A USER-FRIENDLY TOOL FOR THE INTEGRATED SIMULATION OF BUILDING HVAC CONTROL PERFORMANCE

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ABSTRACT

Full simulation of a building's HVAC control is important. *Good control is the most cost-effective way to reduce plant size and save energy and maintenance cost.* To address these issues the control designer needs an easy to use, but accurate tool that simultaneously solves the building thermal, the HVAC system and its control performance.

We have developed such a tool. Our new simplified, yet extensively verified, building model made an efficient integrated tool possible. The system simulation is also done using simplified yet accurate component models. A unique simulation tool resulted.

Any building, any HVAC system and any control strategy can now easily be built up using a graphical user interface. The system is then iteratively solved by obtaining an energy balance for each component and for the system as a whole.

The software was already successfully verified against eight case studies. The results proved to be sufficiently accurate for design as well as control and energy analyses. For example, energy predictions are generally within 10% of measured values while zone temperatures are within 1 ^{o}C for 90% of the time.

A new user typically takes one day to use the software. Computing time for a very involved building, HVAC system and complex energy management control is approximately 10 minutes on a PC. It is thus easy and practical to investigate various control strategies.

INTRODUCTION

Previous simulation tools were primarily aimed at the research community. Control engineers found these tools difficult and cumbersome to use. The level of integration of existing tools is also suspect. This means that real-life situations are not always correctly modelled.

There are a myriad of system simulation tools available. DOE-2[1] was developed by the Lawrence Berkeley Laboratory, while E-CUBE was originally developed by the American Gas Association. AXCESS[2] was developed by Edison Electric Institute, COMTECH[3] by the Electric Power Research Institute, HAP E-20[4] by Carrier and BLAST[5] developed by the US Army Construction Engineering Research Laboratory. TAS[6] was originally developed by the Amazon Energy in the UK but is now supported by Environmental Design Solutions Limited. TRACE[7] was developed by the Trane Company. Of these DOE-2 is probably the most popular and comprehensive while TAS is the most user-friendly.

For most of the calculations in the above-mentioned tools are usually done sequentially. Firstly, a load calculation is done by using a building model and by specifying the indoor temperature. Secondly, the system calculations are done determining the thermodynamic response of the various components in the air-handling units. Thirdly, the plant equipment that are responsible for energy conversion such as boilers and chillers are calculated. For these simulations various control sequences can be specified.

In DOE-2 the load calculation is based on the response factor method. System modelling is done next with the building loads as input. The primary cooling or heating equipment is then solved with the results of the system simulations as input. This uncoupling of the various elements could result in large errors. The real controller will invariably not keep the indoor temperature exactly on the right temperature resulting in the storing effects being incorrectly simulated.

DOE-2 tries to minimize the effect of this problem (see ASHRAE[8]) by using weighing factors. But even so, substantial errors can be introduced if the indoor temperatures vary. Such indoor temperatures can be encountered due to a number of conditions such as large internal loads in a well-insulated building, badly tuned controllers and large diurnal outdoor temperature swings.

As described by Rousseau and Mathews[9] the uncoupling of the system and plant models also poses problems. It could happen that the system requires a larger capacity than the plant can deliver. In DOE-2 an overload is reported, but in real life this would imply that the indoor temperature cannot be maintained seeing that the load cannot be offset.

A separate load calculation model based on the response factor method is used to determine the loads that are used in the building model of HVACSIM+. No load modelling is attempted simultaneously with the system simulation. Thus the problem with varying indoor temperature will also be experienced here.

In the HVACSIM+ program it is assumed that the plant has infinite capacity. A realistic interaction between the plant and the system can thus not be simulated. The program does simulate in detail the plant operation. Unfortunately the execution time for HVACSIM+ is prohibitive.

APACHE makes use of a detailed finite difference technique to simulate the building envelope. It is well known that these techniques require substantial numerical effort to solve. The building model should however be suitable for use as a comparison tool in order to compare its results to simpler solution procedures. (This is done by Tindale[10]).

An integrated thermal simulation tool is presented in this paper. The unique feature is the simplified component models. The component models are empirical models of components, obtained by regressions on the manufacturers' data sheets. The building model is a simplified electrical analogy which has been extensively verified.

Design, optimizing and commissioning of an HVAC system controls can now be accomplished with much more ease and confidence than before.

