



Airflow Network Modeling in EnergyPlus

Authors

Lixing Gu

Original Publication

Gu, Lixing, "Airflow Network Modeling in EnergyPlus",
10th International Building Performance Simulation Association
Conference and Exhibition on September 3-6, 2007 in Beijing, China

Publication Number

FSEC-PF-428-07

Copyright

Copyright © Florida Solar Energy Center/University of Central Florida
1679 Clearlake Road, Cocoa, Florida 32922, USA
(321) 638-1000
All rights reserved.

Disclaimer

The Florida Solar Energy Center/University of Central Florida nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Florida Solar Energy Center/University of Central Florida or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the Florida Solar Energy Center/University of Central Florida or any agency thereof.

AIRFLOW NETWORK MODELING IN ENERGYPLUS

Lixing Gu

Florida Solar Energy Center
1679 Clearlake Road, Cocoa, FL 32922, USA

ABSTRACT

The airflow network model in EnergyPlus provides the ability to simulate multizone wind-driven airflows. The model is also able to simulate the impacts of forced air distribution systems, including supply and return air leaks. The air distribution system portion of the model is currently applicable for constant-air-volume systems. Future enhancements will include adding hybrid ventilation control and possible extension to include variable-air-volume distribution systems.

This paper describes the input objects, calculation procedures, model validation, and example results. The model inputs consist of five main objects: simulation control, multizone data, node data, component data, and linkage data. The model calculates pressure at each node and airflow through each component based on the pressure versus airflow relationship defined for each component. Using these airflow rates and HVAC equipment models, temperature and humidity ratio at each air node are then calculated. All cooling/heating loads resulting from the multizone airflow and air distribution system model are then summed and passed to EnergyPlus' zone air heat and moisture balance model which calculates zone air temperature and humidity ratio. The loads from multizone air flows are used to predict required system loads, while the loads due to the air distribution system are used to recalculate zone air temperatures and humidity ratios.

EnergyPlus' airflow network model was validated against measured data from both the Oak Ridge National Laboratory (ORNL) and the Florida Solar Energy Center (FSEC). Whole building energy simulations were performed using EnergyPlus in addition to validating specific portions of its airflow network model. There was good agreement between the simulation results and the measured data.

KEYWORDS

Air distribution system, Airflow and pressure, Interactions among envelope, HVAC system, and outdoors

INTRODUCTION

Airflows in buildings can have a significant impact on space conditioning loads, energy consumption and

indoor air quality. The airflows can be divided into two types: controlled and uncontrolled. The controlled airflows are mainly driven by fans. Uncontrolled airflows are driven by a combination of wind and forced air flow through the building envelope, leaky air distribution system ducts, and unbalanced return and exhaust air flows. Since fan flow rates are a function of external pressures, the uncontrolled airflows also have an impact on the controlled airflows.

There are several approaches to simulating airflow impacts. One approach is to explicitly input airflow rates (e.g., measured data) to the model. Since airflows depend on wind, the HVAC system, and building envelope air leakage, this simple approach may be acceptable for modeling the impacts of controlled airflows but may not be accurate for uncontrolled airflows. A second, more detailed approach is to establish an airflow network, which basically consists of a set of nodes connected by airflow elements. A relationship between airflow and pressure must be specified for each element. Since this second approach assumes that air flows from one node to another, it simplifies airflows through its pathways and can not predict internal air circulation (e.g., within a thermal zone). A third approach is to use computational fluid dynamics (CFD) to predict airflows. CFD is the most detailed approach to predicting airflows, but it is more computationally intensive and is difficult to integrate into building simulation programs to determine the impacts on heating/cooling loads and building energy use.

The present paper addresses the airflow network approach which is used in EnergyPlus. This approach is more detailed and potentially more accurate than the simple input approach, with the accuracy level of this approach being comparable to the load calculation assumptions used in most building energy simulation programs. For example, 1-D heat transfer through the building envelope is commonly used and each zone is frequently assumed to have uniform temperature and relative humidity. This level of detail for modeling cooling/heating loads in buildings is quite similar to the airflow network methodology.

Several airflow network models have been developed over time. The National Institute of Standards and Technology (NIST) developed the AIRNET program to predict airflows (Walton 1989). In addition to

airflow through envelope leakage and in ducts, AIRNET uses height-independent air density to predict one- or two-way airflows through large vertical openings. A group of researchers led by Lawrence Berkeley National Laboratory (LBNL) developed the COMIS program (Feustel et al. 1990) with a similar approach. They also enhanced the airflow predictions by adding temperature influence factors to predict airflows through envelope leakage, and the ability to model three-way airflows through large vertical openings by assuming the air density varies linearly with height.

