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Modeling and Simulation of Discharging Characteristics of External Melt Ice-on Coil Storage System

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Abstract

In case of energy storage air conditioning system, due to load fluctuation, the traditional control methods can't obtain good effect, the model predictive control method can realize the optimization control system, and can overcome the influence of load fluctuation. In order to realize the predictive control, need to study model of air conditioning system. Ice storage air-conditioning system, by analyzing the mechanism of ice tank, ice melting system outside the tank model is established. First, analyzed the physical structure of ice bath, determine the parameters of ice bath, put forward the control as well as the output of the ice tank. Good model will be built using TRNSYS and MATLAB joint simulation, and the model simulation results and the widely used now BAC coil and TSQINGHUA TONGFANG ice coil characteristic has carried on the contrast, determine the tank model is built by ice in the most good ice tank was simulated under the condition of outlet temperature, and focused on the top 20% of the ice melted and the error of 20%, after put forward the reasonable solution, the interpretation of the ice tank established ice model has practical significance.

Keywords: *Ice storage; modeling; TRNSYS simulation*

1. Introduction

The energy consumption of air conditioning buildings accounts for about 40% to 60% of the total power consumption and the use time of air conditioning is in conformity with the grid of rush hour [1]. In order to meet the rush hour of electricity, power plants are vigorously built in China in which thermal power's capacity of electricity is about 73% of the total installed capacity and power consumption of the raw coal accounts for about 50% of domestic coal consumption [2]. Ice storage system improves the imbalance of power load distribution through the way what reducing peak and filling valley power. It has important significance to reduce carbon emissions and urban haze through reducing installed capacity of generator unit and the amount of the construction of power plant.

Ice storage has recently gained acceptance as a method of reducing the cost of chilled water for air-conditioning systems. The principle is that chillers are run at night to take advantage of the lower electricity tariffs which are available and the energy converted is stored as ice. During the day the ice is melted and provides some or all of the normal chilled water supply for cooling and dehumidification. In addition, a chiller used in conjunction with an ice store can be roughly half the capacity of a chiller used without a store. This means that smaller chillers containing less refrigerant can be specified if space, weight, or capital is limited. An ice store can provide chilled water at very low temperature and can form part of a low temperature supply air system. If this is installed there will be additional economies in duct costs and installation, as well as savings on internal space used. An ice store is required together with additional, valves and heat exchangers to permit controlled charging and discharging. The primary cooling medium is usually glycol since temperatures well below freezing will be needed. At these lower

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temperatures care must be taken to avoid unnecessary heat gain and to keep the efficiency of plant, especially chillers, as high as possible. An advanced control strategy is required to take full advantage of the economies offered by ice storage and to ensure the safety of heat exchangers and other equipment. The principles of ice storage and typical temperatures found during summer daytime operation are shown in Fig. 2. The ice store can be placed in parts of the building where it would not be practicable to site chillers. The store produces no vibration or noise, and no electrical supply is needed, there is even some ad-vantage in burying it. Finally, the chillers and valves tend to last longer as the chillers are run for long period sat full load with no modulation.

In developed countries, ice storage technology is used in the more than 60% of the buildings. In the city district of Chicago a total of four cold station cool more than 600 square meters of urban building. In the city of Chicago the no.3 ice storage station capacity is 125000 tons, electricity load is 438 MW, the daily 4700 tons of ice. Application from America, Japan, Korea and other countries, ice storage technology can promote the use in air conditioning load, large difference of peak valley, building that relatively gathered. At present the gross area of our country is approximately 2 billion square meters, among them, the new urban residential buildings and public buildings is about 800 million - 900 million square meters. There is a huge market for application of ice storage technology. Every year in our country new area of public building is about 300 million square meters, such as 30% of the new public buildings is the ice storage air conditioning system [3-10].

The current control technology of ice storage system adopts PID control method without adaptive capacity, the set temperature cannot be reached accurately and stably when the load is fluctuated. The predictive control is a kind of system according to the dynamic model to predict the future behavior and optimized control strategy which can overcome the disadvantage of parameters' long wave caused by the PID algorithm. On the other hand, the predictive control can realize the optimal control and the aim of saving energy consumption. It needs modeling of circuit and device in the ice storage system to achieve predictive control . The paper mainly studies the melting ice prediction model in the system.