MODELLING

The system modelling in the new thermal analysis tool is done on a component basis. There are individual models for the cooling coils, cooling towers, chillers, fans, pumps etc. The modelling of each of the components are regressions of performance data given in the suppliers' catalogues.

The data from the suppliers' catalogues does not usually provide dynamic performance data. At present the user is required to provide a time constant for the component under considerasion. Future work will be undertaken to improve this situation.

A large number of components are already listed in the database. The user can select a component that is closest to his specific component, or he can give the regression coefficients for the specific component. This is a powerful feature seeing that the regressions can also be obtained from measured data. The actual performance of a given plant can then be simulated exactly. This is very convenient for retrofit studies, for example.

The controller models at present consist of the PID controllers, step controllers and a controller to handle economizer cycle control. Each controller is equipped with scheduling and setpoint setback capabilities.

Energy management strategies are also implemented and the program can handle the important strategies currently used in the industry. These include scheduling, temperature reset, load reset, temperature set point setback, unoccupied time setback, load limiting and optimal start stop.

Approximately 40 man years have been spent on the development of the thermal modelling and the computer program.

SIMULATIONS

The tool provides a menu from which the components that make up the system can be selected. The component is introduced in the graphics user interface as an icon. Clicking on this icon with the right mouse button provides the user with an input screen where details of the component can be specified.

The icon can be dragged and dropped in the user interface at the appropriate position Connections to other components can be achieved by means of left mouse button operation. Where ambiguity exists, the tool prompts the user to select the input. For example, if we are connecting a water pipe to a chiller, the tool needs to know if we are connecting the pipe to the evaporator or to the condenser inlet.

The simulation is performed by obtaining an energy balance for each component, and for the system as a whole. The components are solved in a sequential manner. The solution procedure that is followed uses the TARJAN Depth First Search (DFS) algorithm[11] to obtain the unknowns that must be solved at each iteration. A quasi-Newton solver is then used to obtain the energy balance at each time step.

Integration continues until a preset convergence criteria is reached or the maximum specified days of integration are reached. To reduce the number of days needed to reach convergence a passive simulation is done with an approximate setpoint inside the building. The building has the slowest transients and will therefore determine the number of days needed for convergence. Passive simulations would thus yield a good initial value for the building model.

Controller outputs at each step is only dependent on the previous time step values. This considerably reduces the complexity of the solution algorithm. From a system performance point of view this implies that the controller acts like a controller that has a sampling rate corresponding to the system integration time step size.

The controller implementation as discussed in the previous step implies that the controlled dynamcs do not give rise to instabilities in the solution of the energy balance. Furthermore, the mass flow rates are not solved iteratively. The mass flows through critical components are specified or controlled (as in a VAV system for example), so they are known at the start of the iterative solution procedure. The solution procedure is thus needed to solve the energy balance only. No instability problems are encountered.

Day simulations for the system in Figure 1 with 40 times teps per hour would take 680 to 720 seconds on an Intel Pentium 133MHz processor running under Windows 95. For the system in Figure 1, the mathematical model for each component is solved at each iteration step.

Eight unknown variables are identifiied with the solution algorithm, namely: the enthalpy and humidity of the return air for each of the three duct systems, the temperature of the water in the pipe before the pump in the condenser and evaporator liquid circuits. These need to be solved for at each step.

An experienced user will be able to do a fully integrated simulation for a complete building in approximately a day and a half. If all the components that the user intends to use are already in the database this time will be reduced significantly.

A CASE STUDY

In order to show the power of integrated simulation a real-life case study will be presented in this section. The building formed part of a retrofit project that the authors were involved in. Figure 1 and Figure 2 show a schematic of the building under consideration. The building is a five storey laboratory and office building. There are nine air-handling units supplying conditioned air to each zone. In this context we will lump all the offices or laboratories that are serviced by an AHU into one zone.

A constant volume constant temperature system with re-heat was initially used. Two water-cooled liquid chillers were used at the primary refrigeration equipment. Heating was obtained from a steam line. The steam was used to heat the water in a secondary heating water circuit.

After a number of retrofit simulations the retrofit options with the shortest pay-back period were implemented. This entailed that the supply air temperature would not be held constant any more but would be reset according to the outdoor temperature. This is a common scheme used to reduce the cooling and re-heating loads in systems with these configurations. Furthermore the system was scheduled to be off over weekends and during the night. Not all the units could be turned off overnight seeing that part of the building is used as a laboratory facility.

