PERSONAL COMPUTER-BASED MODEL FOR COOL STORAGE PERFORMANCE SIMULATION

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ABSTRACT

A personal computer based hourly simulation model was developed based on the CBS/ICE routines in the DOE-2.1 mainframe building simulation software. The menu driven new model employs more efficient data and information handling than the previous model, thus reducing the amount of input to basic system information required from the user. A comparison of results between the new model and CBS/ICE shows good agreement, indicating that the new model may be used with confidence.

INTRODUCTION

Air conditioning is a primary contributor to electric peak loads in Texas. Cooling accounts for approximately 80 percent of residential and 50 percent of commercial peak demand. In addition the peaks of the residential and commercial classes are often coincident during the late summer afternoon. As a result during the night, electric utilities face the problem of idle generating capacity for which there is no demand.

One of the ways to solve this problem is to move the loads from peak to off-peak periods without changing overall consumption. Shifting the peak can be achieved by applying cool storage systems which use stored energy for air-conditioning purposes during peak periods.

Customers benefit from cool storage in two ways. First, demand charges are reduced since customers with sufficient thermal storage shift consumption of electricity for air conditioning to the off-peak hours. Second, since the cold storage will be charged at night, this electricity consumption is shifted to those hours when the cost of producing electricity is lowest. These savings may be passed on to the customers through a reduced demand charge and/or through time-of-day rates.

The subject of cool storage systems has been of particular interest to various research organizations, including the Electric Power Research Institute (EPRI), since the early eighties. This institute published over 20 reports and several papers, prepared sets of demonstration slides and video tapes, and co-sponsored several conferences and seminars related to thermal storage technology.

The computer models developed under EPRI sponsorship (COOLAID, COOLCALC) perform the cool storage simulations based on the entire system rather than looking at specific components and the changing performances due to variable operating conditions.

So far the most advanced cool storage simulation was developed by the Center for Energy Studies at The University of Texas at Austin (1). This simulation has become part of the DOE-2.1 building energy analysis computer program, recently released in the personal computer version. The code developed for CBS/ICE was used by the authors as a starting resource for independent cool storage simulation and optimization purposes in the presented work.

SIMULATION

While designing a system, one of the recurring issues is the performance of the system under various conditions. Since it is costly and time-consuming to deal with multiple versions of real-scale models, it seems appropriate to develop a mathematical model of the system and use it to perform the necessary tests. Such system can be defined as a set of components whose performance is interrelated, meaning that a change in performance for one component has an effect, either direct or indirect, on the remaining component(s) (2).

In order to perform a system simulation each of the components has to be described by a set of performance characteristics and equations for the thermodynamic properties of the working substances. The system simulation will perform the calculations of operating variables such as pressures, temperatures, and flow rates of energy and fluids.

Usually a system is designed for maximum load conditions. In reality, most of the time the system operation is at less than (and on occasion even more than) the maximum load. Simulation is a valuable tool in evaluating performance in these cases. It allows the system designer or user to determine the possible operating and control problems as well as predict system behavior.

In a simulation applied in the model, information or flow output from one component becomes the input to preceding as well as following components. In effect, the simulation may start from any component. To solve such a simultaneous system, several methods can be used. A relatively simple and effective procedure is the method of successive substitution. This method assumes a value of one or more variables, begins the calculation, and proceeds through the system until the originally assumed variables have been recalculated. The recalculated values

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are substituted successively, and the calculation loop is repeated until satisfactory convergence is achieved.

The advantages of this method include ease of implementation and minimum use of the computer's memory. The main disadvantage of this method is the sensitivity to the sequence in which the components are modeled. This may lead to slow convergence or, in some cases, to divergence.

The method of successive substitution has been applied in the simulation process described here. It has proven to be efficient and powerful.

