Airflow and Indoor Air Quality Analyses Capabilities of Energy Simulation Software

Lisa C. Ng[1,2,*] and Andrew K. Persily[2]

[1] Drexel University, Philadelphia, PA, USA
[2] National Institute of Standards and Technology, Gaithersburg, MD, USA

[*]*Corresponding email: lisa.ng@nist.gov*

SUMMARY

A wide range of tools are used to design and analyze the energy implications of different ventilation and space conditioning strategies to reduce building energy use. However, questions exist regarding how and whether these tools consider airflow and indoor contaminant concentrations, which is of increasing importance given current efforts to reduce building energy consumption. The airflow and indoor air quality (IAQ) analyses capabilities of several energy simulation programs are investigated and summarized. This study discusses the key question of whether an energy simulation program simulates airflow rates or considers them to be inputs. The manner in which contaminants are simulated (if at all) is also investigated. Both the physical theory behind the simulations and any rule-of-thumb alternatives are summarized and evaluated. Finally, suggestions as to how airflow and IAQ analyses can be more appropriately accounted for when performing building energy simulation are presented.

IMPLICATIONS

If IAQ is to be considered in efforts to improve building energy efficiency, simulation approaches that account for energy, airflow and contaminant transport are needed. Current energy simulation software tends to use overly simplistic approaches, and therefore more rigorous treatment of airflow and contaminants is needed in energy simulation.

KEYWORDS

Energy simulation, Airflow simulation, Contaminant transport, IAQ analyses

INTRODUCTION

Heating, ventilating, and air conditioning (HVAC) systems in buildings are designed to maintain acceptable indoor air quality (IAQ) and occupant comfort. However, the operating costs of HVAC systems is often a large percentage of the total energy cost of buildings, which already constitutes 40 % of the primary energy consumed in the U.S. (DOE, 2008). Due to an increased emphasis on reducing energy consumption and global warming, the use of energy simulation software has increased. In order to comply with energy design standards, such as the California Code of Regulations, Title 24 (CEC, 2008) and the performance path in ASHRAE Standard 90.1 (ASHRAE, 2007), performing energy simulation is required. Energy simulation can also be used to receive points toward Leadership in Energy and Environmental Design (LEED) certification (USGBC, 2010). However, in an effort to design for reduced energy use, IAQ performance may be neglected (Persily and Emmerich, 2010). Though IAQ affects occupant health, comfort, and productivity, it is not always a major design priority relative to first costs, aesthetics, energy use, etc. (ASHRAE, 2010). Even when IAQ is recognized as a priority, energy design software is limited in its ability to evaluate it.

A broad survey of the capabilities of 20 energy simulation software was conducted by Crawley et al. (2005), 12 of which are also the most widely used by building design engineers and researchers according to a recent survey by Glazer (2010). Of these 12, all of them are able to account for outdoor air entry due to infiltration, with a separate value for each zone. Most employ either simplified approaches to correct for wind speed (which impacts infiltration rates) or do not correct for wind at all. More than half are able to account for natural ventilation in some manner and can perform multizone airflow network calculations, which is the only physically sound means of performing such calculations. Only one can calculate contaminant concentrations but the details of these capabilities are not provided in Crawley et al. (2005). The current study provides more detailed discussion on these airflow and IAQ analyses capabilities for five of the most widely used energy simulation software (Glazer, 2010). In this study, the capability to simulate contaminants and to evaluate IAQ are discussed interchangeably as contaminants are used to evaluate IAQ and their effects on human health and productivity.

METHODS

Based on a recent survey of building design engineers and researchers (Glazer, 2010), the most widely used building energy simulation software are: eQuest (17%), EnergyPlus (12%), TRNSYS (8%), DOE-2 (8%), DesignBuilder (6%), and Ecotect Analysis (5%). It should be noted that Ecotect Analysis calculates heating and cooling loads, but not the plant/HVAC energy usage. To perform building energy analysis, the user must export the building model created in Ecotect to eQuest or EnergyPlus. eQuest is a graphical simulation environment based on DOE-2; thus DOE-2 will not be specifically discussed in this study. DesignBuilder is a graphical simulation environment utilizing limited capabilities of EnergyPlus.

