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Numerical Simulation of Internal Melt Ice-on-Coil Thermal Storage System

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Abstract

The mainly purpose of this paper is to simulate the charging and discharging process of internal melt ice-on-coil thermal storage system based on the exited experiment. Its mathematic model is built and the results of the simulation and experiment are compared for verifying the simulation. The further analysis about the influence of whole ice storage and melt process is made from thermal resistance, diameter and pipe material. Analysis indicates that making diameter larger can make heat transfer better. Larger the heat transfer coefficient of the pipe can improve thermal efficiency, but the heat resistance will not be reduced obviously as the coefficient increase.

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Keywords: Internal Melting Ice-On-Coil Tube; Numerical Simulation; Experimental Comparison; Thermal Resistance

1. Introduction

The ice storage air-conditioning technology is one form of the cool-storage air conditioning technology. Ice storage technology can not only realize peak filling and valley clipping for relieving pressure on power, but also reduce the ice storage air-conditioning owner's operation cost to make them obtain more economic benefits, so it is widely used in the world as the demand side management technology of power. In abroad, ice storage research became active gradually since 1987 which concentrated in ice storage system, direct and indirect ice-storage models for energy analysis calculation [1][2], development and evaluation of a rule-based control strategy for ice storage systems, optimal control for cool storage[3][4].In domestic, ice storage cold research is later, the ice storage air-conditioning system equipment is introduced and developed since the 1990s in China, and various storage system forms had been taken into engineering applications in recent years, but most of the research confined to the practical engineering, the research on the influence factor of ice storage process is not much. In this paper, we

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focus on the computer simulation of ice storage to analyze thermal resistances of icing and deicing process with different coil material and coil diameter.

1.1. Ice storage simulation

1.2. Ice storage model

This paper is based on the test of the ice storage cylinder model in order to validate the scientific of the simulation process. Simulation tools Simulink[5] [6] [7] of MATLAB is used to establish the ice storage model of reference [8] and further simplification is made as follows.

Coil is considered as long straight concentric ring; heat transfer process can be considered as one-dimensional radical heat conduction; Temperature of water always maintain 0℃. Experimental design parameters listed in table 1.

Table 1. The arrangement of channels

Type	Value
Import and export temperature of cooling agent (℃)	2
Internal diameter of pipe (mm)	12
Flow of cooling agent (kg/s)	0.22
Tube thermal coefficient (kJ/(kg·k))	0.45
Outside diameter of pipe (mm)	16
Length of pipe(m)	42.68

1.3. Experimental verification

Ode45-variable-step-length algorithm is used in simulation process. The cool storage quantity from simulate calculation and experiment # 3 of reference [8] are compared as shown in Fig.1 (The data is measured after the start of the experiment).

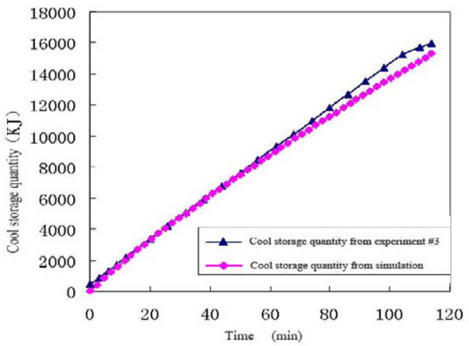

Fig. 1. Cool storage curves of simulation and experiment #3.

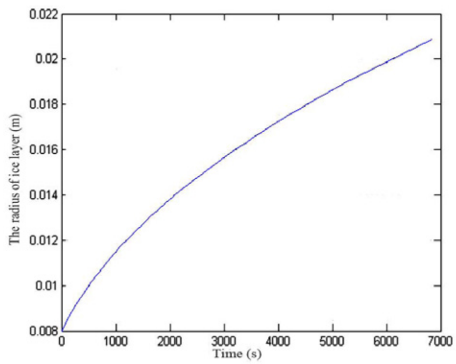

Fig. 2. Outside diameter of ice model

The result of experiment and simulation are very coincident, the maximum error percentage is 6% which is the result of the assumptions in the simulation calculation and the neglect of heat dissipation of cooling barrel to the environment. Simulation model is operated according to the experimental data of the ice storage experiment, Fig.2 shows that ice diameter increases with time, but the rate of change decreases gradually. The result is completely consistent with the laws of physics in ice-storage process.