MODEL OVERVIEW

The majority of the cool storage components used in this analysis are based on the programs originally developed for the Component-Based Simulator (CBS)-ICE portion of the DOE-2.1 computer program. DOE-2.1 is an hourly building energy analysis computer program, widely used in HVAC systems research. Among other features it uses hourly time steps in load profiles analyses, and models HVAC systems based on input weather data and self-generated building data. The CBS-ICE simulation is tied to a DOE-2.1 shell. This means that a user has to have access to this software, and at least have a minimum knowledge on how that shell operates. The DOE-2.1 versions that include the CBS-ICE simulation are most often installed on mainframe computers, which further complicates the issue of user accessibility. Finally, the version of DOE-2.1 for the cool storage system simulation is not suitable for multiple optimization runs. At the present time no solution to this problem within the resources of DOE-2.1 seems to be manageable.

In order to correct these problems, an independent mathematical model of a static ice (ice on coil) storage system has been developed. The cornerstones of this approach were modularity of the system and overall input-output interdependence of each of the components.

Modularity assures multiple choices within a component type. For example, a compressor can be of two different types: reciprocating or screw. Depending on design conditions one or all of them can be tested without going through the tedious component connections changes. The same is true of heat rejection devices (condensers) or pressure reducing elements. Modularity can be also applied to non-engineering analyses such as economic and financial evaluations.

Input/output interdependency of components is directly related to modularity. As stated before, inside one major module several individual components may exist. If the user decides to choose one of them, the inflow or outflow of information or energy will be automatically redirected, based on the choice. This means that replacement of an evaporatively-cooled condenser with a water-cooled one not only automatically restores the proper connections between a condenser and other components, but also it invokes additional connections for a cooling tower. This approach also prevents the user from creating connections between the components which are not physically feasible. Rather than making direct connections between the components every time the simulation is performed, a user defines which components he wants to include. The rest is left to the program, which determines which connections are active and which are idle. All inputs and outputs from the components are stored in matrices. Based on the user-specified configuration, only appropriate elements of the matrices are passed between the components, leaving the configuration connections intact. Instantaneous updates of inputs and outputs occur, thereby making the components use the most recent data, even for the iterating calculations within the hourly increments. The sizes of matrices are negligible compared to standard PC memory capacity.

SYSTEM DESCRIPTION AND SIMULATION

The ice storage system which is considered in this project has been outlined in Figure 1. The components of the system were assigned to three groups: refrigeration loop, heat rejection devices, and chilled water loop. The refrigeration group contains the components utilized in the refrigerant phase changes: capacity controller, compressor, evaporator, receiver, expansion device, interchanger, and balancer. The heat rejection devices group can be considered as an extension of the previous group, where the actual process of heat release from the condensation process takes place in one of the condensers (evaporatively-cooled, air-cooled, or water-cooled) and/or cooling tower. The third group, the chilled water loop, contains the components which control the flow of media as well as freezing or melting of ice: ice tank, agitator, ice tank loop pump, chilled water loop pump, heat exchanger, mixing tee, and diverter valve.

The simulation process begins with the input of data. The model has its own set of default values which can be replaced with user-defined ones. However, these values can not be changed at will; they must represent realistic conditions, and in the case of the size of heat exchangers, the values must fulfill the basic energy and flow balances in the refrigeration loop. At this stage of the project it is solely the responsibility of the user to determine the feasible input data set. It is envisioned that in the next stage, a thorough sizing will be performed, releasing the user from determining most of the input.

One of the inputs is the definition of the simulated system. It is expected that the user will determine which components are to be included in the simulation. Once this is done, the program automatically sets the

