Overview of Technical Session VIII: Experimental Methods and Model Validation

James E. Braun
Ray W. Herrick Laboratories
Purdue University
West Lafayette, IN 47907

Simulation is useful in many aspects of the design, control, and evaluation of buildings and their associated heating and cooling equipment. Pure experimental studies are often limited by the bounds of cost and measurement techniques, whereas simulation studies are limited by theoretical understanding and computational constraints. In particular, experiments are needed to develop the fundamental understanding necessary to create new mathematical models and to validate larger scale simulation models. In some applications involving controls or performance monitoring, measurements and data analysis tools are used to determine the parameters of empirical (black box) or semi-empirical (gray box) models. Papers in this session address both the validation of simulation models used to characterize building and equipment performance and techniques used in obtaining, characterizing, and analyzing measurements. In some cases, validated simulations were used to study the performance and/or design of the system under consideration. The following summary is organized in three sections: 1) room air conditions, 2) system energy requirements and analysis, and 3) equipment. Each section gives an overview of the topic area and describes the contributions of each paper within that topic.

Room Air Conditions

Room air modeling involves predictions of spatial and possibly time varying distributions of air temperatures, humidities, velocities, and pollutant concentrations in buildings. Primarily, room air models are useful in evaluating the impact of design and control variables on human comfort and indoor air quality. Generally, detailed models involve the numerical solution of differential mass, momentum, and energy balances using computational fluid dynamic (CFD) simulations. However, simplified modeling approaches have been developed that give reasonable results. The validation of room air models requires detailed measurements of air conditions at many locations throughout a room. In some cases, measurements are used to obtain parameters of models that are then used to evaluate the performance of the room or used for control purposes.

Hanibuchi and Hokoi used traditional CFD analysis and experiments to study the influence of the location of the supply of heated air to a room on the steady-state distribution of temperatures, velocities, and heat loss. Four different air supply locations were considered including supply from the wall (horizontal jet) and floor (vertical jet). Both measurements and model predictions showed a strong influence of the position of the supply on the temperature distributions, such that the overall heat loss varied by about 15%. Overall, the model did a good job of predicting the temperature distributions within the room.

Chen and Xu present a new simplified model to predict the 3-dimensional distributions of air velocity, temperature, and pollutant concentrations in rooms. Similar to traditional CFD approaches, their method involves solution of the Navier-Stokes equations. Their simplification involves use of an analytic representation for turbulent viscosity as a function of turbulent length scale, turbulent intensity, and local mean velocity. This simplification leads to reductions in the number of grid elements necessary to model a room. Results of the simplified method were compared with those from a CFD analysis and with experimental measurements for four different types of flows: natural convection, forced convection, mixed convection, and displacement ventilation. In general, the simplified method was less accurate than the more detailed CFD analysis in predicting velocities, temperatures, and concentrations of a tracer gas in air. However, the accuracy was acceptable and the computational requirements were two orders of magnitude less than the CFD approach for the cases considered.

Janssens, Berckmans, and De Moor present a semi-empirical model for estimating time varying room air temperature and humidity distributions. The room is divided into a number of relatively large elements with each element's temperature and humidity determined by solution of first-order, linear differential equations that result from mass and energy balances. It is assumed that each element receives a portion of the ventilation flow stream at the same temperature and humidity. This approach decouples the solution of the differential equations for each element. Individual ventilation flow rates and internal moisture and energy gains for each element are correlated to overall ventilation rate by matching the predictions of temperature and humidity to measurements for that element. Although this type of inverse model is not useful for design, it is could be useful for control or for analyzing the performance of an existing air distribution system. The correlation method was tested using measurements from a test room with 24 temperature and humidity sensors. The model was able to accurately capture the dynamic temperature and humidity response due to step changes in ventilation air flow rate.