The chiller power consumption is shown in Figure 3 and Figure 6. The first system uses a reciprocating chiller, and is controlled using a step controller. A centrifugal chiller is used for the second system and the control is approximated with a proportional controller.

One can see that the actual chiller of the first system switches more frequently than the simulations predict. This could be due to two reasons. Either the pump is less efficient than the simulated pump or there are heat gains to the pipes that cause the chilled water to heat more than is simulated. In our model the heat gain to the chilled water is not taken into account.

The simulation tool does predict the cycling of chillers with step control. It is advantageous for the control engineer if cycling can be predicted correctly. Switching chillers so frequently could lead to substantially reduced service life and increased maintenance of this expensive equipment. Engineers can then use the software to decide on alternative strategies for solving the problem.

In our modelling of the fan and the pumps we do not attempt to find the actual operating point of the pump or fan by matching the system and pump or fan characteristics. The mass flow is the specified flow. This simplifies the solution algorithm considerable and also implies that if the mass flow is approximately correct the energy used by the fan and pump should be predicted substantially correct. The results for the two systems can be seen in Figure 4 and Figure 7 and confirm this.

The steam pipeline was not modelled in this case study. Instead, the warm water from the heat exchanger was modelled using a water source. The water temperature was specified at the measured value. Temperature and flow measurement were used to calculate the thermal energy for the heating process.

A comparison between the actual and measured heating loads are shown in Figure 5 and Figure 8. The heating trends seem to be accurately modeled. The peak in the heating load for the second system is primarily due to reheating taking place.

There is no point in having integrated simulation if the indoor temperatures are not predicted accurately. To this end the measured and predicted indoor air temperatures for two typical zones are shown in Figures 9 and 10. There are ten zones in all and the lack of space prevents us from showing all the zone temperatures. However, it was found that the temperatures are within 0.5 °C 50% of the time and within 1 °C for 92% of the time and within 1.5 °C for 94% of the time.

CONCLUSIONS

A new simplified integrated thermal simulation tool is introduced in this paper. Simplified models are used for the HVAC components and a simplified electric analogy is used for the building model. The system with its controls are modelled and simulated. In the one case study reported on here the results are of sufficient accuracy for the program to be used as a simulation tool for yearly energy consumption predictions.

Powerful features such as energy management strategies can now be simulated and predictions of energy savings can be made with confidence.

The tool should be the ideal tool for control engineers.

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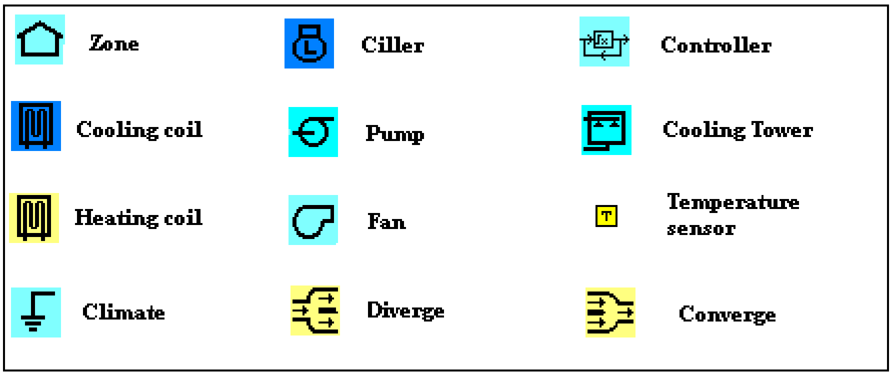
NOMENCLATURE



