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INTEGRATING WHOLE BUILDING AIR LEAKAGE TEST DATA INTO ENERGYPLUS INFILTRATION MODELS

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ABSTRACT

Our presentation for the 2014 ASHRAE/IBPSA conference, "Simulating Air Leakage in a Whole Building Energy Model – An Existing Building Study", summarized our effort to model a building before and after a window replacement project. We obtained very good model correlation to actual heating loads using data from whole building air infiltration tests integrated with an EnergyPlus Airflow Network object. The following reviews our process and results.

INTRODUCTION

Building codes and the construction industry are increasingly recognizing the multiple benefits of air tight building envelope construction. Although alarmed during the 1970's energy crisis when ventilation reductions produced "sick building syndrome", todays building professionals recognize that air tight envelopes and proper ventilation are a winning combination for comfort and efficiency. There is also slow movement toward proving air tight performance with whole building air infiltration testing. The issues of testing larger buildings, defining an acceptable air tightness requirement, and resolving tests that fail to meet criteria hold back universal adaptation of air tightness standards, but they will be coming.

Building Air Leakage Quantification

For years, the recommended infiltration calculation involved looking up leakage values for individual building components in an ASHRAE table and summing results for the whole building. Although based on component testing, this method did not keep up with changing construction methods or workmanship variations in assemblies. Testing and envelope material technologies have advanced to a point where performance by leakage per unit area at a given pressure can be reasonably anticipated.

ASTM Standard E779 defines the air test methods most commonly used. Although the test results can be reported in one of several shorthand notations such as air changes per hour at 50 Pa pressure (ACH50), the E779 methodology actually involves collecting data points to solve a more universal airflow equation, commonly called the power law equation :

$$Q = C \times P^n$$

Where

Q= volumetric air flow

C= flow constant

P= differential pressure across the envelope

n= a dimensionless exponent between 0.5 and 1.0

This equation is a simplification of more general fluid flow relationships. It works for air at typical building operating temperatures because the viscosity of air is not particularly sensitive to temperature or density in normal occupancy ranges. An exponent of 0.5 is typical of sharp edge orifice airflow while an exponent of 1.0 is more indicative of airflow through longer pathways . Since there are multiple types of airflow pathways in building envelopes, the actual exponent varies. When performing whole building air infiltration testing, we often calculate the flow exponent between 0.60 and 0.70, so when in doubt, we recommend ASHRAE Fundamentals which states that a flow exponent of 0.65 is a reasonable assumption. The exponent often differs between positive building pressure tests and negative pressure tests which is reasonable considering the applied pressure will try to further engage or disengage any components with gaskets that are subjected to small movements under pressure. ASTM E779 calls for averaging positive and negative tests and making corrections to standard air conditions. Averaging positive and negative tests allows reporting of a single airflow equation, though occasionally knowing the difference could be useful. Making adjustments to standard air conditions quantifies mass flow rates, but this is not particularly helpful since the flow constant will differ for an orifice plate tested at sea level versus in Denver, just because of air density differences . Some adjustment should be made for differences in inside and outside air temperature that exist during the testing if they are large to more accurately represent the flow through building envelope cracks.

A common and useful reporting metric is to divide the total flow for a fixed pressure by the total surface area of the building , thus the Air Barrier Association of America suggests a performance standard of 2.03 L/s m^2 @ 75 Pa (0.4 cfm/sqft @ 0.3 in. water column). Research by the Army Corps of Engineers requires their new construction to meet 1.27 l/s-m^2 @ 75 Pa (0.25 cfm/sqft @ 0.3 in. water column). Our design and testing experience indicates that new construction could easily reach 0.51 l/s-m^2 @ 75 Pa (0.1 cfm/sqft @ 0.3 in. water column) while many of the problem buildings we investigate may exceed 7.62 l/s-m^2 @ 75 Pa (1.5 cfm/sqft @ 0.3 in. water column).

EnergyPlus Infiltration Calculation

Translating whole building air leakage test data into a building energy model is not a simple or direct process. The most commonly used infiltration definition is ZoneInfiltration:DesignFlowRate where the equation is

$$Infiltration = (I_{design})(F_{schedule})[A + B|T_{zone} - T_{odb}| + C(WindSpeed) + D(Windspeed^2)]$$

This equation does not correlate well to air infiltration testing results. It may indirectly reference some pressure using temperature differences and wind speeds. For instance, we can reference ASHRAE formulas for stack pressure based on air temperature differences:

$$\Delta p_s = (\rho_o - \rho_i) g (H_{NPL} - H) = \rho_o \left(\frac{T_i - T_o}{T_i}\right) g (H_{NPL} - H)$$