2. External Melt Ice-on Coil Storage System

Current ice-storage technology can be separated into two distinct categories: dynamic ice storage and static ice storage according to ice energy storage. And the later one can be divided into external melt ice-on coil storage system and internal melt ice-on coil storage system. It is shown in figure 1

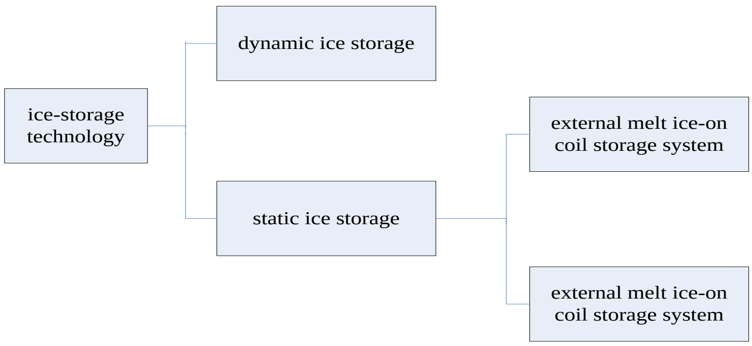

Figure 1. External Melt Ice-on Storage System

External melt ice-on storage system belongs to static ice making mode. It is different that external melt ice-on storage system directly take cold from internal melt ice-on storage system with the secondary heat exchange. Compared to other ways of taking cold efficiency of external melt ice-on storage system is higher, the water temperature is lower, it can smoothly for a long time to take out the water at low temperature. External melt ice-on coil storage system means sending chilled water return with higher temperature to the ice storage tank with coil covered by ice. Ice on the surface of the coil melts gradually from the outside to the inside which is called the melting ice. Due to the direct contact of the chilled water return and the ice on coil, the effect of heat transfer is high. The temperature of chilled water supply from the ice storage tank can be as low as 1 ℃ because of thermal release quickly. In order to make the melting ice system can achieve rapid melting ice cold, the volume of ice storage tank is bigger because ice storage rate (IPF) should not be greater than 50%.

2.1 The Work Mode of External Melt ice-on Storage System

Full storage systems (see this page for a list of terms) have the lowest theoretical running costs, but their use is often discouraged as both the chiller and ice store need to be around twice the capacity required for partial storage. In addition, the ice store in a full storage system must be sized to cope with the peak summer demand, which means that it will be used at well below full capacity for most of the time.

With particle storage the peak cooling load is split roughly equally between the ice store and the chiller ,so for at least a third of the year, when the load is about three-quarters of the peak, both will be used every day. Partial storage systems can be configured with the chiller either upstream or down-stream from the store. Both systems have their ad-vantages, and which is chosen will depend on the exact requirements of the building. Parallel system sallow the advantages of both upstream and down-stream chillers to be realized but at the cost of more pipework, valves and control strategy

Chiller down-stream systems are also used for low temperature supplies as the chiller connects directly to the heat exchanger. Partial systems can be run with either store priority or chiller priority, other factors such as season and time of day, will govern which is selected at any particular time.

Ice slurry systems are relatively new and have had little impact on the British ice storage market. They claim to offer a higher rate of chilled water supply when compared to conventional systems, especially when ice store levels are low. Parallel partial storage is currently the most popular system so the following discussion will concentrate on this type

Ice storage has two kinds of work mode which are charge cold and discharge cold. On discharge cold process storage device and chiller unit can do their work alone or work together to meet the requirements of load. The work mode of external melt ice-on storage system is shown in figure 2.