Both programs (AIRNET and COMIS) predict airflows for given temperatures at each node, so load calculations can not be performed directly. Therefore, other energy simulation programs have to be used to predict loads and system performance when modeling building airflows. However, interactions among systems, the building envelope, and outdoors can not be readily examined when different programs are used.

In order to simulate interactions among systems, the building envelope and outdoors, AIRNET was integrated in the FSEC 3.0 program developed by FSEC (Swami et al. 1993). The University of Strathclyde (Hensen 1991) developed its own airflow network model and integrated it into ESPr (ESP-r 1995). Although LBNL also developed an energy loss model, connected to both the DOE-2 and COMIS programs, the model is not fully integrated (Modera & Treidler 1995).

Due to the importance of accounting for the various interactions when modeling building airflows, an early version of EnergyPlus was linked to the COMIS program. The program-to-program link was mainly used to calculate wind-driven multizone airflows through the building envelope using COMIS and including this information in the EnergyPlus zone load calculations (Huang et al. 1999). Following this, an Air Distribution System (ADS) model was implemented in EnergyPlus, which used equations derived from AIRNET to calculate airflows through an air distribution system and calculate energy losses due to duct heat conduction and air leaks (while lumping zone-level envelope leaks together). Although both the COMIS link and ADS models focused on different aspects, the multizone airflow calculations overlapped somewhat and two airflow network solvers were being used.

In order to better integrate and streamline the airflow calculations in EnergyPlus, the AirflowNetwork model was subsequently implemented in EnergyPlus. The AirflowNetwork model basically replaces the previous COMIS link and ADS model, and has equivalent capabilities. One main difference, however, is that the multizone airflow calculations are now performed at the HVAC system time step instead of

at the zone time step. This enhancement allows the multizone air flow calculations to be synchronized with the HVAC system simulation and provides flexibility for future development of hybrid ventilation system controls.

INPUT OBJECTS

The input specifications consist of five main sections: AirflowNetwork simulation object, AirflowNetwork multizone data objects, AirflowNetwork node data objects, AirflowNetwork component data objects, and AirflowNetwork linkage data objects. Each of these object types is described briefly below.

The AirflowNetwork simulation object provides the basic run parameters for this model, such as model control. The model control has four choices:

- Multizone air flow calculations during all simulation time steps, including the impacts of the air distribution system when the HVAC system fan is operating,
- Multizone air flow calculations during all simulation time steps (except no air distribution system modeling),
- Multizone air flow calculations, including the impacts of the air distribution system, but only when the HVAC system fan is operating, and
- No multizone or air distribution system air flow calculations.

The AirflowNetwork:Multizone data objects are used to calculate multizone airflows. The objects have building zones and the exterior of the building represented as nodes, building surfaces represented as linkages (airflow pathways), wind surface pressure calculation objects, and components that define the relationship between pressure and airflow.

The AirflowNetwork:Distribution:Node object is used to perform air distribution system simulations. Although thermal zones are required to perform distribution system simulations, the thermal zones are already defined in the multizone input section (described previously), so there is no need to repeat the inputs for thermal zones when modeling an air distribution system. The same is also true for surface air leakage inputs.

There are seven available types of AirflowNetwork Components to represent the relationship between pressure and airflow in an air distribution system. All required fields for each component represent a relationship between pressure difference and airflow.

The AirflowNetwork:Distribution:Linkage defines a connection between two AirflowNetwork:Distribution:Node objects and an AirflowNetwork component defined above.

Figure 1 shows the available AirflowNetwork objects and their relationship to other associated EnergyPlus objects. An arrow from object A to object B means that A references B. For example, the AirflowNetwork:Multizone:Surface object uses the name defined in the Surface:HeatTransfer object by reference. The detailed description may be found in the Input Output Reference of EnergyPlus.

MODEL DESCRIPTION

The multizone airflow calculations are highly dependent on the air pressures surrounding the building due to wind. The model provides a choice for wind pressure coefficients, either user input or automatic calculation. The automatic calculation of wind pressure coefficients is restricted to a rectangular building, either low rise (Swami et al. 1988) or high rise (Akins et al. 1979, ASHRAE 2001). The wind pressure coefficients are reported for the user in an output file.

