Sensitivity Analysis of Infiltration Rates Impact on Office Building Energy Performance

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Abstract. Modeling and predicting building infiltration impact on building energy performance presents a challenge. This paper analyses the modeling method of infiltration rates in different simulation programs. Field blower door test results of building infiltration rates are compared and summarized. Based on literature simulation and field study data, this research analyses the building infiltration rates on the office building HVAC energy use under various climate conditions. Suggested and preferred infiltration rates under various climates are listed.

1. Introduction

Different from building ventilation, building infiltration is defined as “the uncontrolled inward air leakage through cracks and crevices in any building element and around windows and doors of a building caused by pressure differences across these elements due to factors such as wind, inside and out temperature differences (stack effect), and imbalance between supply and exhaust air systems” (ASHRAE 2004).

Building infiltration may have an important impact on the building energy performance, depending on the climate where the building is located in, the building types, building envelope contractions and etc. A research by National Institute of Standards and Technology estimated that infiltration is responsible for about 15% of the total heating energy and 4% of the total cooling energy for U.S. office buildings (Emmerich et al. 1995). In newer buildings, infiltration is responsible for around 25% of heating load due to the higher level of insulation. Results also indicate that potential energy savings on the order of 26% for heating load and 15% for cooling load could be realized by tightening building envelopes (Emmerich and Persily 1998). In the building simulation field, how to modeling the building and space infiltration rate and associated energy impacts still have uncertainties due to actual infiltration rates are difficult to predict before building constructed.

2. Modeling infiltration rates

As building and space infiltration rates are impacted by many factors, it is often difficult to precisely predict the space infiltration rates without the actual onsite test data. Some theoretical infiltration calculation models such as LEAKS, SWIFB, LBL, RMS are proposed and compared with a field measurement data for validation (Li et.al. 2004). In modeling the space infiltration rate, the often used method is air change method, which uses the following formula:
\[ Q = \text{ACH} \times \frac{V}{3600} \]  

(1)

where, \( Q \): infiltration rate, \( m^3/s \); \( \text{ACH} \): air change rate per hour; \( V \): space volume, \( m^3 \).

In this formula, it is often difficult to determine the air change rate caused by building infiltration. Various simulation programs provide different default values for modeling building and space infiltration rates, based on the exterior wall and window surface areas.

2.1 **eQUEST**

In the eQUEST simulation program (DOE2.2 calculation engine), the default infiltration rate is set as 0.2 \( L/s \cdot m^2 \), based on exterior wall and window areas for perimeter zones; and 0.05 \( L/s \cdot m^2 \), based on floor area for interior zones (often adjusted to 0 for commercial buildings).

2.2 **EE4**

In the EE4 simulation program (DOE2.1 Calculation engine), the default infiltration rate is set as 0.25 \( L/s \cdot m^2 \) based on exterior wall and window areas for perimeter zones, possibly considering the factors of higher latitude and higher average outdoor air speed in Canada.

2.3 **EnergyPlus**

Infiltration in EnergyPlus is specified as a design level, which is modified by a schedule fraction, temperature difference and wind speed (DOE 2007):

\[ Q = I_{\text{design}} \times F_{\text{schedule}} \times (A + B \times |T_{\text{in}} - T_{\text{out}}|) + C \times V + D \times V^2 \]

(2)

where, \( Q \): infiltration rate from building envelope; \( I_{\text{design}} \): air infiltration rate according to air change method; \( F_{\text{schedule}} \): infiltration rate adjustment schedule, assumed to be 1 for the whole year and can be adjusted in the model; \( T_{\text{in}} \): indoor air temperature; \( T_{\text{out}} \): outdoor air temperature; \( V \): outdoor wind speed; \( A, B, C \) and \( D \): infiltration coefficients, may set as different values.