The airflow and IAQ analyses capabilities of the five software tools listed above (DOE-2 excluded) are investigated and summarized in this study. First, whether the software simulates airflow or considers them to be inputs is discussed. In this study, "airflow" refers to infiltration, natural ventilation, and interzonal airflow. Second, if indoor contaminant levels are considered, the manner in which they are simulated is discussed. Finally, suggestions on how airflow and IAQ analyses can be more appropriately accounted for when performing building energy simulation is presented.

RESULTS

Table 1 summarizes the airflow and IAQ capabilities of the energy simulation software listed above. A "Y" in Table 1 indicates that the energy simulation software has a particular simulation capability. An "O" indicates that the capability is optional. A blank indicates that the capability is not available. All of the energy simulation software reviewed for this study can account for constant infiltration and natural ventilation (NV) rates that are not affected by changes in indoor and outdoor conditions. Infiltration can also be modelled to include wind and stack effects. However, the models employed are based on empirical equations for infilration developed for residential-type buildings (ASHRAE, 2005; Coblenz and Achenbach, 1963; Sherman and Grimsrud, 1980; Walker and Wilson, 1998) and are not applicable to taller buildings or buildings with natural or mechanical ventilation systems. The effect of wind on external pressures, and thus on infiltration and NV, can also be calculated using DesignBuilder or the optional multizone airflow (pressure) network capability in EnergyPlus. Wind pressure coefficients are input in both EnergyPlus and DesignBuilder, or can be calculated by EnergyPlus. All of the reviewed energy simulation software have control options to switch between NV and mechanical ventilation modes, or to concurrently operate

Table 1. Summary of airflow and IAQ capabilities of selected energy simulation software.

	eQuest	EnergyPlus	TRNSYS	DesignBuilder	Ecotect Analysis
Infiltration					
Constant	Y	Y	Y	Y	Y
Accounting for wind & stack effects	Y	Y	O		Y
Natural ventilation					
Constant	Y	Y	Y	Y	Y
Accounting for wind & stack effects	Y	Y	O	Y	Y
Window control based on zone or external conditions	Y	Y	O	Y	Y
Hybrid ventilation	Y	Y	O	Y	Y
Wind pressure coefficients					
Input		O		Y	
Calculated by software		O	O		
Interzonal airflow input		Y	Y	Y	
Multizone airflow (pressure network model)		Y	O	Y	
Contaminants		Y	O		

in both modes (hybrid ventilation). When NV mode is implemented, the NV rates specified by the user are accounted for during the energy simulation.

The multizone airflow network capability in EnergyPlus originally utilized capabilities of COMIS and AIRNET (Gu, 2007). COMIS (Feustal and Smith, 1997) was used to calculate wind-driven multizone airflows through the building envelope. AIRNET (Walton, 1989) was used to calculate airflows through an air distribution system. The current AIRFLOW NETWORK model replaces both COMIS and AIRNET in EnergyPlus, with equivalent capabilities, but is still based on equations used in AIRNET. A simplified treatment of interzonal airflow can be implemented in EnergyPlus, TRNSYS, and DesignBuilder, in which one zone can be specified to receive a fixed amount of air from another zone. Transfer of air can include multiple zones, but the balancing of flows is left to the user. In EnergyPlus, interzonal airflow can also be simulated using the AIRFLOW NETWORK model. Finally, EnergyPlus can calculate CO_2 concentrations with occupants and equipment as sources, though other contaminants are expected to be added later (DOE, 2010). CO_2 concentrations can be used as setpoints for ventilation control in EnergyPlus. In TRNFLOW (Weber et al., 2003), which is the full integration of COMIS into TRNSYS, up to five contaminants can be simulated, but they are not used for ventilation control.

DISCUSSION

Many of the infiltration and NV models employed by the energy simulation software reviewed in this study are based on research for low-rise, residential buildings. Thus, they are not generally appropriate for other types of buildings, specifically taller buildings with mechanical ventilation systems, more airtight separations between floors, and vertical shafts. Also, the implemented infiltration models require the user to specify air leakage coefficients that are best obtained from building pressurization tests (ASTM, 2010), which are not generally done, especially in larger buildings. Thus, many energy simulation software users will assume constant infiltration and NV rates, which do not reflect known dependencies on outdoor and indoor conditions and ventilation system operation. In addition, only open windows, doors, and vents are considered for NV in the energy simulation software reviewed. They do not include ventilation rates through engineered NV strategies, such as the use of atriums and trickle vents. Lastly, interzonal airflows are either not accounted for or are treated as constants, which does not reflect reality.

