ABSTRACT

Thermal storage is becoming a standard consideration in HVAC and process cooling systems. As the technology is refined, more attention is being given to minimize the energy consumption and power demand requirements. This paper addresses a method for optimal control of a harvesting ice storage system. A simplified procedure is used to develop 24 hour load data. Example installations will be shown.

INTRODUCTION

The desire to implement an optimal control for an ice storage system is based on the fact that a higher kw/ton is used to generate ice rather than generate chilled water in the 42° F temperature range. The objective of an optimal control is to minimize the cost of power and energy consistent with a given utility rate structure. Two types of ice storage systems will be discussed in general terms of optimal control with emphasis and detail on the optimal control of ice harvesting thermal storage systems.

OPTIMAL CONTROL AND UTILITY RATE STRUCTURES

To understand the need for optimal control, one has to look at the predominant utility rate structures. Utility rates are divided into two main segments: DEMAND COMPONENT: The demand component is a charge for the capital costs of the power plant. ENERGY COMPONENT: The energy component pays for the commodity used, including fuel, operating and maintenance costs.

In both Figures 1 and 2, the ice is

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built up on the pipe following the general rules shown in Figure 3. As the ice begins to insulate the pipe a lower and lower evaporator temperature is produced showing a higher and higher kw/ton. In systems where the ice is not melted daily, the recharge of the system is done very inefficiently since ice is an excellent insulator. The marginal topping of a system can show seasonal operation of 1.5 to 3.0 kw/ton.

**THE ICE HARVESTING SYSTEM**

Ice harvesting systems separate the function of making ice and storing ice. The ice is formed on the outside of flat heat exchangers arranged in vertical banks to a thickness of less than .25 inches. The ice is harvested by introducing warm gas into the inside of the plates. The warm gas breaks the bond between the ice and the plates causing the ice to drop into the storage tank. By decoupling the manufacture of ice from the storage of ice, the same evaporator surface that makes the ice can also operate as a high efficiency chiller meeting the building loads directly. Figure 4 shows an ice harvesting system. A fully packaged ice harvesting system is placed over a storage tank. The water recirculation pump operates whenever the compressor is operating. If there is no load, the system makes ice. Each pound of ice is made in .25 inch increments at less than 1 kw/ton. The last pound of ice is made with the efficiency as the first pound of ice, whether it is hour one, or year twenty. When the water flowing over the plates is above 32°F, the system operates as a high efficiency chiller. This occurs whenever the building load is directly applied to the ice harvesting system.

### Optimal Control Strategies

Optimal control strategies for static ice builders and harvesting ice generators are the same. However, the execution is much simpler with the harvesting ice generator, and the consequences of control error are much less severe. The basic control strategy is as follows:

**Mode 1.** Daily load less than the maximum load on the system. Operation 1. Make only enough ice in the off peak period to meet the load. Mode 2. Daily load greater than the maximum ice capacity of the system. Operation 2. Make a full charge of ice in the off peak period and minimize the chiller operation to limit demand.

The STATIC ICE BUILDERS will require a predictive strategy to operate efficiently in mode 1. Since it is necessary to completely melt the ice charge prior to rebuilding the next day, the predictive strategy must be accurate and reliable. Far beyond the normal weatherman's predictions, or the depletion of storage will necessitate the restoration of chiller node and the setting of new peaks.

**The HARVESTING ICE GENERATOR/CHILLER** does not require a predictive strategy to operate efficiently in mode 1. Inherently, each pound of ice is made at the same efficiency. Therefore, simply fill the tank each off peak period as required. For example, if the daily load is 25% of capacity only 25% of the ice is melted. Topping the tank is accomplished efficiently. The real advantage is that there is always a full tank to begin the next melting period, and if the loads are higher than expected, the ice stored in reserve is there to meet the loads without bringing a chiller on line and setting a new peak.

Operation in mode 2 requires a predictive strategy for both the static ice builder and the ice harvester. The remaining portion of this paper will address the principles of predictive controls as applied to ice harvesting chillers.

### UNDERSTANDING THE LOAD TO BE PREDICTED

The cooling load on a building consists of the following components.

**EXTERNAL LOADS:**

- **Solar**
- **Conduction**
- **Outside Air (ventilation)**
- **Outside Air (infiltration)**

**INTERNAL LOADS:**

- **Lights**
- **People**
- **Equipment**
- **Appliances**

These loads become loads on the air-conditioning system through a complex interchange of energy to the air mass. Convective loads and latent loads become loads on the air-conditioning system. Radiant loads are absorbed by the building materials and furnishings and become a delayed load, out of phase with the instantaneous loads. Calculation of the actual load in any given hour is quite complex. However, calculation of the 24 hour load is absolutely trivial, if weather can be predicted.

Sizing the outside of an air-conditioning system requires a zone by zone calculation to determine individual peaks. These zones are aggregated on to an air-conditioning unit. The aggregate instantaneous load becomes the coil load and is used for
sizing chilled water piping. In a conventional system, the chiller is sized to meet the instantaneous simultaneous peak of the air handling units. In a thermal storage system, the 24 hour load is the critical information necessary to size the refrigeration plant and storage. This load can be obtained from hourly by hour calculations, or from the simplified procedure proposed.

The 24 hour load = The 24 hour gains regardless of when they occur - the heat loss to the surroundings.

