**ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY**

Comparison of Building Energy Modeling Programs: HVAC Systems

Xin Zhou[1], Tianzhen Hong[2], Da Yan[1]

[1]**Tsinghua University, China**
[2]**Environmental Energy Technologies Division**

August 2013

Disclaimer

Executive Summary

This technical report summarizes methodologies, processes, and main assumptions of three building energy modeling programs (BEMPs) for HVAC calculations: EnergyPlus, DeST, and DOE-2.1E. This is a joint effort between Lawrence Berkeley National Laboratory, USA and Tsinghua University, China. It is part of a research project under the five-year collaborative research program of the U.S.-China Clean Energy Research Center for Building Energy Efficiency (CERC-BEE). Energy Foundation, an industrial partner of the CERC-BEE, is the co-sponsor of this work.

The fact that large discrepancies exist in simulated results when different BEMPs are used to model the same building has caused increasing concern. Immediate research is needed to identify main elements that contribute towards the discrepancies of simulation results. This will help users get an in-depth understanding of BEMPs and how to improve accuracy of simulation results. This will also help build a foundation for building energy code development and energy labeling programs as they rely on building energy simulations. In order to achieve these objectives, it is essential to identify and understand the differences between widely used BEMPs and the way these differences influence simulation results. This will involve a detailed comparison of these BEMPs from key user inputs, modeling methods, and source code to results. The goal of this BEMP comparison work is to develop new methods and processes to perform scientific comparisons, and to summarize a list of advantages and disadvantages of the three BEMPs, based on an in-depth understanding of their modeling capacities, mathematical algorithms, assumptions and limitations.

For comparison purposes, BEMPs can be divided into load modules and HVAC system modules. This technical report predominantly focuses on the latter as a previous report focused on the former. A comparative test method is used mainly for the inter-program comparisons. First, the HVAC system modules of the three BEMPs are summarized, analyzed, and compared to identify differences in the solution algorithms and main assumptions. The component models are important parts of the HVAC system calculations and have an important influence on the HVAC calculation results. The calculation methods and main assumptions of several of the main components are discussed and compared in detail. As the HVAC control strategies of supply air temperature, supply air volume, and other parameters affect the operation of HVAC systems, they have significant impacts on the simulation results. The basic simulation methods of the control strategies in the three BEMPs are summarized and the differences are discussed. Secondly, the limitations of existing HVAC system calculation tests are discussed, and additional tests are designed to allow the HVAC systems to be compared deeply and thoroughly. CAV (constant air volume) and VAV (variable air volume) systems are tested in this study to analyze the HVAC system performance and control strategies under various heating/cooling load ratios. All inputs for the test cases of the three BEMPs are kept constant where possible. For parameters that cannot have same values, equivalent conversions are made, in the interest of consistency. The tests include the system-side and plant-side, so that the test process is similar to real cases. Analytical tests are first conducted to ensure the load-side calculations are consistent, so differences in the following calculation results can only come from the HVAC system modules. Through the CAV tests under

full load and part load conditions, the component models and their influences on the calculation results are compared. Then, based on the VAV test cases, the control strategies used by the three BEMPs are analyzed in detail. Finally, a case study based on a real office building is presented and differences in the simulation results from the three BEMPs are analyzed. Based on the load calculation results, drivers of the differences in the HVAC side are analyzed and discussed.

Main research findings are summarized as follows:

1. EnergyPlus, DOE-2.1E, and DeST all have fundamental capabilities and appropriate modeling assumptions for HVAC system simulations. The results from the comparative tests on component models show small differences, which are mainly due to input settings and algorithms used in each program. Differences between the calculated total energy consumption of HVAC systems from DeST and EnergyPlus can be less than 5%, if all component models are similar, and the same or equivalent inputs for the HVAC systems are used. It is found that the main influencing factors on HVAC discrepancies between DeST and EnergyPlus are the algorithms used for the HVAC component models and their control strategies. For the case that simulates the real building, using design and default values for the inputs of each simulation program, the errors in both load calculations and HVAC system calculations are within 15% of the measured values. This demonstrates good agreement between the simulation programs for modeling real buildings.

