Informed Mechanical Design Through Tested Air Leakage Rates

Jeff Speert[1], Cory Legge[2]

Abstract

Energy efficiency initiatives, such as the 2030 Challenge, hold the integrated design approach as a key for success. Integrated design aims for a collaborative approach between sub-disciplines of building design. However, one relationship not commonly addressed is between building enclosure designers and mechanical engineers. As building insulation and air tightness measures get more sophisticated with corresponding improved performance, there is a need for mechanical engineers to make more accurate assumptions in design in order to reach the efficiency goals for projects. The focus of this paper will be the relation between assumed and actual air leakage rates.

Blower-door testing used to measure air leakage rates of larger new construction buildings is beginning to be required in jurisdictions including Washington State. As a result of the requirements for continuous air barrier design and testing of completed buildings, a body of data on tested leakage rates will soon be available and can be referenced to predict air leakage rates during the design process.

Currently, mechanical engineers make assumptions for air infiltration based on modeling guidelines, sometimes assuming leakage rates 4.5 times or greater more than the prescribed rates under codes. Assumed infiltration amounts typically represent about 35% of building enclosure heat load. This overestimates heating energy requirements and can lead to over sizing of systems when continuous air barriers are installed. By using tested leakage rate data as a basis of assumed leakages, mechanical engineers could create accurate sizing of heating systems which could lead to upfront cost savings, more efficient systems, and operational cost savings.

This paper will examine the potential interaction between post-construction air leakage testing and pre-construction mechanical design parameters. A comparison of various common guidelines for mechanical engineer's infiltration rates will be compared to leakage rates prescribed by codes, protocols, and expected leakages for buildings where attention is paid to continuous air barrier design and execution. Several case studies will be discussed to illustrate current practices. Opportunities for improvement in current practices will be explored.

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[1] Jeff Speert, AIA, MAIBC, LEED®AP, JRS Engineering Corp., Seattle, WA

[2] Cory Legge, AScT, LEED®AP, JRS Engineering Ltd., Vancouver, BC

Introduction

Design and construction trends are toward more energy efficient buildings. Many professionals understand that this goal can be reached by the entire team, including architects, sub consultants and contractors, working openly and collaboratively.

As of yet, the collaboration between mechanical engineers and building enclosure consultants has been lacking. Most enclosure consultants understand the importance of sealing tight and ventilating right, but how tight buildings are created in actual practice is often unknown. When leakage inspection and testing is performed, the results are only available during or at the end of construction. This project specific information comes too late in the process for mechanical engineers to use in load calculations, hence, a chicken and egg problem.

In addition to the sequencing challenges, units of measure are not common between those performing air leakage tests and mechanical system designers. Mechanical engineers commonly use air change per hour (ACH) values that are derived from experience and a variety of reference sources. Whole building air leakage testing of larger buildings is typically reported in CFM/SF of enclosure area at 75 Pascals of differential pressure.

The goal of this paper is to frame existing practices as a first step in initiating discussion between mechanical designers and building enclosure disciplines.

Air Leakage = Infiltration

Whether it is air leakage, coined by building enclosure consultants, or infiltration, coined by mechanical consultants[1], it is time for collaboration between building enclosure consultants and mechanical consultants to create tighter enclosures and optimize mechanical designs. Air leakage accounts for a considerable percentage of heating system capacity in heating climates, although it is not significant for cooling capacity in cooling climates. On average, it is estimated that the assumed air infiltration value accounts for approximately 33% of the heating system size (Emmerich et al. 2005), indicating the real potential for decreasing the net building heating capacity if increased levels of tightness can be achieved. It stands to reason that a building that prevents the free flow of conditioned air out of the building will put less demand on the heating system than one that is not tight and allows conditioned air to leak out through inadvertent breaches in the air barrier.

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[1] The terms air leakage and infiltration will be used interchangeably even though air leakage can take the form of infiltration or exfiltration.

There is an inherent challenge in trying to make assumptions during the design process for how a building will perform once constructed since there is a great variability in the success of continuous air barrier implementation. Current assumptions for infiltration values in most guidelines have been based on research conducted during the 70's, 80's, and 90's. The majority of this research was conducted using blower door test data on existing single family homes. Post construction verifications of infiltration values does identify the building's tightness, however, the values are typically only used to verify enclosure tightness targets for energy performance. Whole building enclosure testing of larger buildings has rarely been conducted, although that is increasing in frequency.