The calculation procedure consists of three sequential steps:

- Pressure and airflow calculations
- Node temperature and humidity calculations
- Sensible and latent load calculations

The pressure and airflow calculations determine pressure at each node and airflow through each linkage given wind pressures and forced airflows. The forced airflows provided by a supply fan depend on fan type and fan operation mode. When a constant volume fan is specified in EnergyPlus, the flow rate is constant for the simulation time step and this fan turns on or off based on an availability schedule.

A constant volume fan that is able to cycle on and off within a simulation time step can also be modeled in EnergyPlus, but it is treated slightly differently from the fan described above. In this case, the full air flow rate is used when this fan is scheduled to operate continuously for a simulation time step (same as for the fan described above). However, the average air flow rate is used when the fan cycles on and off within a simulation time step (e.g., AUTO fan control where the supply air fan cycles on and off with the cooling or heating coil).

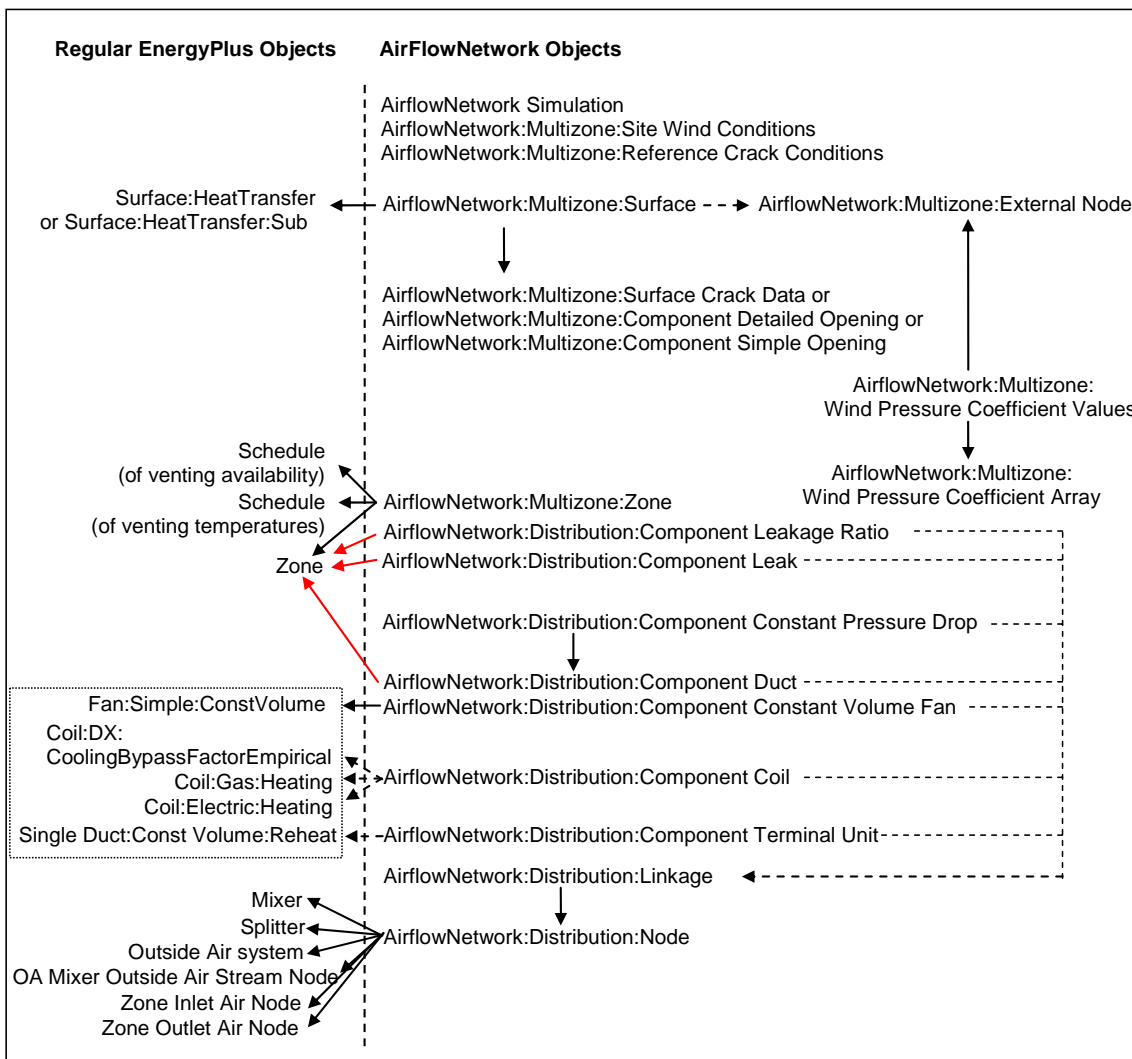


Figure 1. Relationship between AirflowNetwork objects (right hand side) and associated EnergyPlus objects