In the EnergyPlus program, the default coefficients are set as \((1, 0, 0, 0)\), indicating wind and pressure driven factors are not considered. In the DOE-2.1 program, the coefficients are set as \((0, 0, 0.224, 0)\), and in the BLAST program the coefficients are set as \((0.606, 0.03636, 0.1177, 0)\). Based on a review of various infiltration modeling options available in EnergyPlus and sensitivity analysis, US Pacific Northwest National Laboratory report (Gowri et al. 2009) recommends the DOE-2.1 infiltration coefficients setup, which means the wind speed factor in the model are taken into account but need more research on the temperature difference factor.

2.4 **Department of Energy Commercial Prototype Building Models**

US Department of Energy (DOE 2015) Building Energy Codes Program provides Commercial Prototype Building Models for office buildings with the maximum hourly air infiltration rate as 0.56 \( L/s \cdot m^2 \) (HVAC systems off) of exterior wall and window surface areas. The infiltration rates are set as \( 1/4 \) of the maximum infiltration rates, i.e. 0.14 \( L/s \cdot m^2 \) when HVAC systems are operating. The averaged hourly infiltration rate is around 0.35 \( L/s \cdot m^2 \).

3. **Tested infiltration rates**

To explore the actual building infiltration rates under different conditions, US National Institute of Standards and Technology, American Society of Heating and Air-Conditioning Engineers and British Air Tightness and Testing Measurement Association have conducted several filed tests of commercial building infiltration rates under pressure testing conditions. The investigation reveals that different building infiltration rates under various climates, building types, floor heights and construction types
The air infiltration rates tested are based on the blower door test results with indoor-outdoor pressure difference of 50 Pa (ACH 50) and 75 Pa (ACH 75).

US Building Performance Institute (2007) presents a conversion N-factor to convert the pressured infiltration rates to typical natural flow condition infiltration rates:

\[ Q_{\text{natural flow conditions}} = \frac{Q_{\text{ACH}50}}{N\text{-factor}} \] (3)

where N-factors can range from 14 to 26 depends on the building located climate type and N-factors also link to building height factors (0.72-1).

Based on the previous field test results, we summarized the building infiltration rates data and converted to the natural flow conditions infiltration rates in Table 1.

Table 1. Building infiltration rates summary from NIST, ASHRAE and ATTMA Data

| Conditions         | Test Pressure Difference 50Pa | Natural Flow Conditions |
|--------------------|-------------------------------|-------------------------|
|                    | L/s.m² Wall area | L/s.m² Floor area | L/s.m² Wall area | L/s.m² Floor area | ACH |
| ASHRAE Headquarter | 2.8                     | 1.96                 | 2.24             | 0.2               | 0.14 | 0.16 |
| US test high       | 16.7                    | 10.95                | 13.0             | 1.22              | 0.8  | 0.95 |
| US test median     | 5.6                     | 3.69                 | 4.37             | 0.41              | 0.27 | 0.32 |
| UK normal practice | 1.4                     | 0.92                 | 1.12             | 0.1               | 0.066| 0.08 |
| UK best practice   | 0.56                    | 0.36                 | 0.41             | 0.041             | 0.026| 0.03 |

Note: UK normal practice and best practice values are British Building Regulations from British Air Tightness and Testing Measurement Association.

In most countries, there is no target building infiltration control rate required by regulation or building programs for commercial buildings. British Building Regulations have had an airtightness requirement of 10m³/h.m² enclosure area at 50Pa for newly constructed buildings since 2002 (Pickavance and Jones 2006). In recent years, with the fast development of Passive House or near-zero energy building design market, air infiltration rate control has been more strictly and extensively required in the building industry. The Passive House Institute (PHI 2015) and corresponding China Passive Low Energy Building Guideline (MOHURD 2015) require ACH50 air infiltration rate lower than 0.6 ACH under all climates.

4. Sensitivity simulation analysis of infiltration rates

To analyze infiltration rates impact on office building energy performance under different climate conditions, the Medium Size Office Building Model in the Department of Energy Commercial Building Prototype Building Model (Figure 1) is selected for sensitivity analysis. The model basic parametric setting information is listed in Table 2.