Peng and van Paassen also describe a model for predicting time and spatial variations in room air temperature using lumped elements that are larger than those typically required for CFD analyses. Similar to Janssens et. al , the element temperatures at any time are determined by the solution of first-order, linear differential equations that result from energy balances. However, in contrast to Janssens et. al, the differential equations are coupled through convective flows, the flow rates between elements are determined from an isothermal CFD analysis, and local internal heat gains are specified as boundary conditions for each element. A typical CFD analysis involves the simultaneous solution of mass, momentum, and energy balances. The advantage of the simplified method is that the CFD analysis only includes a steady-state solution of the mass and momentum equations. The fixed flow field solution determined through CFD is then used as an input to the energy analysis. This approach significantly reduces the computational requirements as compared with a coupled solution to mass, momentum, and energy equations. The authors show good agreement between model predictions and measurements at three high heights within the middle of a test room during a cooldown period.

Cocora, Allard, and Beghein followed a somewhat similar approach in developing a dynamic model for the pollutant concentrations within rooms. The room is divided into a relatively small number of elements. Similar to Peng et. al, the element concentrations at any time are determined by the solution of coupled, first-order, linear differential equations that result from pollutant mass balances and using a fixed air flow field. The air flow rates between elements are determined from a steady-state analysis based upon a simple network model. The model was validated through comparisons with measurements in a room where a tracer gas was injected in the supply air at a constant rate until the gas concentration reached equilibrium. Overall, the model captured the dynamic response extremely well and predicted concentrations within 10% of the measurements.

Takahashi and Kong are interested in predicting the distribution of outlet air velocities of outlet diffusers along the floor in underfloor air distribution systems. They developed a model for an underfloor air distribution chamber based upon simple mass and momentum balances. The velocities at each diffuser are determined from the local underfloor pressure using a model that incorporates a discharge coefficient. A reduced scale system was constructed for the purpose of validating the model. The model performs well for cases where the cross-sectional area for flow within the underfloor chamber is greater than the combined area of all diffusers. In these cases, both model and experimental results showed that the discharge velocities varied by less than 10% between different diffusers.

System Energy Requirements and Analysis

The modeling of buildings and their HVAC systems is useful for evaluating overall energy requirements in the process of making design and retrofit decisions based upon economic criteria and for establishing control strategies. Many commercial simulation programs have been developed for this purpose. Although there have been numerous comparisons between simulation predictions and measurements of energy use, work continues in this area due to its importance and the number of possible systems that exist. Some of the new developments involve integration of dynamic equipment models into existing simulation programs so that the penalties associated with equipment cycling and the impacts of different control methods can be considered. System simulations can also be used to evaluate the performance of existing systems and characterize the savings associated with retrofits. One approach to this problem involves using detailed measurements to “tune” the parameters of a detailed simulation model. The model could then be used to evaluate the retrofit in either a decision phase or after the retrofit has been made. In situations where retrofits have already been installed, black-box models can be used to characterize energy use both before and after the retrofit. The models are then used with measured input data to estimate overall energy savings.

Guyon describes comparisons between measurements and predictions from an existing computer program of heating requirements for a house during 7 months of the winter. The house is typical of new construction in France and is heated electrically. Thermostats were set at 19 C in each room for the entire test period. The measured weather data used for the simulation included global and diffuse solar radiation, ambient air temperature, humidity, pressure, and wind velocity, and room temperatures. The simulation assumed a single zone with a setpoint for heating equal to the average of the room temperatures. For the heating season, the simulation predicted heating requirements within about 5% of the measurements. It was found that the errors were largest in fall and spring months due to the combination of greater solar radiation and simplifications used in analyzing solar gains. Details of the modeling approach incorporated within the simulation program were not described in the paper, but were referenced to previous publications.