Based on the airflow calculated for each linkage and the HVAC system performance models, the AirflowNetwork model calculates node temperatures and humidity ratios with given zone air temperatures and zone humidity ratios. Using these node temperatures and humidity ratios, the sensible and latent loads from duct system conduction and leakage are summed for each zone. With a fan is operating in the cycling (on/off) mode, the loads are calculated during both the fan on and fan off periods, and the results are then weighted based on the system run time fraction to determine the load for the simulation time step. These sensible and latent loads are then used in the zone energy balance equations to predict HVAC system loads and to calculate the final zone air temperatures, and humidity ratios.

The AirflowNetwork model calculates loads from the multizone airflow and air distribution system. The loads from multizone air flows are used to predict required system loads, while the loads due to the air distribution system are used to recalculate zone air temperatures and humidity ratios. The prediction of system loads due to multizone air flow is independent of HVAC system operation, while the calculation of zone temperatures and humidity ratios are dependent on HVAC system operation. There are two approaches to integrate HVAC system and airflow models. The AirflowNetwork model interacts with the HVAC system iteratively until the differences between two iterations are less than the convergence tolerance in a simulation time step.

The AirflowNetwork model is currently able to model a wide range of multizone air flow scenarios. However, only a single air distribution system with a constant volume supply fan can be included as part of the airflow modeling. The model currently excludes the thermal capacitances of the air and air distribution systems (e.g., ductwork). The impact of thermal capacitance will be addressed in future upgrades to this model.

MODEL VALIDATION

Model validation is a very important step in providing users with the confidence to use simulation tools, in addition to model verification and model-to-model comparative tests.

ORNL data comparison

The EnergyPlus airflow network model was validated by comparing model results with a large set of high-quality laboratory measurements from ORNL. A description of the ORNL test facility and

measurements are available in other papers (Gu et al. 1998, Petrie et al. 1998).

Table 1 shows the comparison of predicted and measured pressures and air leakage percentage (% Leak) for two steady-state tests. The first column lists the simulation case. The second and third columns show the air leakage as a percent of the maximum supply airflow due to hole openings determined by measurement and prediction using EnergyPlus. The fourth column represents the percentage difference between the measured and predicted leakages. A positive percentage difference represents over-prediction compared to the measured data, while a negative percentage represents under-prediction compared to the measured data. Columns five through seven contain the total air pressure measured at three different locations using pitot tube probes (near the inlet, middle and outlet of the duct system). These probes were placed at the centerline of the duct near the three leakage sites. Columns eight through ten list the predicted total pressures at the same locations where the pressures were measured. The last three columns show percentage differences between the measured and predicted pressures. In the same manner, positive and negative values represent over-prediction and under-prediction, respectively. The maximum differences in airflow and pressure were 4.1% and 3.5%, respectively for these comparison cases.

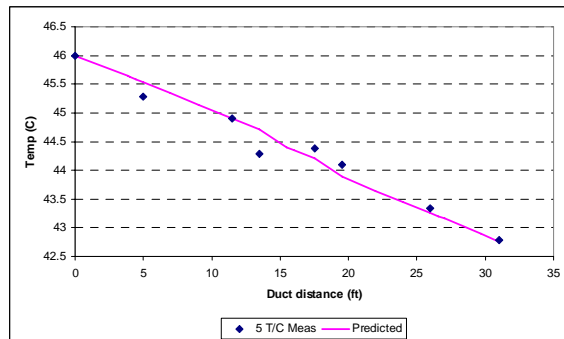


Figure 2. Comparison of ducted air temperatures under winter condition (leak, uninsulated duct, and winter conditions)

Figure 2 presents a comparison of predicted and measured duct air temperatures under winter conditions. The test conditions were with no duct insulation, winter conditions and full leakage with holes fully open. Opening the holes caused 16% of the total airflow to leak into the attic space. In this case, airflow leakage into the attic from the ducts results in warmer attic air temperatures and less

Table 1. Comparison of measured and predicted airflows and pressures for two steady-state tests

Case	Meas	Pred	Diff	Meas Pres (Pa)			Pred Pres (Pa)			Diff (%)		
	%Leak	%Leak	%	Inlet	Middle	Outlet	Inlet	Middle	Outlet	Inlet	Middle	Outlet
4e	15.6	16.3	4.1	228	319	460	224	320	470	-1.8	0.3	2.2
8e	17.2	17.6	2.4	376	461	598	375	477	592	0.4	3.5	-0.9

airflow passing through the exit of the duct. The legend of “5 T/C Meas” indicates the measured temperatures averaged with 5 thermocouples, while the legend of “Predicted” represents simulation results from EnergyPlus.