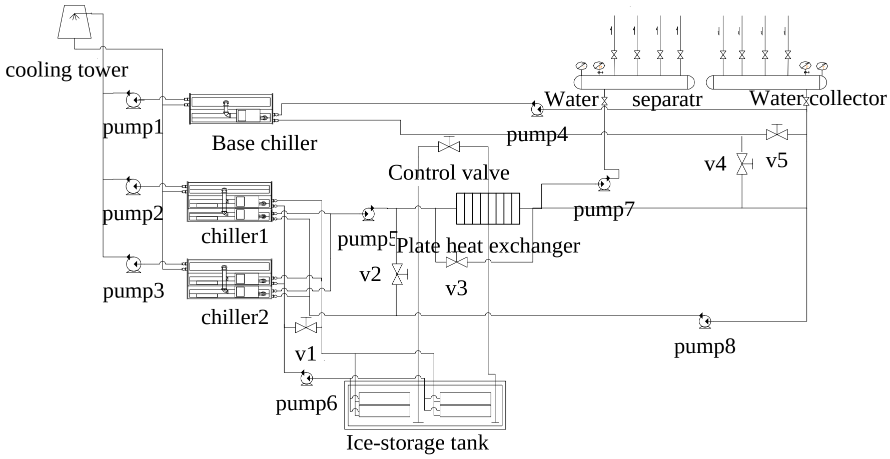

Figure 2. External Melt Ice-on Storage System

There are five work conditions respectively through operating the control valve to convert the working condition in external melt ice-on storage system. As shown in table 1.

Table1. Melting Ice System Operation Condition

Working conditions	Ice-storage tank charge cold	chiller	Ice-storage tank discharge cold	chiller + Ice-storage tank discharge cold
V1	OFF	OFF	OFF	OFF
V2	OFF	OFF	ON	OFF
V3	OFF	ON	OFF	OFF
V4	ON	ON	OFF	OFF
V5	OFF	OFF	OFF	ON
chiller	ON	ON	OFF	ON
Base chiller	ON	ON	OFF	ON

The condition of chiller + Ice-storage tank discharge cold is that part of the chilled water return is pumped to base chiller which is precooled. The water which is pumped to base chiller is mixed with another part of chilled water return by V4 control valve. The mixed water is pumped to chillers by pump8 to be cooled to set data, which is sent to plant heat exchanger by pump 5. The flow of ice water in plant heat exchanger is controlled according to the load fluctuation to make the temperature of chilled water supply 2.2 ℃. The temperature of air-conditioning chilled water return is 13.2 ℃, forming the difference in temperature of 11 ℃ with the temperature of chilled water supply. Due to the large temperature difference system greatly reduced the flow of chilled water, so that we can reduce the investment of air conditioning system, optimize energy consumption ratio between the various equipment of the air conditioning system.

2.2 Ice-storage Tank Physical Structure

Ice-storage tank is generally built in the basement of buildings because of the huge volume. First the parameters of Ice-storage tank are set. Where A is wide, B is long, C is high, as shown in figure 3。

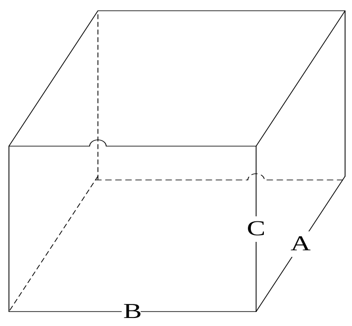

Figure 3. Ice-storage Tank Physical Structure

Ice-storage tank is not according to uniform standards. The length of the coil in the ice-storage tank is calculated by load demand, as shown in figure 4.

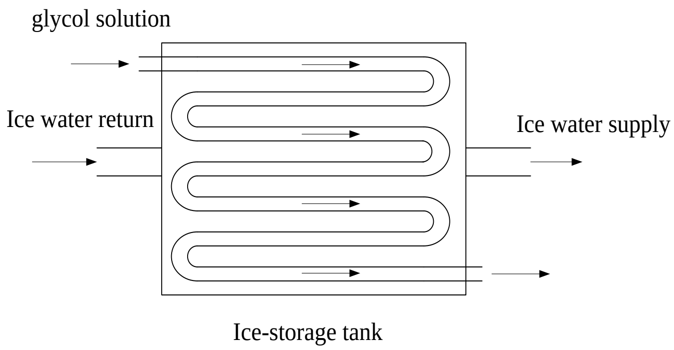

Figure 4. Ice-storage Tank Physical Structure

In working condition of charge cold, glycol solution flowed in coil makes water freezing with that in adjacent coil and makes the coil covered with ice. As shown in Figure 5, the distance of adjacent coil is D_{cr} ,the external diameter of coil is D_o ,the internal diameter of coil is D_i ,the maximum diameter of freezing is D_{ice}.It is shown in figure 5.