Garde, Boyer, Pignolet, Lucas, and Brau integrated models for air-to-air residential heat pumps into an existing building simulation program and compared predictions of indoor temperature, sensible and total cooling capacity, and power for a week period. Three different heat pump models were considered: 1) The heat pump operates continuously and provides the required cooling rate at constant COP. Although not clearly described, it appears that the model also assumes a constant ratio of sensible to total cooling capacity. 2) The heat pump cycles on and off to meet the cooling requirements. The cooling capacity and power at steady state are assumed to be constant, independent of the zone and ambient conditions. However, after each off cycle, the transient cooling capacity is modeled using a first-order differential equation with a specified time constant, while the power consumption is determined with a constant COP. Again, the sensible heat ratio is assumed to be constant. 3) This model uses the same dynamic modeling approach as the second model. However, the steady-state total capacity, sensible capacity, and power consumption are determined from correlations of manufacturers' data as a function of room and ambient conditions. The measurements that were compared with model results were obtained from an instrumented test cell. It appears that the third model was more accurate in predicting the power consumption for the one week test. However, the authors' did not thoroughly document the accuracy of the models in predicting the total and sensible cooling capacities.

Moinard and Givois present a relatively simple, yet mechanistic dynamic model for a gas-fired, absorption cooling system. An initial validation was performed by comparing steady-state predictions with manufacturers' data at a single point, where excellent agreement was shown. The model was then incorporated in an existing system simulation program and predictions of gas consumption were compared with measurements from an existing commercial system. For a nine day summer period, the overall predictions were within about 2% of the measurements. The model was then used to study the impact of design and control improvements on annual gas consumption. Simulated results showed that it should be possible to reduce gas consumption by about 45% through chiller resizing and improved controls. An additional 10% savings would be possible with the incorporation of a thermal storage that reduces the on/off cycling of the chiller. This paper demonstrates a good approach for using simulations and measurements in the optimization of systems. The measurements provide validation and data for "tuning" of the models, whereas the simulations allow the investigation of control and design improvements.

Lapenu and Milcent were also interested in using a validated model to study the sensitivity of energy requirements to design and control changes for a commercial building with an absorption cooling system. Their modeling involved the use of an existing simulation program in which the building was divided into several separate thermal zones. In the validation, measurements of air temperatures and heating requirements showed excellent agreement with predictions for a 5-day period in winter. The authors used the validated model to study the influence of setpoint temperatures, the opportunity for simultaneous heating and cooling for different zones, the building insulation, and the window area on annual heating and cooling requirements. An economic analysis would be necessary in order to make any general conclusions from these results.

Haberl, Sparks, and Chambers discuss the data handling and analysis software that has been developed as part of a large energy conservation program. Primarily, the data analysis is used to evaluate energy savings for retrofits that have been installed. The methodology involves determining empirical relationships between energy use and ambient temperature for time periods before and after the retrofit. In cases where pre-retrofit data is not available, more fundamental models are calibrated to the post-retrofit data and then used to estimate requirements before the retrofit. In either case, the models are used with measured input data to estimate overall energy savings.

Constantinescu describes another approach for evaluating the performance of existing systems. The method is based upon the use of physical models whose parameters are estimated from detailed measurements. The “tuned” model can then be used to evaluate the impact of system improvements. Although the author presents the models used to characterize the building, heat exchangers, and distribution system, he does not describe the parameter estimation methods. System parameters are estimated for a central heating system serving a number of residential buildings. However, the system and the ability of the model to predict performance are not well documented in the paper. This approach would require many detailed measurements and significant computer resources to be an effective tool.

The accuracy of the calibrated simulation approach to retrofit analysis described by Haberl et. al can be improved when local solar radiation measurements are available. For this purpose, Munger and Haberl describe a low cost multipyranometer array (MPA) for continuous measurement of direct and diffuse solar radiation. The MPA consists of four relatively low cost, photovoltaic-type solar sensors that each see a different portion of the sky. The direct normal and diffuse radiation are estimated from a model that relates incident solar radiation for each surface to these unknowns. Corrections are made for the spectral response of the devices based upon comparisons with more accurate measurements. An artificial horizon is also added to eliminate reflected radiation from the ground. Finally, unstable solutions to the solar equations are eliminated through filtering. Measurements from the MPA were compared with more accurate approaches resulting in a root-mean-square error of about 100 W/m^2. This approach shows promise as a low cost measurement for solar radiation.