2. EnergyPlus has more comprehensive component models than DOE-2 and DeST. The three programs have consistent component models for pumps, fans, and boilers. The coil models in EnergyPlus and DeST are based on engineering/physics equations while the coil model in DOE-2 is based on assumptions and empirical data. The influences of load ratio, condenser inlet water temperature, and evaporator outlet water temperature on the chiller efficiency are considered in all three programs. Three chiller performance curves with user-specified coefficients are used in EnergyPlus and DOE-2, while one hard-wired performance curve is used in DeST. In EnergyPlus and DOE-2.1E, the fan power of the cooling tower is related to the load ratio, so the fan can cycle on and off during a particular hour if the load is small. In DeST, the fan power draw remains constant whenever the cooling tower has a load for any particular hour.

3. To complete a comprehensive comparison of the three different simulation programs, several requirements are needed: 1) the test cases should be broad enough to cover most modeling features; 2) the test cases should be detailed enough to isolate influencing factors; 3) special cases should be designed to test the unique limitations of each program. Based on the current development of HVAC system tests, a test concept is introduced in this study to develop a better method of comparison. As each component in a HVAC system is connected and influenced by one another, the whole HVAC system should be considered when the comparison is conducted. This means that both air-side and plant-side components should be tested together. Imposing steady-state conditions makes it possible to compare each component model in detail and calculate the

analytical results. Considering the whole system makes the test process more practical.

It should be noted that further research is needed to compare more HVAC system types and control strategies, especially how low energy systems, e.g. natural ventilation, radiant systems, displacement ventilation, to understand the differences and limitations of the three BEMPs. This study can be a supplement to the on-going development of HVAC test cases for ASHRAE Standard 140.

Table of Contents

1 Introduction

1.1 Background

Computer simulation is one of the most effective and economic methods to predict and analyze building energy consumption and performance. The simulation industry has developed rapidly since the 1960s, with hundreds of Building Energy Modeling Programs (BEMPs) developed and used around the world. Well known BEMPs include DOE-2 and EnergyPlus from the U.S. Department of Energy, ESP-r from the University of Strathclyde, U.K., and DeST from Tsinghua University, China. These BEMPs are widely used in the design stages of new energy efficient buildings, the planning stages of energy retrofits for existing buildings, and the development of building energy codes and standards and energy labeling programs in the building industry.

However, more and more practical applications show that large discrepancies exist in results from different modelers using different BEMPs for the same building. This is a large problem for the simulation industry and the subject of much attention. Some believe that the simulation methodology is flawed and attribute the discrepancies to the different calculation engines of different BEMPs. This may hinder the development and application of BEMPs. Consequently, it is important for the simulation industry to understand the reasons for these discrepancies and define the application scope of each program. To solve the problem and promote the development of BEMPs, the detailed comparison of BEMPs' engines is a fundamental and significant step.

A number of studies have been conducted to compare the advantages and disadvantages of several BEMPs. For comparison purposes, BEMPs can be divided into two parts: the load-side calculations and the HVAC system-side calculations. This report focuses on the HVAC system-side calculations. A previous report discussed the load side comparisons (REF). Compared to methodologies for testing load-side calculations, the HVAC system comparison process is at an early stage. There exists no widely accepted testing procedure that can be used directly. The inter-program comparison of HVAC system calculations for commonly used BEMPs is of great significance for users to gain a better understanding of each simulation program. This will also lead to a more effective use of building simulation in scientific research and engineering practice.

1.2 Objectives

EnergyPlus, DeST, and DOE-2.1E are compared in this technical report. These three BEMPs are used widely in the U.S. and China. The comparison will focus on the solution algorithms of the HVAC systems, component models, how the control strategies are modeled, and default program inputs.

The objectives of the comparison include:

1. Better understanding of the HVAC system calculations in each program, including the simulation structure, application scope, advantages,

disadvantages and limitations;

2. Identify key elements leading to the different results from EnergyPlus, DeST, and DOE-2. Attention is paid to the BEMP algorithms, modeling capabilities, and the main assumptions for the HVAC calculations;

3. Provide a list of advantages and disadvantages for each program. This is to allow the correct application of each BEMP to the building life cycle design process (including planning, design, operations, and retrofits) to achieve the goal of reducing building energy use. This important work also provides technical guidance on the use of different building simulation programs to support the development of China's building energy standards and energy labeling programs;

4. Explore a more comprehensive test method for HVAC simulation systems, and from the results, analyze the impact of key elements on the simulated HVAC system energy consumption;

5. Apply the research findings to a real building case study to help test and analyze the differences in simulation results caused by using the three different simulation programs.