The 24 hour loads may be computed as follows:

The 24 hour solar and conduction loads are computed as follows:

**Solar**

The solar contribution is computed with Equation 1.

\[ Q_{SO\ell} = \sum_{i=1}^{N_{\text{EXP}}} \left( \text{AG}_{i} \times \text{MSHGF}_{i} \times \text{AG}_{i} \times \text{SC}_{i} \times \text{CLFTOT}_{i} \right) \]

where

- \( N_{\text{EXP}} \) = number of different glass exposures
- \( \text{AG} \) = glass area exposure \( i \)
- \( \text{SC} \) = shading coefficient of glass for exposure \( i \)
- \( \text{CLFTOT} \) = 24 hour sum of CLF for orientation \( i \), Table 1

**Transmission load**

The transmission load consists of conduction through walls, roof, and glass.

1. **Glass**: The contribution due to glass is computed from Equation 2.

\[ Q_{T} = N_{\text{surf}} \times \left( \text{AG} \times x \text{UG}_{i} \right) \times \left( T_{o} - T_{i} \right) \times 24 \]

where \( N_{\text{surf}} \) = number of conduction surfaces in the zone

- \( \text{AG} \) = glass area
- \( \text{UG} \) = U value of the glass

2. **Opaque surfaces (walls and roof)**

The contribution from the opaque walls consists of a contribution due to the air-to-air temperature difference, and a time averaged solar component due to absorption of solar radiation on the outer surface.

Equation 3 is used to compute the contribution due to air-to-air temperature difference.

\[ Q_{T} = N_{\text{surf}} \times \left( \sum_{i=1}^{N_{\text{EXP}}} \left( \text{AG}_{i} \times \text{UG}_{i} \times \left( T_{o} - T_{i} \right) \times 24 \right) \right) \]

**Table 1**

<table>
<thead>
<tr>
<th>CLF for Glass</th>
</tr>
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<tbody>
<tr>
<td>CLF SUM 12 HR AVG 24 HR AVG</td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>NE</td>
</tr>
<tr>
<td>E</td>
</tr>
<tr>
<td>SE</td>
</tr>
<tr>
<td>S</td>
</tr>
<tr>
<td>SW</td>
</tr>
<tr>
<td>W</td>
</tr>
<tr>
<td>NW</td>
</tr>
<tr>
<td>HOR</td>
</tr>
</tbody>
</table>

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Table 2

CLTD Solar Component 24 Hour Average (CLTDS)

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Dir 16 24 32 40 48 56</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>966555</td>
</tr>
<tr>
<td>NE</td>
<td>14 15 16 16 16 17</td>
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<td>9 11 13 14 17 17</td>
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<tr>
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<td>3 4 7 10 14 17</td>
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<tr>
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<td>9 11 14 17 17 17</td>
</tr>
<tr>
<td>W</td>
<td>14 15 15 15 16 17</td>
</tr>
<tr>
<td>NW</td>
<td>14 12 12 11 11 11</td>
</tr>
<tr>
<td>Roof</td>
<td>22 23 23 22 22 20</td>
</tr>
</tbody>
</table>

January

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Dir 16 24 32 40 48</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>NE</td>
<td>432100</td>
</tr>
<tr>
<td>E</td>
<td>11 9 7 6 4 1</td>
</tr>
<tr>
<td>SE</td>
<td>18 17 16 15 14 8</td>
</tr>
<tr>
<td>S</td>
<td>22 23 26 31 18 12</td>
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<tr>
<td>SW</td>
<td>18 17 16 15 9 8</td>
</tr>
<tr>
<td>W</td>
<td>11 9 7 6 4 1</td>
</tr>
<tr>
<td>NW</td>
<td>4 3 2 1 0 0</td>
</tr>
<tr>
<td>Roof</td>
<td>15 11 7 3 -2 -5</td>
</tr>
</tbody>
</table>

Color Correction Multipliers K

Wall 1 .83 .65
Roof 1 .75

The net effect is that a complex hourly load shown in Figure 5 may be computed easily and represented accurately by Figure 6. This works very well for design purposes, but what about off design days?

PREDICTIVE CONTROL TECHNIQUES

1. Lighting schedules
2. People occupancy schedules
3. Equipment schedules
4. Appliance schedules
5. Outside air schedules
6. Fraction of cloud cover
7. Daily average temperature

The techniques defined above are used for load calculations.

Figures 7a and 7b show the typical effects of the loads. As the ambient conditions change, the operational modes change. Figure 7a shows the summer design day loads with mode 2 operation. Figure 7b shows winter day loads with mode 1 operation.

Once the 24 hour load is known for any given system, the ice storage capacity is known and the available run time of the equipment is known. If the ice capacity is greater than, or equal to the load, mode 1 prevails. If the load is greater than the ice capacity, the chiller operation is computed as follows:

\[
\text{Chiller average tonnage} = \frac{24 \text{ hour load} - \text{ice capacity}}{\text{chiller runtime}}
\]

Operation of the chiller at this tonnage will minimize total system demand. Figure 8 shows a typical operating scenario for heating the load in mode 2.

This level of predictive control may be implemented using a microprocessor control system.

CONCLUSION

Optimum chiller operation can be obtained with predictive control using simplified algorithms.

The 24 hour future load may be predicted by knowing the following:

1. Lighting schedules
2. People occupancy schedules
3. Equipment schedules
4. Appliance schedules
5. Outside air schedules
6. Fraction of cloud cover
7. Daily average temperature

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Figure 2  Pipe Coil Data

Figure 3  Ice Storage/Parallel Evaporator Arrangement
Figure 4 Icemaker Plate Module

Figure 5 Capacity and Load—Daily Load Leveling for Tuesday

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Figure 6  Capacity and Load—Daily Load Leveling for Tuesday with Simplified Load Superimposed

Figure 7a  Summer Design Day—Mode 2
Figure 7b  Winter Day—Mode 1

Figure 8  Intermediate Day—Mode 2