From the analysis above: simulation effect is good enough to satisfy the research needs.

1.4. Simulation results and analysis

1) Impact of coil diameter on heat transfer

Different diameters of aluminum tube are set as the simulation condition, in the same time, with the same cooling agent flow, same pipe material and length (unit length 1m).

Fig.3 shows the changes of cool storage quantity over time .The tubing sizes are listed in table 2. The result indicates that with the same time frame and the same cooling agent velocity, the cool storage quantity is more, and the cool storage speed is faster as the diameter increases.

Table 2. Aluminum tube specification sheet

Type	External diameter (mm)	Inner diameter (mm)
1014	14	10
1216	16	12
1418	18	14
1620	20	16
2025	25	20
2632	32	26
3240	40	32

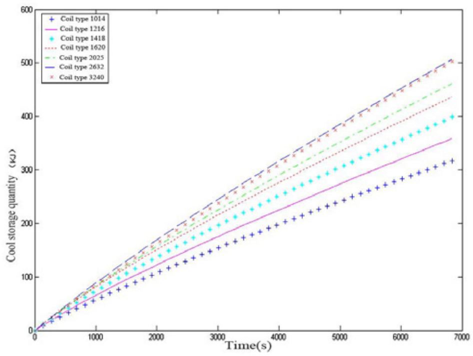

Fig. 3. Cool storage comparison between experiment and simulation with different types

The heat transfer area of big diameter pipe is lager than small one. So cool storage quantity of large-diameter pipe is bigger than small-diameter pipe per unit length within the same time frame.

In summary, the big-diameter pipe should be used for designing system. However, big-diameter tube need high, investigation, technical and economic comparison should be made for specific selection.

2) Impact of pipe material on heat transfer

The comparative analysis of the heat transfer bases on simulation of different pipes.

Fig.4, Fig.5, and Fig.6 show the changes of ice radius, cool storage quantity and thermal resistance from simulation at the same condition and unit length (1m).

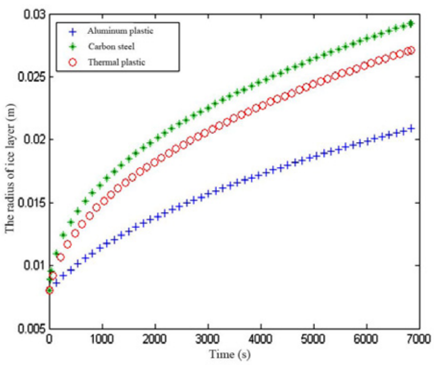

Fig. 4. Radius variation in of three materials in the same condition

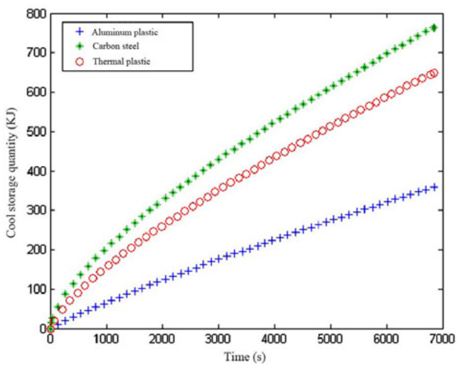

Fig. 5. Variation in cool storage of three materials in same condition

It can be seen from the Fig.5 and Fig.6, although thermal conductivity of carbon-steel material is 18 times more than thermal-plastic and 100 times more than aluminum-plastic, the ice radius and cool storage quantity do not differ greatly in the process. The cool storage quantity of carbon-steel material is

1.2 times more than thermal-plastic and 2.1 times more than aluminum-plastic.

As is shown in Fig.6, the difference of the total-thermal resistance between carbon-steel and thermal-plastic is little (the former is 90% of latter at the end of ice-storage process), but the thermal resistance of aluminum-plastic differs greatly with carbon-steel and thermal-plastic (the total-thermal resistance of aluminum-plastic is 1.58 times more than carbon-steel, and 1.77 times more than thermal-plastic at the end of the ice storage process).

In summary: Coil material's influence on total-thermal resistance and cool storage quantity reduce gradually when heat transfer coefficient of coil is larger than ice (2.22 W/(m·K)).