1.3 Methodology

The methodology of this study is shown in Figure 1.
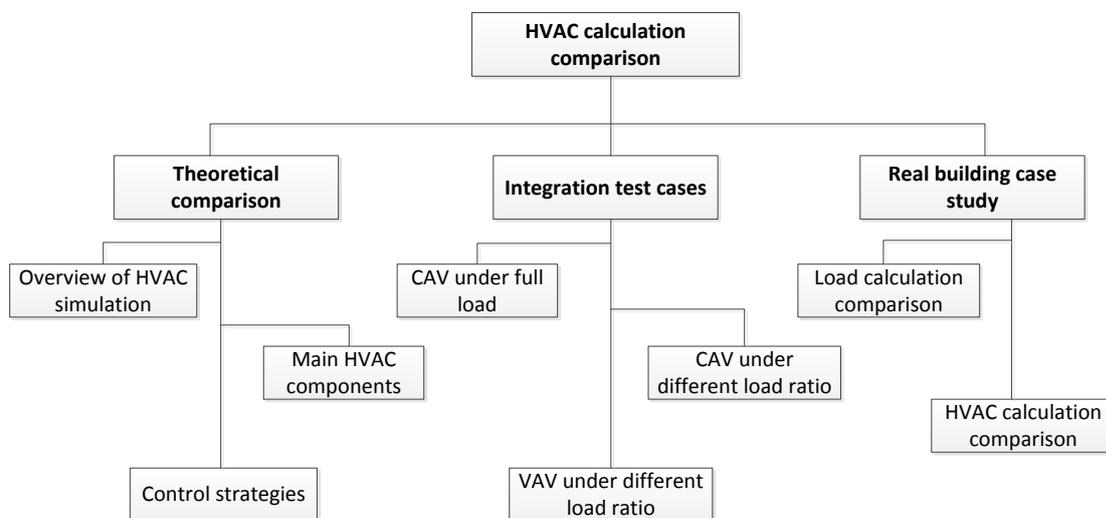
Figure 1 Technical roadmap of HVAC calculation comparisons

The HVAC calculation comparison in this technical report is composed of three main parts as follows:

Theoretical comparison

First, in Section 2, each of the three BEMPs is reviewed in terms of HVAC simulation methods, and their advantages and disadvantages are summarized. Then, focusing on the main HVAC components in Section 3 and HVAC control strategies in Section 4, the differences between simulation methods (including solution algorithms, modeling assumptions, and simplifications) are discussed and analyzed in detail. This is a key

step to identifying the inter-program discrepancies.

<u>Integrated test cases</u>

Based on the review of existing HVAC system tests, an integrated test method is proposed and used. Due to the similarity of EnergyPlus and DOE-2 in the use of steady-state HVAC models, the test process is only applied to EnergyPlus and DeST. Two types of HVAC systems (CAV and VAV) are tested under different load conditions. Comparisons of each component model and control strategy are made and analyzed in detail.

<u>Case study with a real building</u>

Based on the findings of the previous two comparisons, a real building case study is conducted using the three simulation programs. The differences in the load-side calculations are compared first. Then, on the foundation of the load-side results, the errors in the HVAC system energy consumption results are compared and analyzed to ascertain the differences between measured and simulated results, for each program.