For energy simulation software that are able to simulate airflow (EnergyPlus, TRNSYS, and DesignBuilder), the capabilities are often limited and/or can be difficult for users to employ. The AIRFLOW NETWORK model in EnergyPlus is restricted to a single forced air system with a constant volume supply air fan. DesignBuilder implements limited capabilities of the AIRFLOW NETWORK model. In COMIS, the building model is represented as a block diagram linking each component to be simulated (zone, crack/door/window, duct, air handling unit/fan, etc.) rather than as a floor plan. Thus, it can be challenging for users to visualize a building. TRNSYS is similar to COMIS in that blocks are also linked. Only limited capabilities of the multizone airflow model CONTAM (Walton and Dols, 2008) are incorporated into TRNSYS. Full capabilities of COMIS (multizone model) are incorporated into TRNSYS.

Appropriate treatment of airflow and contaminants for energy simulation is currently done by coupling airflow and thermal calculations. There are three coupling methods reported in the literature: ping-pong, onion, and full integration (Hensen, 1999; Kafetzopoulos and Suen, 1995). Figure 1(a) shows that in ping-pong coupling, temperatures are first assumed in the airflow model. The calculated airflow rates are then passed to the energy model to calculate actual temperatures. These temperatures are then passed back to the airflow model at the next time step. Figure 1(b) shows that in onion coupling, the results of both models are exchanged within a time step until convergence criteria are satisfied. EnergyPlus and the AIRFLOW NETWORK model are ping-pong coupled. TRNSYS and CONTAM (or COMIS) are onion-coupled. Coupling of airflow and energy simulation can also be internal or external. When a simulation software contains both airflow and energy simulation capabilities, they are internally coupled, such as the AIRFLOW NETWORK model in EnergyPlus. TRNSYS and CONTAM (or COMIS) are externally coupled because they are separate simulation engines. Other tools for external coupling include co-simulation platforms such as the Building Controls Virtual Test Bed (BCVTB) (Trčka et al., 2009). BCVTB couples simulation software such as EnergyPlus, Matlab Simulink (for controls), and Modelica (energy and airflow simulation, controls, and others). Co-simulation requires software to be re-configured and is thus not as accessible to design engineers as it is to the research community.

For the same time step, ping-pong coupling results in larger errors than onion coupling (Hensen, 1999) since the temperatures from the energy model are not used to correct the ones

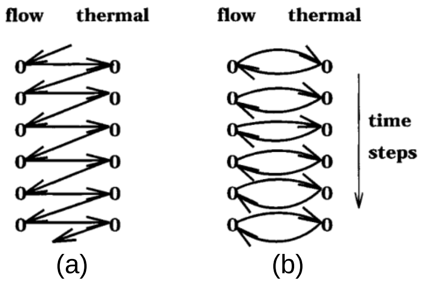

Figure 1. Schematic representation of (a) ping-pong and (b) onion coupling (Hensen, 1999).

assumed by the airflow model. Thus, airflow results may be inaccurate when passed to the energy model. Nevertheless, ping-pong modelling requires less computational effort compared to onion coupling, which requires iterating between the airflow and thermal calculations within a time step. It has been shown that ping-pong coupling produces airflow results comparable to onion coupling when a small time step (6 min in Hensen (1999)) is used. Further, reducing the time step to 6 min for onion coupling did not greatly improve results over a 1 h time step. For highly coupled thermal-airflow problems, full integration coupling is a promising technique, though still under development (Wang et al., 2010). Fully integrated coupling creates and then solves an entire system of equations for energy and airflow, but requires increased computer storage and computational time relative to the other two coupling methods. Thus, trade-offs between computational effort and accuracy need to be considered when selecting the coupling method and time step.

The appropriate treatment of airflow and contaminants in energy simulation software is needed to quantitatively evaluate the energy and IAQ impacts of ventilation and space conditioning strategies that reduce building energy use.

CONCLUSIONS

Due to an increased emphasis on energy consumption and global warming, the potential savings from energy efficiency measures (EEMs) is often analyzed using energy simulation software. However, the impact on IAQ of implementing EEMs is oftentimes not considered because IAQ may not be a design priority and because energy simulation software does not account for airflow and contaminants. This study summarizes the airflow and IAQ analyses capabilities of the most widely used energy simulation software (eQuest, EnergyPlus, TRNSYS, DesignBuilder, and Ecotect Analysis). Many of the airflow models implemented in these software are inappropriate for large buildings or are limited in simulation capabilities. In order to fully understand the impact of EEMs on the whole building, airflow and contaminant analyses should be incorporated into energy simulation software.