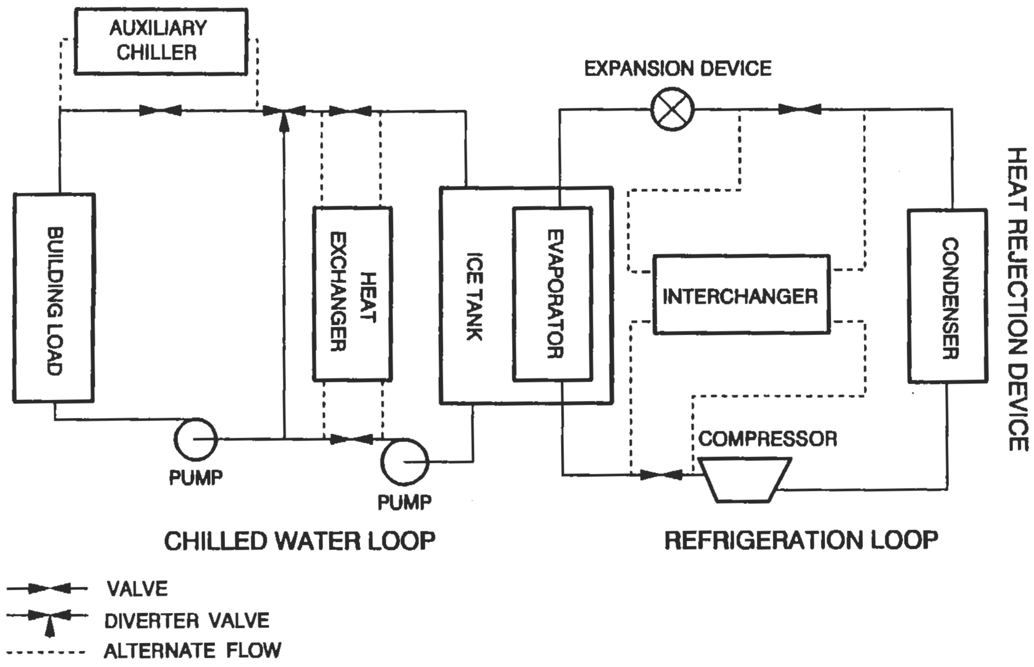

Figure 1. Components of the ice storage system.

necessary connections between the modules. If a module has multiple components, the appropriate connections are established among the ones chosen by the user.

The main simulation stages involve the following. At first the model determines the time of day, the cooling load, and the available cooling capacity in the ice tank(s) and from the auxiliary equipment. Based on the user-defined strategy the decision is made whether ice should be built or melted. If ice needs to be built, an appropriate signal is sent to the refrigeration loop components. The necessary operating conditions in this loop are maintained as close as possible to the values specified by the user. Depending on the ice building/ melting process, the chilled water loop components control and maintain appropriate temperatures and flows of media which supply the ice tank and building cooling coils. Since chilled water loop components are taking an active part in energy and media distribution in every hour, the components have to be simulated whether the main compressor is on or off.

Based on the user-supplied hourly load profile, weather data, and the ice building strategy, the simulation proceeds from hour to hour. At the beginning of each time step, the inputs to all components are set equal to the corresponding outputs from other components in the preceding hour. For the first hour the components are initialized with appropriate values. During the simulation the constant updating of input and output values takes place, so that the most recent values are always used.

The simulation for a single hour is considered complete if the difference in the refrigerant's flow, temperature, and pressure between the successive iterations is lower than the user specified value. Obviously, the lower the value the more precise the results. However, each additional iteration results in additional execution time, and thus a reasonable value of the convergence criteria has to be applied.

MAIN FEATURES OF THE COOL STORAGE MODEL

The cool storage model uses accurate heat transfer and thermodynamics algorithms in the component models. It allows the user to examine the effects of detailed equipment design parameter changes. Also, the model offers the user various component combinations and control strategies. The main features of the model include:

Control Alternatives

- Chiller, ice, or constant priority to meet cooling loads;
- User-defined start/stop time for ice building cycle;
- Compressor capacity control option (full, fixed, or variable capacity);
- Fixed or floating condensing temperature;
- Constant or variable-speed chilled water pumps; and
- DX, gravity, or overfeed refrigeration system control.

Multiple Equipment Options

- Multiple evaporator coil banks;
- Multiple ice storage tanks; and
- Multiple refrigerant compressors.