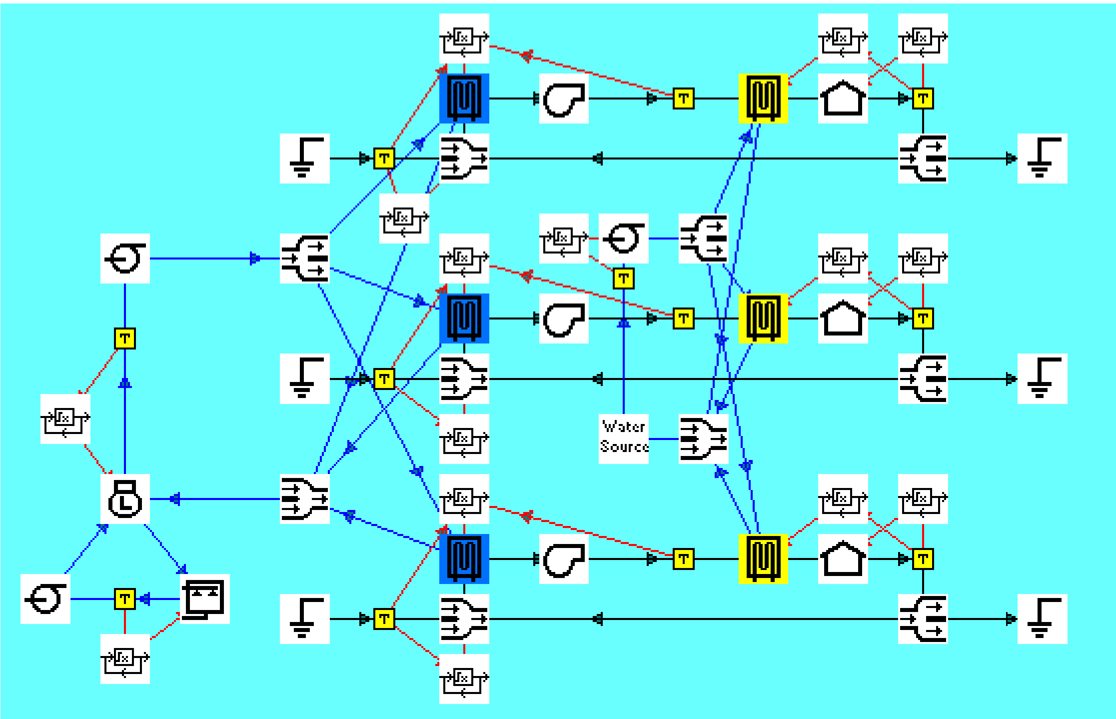


Figure 1: Schematic of first HVAC system.