2 Overview of the three programs
2.1 EnergyPlus

2.1.1 Overview

The entire integrated program can be represented as a series of functional elements：BUILDING/Zone, SYSTEM, and PLANT subroutines are integrated and controlled by the integrated solution manager. These elements have to be linked in a simultaneous solution scheme. The solution scheme generally relies on successive substitution and iteration to reconcile all of the elements using the Guass-Seidell philosophy of continuous updating.
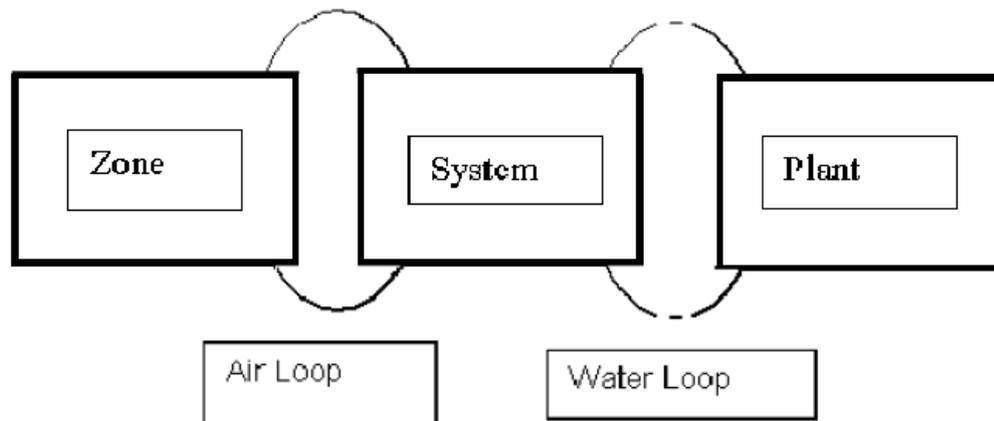
Figure 2   Schematic of simultaneous solution scheme

The elements are connected by fluid loops, and each loop is divided into supply and demand sides.

Air loops are divided into two parts as per the following：

Primary air system: the supply side of the loop, including supply and return fans, central heating and cooling coils, outside-air economizers, and other central conditioning equipment and controls.

Zone equipment: the demand side of the loop, including air terminals as well as fan coils, baseboards, window air conditioners and so on.

The water loop can be separated into a plant loop and a condenser loop. Similarly, the supply side and demand side can be ruled as following：

Plant demand side: equipment (coils, baseboards, radiative systems, etc.) that places a load on the primary equipment (e.g. chillers and boilers).

Plant supply side: chillers, boilers, etc.

Condenser demand side: chiller condenser

Condenser supply side: cooling tower that cools the condenser water

Figure 3   Connections between the main HVAC simulation loops and sub-loops

2.1.2   Assumptions
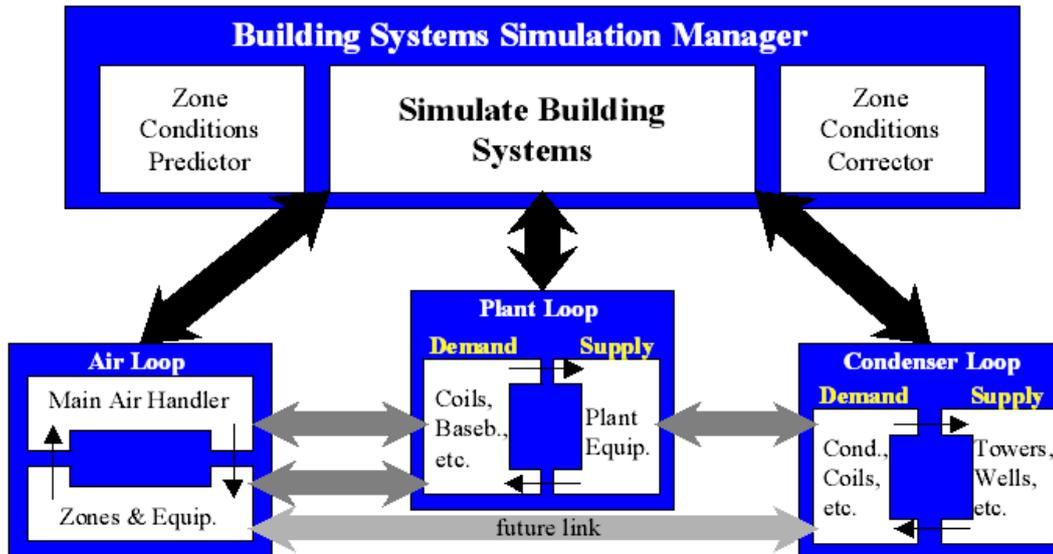
There are several main assumptions made in EnergyPlus. For reasons of consistency and comprehensibility, it is required that all EnergyPlus models be forward models. That is, the component inputs correspond to the inlet conditions and the outputs correspond to the outlet conditions. For each component several choices of inputs and outputs are possible.