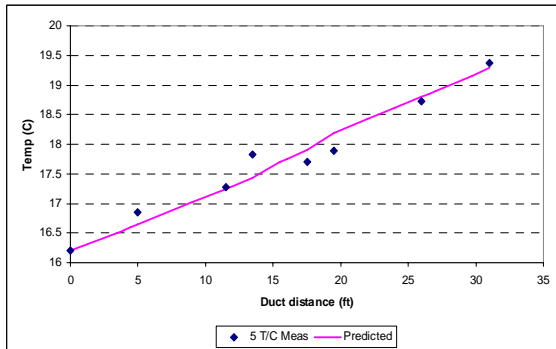


Figure 3. Comparison of ducted air temperatures under summer condition (leak, uninsulated duct, and summer conditions)

Figure 3 compares duct air temperature distributions under summer conditions. The test conditions were with no duct insulation, summer conditions and full leakage with holes fully open. Opening the holes caused 17% of the total airflow to leak into the attic space. In this case, airflow leakage into the attic from the ducts results in colder attic air temperatures and less airflow passing through the exit of the duct. Again, the air temperatures predicted by EnergyPlus are in good agreement with the measured temperatures.

Building Science Laboratory at FSEC

Validation of the EnergyPlus airflow network model was also performed using measured data obtained from the Building Science Lab (BSL) at FSEC (Henderson et al. 2006). For one set of test cases, the measured supply air conditions at the discharge of the cooling coil and the surrounding attic zone conditions were used as boundary conditions for validating the model. Given those boundary conditions, supply airflow rates and temperatures were modeled. Table 2 provides a comparison (percent difference) between the simulation results and measured data. The average percent airflow difference between simulation and measurement was obtained from 16 points within the air distribution system, including ducts, supply registers, and return grills. The average percent temperature difference between simulation and measurement was obtained from 17 points within the air distribution system, including coils, ducts,

Table 2. Air distribution system model validation against measured data

Case	Description	Airflow		Temperature	
		Ave (%)	Max (%)	Ave (%)	Max (%)
1	No leak	1.5	-4.1	2.0	3.8
2	30% Return leak	1.6	-3.0	1.8	3.1
3	30% Supply leak	2.8	-6.2	1.8	8.1
4	30% Supply and return leaks	3.0	-5.3	2.5	9.4

supply registers and return grills.

Whole building energy use validation

The above validation cases were for the air distribution system model. This section addresses whole building energy use validation. Detailed instrumentation at the FSEC Building Science Lab was used to collect measured data which was used as the basis for model validation. The measured data included internal sensible and latent loads, indoor and attic temperatures and relative humidity (RH), cooling system energy use, airflows, air distribution system temperatures and RH, and weather data (horizontal solar radiation, drybulb temperature, relative humidity, wind speed and wind direction).

Measured data were collected in the BSL building for four test configurations: 1) no duct leakage, 2) 15% return leakage, 3) 15% supply leakage, and 4) 15% supply and 15% return leakage. The measurements were obtained between 6/10/2004 and 8/10/2004. Measured indoor air conditions and cooling energy use were used to validate the simulation results for whole building performance. The modeled building was divided into two thermal zones (Office zone and Attic zone), with the building air barrier located at the roof and the thermal barrier (R-19 fiberglass batts) located on top of the acoustical tile ceiling. The following assumptions were used in model validation:

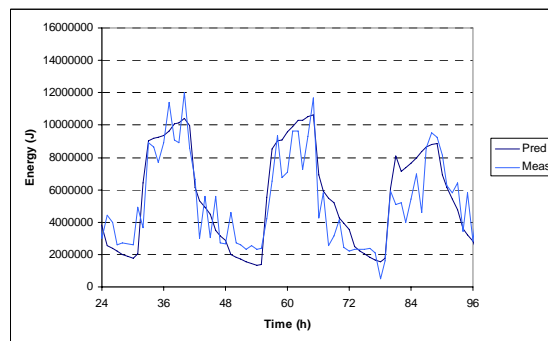


Figure 4 Predicted and measured delivered cooling energy in the BSL building (no duct leakage)

- No detailed moisture transfer through the building envelope was modeled. Instead, the EMPD model in EnergyPlus was used to model moisture capacitance in the zone.
- Very leaky acoustical tile is used to separate the office and attic zones. The AirflowNetwork model can not simulate two-way flows across the acoustical tile.