The building average hourly infiltration rates settings for the working day are set as 0.05 L/s.m² of the exterior wall surface area (Passive House Institute setting, crude approximation to the UK best practice in the industry), 0.1 L/s.m² (UK normal practice), 0.2 L/s.m² (typical simulation set values), 0.41 L/s.m² (US test median infiltration value). The simulated building HVAC energy uses under hot summer and warm winter climate (ASHRAE 2A), hot summer and cold winter (ASHRAE 3A), mild climate (ASHRAE 3C), cold climate (ASHRAE 5A) and extremely cold climate (ASHRAE 6A) are presented in Figures 2-6.
Figure 1. DOE Prototype Medium Office Building Model

Table 2. Simulation model basic parametric settings

| Parameters                | Setting values                                                                 |
|---------------------------|-------------------------------------------------------------------------------|
| Dimensions of building    | 50*33*3.9 m³ 3Floors                                                          |
| Window-to-Wall ratio      | 33%                                                                           |
| Foundation type           | Slab on the ground (unheated)                                                 |
| Building envelope         | ASHRAE 90.1-2013 Standards requirements                                      |
| Heating and cooling       | Gas furnace with packaged terminal VAV air conditioning unit; Packaged terminal VAV air conditioning and reheating coil unit |
| HVAC efficiency           | ASHRAE 90.1-2013 Standards                                                    |
| Thermostat settings       | Cooling (24°C) / Heating(21°C)                                               |
| Ventilation rates         | ASHRAE 62.1 Standards Minimum outdoor air requirements                        |
| Basic air infiltration    | Peak: 0.56 L/s.m² hourly of above grade exterior wall surface area, adjusted by wind (when fans turn off); Off Peak: 25% of peak infiltration rate (when fans turn on) |
|                           | Additional infiltration through building entrance                             |

4.1 Infiltration rate energy impact under hot summer and warm winter climate

As can be seen from Figure 2, the increment of infiltration rate from around UK best practice to normal practice and then simulated average practice, the building HVAC energy use only increases around 1.6%, which is considered only marginal impact on the building HVAC energy use. When infiltration rate increases to US test median conditions, the HVAC energy uses increase around 7%, not a linear increment, especially for the heating energy use part with around 30% increment.

Figures 2 (left) & 3 (right). Infiltration rates energy impact on Office building HVAC energy uses under hot summer and cold winter climate (left) and results under hot summer and warm winter climate (right).
4.2 Infiltration rate energy impact under hot summer and cold winter climate
The building HVAC energy uses with various infiltration rates are illustrated in Figure 3. Similar to the results under the hot summer and warm winter climate, the increment of infiltration rate majorly has moderate to significant impact on the building heating energy use. With the infiltration rates increment from 0.05 to 0.41 L/s.m², the heating energy increases around 33% and total HVAC energy uses increase by 14%.

4.3 Infiltration rate energy impact under mild climate
Under mild climate such as ASHRAE climate 3C, the infiltration rates increment has a minor impact on the total HVAC energy uses. When the infiltration rate increases from 0.05 to 0.2 L/s.m², the total energy uses increase by only 1.8% even though the heating energy use increases by 14.7%. With the infiltration rate increment to 0.41 L/s.m², the increment for HVAC energy use is 4.2%, but 27.8% for heating energy.

4.4 Infiltration rate energy impact under cold and extremely cold climates
The building HVAC energy uses profiles with various infiltration rates under cold and extremely cold climates are plotted in Figures 5 and 6. Two figures present similar trends regarding the HVAC energy use trends with the increment of envelope infiltration rates. Under cold and extremely cold climates with the infiltration rates increase from 0.05 to 0.41 L/s.m², the simulated total HVAC energy uses increase by 21.6% and 24.2%, and heating energy uses increase by 33% and 32.4%, respectively. The values indicate the infiltration rate and building airtightness design have a critical impact on the building HVAC energy uses, especially heating energy uses under cold and extremely cold climates. Due to the average cooler outdoor weather conditions, the increment of outdoor infiltration air actually reduces the cooling energy uses for buildings under extremely cold climates. Under the cold and extremely cold climates, office building total HVAC energy uses are very sensitive to the increments of infiltration rates. When the infiltration rates increase to the general practice as simulated such as 0.2 L/s.m², the energy increment are over 10% (significant impact) for office buildings under the cold and extremely cold climates.