1、 AIR SYSTEM CONTROL uses a predictive system energy balance method. It has many characteristics of a predictor-correct method. An assumption was made that if the air system has sufficient capacity (based on the desired zone air temperature) to meet the zone conditioning requirements, those requirements will be met. On the other hand, if the air system cannot provide enough conditioning to the zone, the air system provides its maximum capacity.

2、 Simultaneous solution of the system and plant operating parameters requires that the temperature of the water entering the coils must be the same as the temperature leaving the chillers or boilers. Also, the temperature of the return water from the coils must be equal to the chiller or boiler supply water temperature. If the plant has adequate capacity, no iteration is needed (i.e. the supply water temperature equals the set point). But when the plant is overloaded, the plant outlet water temperature is calculated iteratively using the secant method.

3、 During each system simulation time step, new zone temperatures and humidity ratios are predicted using previous values. The zone temperatures and humidity ratios are then held constant during the simulation of the air system (and the plant). Then the zone temperatures and humidity ratios are corrected using results from the system simulation. As a result the usual algebraic loops arising from steady-state air system simulations are eliminated.

4、 The properties of the loop (temperature, enthalpy, flow rate, etc.) are stored in the branch nodes. Components on the branch take the conditions of the nodes at their inlet and use that information as well as overall control information to perform calculation for the components. Simulation results are written to the outlet nodes of the component, and also copy to the down streaming nodes on the branch.

5、 The plant flow resolver is used to adjust the flow rate within the plant and condenser loops. First, the loop manager would simulate all the components on each branch of the loop purely based on the components' own control to satisfy the desired flow rate. Then, the loop manager would resolve the flow and the components are re-simulated with the corrected flows. During this iteration, the flow resolver sets the flow rate. In order not to resort to a pressure-based flow network, a rule-based "flow resolver" was employed. The flow resolver uses a simple predictor-corrector algorithm to enforce mass continuity across the plant splitters.

6、 To control the fluid temperature, thermal capacitance is added to the plant loop. This adds stability to the calculations. Once the set point temperature is reached, the storage effects are not included.

7、 The loops essentially ignore the node pressures. This is suitable for many applications; however it may cause inaccuracies in the calculation of the pump power. The loop pressure drop is used as the new pump head. If a pump curve is not specified, it is assumed that the pump will always be able to meet the operating point.

8、 When a parallel system is encountered, the parallel system is set to use the highest pressure drop found on the parallel branches. There are two types of pressure drop curves that can be entered: generic (a function of current mass flow rate), and pressure information (frictional effects and minor losses).

9、 EnergyPlus can also perform a "loop level" pump-system flow resolution to calculate the loop pressure drop. The flow resolver reads the non-dimensional pump curve, loop pressure constant and rated mass flow rate (or mass flow rate from the last iteration) to calculate the pump operating point.

2.1.3 Summary

In conclusion, EnergyPlus is a powerful simulation program. The main idea is successive iteration and analogue simulation. This calculation method leads to a high requirement on convergence and stability, so a series of measures has been taken to improve the performance of the solver. However, EnergyPlus allows users to overwrite internal algorithms or add new calculations via the Energy Management System feature, which improves the flexibility of HVAC simulations.

To eliminate the necessity of solving the interactions between pressures and flow rates, EnergyPlus currently has no duct system model, so the flow rates of different ducts are determined by a ruled flow resolver. The flow resolver distributes the flow rate according to the characteristics of each branch. This assumption is an effective

way to reduce the complexity of the model and improve the speed of convergence. But it does not accurately address the interactions between branches that affect the balance of the flow. Such limitations lead to several un-resolved operating problems, e.g. flow rate adjustments and coil dynamic characteristics.

EnergyPlus calculates the pressure drop based on the flow rate. However, the change of pressure does not affect the branch flow rate. Additionally, the flow rate of each branch has nothing to do with the branch's resistance characteristics. Therefore, the resultant pressure has no practical meaning, and can only be regarded as a reference.