By conducting post construction whole building air leakage testing, there is the potential to gain a better understanding of how buildings actually perform from an infiltration standpoint. In turn, this information can be used by mechanical engineers to more accurately size HVAC equipment.

How Mechanical Engineers Calculate

One component of sizing mechanical systems is an assumption for the amount of uncontrolled air leakage through the building enclosure. The leakier the building enclosure, the greater the heating system capacity will typically need to be to meet this load[2]. Common estimates for infiltration come from reference books (*HVAC Equations, Data, and Rules of Thumb* by Arthur A Bell), ASHRAE (Handbook) Fundamentals, Codes (California Title 24), Manuals (Carrier Manual), modeling guidelines (eQuest for example) and in some cases, the designer's own experience or rules of thumb.

Within and between these guidelines, there is a sizable range in values, from 0.1 ACH to 2.0 ACH Natural for residential buildings, or 0.1 CFM/SF to 9.2 CFM/SF at 75 Pascals for commercial buildings (Emmerich Persley 2005). See Figure 1.

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[2] With the exception of latent loads in certain climates, infiltration assumptions often do not play a significant role in cooling load calculations.

Figure 1: Common Infiltration Assumptions

Source	Infiltration Value
Typically used value	0.35 ACH
eQUEST (DOE)	0.038 CFM/SF of envelope area, or 0.5 ACH
EnergyPlus	1.8 CFM/SF @ 75 Pa
ASHRAE – Fundamentals Chapter 16.15 and 16.29	0.1-2.0 ACH (Residential) 0.5-2.0 ACH (Commercial)
RS-29 (Seattle Energy Code)	Designed leakage of 0.4 CFM/SF at 75 Pa to be modeled at 0.045 CFM/SF

Yet, in discussions with seven mechanical engineers the authors have worked with on multi-family housing projects each had a different method to arrive at infiltration values and stated that they made decisions for the purposes of system sizing based on previous experience. This is because infiltration, along with occupant behavior, remains the biggest unknown impacting the loads on a new building when in design. Many mechanical engineers are conservative when estimating these values for fear of under-sizing capacity. As one engineer stated, he will hear complaints if people are cold, but not if the system is too large. As there is no feedback when a system is too big, the engineer will tend to repeat their assumption which may be invalid.

Unit Conversions

One of the challenges in comparing design parameters and tested leakage rates is inconsistency in units of measure. Leakage rates can either be described in reference to volumes or surface area. The volumetric measure is air changes per hour (ACH) and the surface area measure is cubic feet per minute (CFM) per square foot of enclosure area. Both of these measures are in reference to differential pressure between inside and out.

Most of the historical data is based on blower door test of single family homes with uses ACH at 50 Pascals (ACH50). Current testing standards are moving towards CFM/SF at 75 Pascals. Making conversions between these leakage rates at test pressures and common natural pressure differences is one of the key challenges in collaboration.

Established methods of conversion are used in this paper. ACH natural is converted to ACH50 by multiplying ACH_{NAT} by 20 (Sherman, 1998). In 2009, the Pacific Northwest National Laboratory completed an analysis for infiltration modeling guidelines which presented a methodology for modeling air infiltration using the EnergyPlus software (Goweri et al. 2009). CFM/SF natural is converted to CFM/SF at 75 Pascals by dividing by 0.112. Conversions of ACH and CFM/SF in this paper are done consistent with these two recommendations.

Being Part of the Equation

Large whole building air leakage rates are commonly measured in units of CFM/SF of enclosure area at 75 Pascals of different pressure, whereas single family homes are commonly measured as air changes per hour (ACH) at 50 Pascals of differential pressure. If tested flow rates along with building volumes and enclosure areas are recorded, either of these values is easily determined.

To understand air leakage rates through the building enclosure, it is informative to begin with a scale of relative tightness. The ASHRAE Handbook of Fundamentals in Chapter 16.25 states infiltration values for the building enclosure as 0.6, 0.3, and 0.1 CFM/SF at 75 Pascals for leaky, average, and tight respectively for commercial construction.