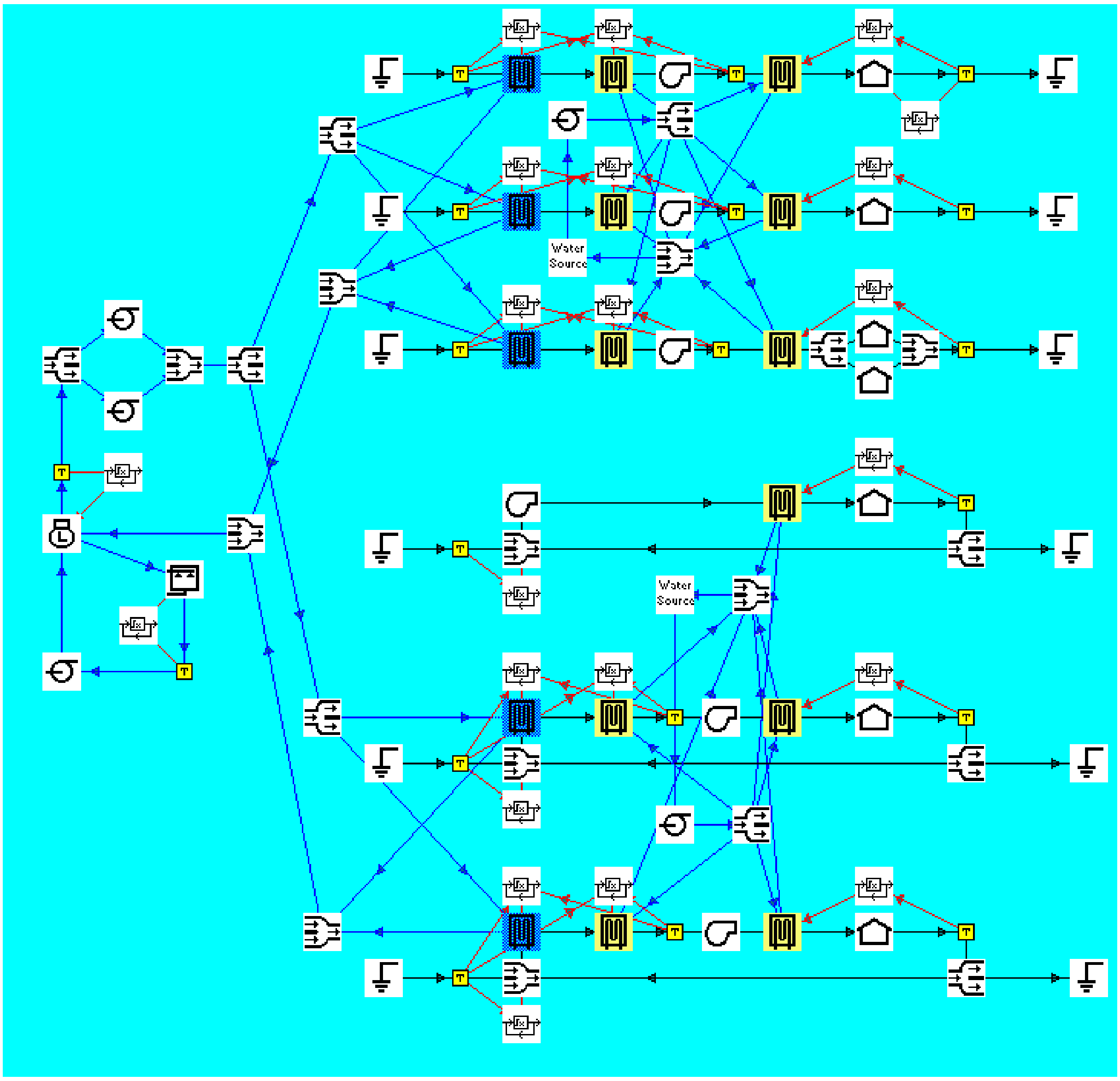


Figure 2 : Schematic of second HVAC system

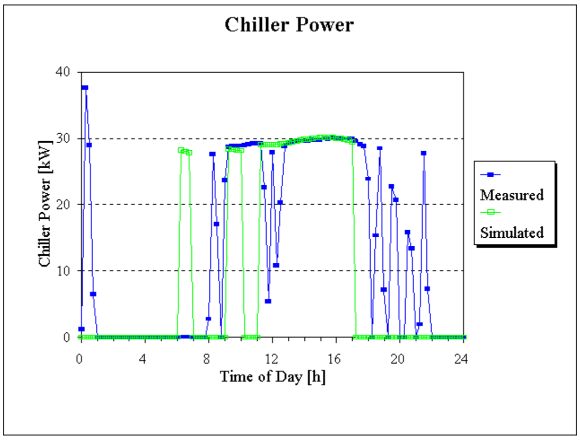


Figure 3: Chiller power for first system

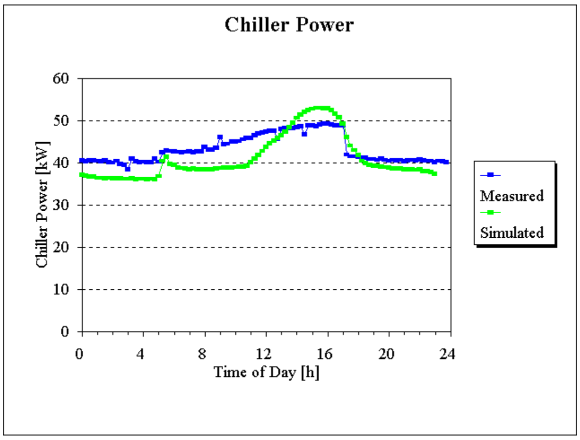


Figure 6: Chiller power for second system

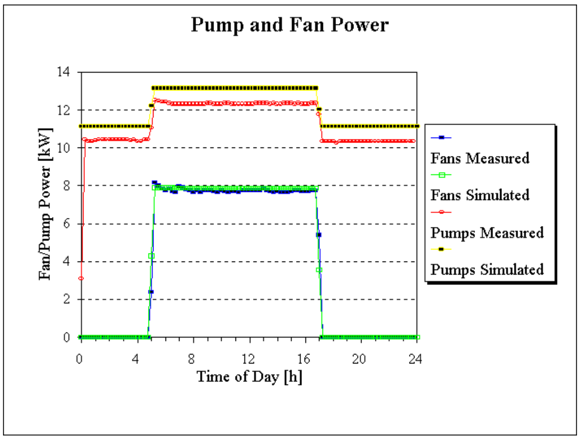


Figure 4: Fan and pump power for first system

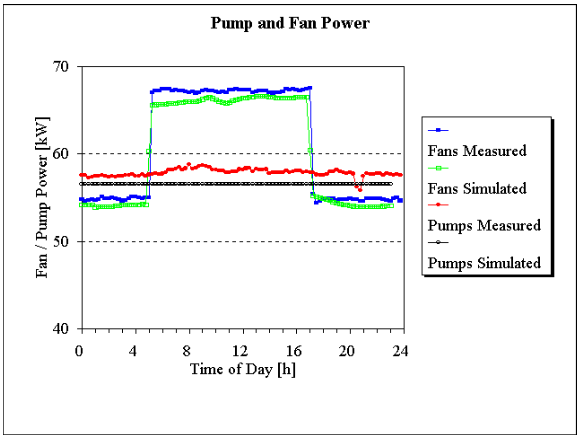