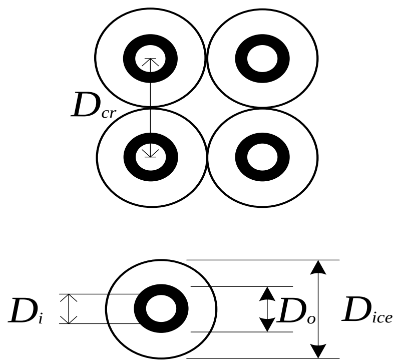

Fig 5. Ice-storage Tank Physical Structure

3. Mathematical Model of Discharge Cold in Ice-storage Tank

Due to the ice, the ice water in the ice tank will take away part of the amount of cold which is defined heat loss Q_{lost} through air heat exchange in large volume of the ice tank. the heat dissipating mostly from the upper surface of ice tank because ice-storage tank normally does not add the head cover. The heat loss of air pump is zero in external melt ice-on coil storage system for it is off in melting. It is shown in figure 6 and figure 7.

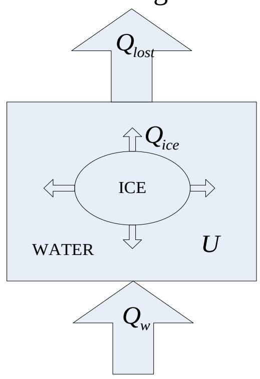

Figure 6. Parameter of Ice-storage Tank

Chilled water supply is exchanged in plate heat exchanger. Plate heat exchanger is a series of certain the shape of corrugated metal piled up and become a new type of high efficient heat exchangers. It is in high thermal efficiency, small heat loss, the structure is compact and lightweight, cover an area of an area small, easy installation and cleaning, wide application, long service life, *etc*.

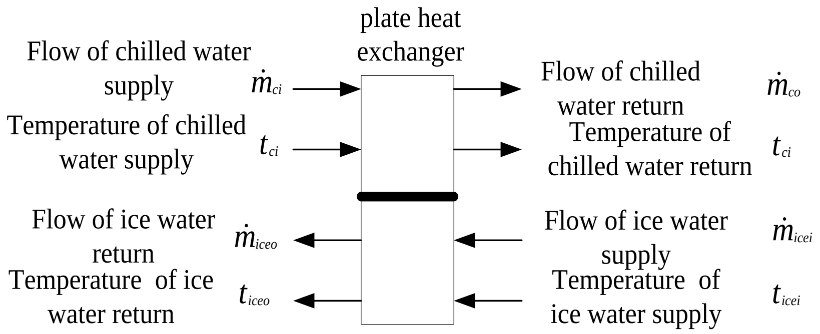

Figure 7. Parameter of Plate Heat Exchanger

It is mixture of ice in the ice-storage tank because external melt ice-on coil storage system is not completely frozen type. Now the water in the ice tank is chosen as the research object. The equation is expressed as

$$Q_w + Q_{lost} + Q_{ice} = \frac{dU}{dt} \qquad (1)$$

$$Q_{ice} = r\frac{dM_{ice}}{dt} \qquad (2)$$

$$Q_w = \dot{m}c\left(\dot{T}_r - T_w\right) \qquad (3)$$

Where

Q_w = energy of ice water return carried back to ice-storage tank

Q_{lost} = energy of the external environment exchanging with ice-storage tank

Q_{ice} = released energy of ice melting

U = energy of water in ice-storage tank

M_{ice} = the quality of ice

r = specific heat capacity of ice

$\dot{m}$ = the flow of ice water

c =specific heat capacity of water

$\dot{T}_r$ = the temperature of ice water return

$\dot{m}$ and $\dot{T}_r$ are inputs of model.

$$U = cM_w\left(T_w - T_{ice}\right) \qquad (4)$$

Where

M_w = the quality of water

T_w = the temperature of the water in ice-storage tank

T_r = the temperature of ice water return

The temperatures of the ice inside and outside are all zero based on Lumped Parameter Method [11] $T_{ice} = 0$

$$\begin{aligned}\frac{dU}{dt} &= \frac{d\left(cM_w T_w\right)}{dt} \\ &= cT_w \frac{dM_w}{dt} + cM_w \frac{dT_w}{dt}\end{aligned} \qquad (5)$$

$$\frac{dM_w}{dt} = -\frac{dM_{ice}}{dt} \qquad (6)$$

While external melt ice-on coil storage tank is not equipped with the top, ice storage equipment such as generally ice-storage tank and chiller are designed to install in a closed space. The typical value of cold loss of ice-storage tank is about 1-5% [12] of cool storage quantity of every day because space temperature is low. In order to simplify the algorithm Q_{lost} is ignored. Simultaneous equations (1) (2) (3) (4) (5) (6)

$$c\dot{m}\left(T_r - T_w\right) = cM_w \frac{dT_w}{dt} - \left(cT_w + r\right)\frac{dM_{ice}}{dt} \qquad (7)$$