- A constant volume supply air fan was modeled based on an availability schedule.

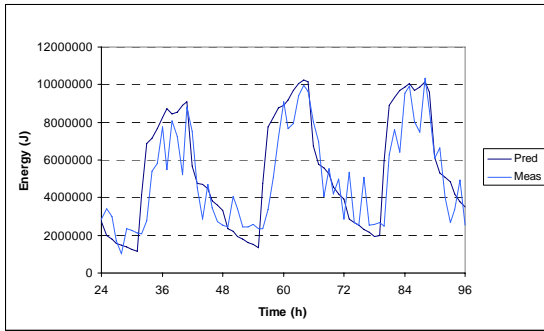


Figure 5. Predicted and measured delivered cooling energy in the BSL building (15% return leakage)

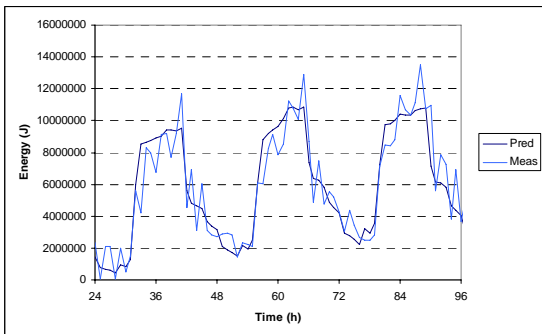


Figure 6. Predicted and measured delivered cooling energy in the BSL building (15% supply leakage)

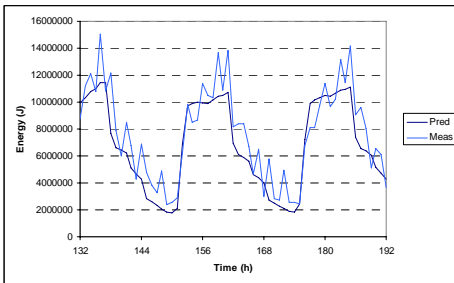


Figure 7.

Predicted and measured delivered cooling energy in the BSL building (15% return and supply leaks)

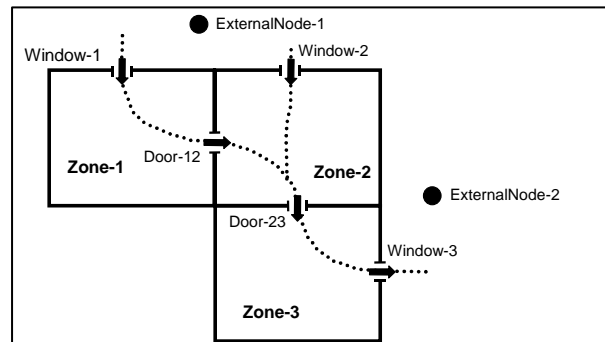
Figures 4 through 7 present the measured and predicted cooling coil energy use for the four cases listed above. Although the assumptions listed above differ somewhat from the actual test conditions, there is relatively close agreement between the simulation results and the measured data.

Table 3 presents a summary of absolute and percent differences between measured and modeled air-conditioning (AC) energy use. There appears to be a

systematic error in the modeling results, with the model over-predicting cooling energy use for no duct leaks with a trend toward underpredicting AC energy use with supply leaks and balanced supply/return duct leaks. Due to these limitations, the model overpredicts by about 10% for the case of no duct leaks and underpredicts by about 12% for the case of 15% return and 15% supply leaks.