Blower door testing has been a valuable tool in measuring and validating the tightness of home construction and targeting areas for corrective work under weatherization programs. Concurrent with advancements in the technology and methods in blower door testing, there has been an industry push towards tighter construction. This is in part a factor of industry and consumer demand to reduce energy use costs, but is also being driven by building and energy code changes that are happening in some jurisdictions around the United States.

Washington State's 2009 Energy Code has included for the first time air barrier requirements for buildings over five storeys in height. The prescribed leakage rate is 0.4 CFM/SF at 75 Pascals. Buildings will be required to have an air barrier designed to meet this requirement and testing must be conducted at the conclusion of construction. At this time, compliance with the Code only requires reporting the tested leakage rate. However, there is an expectation that future Code revisions will require compliance with minimum leakage provision.

The US Army Corp of Engineers (USACE) has established a requirement for continuous air barriers and air leakage testing which has been implemented in many buildings on military bases. The USACE prescribed leakage rate is 0.25 CFM/SF of enclosure area at 75 Pascals, and seems to be a target that has gained traction for high-performance buildings, as it is also been the leakage rate required by the International Green Construction Code (IGCC).

However, outside of research and the practices of some organizations, large, commercial or multifamily building air leakage testing is in its infancy. For this reason, a published compilation of test results for buildings where continuous air barrier design was considered and implemented has not been available to the general building and mechanical design community.

Inconsistencies Between and Within Guidelines

Historically, there has been no correlation between assumed infiltration values and leakage rates.

As earlier stated, in Chapter 16.25 of ASHRAE Handbook of Fundamentals the suggested leakage rates for commercial building enclosures are 0.6, 0.3, and 0.1 CFM/SF at 75 Pascals, for leaky, average, and tight walls, respectively. The ASHRAE Standard 90.1 Envelope Subcommittee, however, recommends using 1.8 CFM/SF at 75 Pascals (Gowri et al. 2009) of exterior, above grade enclosure area as the baseline assumption for energy modeling of enhanced air barrier requirements.

Also within Chapter 16 are recommended ranges of infiltration from 0.1 – 2.0 ACH as listed in Figure 1. Using areas and volumes from Case Studies One and Two as reference for these values, CFM/SF at 75 Pascals equivalents would be a range from approximately 0.40 – 5.33. Clearly this is far from the tight, average and leaky values listed in ASHRAE Handbook of Fundamentals Chapter 16.25.

It is our understanding, in discussions with mechanical consultants and reviewing examples in the ASHRAE Handbook of Fundamentals, that a building's mechanical system is designed and sized based on infiltration loads expressed in ACH Natural. Relating ACH Natural values to the metric used in testing (CFM/SF at 75 Pascals) is a challenge and one of the impediments preventing collaboration between mechanical system designers and building enclosure professionals. In the ASHRAE Fundamentals examples, the suggested infiltration air flow for both residential and commercial building load calculations is 1.0 ACH Natural. This correlates to 20 ACH at 50 Pascals which far leakier than tested leakage rates when a continuous air barrier is included in a building design.

Case Studies

Building 1:

In October of 2010, the authors performed a blower door test of a new multifamily building to determine an air leakage rate and identify breaches in the air barrier's continuity. This test involved using multiple high-powered fans to depressurize the entire enclosure and measure the flow of air at a variety of pressures. The method of testing was consistent with current Washington State Energy Code requirements. See Figure 2

Figure 2: Subject Building for Case Study 1

The building is a 40-unit four-story apartment in Bellingham, Washington owned by a non-profit housing authority. The structure includes 2,500 SF of ground floor retail space. The total enclosure area was 52,911 ft^2, with an enclosed floor area of 41,359 ft^2 and volume of 427,470 ft^3. The tested leakage rates were as follows:

- 0.40 CFM/SF of enclosure area at 75 Pascals
- 2.995 ACH50

This tested value was relatively good considering there was no intent in the design documents for a continuous air barrier. Air barrier rated materials were used, but integration at transition and penetrations was not well considered by the designers.