The majority of inputs for EnergyPlus are determined by the user. This requires a high level of expert knowledge in buildings and HVAC systems. The amount of input data is large, which is one of the main reasons for long execution times.

2.2 DOE-2.1E

2.2.1 Overview

DOE-2 is a program that uses sequential simulation modules. It has one subprogram for the translation of user inputs (the Building Description Language (BDL) processor), and four simulation subprograms (LOADS, SYSTEMS, PLANT, and ECON). The SYSTEM and PLANT subprograms constitute the HVAC subroutines. LOADS, SYSTEMS, and PLANT are executed in sequence. Outputs from the SYSTEMS and PLANT modules become inputs to the ECON module. Then the ECON subprogram calculates utility cost as part of the economic reports.

The SYSTEMS subprogram uses the output information from the LOADS program and a list of user-defined system characteristics to handle secondary systems. The PLANT subprogram uses hourly results from the LOADS and SYSTEMS programs, combined with user instructions, to handle primary systems. SYSTEM calculates the performance of air-side equipment (fans, coils, and ducts). It corrects the constant temperature loads from the LOADS subprogram by taking into account outside air requirements, hours of equipment operation, equipment control strategies, and the thermostat set points. The outputs of SYSTEMS are airflow rates and coil loads. PLANT calculates the behavior of boilers, chillers, cooling towers, storage tanks, etc., in satisfying the secondary systems heating and cooling coil loads. It takes into account the part-load characteristics of the primary equipment in order to calculate the fuel and electrical demands of the building.
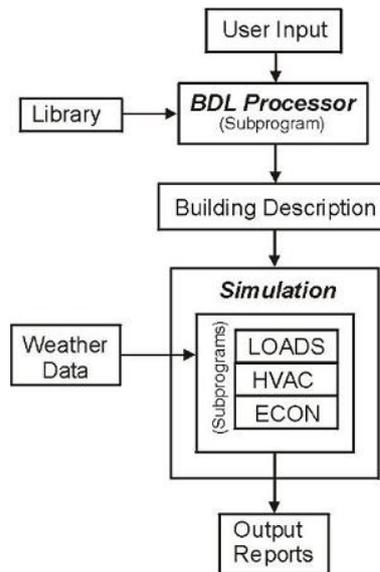
Figure 4   DOE-2 calculation flow chart

2.2.2   Assumptions

Several assumptions are made in DOE-2.1E, including：

1.   The dynamics of the interactions between the HVAC equipment and the building are calculated by the simultaneous solution of the room air temperature weighting factors with the action of equipment controller. To eliminate the necessity of solving the interactions of all the zones simultaneously, the zone temperatures from the previous hour are used to approximate the heat flow across internal walls. Likewise, to eliminate the need to iterate until all of the temperatures in the equipment loop converge, temperature histories are used in the calculation of equipment capacities. This is a good approximation if the derivative of the zone temperature is roughly constant.

2.   The moisture content of the air is calculated by assuming a steady state solution of the system moisture balance. The moisture condensation on cooling coils is simulated by characterizing the coils by their bypass factors and then solving the bypass relation simultaneously with the system moisture balance.

3.   A linear relationship is assumed to describe the interaction of the thermostat, space temperature, and equipment output. First, the capacity is estimated by using the dry- and wet-bulb temperatures from the end of the previous time step (hour). Then according to the estimated equipment capacity, the corresponding relationship with zone temperature is used to decide the equipment's capacity.

4.   The equipment capacity and energy input are expressed as the product of a "rated" value and modifier functions. It is assumed that it can be well approximated by the product of multiple modifier functions.

5.   As all of the information is communicated in one direction only, a subprogram "upstream" cannot make use of any information "downstream", like the overload cases. In the PLANT subroutine, if the coil load is not met, it will pass the

8

overload to successive time steps until it is finally met, or the heating or cooling is scheduled to be switched off. The one-way flow of information also does not allow several building control strategies to be simulated, such as adjusting the lighting loads according to the electrical loads.

6. If multiple sizes of given equipment type are operating simultaneously, the program models them as if all the equipment was lumped together into one large unit. It assumes that the same type of equipment will have identical performance curves regardless of their sizes. Also, it is assumes that all equipment of the same type will be operating at the same fraction of their design capacities.