Choice of Heat Rejection Devices

- Air-cooled condenser with or without direct evaporative pre-cooling;
- Water-cooled condenser with cooling tower; and
- Evaporatively-cooled condenser.

Choice of Compressor Types

- Reciprocating compressor
- Screw compressor

Also there are several limitations and restrictions which apply to the model at this time. The current constraints include:

- Dynamic and other than water-based storage systems are not modeled;
- The cool storage system compressors are dedicated to the ice builder evaporator coils and can not be assigned to directly meet building load;
- The cool storage equipment is not self-sizing and therefore the user has to choose the appropriate sizing and control of components;
- The ice builders will build a prescribed quantity of ice regardless of the current, previous, or projected load profile;
- No apportioning of cooling load between ice storage and auxiliary chillers other than straight chiller priority, ice priority, or constant proportional control is provided; and
- Only refrigerants R-12, R-22, R-500, R-502, and ammonia are presently modeled.

PROGRAM DESCRIPTION

The cool storage simulation model is written in FORTRAN. The user interface module is written in BASIC. The model can be run on any IBM or IBM-compatible personal computer, provided that:

- The system operates under DOS 3.2 or a later version;
- The available hard disk storage capacity is in excess of 0.6 Megabyte if the simulation is run for a 24-hour period, or in excess of 6 Megabytes (estimate) if the simulation run is based on data for 8,760 hours; and
- The available random access memory is not less that 512 kilobytes.

Additional enhancement, such as an expanded memory, may positively affect the program execution.

SAMPLE RUNS AND RESULTS

The building load profile for one week of operation starting at midnight Monday (shown in Figure 2) was generated using the DOE-2.1 building simulator, modeling an existing office building in Austin, Texas. Typical occupancy and equipment schedules included operation from 6:00 a.m. until 10:00 p.m., with varying occupancy during this time. The peak cooling load on the equipment was 1,280,000 Btu/h, with a typical integrated daily cooling requirement of 1,820 ton/hours per day for the five day work week. Spikes at the beginning of each day represent the pull down loads. The hour "0" refers to Sunday midnight.

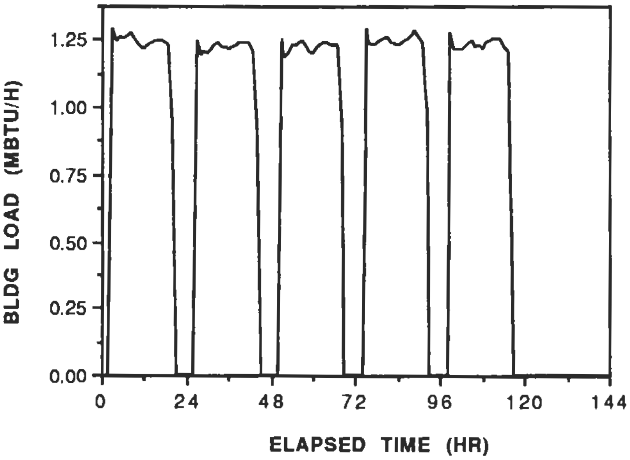

Figure 2. Building load profile for one week, Monday through Saturday.

The HVAC system included a 58-ton auxiliary chiller, and an 85,500 pound capacity ice storage tank. One screw compressor nominally rated at 90 tons was used to generate ice, and was coupled to an evaporatively-cooled condenser. The system was operated in an ice priority mode; the on-peak cooling requirement was met by the ice in storage, while off-peak requirements were met by the auxiliary chiller as well as by ice.

The system was allowed to run unloaded on Sunday to build ice inventory for use on Monday. Peak time was defined as 12:00 noon through 8:00 p.m.

Figure 3 shows the ice charge versus time for the week, starting at midnight on Sunday. As seen in the figure, ice volume is at its peak on Monday morning and varies through each day as the building load increases and as the ice building system restarts each evening. The ice inventory is nearly depleted each afternoon, and is rebuilt to full capacity on Friday evening and Saturday. The assumed size of the ice tank and the weather pattern contributed to the complete ice depletion on Friday.