The mechanical consultant, using ASHRAE's Handbook of Fundamentals, estimated an infiltration value of 1.0 to 1.5 ACH_{NAT}, or 20-30 ACH50 when converted. The system capacity was over-estimated by about 800%. An over estimation in the infiltration rate might have led to an under designed ventilation capacity. This may have an impact on the fresh air supply into the building in the form of uncontrolled humidity level and a less than code required air change. In addition the heating capacity required to keep the building at a service temperature might be oversized.

Building 2:

In August of 2011, the authors conducted a whole building blower door test on a newly constructed apartment building developed and operated by the Seattle Housing Authority. Testing methods were very similar to the ones used for Building 1 noted above. See Figure 3.

Figure 3: Subject Building for Case Study 2

The building is an 86 unit, four-story wood framed structure with a below grade parking level; there are no commercial spaces in the building. The total enclosure area was

121,380 ft^2, with a floor area of 110,822 ft^2 and an enclosure volume of 1,114,163 ft^3. Tested leakage rates were as follows:

- 0.45 CFM per SF of enclosure area
- 2.3 ACH50

The tested result was more leaky than the desired target of 0.4 CFM/SF75. We believe this was most likely due to a modulated building design which made continuity at building plane changes difficult for subcontractors who had limited experience with continuous air barrier implementation. There were also changes made in methods and materials for obtaining continuity during construction.

The mechanical engineer for this project assumed 0.5 ACH in bedrooms and smaller spaces and 0.4 ACH in living spaces. However, these values include ventilation air induced by exhaust fans pulling fresh air through trickle vents installed in the window systems. The mechanical engineer estimated that about one quarter of the ACH value can be attributed to uncontrolled air leakage, with the remaining 75% induced by the exhaust fans. Using Sherman's ACH conversion value, the tested value of leakage to an ACH_{NAT} amount is 0.115. This is consistent with the engineer's assumptions, and in this case, knowledge of the expected air leakage rate would likely not have led to significant changes in the sizing of the heating capacity for the building.

Discussion

If, as has been suggested by this research and illustrated in one of the building case studies, mechanical engineers are frequently overestimating the amount of fresh air that will be brought into a building through incidental breaks in the air barrier, there is an increased probability that ventilation may be affected.

Overestimation of air leakage through the enclosure has several impacts on the mechanical equipment sizing; all related to energy use and efficiency. When sizing mechanical systems, values of infiltration typically account for about 33% of heating capacity. If infiltration numbers were better understood, this value would likely decrease by a significant amount given that overestimation ranges from 200% - 800%. In this way there are potential first cost savings in right sizing equipment.

In addition to first costs, if the building is tighter than anticipated during design and heating systems are designed without adequate capacity modulation, operating costs may be unnecessarily higher. For systems without good capacity modulation, increased cycling of heating equipment is expected. In the case of combustion-based (furnaces, boilers) or compressor-based (heat pumps) heating sources, this can lead to reductions in efficiency and potentially reduced equipment life. In the case of electric resistance heating equipment, over-sized heaters can translate to higher electricity costs.

Creating an Accurate Equation

For many decades, research regarding air tightness of buildings has been ongoing from both a mechanical and building enclosure perspective. The ultimate goal for most of these studies is to design and build better buildings to improve comfort while decreasing energy use. It is at the design table that mechanical and building enclosure consultants should be coming together to create these better buildings.

As noted in the tables above, there have been various standards, authorities, and methods of testing for air tightness, but they do not all correlate. Air tightness testing of the building enclosure is typically done in CFM/SF at 75 Pa, while mechanical design software and guidelines typically attempt to prescribe the infiltration rates under typical conditions (ACH natural or other metric). It can be difficult at times for one profession to make sense to the other.

Currently, there are jurisdictions that require whole building air tightness testing, and while we are moving forward with the testing requirements, do they do enough to meet our energy reduction goals? If the building enclosure meets the mandated leakage requirements, does that mean the mechanical system was appropriately designed? Are designers aware of the required standards? If so, are the mandated air leakage rates being used to change assumptions in sizing the heating system? It has been stated that natural air leakage through the enclosure can account for one third of the buildings heating capacity. If natural leakage can be minimized, what is the financial impact on the heating system by reducing this capacity?

These are still some of the questions we are left with after our initial research and the types of questions that we believe need to be discussed between the mechanical and building enclosure consultant at the design stage.

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