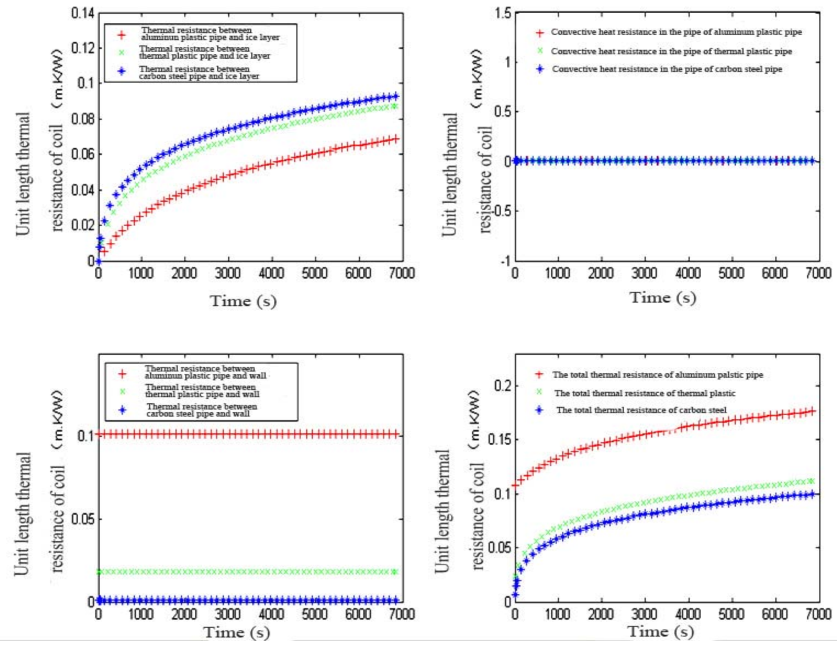

Fig. 6. Variation in thermal resistance of three materials in same condition

The coil material whose thermal conductivity is bigger than ice should be chosen in the system design. According to the comparison between carbon-steel and thermal-plastic, ice storage performance of thermal-plastic approaches carbon-steel, but thermal-plastic is more energy efficient, and cheaper.

2. Ice-melting Simulation

2.1. Ice-melting model

The increase of water layer decreases ice-melting efficiency and outlet temperature in ice-melting process with time.

This paper made further simplification as follow in this complex process.

(1) Coil length is long enough to ignore its axial heat transfer (2) Coil tube outer layer and ice is concentric ring (3) Heat convection of tube outer layer is regarded as equivalent-heat conduction[9] in the ice-melting process.

According to the measured data of reference[8], simulation tool Simulink[10] is used to establish the ice-melting model and experimental design parameters are listed in table 3.

Table 3. Design parameters of melting ice experimental simulation

Type	Value
Flow volume of cooling agent (kg/s)	0.22
specific heats of cooling agent kJ/(kg·k)	3.679
Length of pipe (m)	42.68
Outer diameter (mm)	16
Inner diameters (mm)	12
Heat transfer coefficient of pipe kJ/(kg·k)	0.45
Density of ice (Kg/m^3)	921
Latent heat of ice-melting (Kg/m^3)	334
Inlet temperature of cooling agent（℃）	12.1

2.2. Experimental verification

Ode45-variable-step-length algorithm is used in simulation process. The ice-melting quantity from simulate calculation and experiment #3 of reference [8] compared in Fig.7 (3 # experiment's date is measured in the end of melting)

The results of experiment and simulation are very coincident. The maximum error percentage is 7%. The result completely accords with the laws of physics in ice-melting process. Simulation result is good enough to satisfy the research need.