ACKNOWLEDGEMENT

The contributions of Drexel University to this work were funded under Measurement Science and Engineering Research Grant No. NANB10D219 from the National Institute of Standards and Technology.

REFERENCES

ASHRAE. 2005. ASHRAE Handbook Fundamentals. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. 2007. ANSI/ASHRAE/IESNA Standard 90.1-2007: Energy Standard for Buildings Except Low-Rise Residential Buildings. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. 2010. The Indoor Air Quality Guide: Best Practices for Design, Construction and Commissioning. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASTM. 2010. ASTM E779-10 Standard Test Method for Determining Air Leakage Rate by Fan Pressurization. West Conshohocken, PA: American Society of Testing and Materials.

CEC. 2008. 2008 Building Energy Efficiency Standards for Residential and Nonresidential Buildings. Sacramento, CA: California Energy Commission.

Coblenz, C.W. and Achenbach, P.R. 1963. Field Measurement of Ten Electrically-Heated Houses. *ASHRAE Transactions*, 69(1), 358-365.

Crawley, D.B., Hand, J.W., Kummert, M. and Griffith, B.T. 2005. Contrasting the capabilities of building energy performance simulation programs. In: *Building Simulation (BS) 2005*, Montreal, Canada, 231-238.

DOE. 2008. *Building Energy Data Book*, Washington, D.C., Department of Energy.

DOE. 2010. EnergyPlus 6.0.0, Washington, D. C., U. S. Department of Energy.

Feustal, H.E. and Smith, B.V. 1997. COMIS 3.0 - User's Guide. Berkeley, Lawrence Berkeley National Laboratory, 151 pages.

Glazer, J. 2010. Survey on Building Simulation and Programming. http://www.kwiksurveys.com/results-overview.php?surveyID=KJNEJM_c97fe163&mode=4.

Gu, L. 2007. Airflow network modeling in EnergyPlus. In: *Building Simulation (BS) 2007*, Beijing, China, 964-971.

Hensen, J.L.M. 1999. A comparison of coupled and decoupled solutions for temperature and air flow in a building. *ASHRAE Transactions*, 105(2), 1-8.

Kafetzopoulos, M.G. and Suen, K.O. 1995. Coupling of thermal and airflow calculation programs offering simultaneous thermal and airflow analysis. *Building Services Engineering Research and Technology*, 16(1), 33-36.

Persily, A.K. and Emmerich, S.J. 2010. IAQ & High Performance. *ASHRAE Journal*, 52(10), 76-83.

Sherman, M.H. and Grimsrud, D.T. 1980. Measurement of Infiltration using Fan Pressurization and Weather Data. LBL-10852, Berkeley, CA, Lawrence Berkeley National Laboratory, 63 pages.

Trčka, M., Hensen, J.L.M. and Wetter, M. 2009. Co-simulation of innovative integrated HVAC systems in buildings. *Journal of Building Performance Simulation*, 2(3), 209-230.

USGBC. 2010. Advanced Energy Modeling for LEED. Washington, DC, U. S. Green Building Council, 11 pages.

Walker, I.S. and Wilson, D.J. 1998. Field validation of equations for stack and wind driven air infiltration calculations. *HVAC&R Research*, 4(2), 119–139.

Walton, G.N. 1989. AIRNET - A Computer Program for Building Airflow Network Modeling. Gaithersburg, MD, National Institute of Standards and Technology, 83 pages.

Walton, G.N. and Dols, W.S. 2008. CONTAM 2.4 User Guide and Program Documentation. Gaithersburg, MD, National Institute of Standards and Technology, 285 pages.

Wang, L.L., Dols, W.S. and Emmerich, S.J. 2010. Simultaneous Solutions of Coupled Thermal Airflow Problem for Natural Ventilation in Buildings. *HVAC&R Research*, Submitted.

Weber, A., Koschenz, M., Dorer, V., Hiller, M. and Holst, S. 2003. TRNFLOW, a new tool for the modelling of heat, air and pollutant transport in buildings with TRNSYS. In: *Building Simulation 2003*, Eindhoven, Netherlands, 1363-1368.