Building simulation programs are continually being improved through the incorporation of more efficient algorithms for representing building dynamics. Dautin, Deque, Petit, and Gaillard investigated simple state-space models to characterize the dynamics of buildings. The goal of their work was to evaluate model-order reduction techniques in order to determine the proper order for capturing the important dynamics. A single zone of a test building was initially described with 56 state equations and then three different model-order reduction techniques were applied. The method of Moore determined a third-order reduced model and gave the best results in matching the dynamics of the air temperature variation to the detailed model. Results were not compared with measurements in this paper.

Equipment

Much of the recent development in equipment models has focused on including dynamics for the purpose of control studies. For this application, empirical (black box) and semi-empirical (gray box) models are often used where parameters are estimated from measurements. Typically, the training involves the application of linear or non-linear optimization techniques to minimize model prediction errors.

Hansen, Madsen, Holst, Bidstrup, and Vadstrup present a gray-box, dynamic non-linear model for thermostatic valves used in a water-based heating system. The valve includes a gas sensor and valve body where the valve opening responds to changes in ambient temperature. The model can be used to predict water flow rates in response to changes in ambient temperature and pressure difference and is based upon fairly simple physics. The only dynamics considered are associated with the sensor and are characterized with a simple first-order differential equation. Hysteresis in the valve is not considered. Parameters of the model are determined from measurements using a maximum likelihood method. Measurements were obtained from a test heating experiment where the ambient temperature was varied using a heater. Overall, the model provided a good description of the measurements for two sequences of measurements.

Roberge, Lamarche, Kajl, and Moreau present two dynamic models for a room heater with bricks as thermal storage. The first model is based upon a physical description and is useful for evaluating design changes. Model predictions were in good agreement with measurements obtained from calorimeter tests. The second model is a black-box representation based upon the use of an artificial neural network. This type of model could be used for system simulations or control. Parameters of the neural network model were determined using the Levenberg-Marquardt method using the calorimeter test measurements. Only 40% of the measurements were used to train the neural network, while the accuracy of the model was evaluated using all of the measurements. During the tests the power input was constant and the room temperature was varied. For the test conditions, the neural network model was able to capture the dynamic variations in the storage temperature. However, when compared with predictions of the physical model for other power inputs and room temperature variations, the neural network model performed very poorly. It can be concluded that a “rich” set of data inputs is required to adequately train this type of black-box model.

Ternoveanu and Ngendakumana present a dynamic model for a hot water boiler that is based upon simple physics, but where model parameters are estimated from measurements. The model utilizes a system of first-order differential equations that arise from energy balances to characterize the short-term dynamics of the water and flue gas temperatures. Predictions of the model compared well with data obtained from a fuel-oil boiler.

Conclusions

Although the title of this session implies an emphasis on experimental techniques, the papers in this session primarily describe the development, validation, and application of models for predicting building, equipment, and overall system performance. These papers provide new tools that are useful in evaluating the impact of design, retrofit, and control alternatives. The major contributions involve the development of dynamic models and their integration within system simulation programs. For room air modeling, simplified dynamic models have been developed that predict the response of local zone air conditions to changes in supply air conditions. For the most part, these approaches do not rely on CFD solutions. Most of the dynamic equipment models presented in this session are based upon a relatively small set of first-order differential equations. In many cases, parameters of the models are determined by matching model outputs to measurements. The models that are based upon physics require more detailed measurements for parameter estimation, but are more robust in extrapolating performance as compared with black-box models. However, with a “rich” data set, black-box models provide a simple, accurate, and efficient means of predicting dynamic performance that is useful for component analysis, control, or system simulation. Some simple dynamic equipment models were incorporated within system simulation programs and used to study the impact of design and control changes on energy use. In addition to identifying improvements for the systems considered, these studies demonstrated the importance of considering equipment dynamics in analyzing system energy requirements.