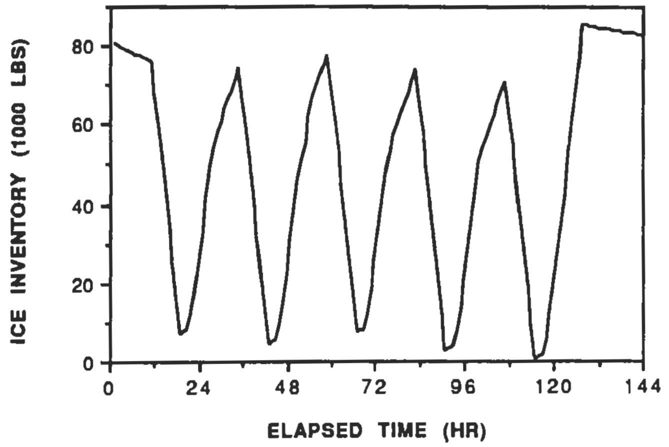

Figure 3. **System ice charge for one week, Monday through Saturday.**

Figure 4 shows the system power draw in kilowatts for the five day period. Values in the power consumption included the auxiliary chiller (at 1 kW per ton), the building and ice tank circulating pumps, the power to operate the ice tank agitator, the ice building compressor, and the condenser fan. Only the chilled water side of the system was modeled; building fans were not included in the simulation.

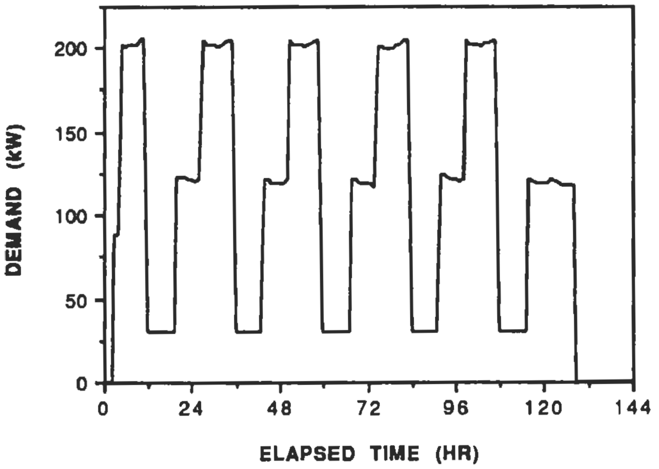

Figure 4. **System electricity demand for one week, Monday through Saturday. (Chilled water and ice components only.)**

As seen from the figure, the on-peak demand was approximately 30 kW, consisting of circulating pumps and the ice tank agitator. Off-peak demand was approximately 205 kW when the entire system was on and 120 kW at times when only the ice-building equipment was on. The maximum electricity demand for the components modeled was divided as follows: 46% ice building compressor, 10% condenser fan, 13% circulating pumps, 2% ice tank agitator, and 29% auxiliary chiller.

CONCLUSION

The newly developed model of cool storage systems has proven to be useful in understanding the performance of thermal storage systems. The model was successfully used to simulate an ice storage system, showing the ability of the system to build and store sufficient ice for the next on-peak period, and showing the substantial on-peak demand reduction available through the use of ice storage.

Typical execution times for the one week simulation were approximately 7 minutes. Output from the program was easily input into graphics software to demonstrate the results of the simulation.

It is expected that the final optimization model will enable cool storage designers, installers, as well as architects and building managers, to evaluate the benefits from storage system installation. It will also allow them to study various storage configurations and find the optimal system size under specified economic and engineering constraints.

The program will also be a useful tool for electric utility marketing, research, and rate design specialists in evaluating electric rate structures and possible financial incentives, with the objective of attracting customers to cool storage.

REFERENCES

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