Where:
T_o = outdoor temperature
T_i = indoor temperature
ρ_o = outdoor air density
ρ_i = indoor air density
H_{NPL} = height of neutral pressure level above reference plane

Looking at wind speed, we find

$$p_w = C_p \rho \frac{U^2}{2}$$

Where:
ρ = air density
U^2 = wind speed
C_p = wind surface pressure coefficient

These pressure relationships can be positive or negative, but the EnergyPlus infiltration result cannot be negative and does not account for heights , surface location, or whether it is on a windward or leeward side of the building. If the coefficients of ZoneInfiltration:DesignFlowRate are manipulated to represent a pressure, the flow exponent will be 1.0 for the calculation. Ng et al has had some success calculating best fit coefficients for EnergyPlus from airflow simulations using CONTAM software, but the major limitation of this approach is it is not a true a dynamic process.

ZoneInfiltration:EffectiveLeakageArea is another EnergyPlus model developed by Sherman and Grimsrud for smaller residential buildings. The effective leakage area is actually calculated from the results of the whole building air testing. The equation used is:

$$Infiltration = (F_{Schedule}) \frac{A_L}{1000} \sqrt{C_s \Delta T + C_w (WindSpeed)^2}$$

This looks more like the universal flow equation with an exponent of 0.5. Again there is no accounting for height, location or wind direction and the infiltration is an averaged value.

Group – Airflow Network in EnergyPlus offers a closer, but not perfect, match to the universal flow equation at the expense of more complex modeling. The Airflow Network requires:

- Definition of all surfaces that are airflow paths.
- Definition of all connections for airflow between zones.
- Calculation of C_p for all exterior flow surfaces and wind directions.
- Specification for type of crack and airflow coefficients.

The AirflowNetwork:MultiZone:Surface:Crack object in EnergyPlus looks almost identical to the universal flow equation:

$$Q = (Crack\ Factor) \times C_T \times C_Q (\Delta P)^n$$

Where:

Q = air mass flow
C_Q = air mass flow coefficient
C_T = reference condition temperature correction factor
ΔP = pressure difference across crack
n = air flow exponent

When used with AirflowNetwork:MultiZone:Component:DetailedOpening the crack is further modified by a coefficient defining flow per unit length of crack. Although direct entry of either the universal flow equation coefficients for the entire building or for a unit area is not available, it is possible to convert whole building air test results to mass flow coefficients, generate density correction information for the test, and divide the leakage across building model surfaces.

There are two options for generating wind pressure coefficients for exterior surfaces. EnergyPlus can calculate pressure coefficients for simple shape buildings. The pressure coefficients are described in ASHRAE Handbook of Fundamentals 2013, Chap 24 as well as other texts on wind engineering. Complex shape buildings require calculation of coefficients external to EnergyPlus and brought into the EnergyPlus environment as lists of coefficients for each surface in order of wind direction.

When properly defined, Airflow Network solves a set of linked equations for pressure and air flow in all nodes defined in the flow path. While this potentially adds significant overhead to the solution for large models, it can provide a more realistic infiltration analysis on the fly that includes variable airflow rates for different parts of the building under different weather conditions.

Case Study

We had the opportunity to perform whole building air infiltration testing at a New England school campus on an older solid masonry building primarily used for classrooms and offices, where we designed a window replacement project. Existing windows were typical steel frame with leaded, single pane glass. Replacement windows were also steel frame, but used insulating glazing units with applied lead details and gaskets on frames for operable windows. The building is heated with radiators, and only a computer room has summer cooling. Our client had a campus energy monitoring system and enough metering to record daily steam and electric use for the building. We also installed a weather station on the building roof to record actual local weather conditions. Our study was to generate energy models using the data we collected and see if we could accurately predict building energy consumption using EnergyPlus features.

We monitored the building and site with the existing windows for one winter and performed whole building air leakage testing. Once the windows were replaced, we continued to monitor conditions the next winter, and repeated the whole building air leakage test. Schedules were relatively easy to model because the school had a well-defined class year and constant student population. We used the daily electrical use directly for lighting and power with a small percentage allocated to outdoor lighting and a load split to place more usage on the occupied classroom time of day.

Our first whole building air test involved some extra testing and evaluation. The building included an exhaust fan system for ventilation, but it was only marginally effective and had little impact on building pressurization. Several usable fireplaces also had good dampers that virtually sealed the flue openings, but we installed plugs to seal the firebox openings in case the flues leaked. We did discover some roof vents in a cold attic space. As is typical with older construction, there are a lot of interconnected framing voids that communicate from the regularly occupied spaces to this cold attic and roof vents. Consequently this attic vent is a significant discontinuity of the building envelope air barrier, and therefore needed to be accounted for accurately in our energy model.