7. Electricity needed to operate a boiler or a storage tank pump is not accounted for in the total energy of PLANT.

8. The PLANT subprogram does not make checks to see if the type of equipment and fuel types the user inputs are compatible.

2.2.3 Summary

DOE-2.1E is a simulation program with a long history and a comprehensive set of functions. However, due to the lack of further development since the early 1990s, there are several weaknesses in the software. The main problem is the structure of the software. It has no feedback process, and the one direction calculation flow contains a lot of simplifications compared to real HVAC systems. Facing the increasingly complex system schemes and control methods which are currently emerging, DOE-2 cannot adequately satisfy some user requirements, particularly those with feedback situations.

To simply the calculation process and avoid iterative calculations, in DOE-2 the zone temperatures from the previous hour are used to approximate the heat flow across internal walls and temperature balances. This method will introduce inaccuracies when the zone temperatures fluctuate significantly.
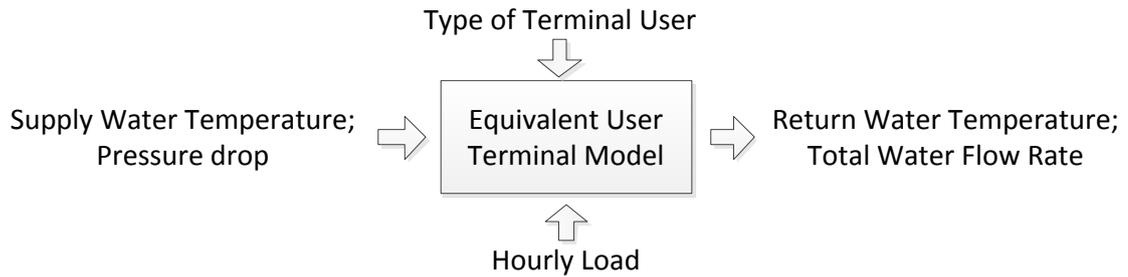
Meanwhile, the SYSTEMS subroutine corrects the constant-temperature loads by the LOADS subprogram using room air temperature weighting factors. It does not perform a true zonal heat balance and will also lead to inaccuracies.

2.3 DeST

2.3.1 Overview

DeST separates the heating/cooling station (central plant) from the supply side, dividing them into two modules (equivalent user terminal and heating/cooling station). The equivalent terminal model is a simplified model to reflect the main properties of air terminals. The two modules iterate to obtain the results. DeST performs detailed modeling of ducts, chillers, and pumps in the heating/cooling station side. Exact and strict physical equations based on first principles are used, but

in the user terminal side, a curve is used to reflect the changes of whole flow rate, pressure drop, and heat transfer.

Type of Terminal User

Supply Water Temperature;   Equivalent User   Return Water Temperature;
Pressure drop   Terminal Model   Total Water Flow Rate

Hourly Load

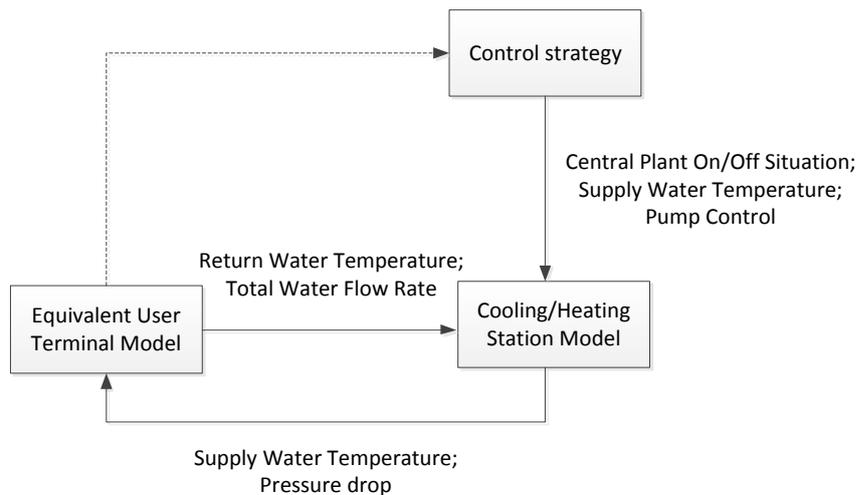**Figure 5 Equivalent user terminal model**

