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Effect of material characteristics on ice storage performance of an external melting ice-on-coil tube

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ABSTRACT
The coil material has an effect on the icing performance. In this paper, the dynamic simulation of the icing process of three different coil materials is carried out. The variation of temperature field and liquid phase rate over time at the characteristic sections were analyzed. The results show that the ice layer first appears on the lower and outer side of the coil and gradually wraps all the outer wall of the coil.The thermal conductivity of ice coil material has an effect on the icing process. Especially when the thermal conductivity of coil material is lower than that of ice, the lower the thermal conductivity, the longer the time required for icing. But it change when the thermal conductivity of coil material is higher than that of ice, the improvement of thermal conductivity of coil material has little effect on the time required for icing. The thermal conductivity of reinforced polyvinyl chloride is only 2.3 W/(m·K) higher than that of polyvinyl chloride, but the time required for water outside the coil to completely freeze is reduced by 46%. The thermal conductivity of steel is 37.5 W/(m·K) higher than that of reinforced polyvinyl chloride, but the time required for water outside the coil to completely freeze is only reduced by 7%. In terms of the time required for icing, reinforced polyvinyl chloride is expected to replace steel. The natural convection of water has an effect on the icing outside the coil.

Keywords: cold storage, ice-on-coil, thermal conductivity , liquid phase ratio, phase change

NONMENCLATURE

Abbreviations	
CFD	Computational Fluid Dynamics
PVC	Polyvinyl Chloride
RPVC	Reinforced Polyvinyl Chloride

Symbols	
c_p	Specific Heat, kJ/(kg·K)
g	Acceleration of Gravity, m/s^2
H	The Sum of Sensible Enthalpy and Latent heat
h	Enthalpy, kJ/kg
κ	Kinetic Energy
L	Length,mm
l	Liquid Phase
r_1	Inner Radius of Coil,mm
r_2	Outer Radius of Coil,mm
r_3	Radius of Domain,mm
ref	Reference Value
γ	Liquid Fraction
s	Solid Phase
S	Damping soure term
T	Temperature, K
t	Time, s
λ	Thermal Conductivity, W/(m·K)
ρ	Density, kg/m^3
μ	Dynamic Viscosity, kg/(m·s)
β	Thermal Expansion Coefficient,1/K
$\vec{u}$	Velocity Vector

1. INTRODUCTION

Energy consumption is the primary problem restricting social sustainable development. With the increasing proportion of power consumption, the problem of insufficient power supply during the peak period is becoming more and more serious[1]. Through the management of the power demand side, the use of cold storage technology can effectively transfer the peak power load to the off-peak power consumption, which can not only reduce the peak load of the power station, but also reduce the operation cost by using the difference of peak and valley electricity price, so as to bring better social and economic benefits. In the cold storage air conditioning system, ice is one of the most commonly used cold storage media, which has the advantages of hige phase change latent heat and low cost. Ice storage air conditioning uses electric power for refrigeration in the off-peak power consumption period at night to store the cooling capacity in the form of ice. During the peak period of power consumption in the daytime, the cooling capacity is released to cool down the temperature of the building, so as to alleviate the power load of the power grid. The coil type ice storage tank is characterized in that the coil is placed in the ice storage tank. The ice storage tank is filled with water for cold storage. The low-temperature refrigerant flowing in the coil (usually ethylene glycol solution) transfers heat with the water outside the pipe to reduce the temperature of the water and freeze when it is lower than 0 ℃. Awasthi Abhishek et al.[2] studied the influence of coil arrangement direction on cold storage performance. The results show that the heat release performance of ice coil arranged in vertical direction is 30.15% more than that arranged in horizontal direction. However, there is no significant difference in the heat charging performance between the two methods. Woo Hong Sang et al.[3] proposed the sample and interpolation method (SI) to analyze the phase transition of full-size vertical ice coil. The effective thermal conductivity method was used to ignore the influence of natural convection and reduce the calculation time. Mehmet Akif Ezan et al.[4] proposed that the energy and exergy characteristics of the system should be comprehensively considered in the working and design parameters of ice-on-coil cold storage system. Hossein Akhavan Hamzeh et al.[5] concluded that the fin height is a very effective parameter to improve the freezing rate of ice-on-coil tube. Zichu Liu et al.[6] researched and developed an ice energy storage device with micro heat pipe array as enhanced heat transfer element, and achieved obvious improvement results. There are some technical problems in ice energy storage technology, such as ice coil corrosion, economy need to be improved, low thermal conductivity of water and thermal stratification, which restrict the further development of ice energy storage technology. The pipe of ice storage coil has a certain impact on the ice storage performance, and there is little research in this field at present. According to the actual ice storage device and operating conditions, this paper establishes a three-dimensional physical model of a single coil, and compares the ice storage performance of a single coil under the conditions of polyvinyl chloride(PVC), a kind of graphite heat conduction reinforced polyvinyl chloride(RPVC) and steel by computational fluid dynamics(CFD) simulation. The unsteady state simulation analysis of a single coil is carried out by using the solidification melting calculation model, which reflects the phase change process of coil ice storage and the change of ice layer outside the pipe with time.