For the convenience of calculation, $\frac{dM_{ice}}{dt}$ is processed to an approximation [13]. The ice melting radius is in a linear relationship with time in the ice coil. We can get the absorption energy of ice melting with the corresponding ice melting radius which can be calculated by the time of ice melting according to the change of the load. The values of variables in the n time are expressed as

$$Q_{wn} = cm_n\left(T_{rn} - T_{wn}\right)$$

$$M_{\max ice} = \rho_{ice}\pi L\left(\left(\frac{D_{ice}}{2}\right)^2 - \left(\frac{D_o}{2}\right)^2\right)$$

$$t = \frac{Q_{\max ice}}{Q_{wn}}$$

$$a = \frac{D_{ice} - D_o}{t}$$

$$M_{icen} = \rho_{ice}\pi L\left(\left(\frac{D_{icen}}{2}\right)^2 - \left(\frac{D_{icen} - a}{2}\right)^2\right)$$

at time n by analysis

Q_{wn} = energy of ice water return carried back to ice-storage tank

m_n = the flow of ice water return

T_{rn} = the temperature of ice water return

T_{wn} = the temperature of the water in ice-storage tank $M_{\max ice}$ = the maximum quality of ice

ρ_{ice} = ice density

L =the length of ice coil
t = time of ice melting
a =the change volume of ice diameter around the ice coil

D_{icen} =ice diameter around ice coil

M_{icen} is quality of the ice melting . Selecting time step for 0.01 hours, M_{icen} will be brought into (7)

$$cm_n\left(T_{rn}-T_{wn}\right)=cM_w\left(T_{r(n+1)}-T_{rn}\right)-\left(cT_{wn}+r\right)M_{icen}$$

$$T_{r(n+1)}=\frac{cm_n\left(T_{rn}-T_{wn}\right)+\left(cT_{wn}+r\right)M_{icen}+cM_wT_{rn}}{cM_w}$$

From the above equation, we can get in turn the outlet temperature of each time period and the change of icicles' diameter, constantly revising the quality of the ice water in the ice-storage tank according to the variation of ice change calculated by the change of the diameter.

4. The Simulation Verification

In this paper, the object of study is a large building in Beijing which is defined as 4-2 project here, setting up the model of initial ice storage system based on the 4-2 project of building data. Ice coil is specification for DN350 - DN377X9.0, length of 1200 m. The ice-storage tank is 24.45 meters long, 12.05 meters wide, 4.5 meters high. The maximum thickness of ice on the coil is 25 mm. The quality of water in the ice-storage tank is calculated with the volume of the ice-storage tank and the volume of the ice coil. The initial ice tank water temperature is zero degrees in the design with maximum ice storage quantity, namely the ice in adjacent coil overlaps with each other. In this paper, the model simulation data are compared respectively with BAC coil and TSINGHUA TONGFANG ice coil characteristics.

4.1 The Simulation Environment

TRNSYS consists of a suite of programs: The TRNSYS simulation Studio, the simulation engine (TRNDll.dll) and its executable (TRNExe.exe), the Building input data visual interface (TRNBuild.exe), and the Editor used to create stand-alone redistributable programs known as TRNSED applications (TRNEdit.exe).TRNSYS is a complete and extensible simulation environment for the transient simulation of systems, including multi-zone buildings. It is used by engineers and researchers around the world to validate new energy concepts, from simple domestic hot water systems to the design and simulation of buildings and their equipment, including control strategies, occupant behavior, alternative energy systems (wind, solar, photovoltaic, hydrogen systems), *etc.*

MATLAB is the combination of two words 'matrix & laboratory ', meaning a matrix factory (matrix laboratory). The American MATHWORKS company mainly face of scientific calculation, visualization and interactive program design of the high-tech computing environment. It is in an easy to use Windows environment such as numerical analysis, matrix calculation, scientific data visualization nonlinear dynamic system of modeling and simulation, and many other strong function integration, for scientific research, engineering design and many fields of science, provides a comprehensive solution, and get rid of the traditional non-interactive programming language such as C, Fortran.