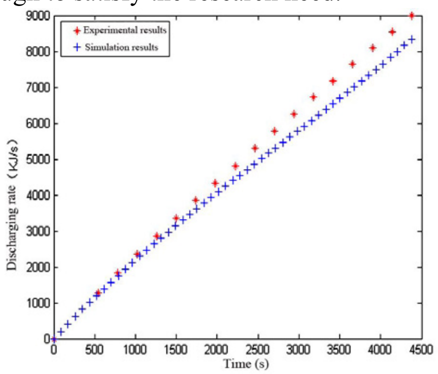

Fig. 7. Cool comparison between simulation and experiment

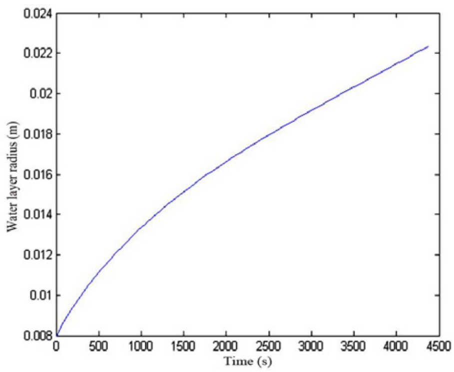

Fig. 8. Variation in radius of water in ice melting simulation

2.3. Simulation results and analysis

Effects of thermal resistance on heat transfer.

The change of water-layer radius outside the coil in the ice-melting simulation experiment platform is shown in figure 8 .The results indicate that water radius increases gradually but the rate reduces with time. This is because thermal resistance between coil and ice increases with the increase of the water radius.

Variation of thermal resistance between coil and ice is made by analyzing thermal resistance between cooling agent and ice. Convective heat resistance and thermal resistance of wall in the pipe is invariant with time, but equivalent–thermal resistance (integration of water layers convective with equivalent-thermal resistance) between coil and ice increase gradually with time. The results suggest that, although heat transfer exists between coil and ice water, as the water is imprisoned in narrow space, convective heat is not in the dominant position.

Fig.10 shows the percentage of total-heat resistance change between coil and cooling-agent heat resistance. The total-thermal-resistance is dominated by pipe-wall thermal resistance because water layer is very thin, thermal resistance is very small, and water layer equivalent thermal resistance had little influence on total thermal resistance in the early stage. The percentage of thermal resistance of pipe wall decreases gradually (93%to 25.8%), the percentage of water-layer-equivalent thermal resistance increases (0 to 72.28%) with water-layer radius increases. The percentage of convective heat resistance in the pipe falls from 7% to 1.92% in the whole process of melting, so its influence to the total-thermal resistance is minimum.

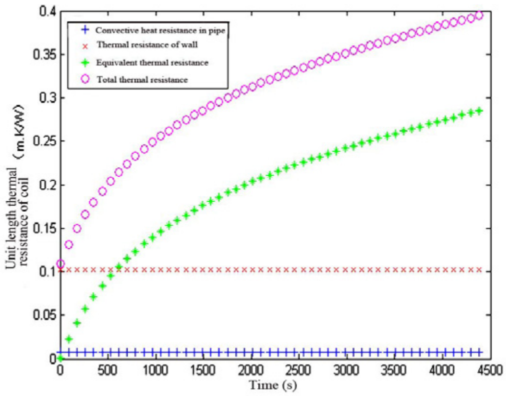

Fig. 9. Variation of thermal resistance between cooling agent and ice in simulation

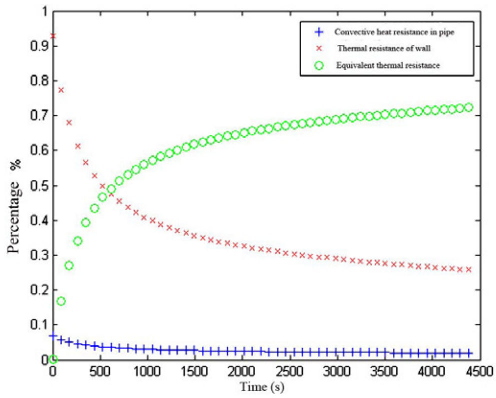

Fig. 10. The percentage changes in the total thermal resistance in simulation

The result can be summarized: Increasing the cooling agent flow can improve coil convection effect, but that may bring series of problems (pump power dissipation, noise increasing, leakage problem from increasing the pressure in pipe). There are so many limitations for increasing the cooling agent flow, so reducing the coil-thermal resistance and water-layer equivalent thermal resistance is the best way to enhance heat transfer performance.

3. Conclusions

Results indicate that: Making the diameter larger can make the heat transfer better in the same working condition. Ensuring the pipe heat transfer coefficient bigger than ice can improve thermal efficiency , however, as the thermal conductivity of pipe increases, heat resistance will not be reduced obviously, so technical economy should be taken into consideration in choosing pipe rather than just increasing the conductivity heat transfer coefficient.

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