location at the blower door as is the standard practice in blower door testing. However, this might be different from the pressure at the external boundary of the tested unit.

Buildings F and G are brownstone dormitory buildings at Boston University built circa. 1900 and had unusually high leakage especially through internal boundaries. Structurally, these buildings also had large interstitial spaces (chimneys and shafts) that could well be affecting the leakage. For buildings H and I, the ZMPT algorithm did not converge to a solution. For these buildings, a calibrated fan was used instead of the powered flow hood to measure panel flow rate and its accuracy needs to be tested for this specific application. In H and I, non-convergence of the algorithm could also be a numerical issue related to operating conditions used. In Building J, there was an uncovered internal vent in the tested unit that caused large errors in even conventional testing. In addition to these specific issues, air leakage across a boundary was generally taken to be symmetric for both directions but this is not necessarily the case for all buildings.

CONCLUSION

This paper presents our research to develop a simplified testing method that can determine infiltration characteristics of both external and internal pressure boundaries of units in a multifamily building. Building models were used to evaluate the proposed Zonal Multipoint Pressure Testing (ZMPT) method and the numerical algorithm, and the solution procedure was verified using a truth model which was able to recover leakage parameters (leakage coefficient and leakage exponent) successfully. Sensitivity analysis showed a less than +/-3% variation of results for measurement errors up to +/-5%.

We also conducted field test experiments on 10 commercial buildings. In 3 cases, agreement was shown to be within +/-7% between the ZMPT results compared to conventional testing results. However, in 4 tests, there were significant differences (>20%). These cases highlighted issues including accuracy of both conventional and proposed testing, building and climate specific issues such as interstitial spaces, presence of wind, as well as calibration accuracy of our current airflow measurement devices. In 2 cases, our algorithm did not converge, indicating the need to better specify testing conditions to achieve independent conditions.

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DISCLAIMER

NOMENCLATURE

P = Pressure (Pa)
Q = Airflow rate (CFM / L/s)
$\tilde{Q}$ = Normalized airflow rate (CFM/ft^2 / L/s-m^2)
A = Area (ft^2 / m^2)
V = Volume of spaces (ft^3 / m^3)
$\tilde{C}$ = Normalized leakage flow coefficient
n = Leakage pressure exponent

Subscripts

ext = External
int = Internal
Rm = Room
Bldg = Building
atm = Atmosphere
compart. = compartmentalization

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