The modeling is based on TRNSYS and MATLAB simulation. TRNSYS is mainly used in building simulation model and system model. MATLAB is mainly used for numerical calculation and the simulation of the controller. These two software are modular software structure, namely the different physical components can exchange data, the parameters input of the parts type defines the form of data exchange between components and other parts in system. The two of the definition of software components in the language and grammar structure is different. TRNSYS TYPE155 can call the MATLAB program with running under the same operating system, Windows, and providing TRNSYS TYPE155 components written in FORTRAN language. The realization of the simulation environment is as shown the figure 8 figure 9 below.

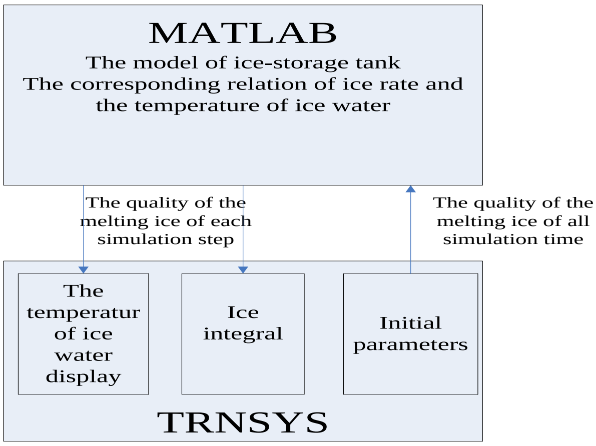

Figure 8. TRNSYS and MATLAB Interactive Simulation

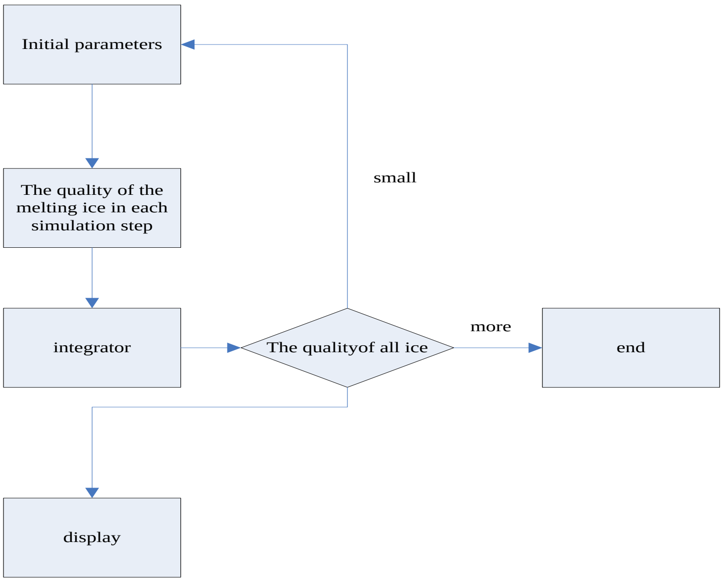

Figure 9. Program Flow

4.2 Compared with BAC Ice Coil Properties

Ice storage may be used in a number of different ways, and the se-lection of different options will depend on the requirements and limitations of each building. For example, an old building used as an office may only be able to take the weight of a small chiller on the roof but may also have cellars which could be used to house the ice store.

The main advantages of ice storage are due to the price difference between peak and off-peak electricity, coupled with more efficient use of the chillers. With increasing competition between electricity suppliers the price difference may increase in the future.

BAC ice coil has been widely used in integrated office, shopping malls, schools, residential areas such as building system with the characteristics of the stable and reliable application. It is a good way to meet engineering requirements of the ice storage capacity is 90-287000 TH, and BAC put forward the "external finned coil pipe principle of melting ice storage air-conditioning system" [13 14] theory with the advantages of the structure. BAC ice coil of serpentine coil can achieve reverse heat exchange, thus it can provide the low temperature water for a long time. Figure 10 and figure 11 is the comparison curve of the design model in this paper with the BAC specifications melting.