5. Discussions
The research presents the finding of building HVAC energy use sensitivity to the infiltration rates variation under different climates. If we use 5% (moderate), 10% (significant), and 20% (critical) criterion as the evaluation standards on office building HVAC energy uses, then one can see a relatively clear map of the infiltration rate impacts from above results. Under the mild climate (ASHRAE 3C), the infiltration rates have a marginal impact on the building HVAC energy use due to the relatively small temperature differences between indoors and outdoors. From the building energy point of view, maintain the conventional construction at normal airtightness with the infiltration rate of
0.41 L/s.m² should be of minor penalty on the building energy performance and no need to increase building airtightness standards under mild climate conditions.

Under hot summer and warm winter climate (ASHRAE 2A), maintaining the office building hourly infiltration rate at standard default values 0.2 L/s.m² only have the minor impact (<5%) on the building HVAC energy performance and more energy saving strategies and investment would be preferred on the building shading part.

Under hot summer and cold winter climate (ASHRAE 3A), increase the office building infiltration rate to British normal practice of 0.1 L/s.m² only gives rise to minor impact (<5%) on the building HVAC energy use, but the increment of air infiltration rate to 0.3 L/s.m² will have the significant impact (around 10%) on the total building HVAC energy use.

Under cold and extremely cold climates, the increment of air infiltration from best practice level which is the crude approximation to the Passive House Institute requirement of 0.6 ACH to the UK normal practice level of 0.1 L/s.m² starts to show the moderate impact (5%) on building HVAC energy use. It is suggested to strictly control building infiltrations rates under cold and extremely cold climates as the increment of infiltration not only significantly impact building energy performance but also the indoor occupant thermal conditions.

From the above discussion and we conduct a simple linear infiltration energy impact correlation analysis, the suggested control and preferred air filtration rates under different climates are listed in Table 3.

A further sensitivity study is conducted to analyze the increment of building envelope construction to the Passive House Standard level (PHI 2015) under various climate conditions. The simulation results show very similar impacts with infiltration rates changes under various climate conditions.

![Figure 4 (left) &5 (right). Infiltration rates energy impact on Office building HVAC energy uses under cold (left) and extremely cold climates (right)](image)

**Table 3. Suggested control and preferred infiltration rates**

|                     | Suggested control infiltration rate L/s.m² | Preferred infiltration rate L/s.m² |
|---------------------|------------------------------------------|----------------------------------|
| Hot summer and warm winter | 0.35                                      | 0.3                              |
| Hot summer and cold winter     | 0.15                                      | 0.1                              |
| Mild climate                 | 0.41                                      | /                                |
| Cold climate                  | 0.1                                       | 0.05                             |
| Extremely cold climate        | 0.1                                       | 0.05                             |
6. Conclusions
Based on previous literature simulation studies and filed test results from various countries and climate conditions, this research analyzed various infiltration rates on office building HVAC energy performance under various climate conditions. The research finds that the increment of building infiltration rates mainly has a significant impact on the building heating energy use. Under mild climate, infiltration rate variations with reasonable ranges have a minor impact on building energy performance. Under hot summer and warm winter climate, the conventional practices of air tightness will not have a significant impact on building energy performance. Under hot summer and cold winter climate, the increment of infiltration starts to play an important role in the office building total HVAC energy use. Under cold and extremely cold climates, infiltration rates have a significant impact on the building HVAC energy, especially heating energy use. Based on the above simulation results and analysis, suggested control infiltration rates and preferred infiltration rates under various climate conditions are discussed, to reduce the negative impact on building energy performance and indoor occupant thermal comfort.

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