INPUT PREPARATION

Since the model is based on a network approach, it is necessary for users to build the network correctly. The network nodes (including zones and air distribution system nodes) must have some pathways to be connected to each other. Although the EnergyPlus model provides a significant amount of error checking to help determine if the model inputs are correct, it is impossible to account for all possible errors caused by violating network rules. Figure 8 shows a simple airflow network used in a multizone airflow calculation with a possible airflow pattern in which all of the windows and doors are open. Figure 8. Plan view of a simple airflow network showing a possible airflow pattern



The inputs for an air distribution system are relatively simple. All nodes and components defined in EnergyPlus Air Loop and Zone Equipment object must also be defined in the AirflowNetwork inputs, including mixers and splitters. All of the Air Loop nodes are a subset of AirflowNetwork:Distribution:Node, and all of the components, such as coils and a fan, must be defined in the AirflowNetwork components and used in the linkage. The airflow directions should be defined correctly in the Linkage objects (i.e., from Node 1 to Node 2), following the airflow directions defined in Air Loop and Zone Equipment objects.

When supply and return leaks are being modeled, the leaks can only be defined in the Zone Equipment

Table 3. Measured versus modeled AC energy use for four duct leak configurations (unvented attic)

Case	Description	Period (day)	AC Energy use (kWh)			
			Measured	Predicted	Difference	% Difference
1	No leak	3	101.25	111.30	10.05	9.9
2	15% Return	3	107.29	113.29	5.99	5.6
3	15% Supply	3	121.22	120.10	-1.12	-0.9
4	15% Return & Supply	2.5	130.66	115.50	-15.16	-11.6

section, so that the air flow rate provided by the supply air fan remains the same through all Air Loop components. In this case, the air leaks only change the amount of air being supplied to or removed from the zone(s).

AN EXAMPLE

An example input for a small office is described here with a single-story building divided into three interior conditioned zones and one unconditioned attic zone over the conditioned zones. The office has a single air distribution system located in the attic zone with four supply leaks and three return leaks. A schematic drawing is shown in Figure 9.

Figure 10 plots zone air and ambient air temperatures for a summer design day. The HVAC system is scheduled to operate between 7 AM and 5 PM. Due to energy losses from duct conduction and air leaks, the attic zone temperature rises slowly during HVAC system operation, until the HVAC system turns off. After the HVAC system turns off, the attic temperature floats and is mainly driven by outdoor temperature. Without the duct loss modeling capability, the attic air temperature would be predicted very differently; in this case the attic temperature would rise much more quickly during daytime hours without the impact of heat conduction through the ductwork and cool air from air leakage on the supply side of the air distribution system.

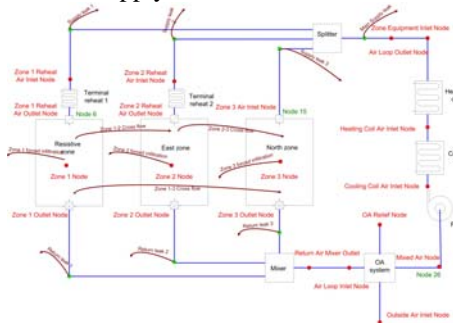


Figure 9. Schematic of small office

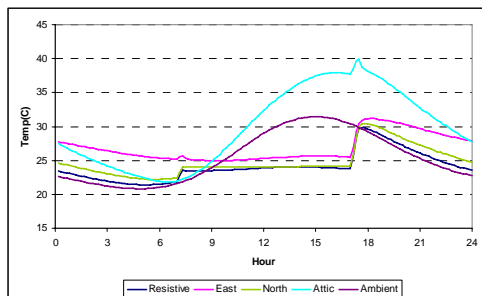


Figure 10. Air temperature profile for a small office on a summer design day.

CONCLUSIONS AND RECOMMENDATIONS

EnergyPlus now contains a fully-integrated network model for calculating building air flows and their

impact on building energy use. The model can be used for simulating the impacts of multizone airflows due to wind pressure and stack effects. The impacts of a single constant-air-volume distribution system can also be modeled. The airflow network model has been validated using several sets of measured data. The airflow calculations are performed at the HVAC system time step, laying the groundwork for future model improvements such as hybrid ventilation controls.

Some recommendations for future model development are:

- The model is currently unable to accurately simulate airflows through large horizontal openings. The existing algorithms for modeling large vertical openings assume the pressure difference across the opening is a function of height along the opening to obtain possible two- or three-way flows. When openings are horizontal, the pressure difference across the opening is constant, so that the existing approach fails to predict two-way flows. A possible solution was found in the work of Bolmqvist and Sandberg (2004) which generated two-way flows through a large horizontal opening by assuming the zone air mass varies with time.
- Currently, the air pressure across the fan is assumed to be fixed and fan flow rate is assumed to be independent of external pressures. In reality, fan flow rate is a function of external fan pressure. Accounting for variations in fan flow rate can be added since external pressures are calculated by the AirflowNetwork model.
- Add the ability to model variable-air-volume fans.
- Steady-state conditions are assumed when calculating duct system energy losses. Therefore, duct system energy losses during periods when the fan cycles off are not currently simulated. The model currently assumes that the duct system energy losses are zero when the supply air fan is not operating.
- Although the model is able to predict airflow due to different natural ventilation controls, such as window or door openings, the opening control is independent of air distribution system operation. A master control to coordinate natural ventilation and system operation is required.