Our model building geometry was developed to use the computational fluid dynamics (CFD) virtual wind tunnel (VWT) simulation developed by ODS Engineering. ODS Engineering uses Blender as a geometry platform and while it could import the plane shapes and coordinates of walls, floors, windows and doors, the windows were not parented to walls as required for proper definition for EnergyPlus .IDF generation in ODS Studio. With over 500 windows and more than 35 sizes and shapes, considerable effort went into simply generating a functional building model and verifying proper window types and locations.

After reviewing the results of our first whole building air leakage test and reviewing the available Airflow Network objects, we decided to use AirflowNetwork:MultiZone:Component:DetailedOpening to define windows that remain closed, but leak air at a perimeter cracks, and to define a crack in the cold attic roof to simulate the roof openings we discovered. Using the windows to define air leakage reasonably distributes the leakage through the building to objects that can accept a flow rate that is size dependent. Additional air leakage could be expected at the roof to wall joint of the building, but implementing that crack distribution would require generating individual crack flow equations for each surface adjacent to the roof edge. For this analysis we decided to lump the flow into the attic roof. The math for defining flow per unit length of crack is simple, but unlike reporting glazing areas, there is no single report variable we could find for window perimeter crack length. Instead we generated a detailed window report and pulled all the length and width data from the table generated. To use exterior wall surfaces for this analysis would require separate calculations for each surface to evenly distribute the leakage over the wall area because there is no area weighted input similar to the flow per unit crack length.

The ODS Engineering software allowed us to define the windows and attic roof as air flow objects for pressure coefficient calculations. Proper CFD simulation is not a simple task. The VWT simulation runs an initial wind direction until the residuals used to evaluate convergence are acceptably small. The resulting surface pressures are calculated for each referenced air flow surface. The inner mesh with the building model is then rotated and the calculation is repeated for the new wind direction. We used 10 degree rotation increments. Our initial VWT model had 200 iterations for the initial direction and 100 iterations for each rotation increment. Running on a quad core workstation notebook, the VWT simulation took 1.5 days to complete. The resulting residuals for each run were not as good as we would like, but we accepted the calculated coefficients for our initial models.

We simplified the nodes by making each floor a single zone and using an internal mass object to account for corridor walls. Attic spaces remained as individual zones. Modeling individual classrooms connected by corridors did not seem like it would add significant value to the simulation. Openings between floors were given very large crack airflow definitions to reflect the existing open stairs in the building.

Splitting the total measured leakage between the roof crack and the windows is more experience-based than calculated. In other whole building air tests we have been able to pressure balance zones of the building and quantify airflow in individual zones, but that was not possible for this building. We decided that 1/3 attic and 2/3 window split was a reasonable guess that could be modified later if needed.

The split for the second whole building air test after window replacement was different. Since only the windows were modified by the window replacement project, the air leakge through windows would be substantially reduced. However, it could be assumed that air leakage through the roof crack would be the same for both tests given that no work was performed to address this leakage as part of the window replacement project.

Model Correlation Results

We plotted the daily energy use calculated by our initial models against the metered usage provided by our client (Figure 1).

Correlation of the model with old windows to actual energy use was very poor . This result was initially discouraging for the modeling effort. Correlation of the model with new windows to actual energy use was poor in the fall, then became very good, and finished the heating season poor again. This result holds the key to understanding what is happening.

The old windows were in very poor condition. They had no gaskets, they were difficult to operate, and they had broken hardware. The occupants were accustomed to these conditions and compensated for discomfort in other ways. As part of our air testing we operated and closed every window in the building. This included some rather inaccessible windows that had been open through the winter of our data collection. Consequently, our air leakage measurement for old windows was likely unrepresentative of the actual window performance in previous winters. We could likely improve some of our results for old windows by increasing our airflow rates.