Figure 7: Fan and pump power for second system.

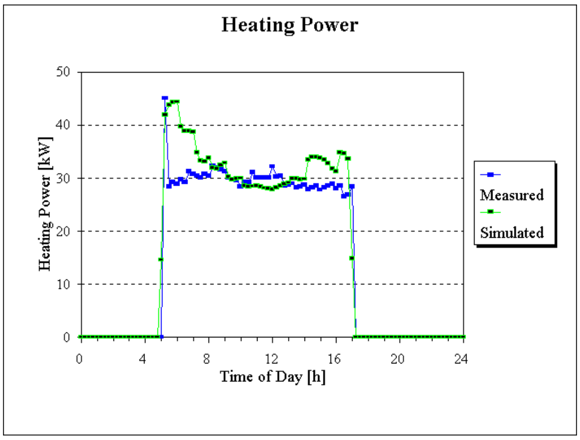


Figure 5: Heating power for first system

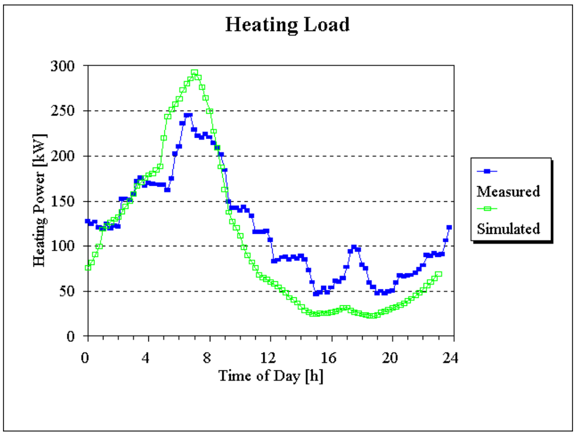


Figure 8: Heating power for second system.

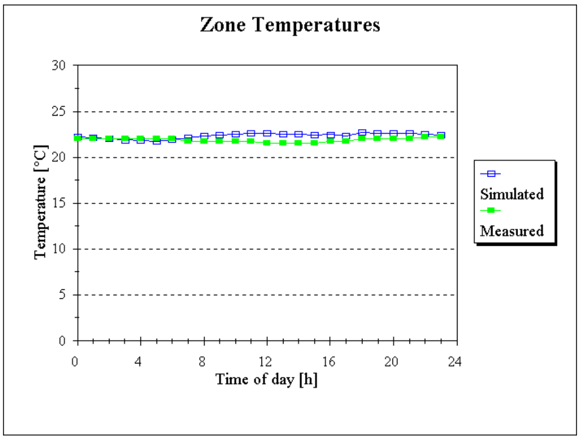


Figure 9: Zone temperature for a zone in first system.

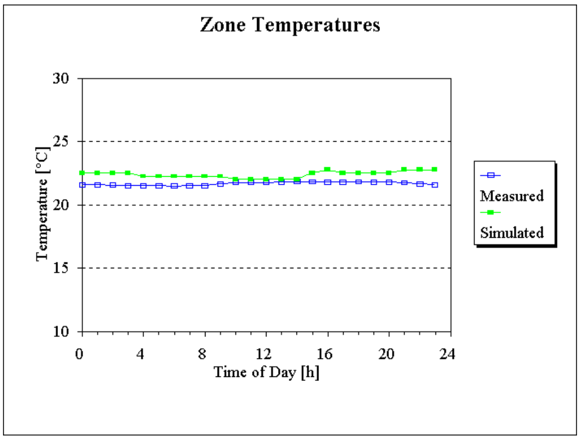


Figure 10: Zone temperature for a zone in second system