ACKNOWLEDGMENT

The authors thank the US Department of Energy and program manager, Dru Crawley, for funding this work. The authors also thank the EnergyPlus development team members for providing valuable comments. Sincere appreciation is expressed to the Oak Ridge National Laboratory and our colleagues,

Don Shirey and Rich Raustad at FSEC, who review the model and this paper extensively, James Cummings and Chuck Withers at FSEC, who provided measured data for model validation.

REFERENCES

- Akins, R.E., J.A. Peterka, and J.E. Cermak. 1979. "Averaged Pressure Coefficients for Rectangular Buildings," Wind Engineering. Proc. Fifth International Conference 7:369-80, Fort Collins, CO. Pergamon Press, NY.
- ASHRAE, 2001, "Handbook of Fundamentals," 2001 p. 16.5, Fig. 7, and p.16.6, Fig. 9.
- Bolmqvist, C. and M. Sandberg, 2004, "Air Movements through Horizontal Openings in Buildings – A Model Study," International Journal of Ventilation, Vol. 3, No. 1, pp. 1-9.
- COMIS Fundamentals, 1990, Edited by Helmut E. Feustel and Alison Rayner-Hooson, LBL-28560, Lawrence Berkeley Laboratory, Berkeley, CA.
- ESP-r, 1995, "A building Energy Simulation Environment, User Guide Version 8 Series," ESRU Manual U95/1, University of Strathclyde, Energy System Division, Glasgow, UK.
- Gu, L., M. V. Swami, J. E. Cummings, P. W. Fairey, T. W. Petrie, and J. E. Christian, "Comparison of a Duct System Computer Model with Measured Data in a Residential Attic with a Duct System," TO-98-17-1, ASHRAE Trans. 1998.
- Hensen, J. L. M. 1995. Modeling coupled heat and air flow: ping-pong vs. onions. proc. 16th AIVC conference, Palm Springs, USA, 19-22 September, 1995.
- Huang, Joe, Fred Winkelmann, Fred Buhl, Curtis Pedersen, Daniel Fisher, Richard Liesen, Russell Taylor, Richard Strand, Drury Crawley, and Linda Lawrie. 1999. "Linking the COMIS Multi-Zone Airflow Model With the EnergyPlus Building Energy Simulation Program," in *Proceedings of Building Simulation '99*, Volume II, pp.1065-1070, Kyoto, Japan, September 1999. IBPSA.
- Henderson, H. I, A. Walburger, J. B. Cummings, C. Withers, L. Gu, J. Zhang, M. Bomberg, M. Salonvaara, T. Brennan, and M. Clarkin, 2006, "Mitigating the Impacts of Uncontrolled Air Flow on Indoor Environmental Quality and Energy Demand in Non-Residential Buildings," DOE Contract #DE-FC-36-02GO12012, Submitted to New York State Energy Research and Development Authority.
- Modera, M. P. & B. Treidler, 1995, "Improved Modeling of HVAC System/Envelope Interactions in Residential Buildings," the ASME International Solar Energy Conference, March 19-24, 1995.
- Petrie, T. W., K. E. Wilkes, P. W. Childs, and J. E. Christian, "Effects of Radiant Barriers and Attic Ventilation on Residential Attics and Attic Duct Systems: New Tools for Measuring and Modeling," TO-98-20-1, ASHRAE Trans. 1998.
- Swami, M. V. and S. Chandra. 1988. Correlation for pressure distribution on buildings and calculation of natural-ventilation airflow. ASHRAE Transactions 81(1):202.
- Swami, M. V., L. Gu, & V. Vasanth, 1992, "Integration of Radon and Energy Models for Building," FSEC-CR-553-92, Florida Solar Energy Center, Cocoa, Florida.
- Walton, G. N. 1989, "AIRNET – A Computer Program for Building Airflow Network Modeling," NISTIR 89-4072, National Institute of Standards and Technology, Gaithersburg, Maryland.