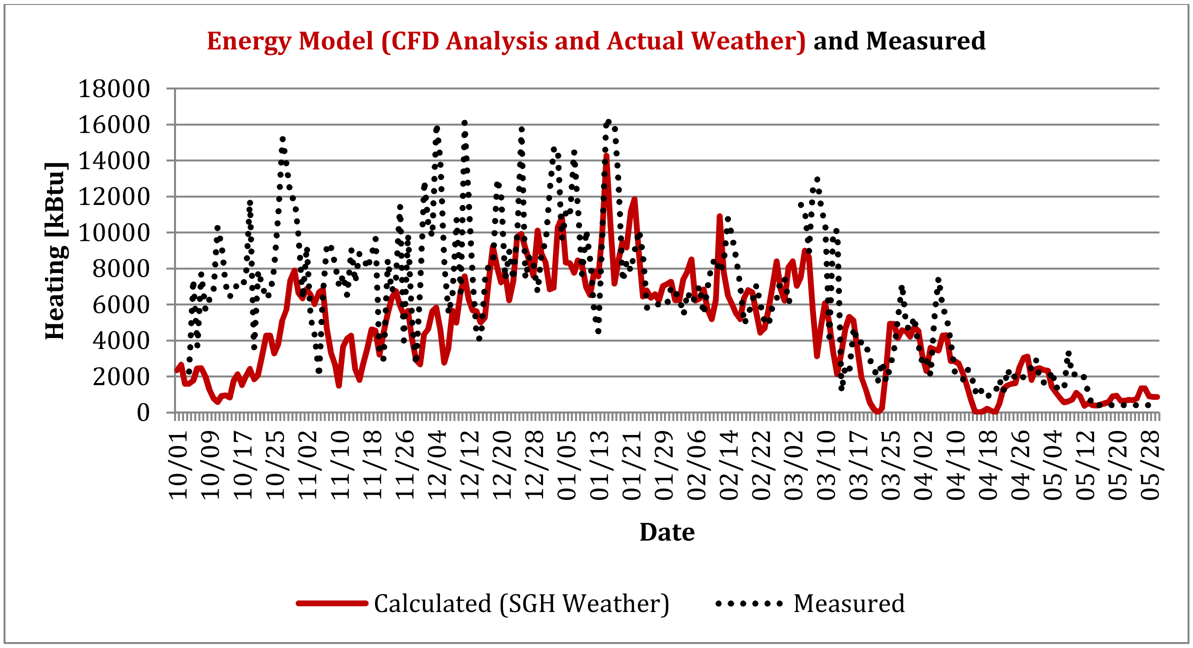

Figure 1 Heating loads calculated from energy model and measured

During the summer the windows are the only source of cooling and are frequently left open. The weather for the initial heating season of our new window model was exceptionally mild. Very cold winter conditions did not occur until January, coincidentally when our model correlation dramatically improved. We speculate that occupant behavior used with the older windows perhaps acceptably comfortable with the new windows until the weather became cold enough to make occupants fully close the windows. Our predicted performance correlates well with actual performance until the weather becomes mild enough to revert to opening windows again.

CONCLUSIONS AND RECOMMENDATIONS

Subsequent refinement of the VWT calculation on a more powerful multiple processor computer resulted in good residual values with 400 initial iterations and 200 iterations per compass turn. For this simulation, the CFD refinement was inconsequential, but for an even more complex shape and larger rotations, the number of iterations and ending residual values would be more important.

The airflow network can do a very good job of quantifying and distributing infiltrating air in models where wind and stack effect buoyancy are primary airflow drivers. The good results for a portion of our new window model were generated by the initial simulation run without any additional model calibration adjustments. An open question remains about the viability of running large airflow network simulations and the relative value of doing so.

Occupancy behavior is likely to be a wild card in any simulation, especially one that includes operable windows and vents. While it may be possible to generate an algorithm to modify our model's window opening operation to better match simulated to actual energy use, the more pressing question is whether more general behavioral algorithms can be developed and correlated to multiple models without additional calibration.

The Airflow Network programmers have a great implementation that can simulate actual building response to environmental conditions. It would be more easily usable if there were an object that could take a unitized air leakage rating and generally apply it to selected building surfaces.

More simulation and correlation of energy models and existing buildings with measured air tightness is needed. We are currently studying our own main office building which we have found to be reasonably air tight. At the same time we discovered that the occupancy schedule for the building leaves all equipment running 24/7 and only changes the ventilation air quantity. This results in a fairly consistent positive pressure during occupied hours when the ventilation is operational and a fairly consistent negative pressure during unoccupied times when only exhaust fans remain running. This mechanical system behavior coupled with air tightness may overwhelm the normal wind and temperature driven infiltration that the airflow network calculates. It is possible that appropriately tight buildings with mechanical systems capable of adequately pressurizing all areas of the building to recommended levels could have negligible infiltration loads most of the time.

REFERENCES

ASTM International 2010 Standard Test Method for Determining Air Leakage Rate By Fan Pressurization, Para 9.5, Eq 3.

American Society of Heating Refrigeration and Air-Conditioning Engineers Handbook Fundamentals 2013, Chap 16.15; Chapter 16.7 Eq. 24 and 25.

EnergyPlus Input Output Reference

National Institute of Standards and Technology, CONTAM Software, Multizone Airflow and Contaminant Transport Analysis Software

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