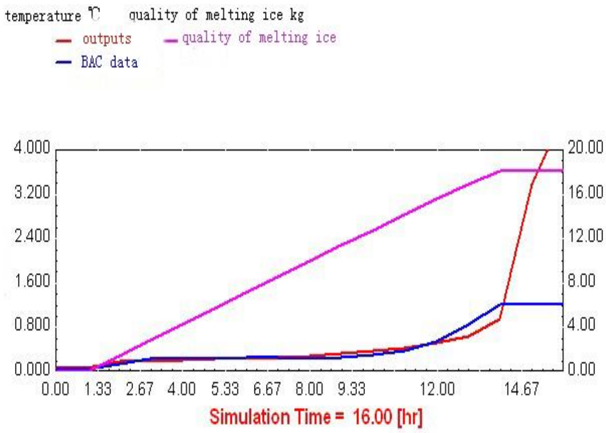

Figure 10. Compared with BAC Ice Coil Properties for 12 Hours

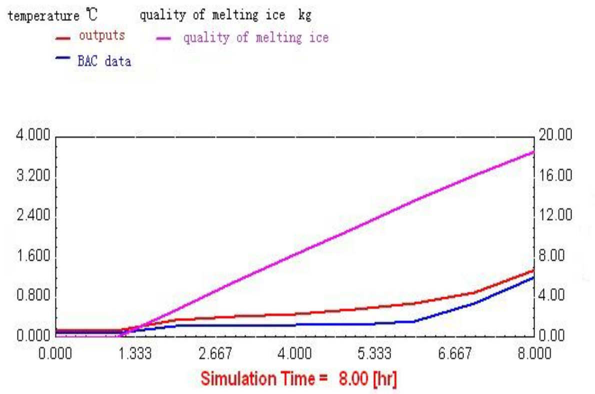

Figure 11. Compared with BAC Ice Coil Properties for 6 Hours

BAC product manual provides only a curve which did not specify the change range of temperature and flow in chilled water supply. It just shows that ice-storage tank with BAC coils can provide the low temperature water over a long period of time under a certain flow. The simulation of two groups of different ice rate change shows the input of the model with the different flow and chilled water return temperature. The first figure shows output of model accurately simulate the temperature of chilled water return when the ice in tank melted for 12 hours. The second figure shows that output of model is slightly higher than the temperature of chilled water supply with BAC coils for 4 hours melting ice. But the biggest error value is only 0.65 ℃.

4.3 Compared with TSQINGHUA TONGFANG Ice Coil Properties

RH series ice storage equipment are produced by Tsinghua tongfang co., LTD . Ice-storage RH series equipment rate (IPF) is not greater than 50% because of the ice tank volume is larger. The RH series production coiled metal ice coil are heat exchanging fully and fast and stably melting ice because its single plate is 100 meters length. Tsinghua tongfang ice coil is given in the product manual cold five release curve, as shown in figure 6. By a figure the temperature of chilled water return is correlation with melting rate.

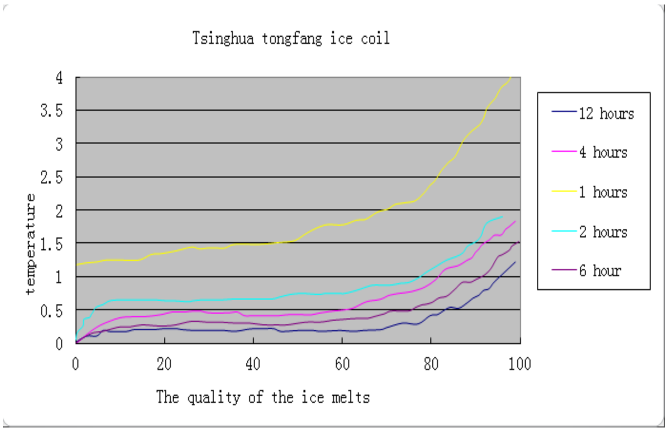

Figure 12 TSQINGHUA TONGFANG Melt Curve

In figure 7 figure 8 and figure 9, the outputs of model in 12 hours of melting ice, 6 hours, 4 hours respectively are compared with the actual data provided by TONGFANG. Figure illustrates the outputs of model are consistent with the actual curve under most conditions. The outputs of model accurately simulate the temperature of ice-storage tank chilled water return. The ice-storage tank model is a foundation of setting up the whole simulation system and realizing the predictive control.