DeST builds equivalent user terminal models for different end types. As Figure 5 shows, in the terminal model, when the terminal user type and hourly load have been input, and the user side supply water temperature $t_{w,in}$ and the pressure drop ΔP have been calculated, then through the equivalent user terminal model, the chiller water flow rate in user side and the return water temperature $t_{w,out}$ are calculated. The equivalent user terminal model can reflect the overall performance and the time average situation. In this way, the terminal system is separated from the complex dynamic control. In the heating/cooling station model, as Figure 6 shows, when the control strategy of heating and cooling station has been determined, and the return water temperature and flow rate have been input, the supply water temperature and pressure drop can be calculated.

Control strategy

Return Water Temperature;   Cooling/Heating   Supply Water Temperature;
Total Water Flow Rate   Station Model   Pressure drop

Pump Consumption;
Central Plant Consumption
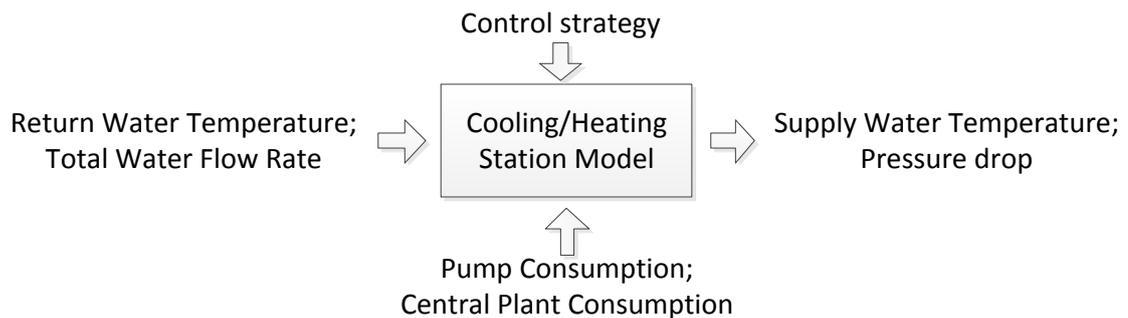
Figure 6   Heating/cooling station model

After the modeling of equivalent user terminal and heating/cooling station, based on the inside coupling relationship, iterative calculations are performed to obtain the actual flow rate, pressure drop, and water temperature, thus maintaining the consistency of water flow rate, pressure drop, and heating/cooling load on both the

user side and supply side. The combined iteration method is illustrated in Figure 7.

Figure 7 Iterations between equivalent user terminal model and the heating/cooling station model

2.3.2 Assumptions

DeST makes several important assumptions：

1. For the lower level closed-loop controls, DeST only checks to see whether a set point can be met by regulating equipment. If the set point can be met, DeST calculates the regulated variables, such as the cooling outputs, pump rotation speed, and valve pressure drops. Otherwise, the control apparatus will be opened to the maximum position.

2. For the overall upper level control strategies for the cooling and heating plants, DeST uses detailed simulations, e.g., when determining the operating status of each chiller and pump. Because control strategies can vary significantly, DeST cannot cover all possibilities, but it does provide a few simple control strategies for users to choose. Users can enter code for control strategies based on their needs using a list of parameters and variables provided by DeST.

2.3.3 Summary

With the concept of an equivalent user terminal, the iterative calculations between demand side and supply side has been simplified, which also decreases the complexity of the iterative calculations and improves the chance of convergence. DeST's whole simulation structure is simpler and clearer compared to other programs. So far the equivalent user terminal has covered several typical HVAC systems. This needs to be expanded for new HVAC systems.

Thank You for previewing this eBook

You can read the full version of this eBook in different formats:

- ➢ HTML (Free /Available to everyone)

- ➢ PDF / TXT (Available to V.I.P. members. Free Standard members can access up to 5 PDF/TXT eBooks per month each month)

- ➢ Epub & Mobipocket (Exclusive to V.I.P. members)

To download this full book, simply select the format you desire below