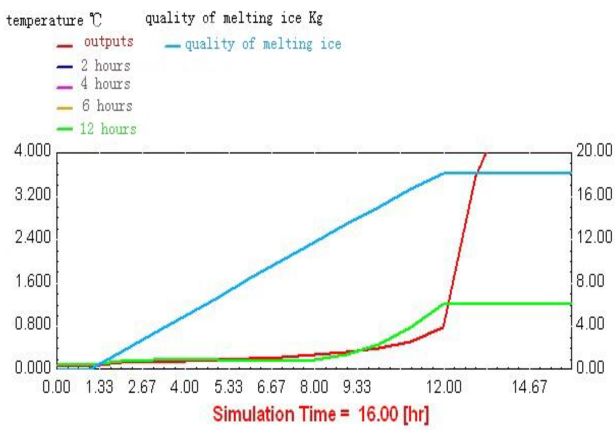

Figure 13. Compared with TONGFANG Ice Coil Properties for 12 hours

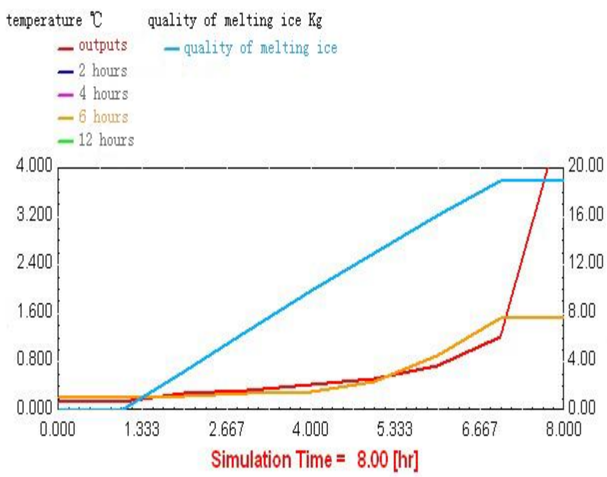

Fig 14 Compared with TONGFANG ice coil properties for 6 hours

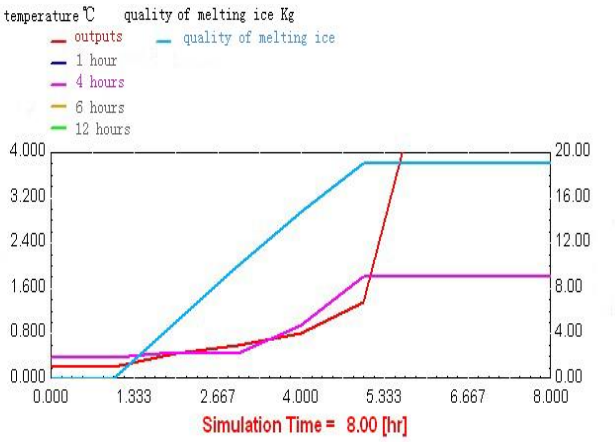

Fig 15 Compared with TONGFANG Ice Coil Properties for 4 Hours

5. Conclusion

The mathematical model of ice-storage is established from the perspective of the mechanism. Because of ice-storage tank model is not generic, the simulation needs initialize parameters of the model according to the actual engineering configuration. After the model equation is put forward, using the 4-2 project of ice storage system of the building is the actual parameters for the simulation of the model, in the different flow and different melting speed, by analyzing the temperature of ice-storage tank chilled water. The outputs of model can accurately simulate the temperature of chilled water equipped with BAC ice coil and TSINGHUATONGFANG ice coil under most conditions. In 20% to 80% melting time period, the outputs of simulation consistent with the data provided by BAC and TSINGHUA TONGFANG in actual operation condition. But there is a deviation in the amount of melting ice in the top 20% and 20% of the end time. The main reason has the following three points: 1) the chilled water return into the ice-storage tank does not exchange fully with the cold ice release; 2) in the end of 20% , many ice fell from the coil, floating in the water surface, influence of ice and water in thermal efficiency; 3) because the volume of ice-storage tank is great, there is a temperature field in the ice-storage tank. It takes time to cool the chilled water return, the temperature not falling rapidly.

In most conditions, the ice-storage tank model set up can simulate better dynamic characteristic of the ice-storage tank. In the most time of ice-storage tank running the model accurately simulate in the different flow and different temperature of chilled water return. It is of great significance to the optimization control of the ice-storage tank.

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