2. MODELING

2.1 Geometric model and physical parameters

The geometric model of a single ice-on-coil tube was shown in Fig.1. The geometric parameters of coil tube is listed in Tab.1.The research area of the ice storage tank around the pipe section is a cylinder with a length of 1 m and a diameter of 65.4mm. Low temperature ethylene glycol solution is introduced into the tube, and water is flow in the gap between the outside the tube and the outer wall of calculation area.

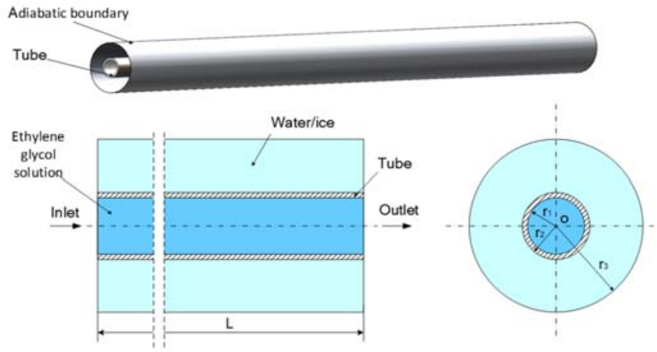

Fig.1 Geometric model of the ice-on-coil tube

Tab.1 Geometric parameters of coil tube

L	r_1	r_2	r_3
1000.0	10.7	12.7	32.7

The physical parameters of fluids were listed in Tab.2.

Tab.2 Physical parameters of fluids

Physical parameters	ρ	c_p	λ	μ	β	*h*
Water-liquid	999	4.212	0.4	0.001003	0.00013	335
Ice	999	4.212	2.2			
Ethylene-glycol solution	1045	3.662	0.4	0.004630		

The cold storage performance of steel, PVC and RPVC coil tube materials was studied in this research. The physical parameters were listed in Tab.3.

Tab.3 Physical parameters of coil tube materials

Physical parameters	ρ	c_p	λ
Steel	8030	0.502	40.0
PVC	1400	2.200	0.2
RPVC	1400	2.200	2.5

2.2 Mathematical model and grid

The governing equation could be expressed as follows[2].

1) Water/ice side

Continuity:

$$\frac{\partial \rho_p}{\partial t} + \nabla(\rho_p \vec{u}) = 0 \qquad (1)$$

Momentum:

$$\rho_p \frac{D\vec{u}}{Dt} = -\nabla p + \mu \nabla^2 \vec{u} + \rho_p \vec{g} + S \qquad (2)$$

$$S = -\frac{C(1-\gamma^2)}{\gamma^3}\vec{u} \qquad (3)$$

$$\gamma = \begin{cases} 1 & (T > T_l) \\ \frac{T-T_s}{T_l-T_s} & (T_s < T < T_l) \\ 0 & (T < T_s) \end{cases} \qquad (4)$$

Energy:

$$\rho_w \frac{DH}{Dt} = \lambda \nabla^2 T \qquad (5)$$

$$H = h + \gamma L \qquad (6)$$

$$h = h_{ref} + \int_{T_{ref}}^{T} c_P dT \qquad (7)$$

2) Ethylene glycol solution side

$$\rho_b c_{P,b} \frac{\partial T_b}{\partial t} + \frac{\partial(\rho_b c_{P,b} u_b T_b)}{\partial z} = \frac{\partial}{\partial z}\left(k_b \frac{\partial T_b}{\partial z}\right) + S_h \qquad (8)$$

3) Tube side

$$\rho_{tube} c_P \frac{DT}{Dt} = k_c \nabla^2 T \qquad (9)$$

The inlet flow rate of ethylene glycol solution is 0.9m/s and the temperature is 267.15K. The initial temperature of water is 274.15K.

2.3 Methodology and mesh grid

The ice storage process of a single coil is numerically simulated under three-dimensional unsteady conditions. The SIMPLE algorithm is used to simulate the turbulent flow field in the coil tube and the phase change process of water to ice outside the tube. The influence of natural convection of water and the difference of main physical properties of water and ice are considered. The velocity inlet boundary condition and free outlet boundary condition are adopted. The inner and outer walls of the coil are set as fluid solid coupling boundary conditions, and the other walls are set as non slip solid walls. The criterion of convergence is that the residual value reaches and stabilizes below 10^{-5}. Standard k- ε Turbulence model, energy model and solid notification & melting model were adopted in the simulation. Fig.2 shows the mesh grid of the whole computational domain. The influence of the mesh spacing and time step independence have been considered. A grid of 391600 and a time step of 0.5 s were chosen for the following simulations.

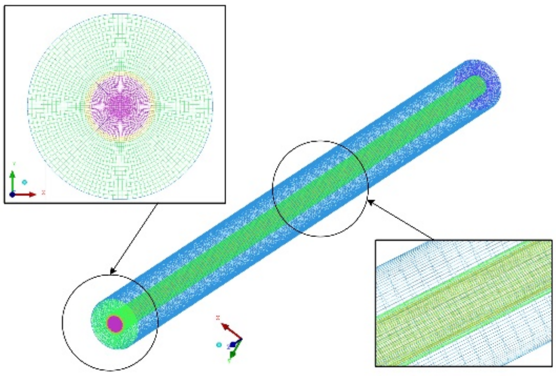

Fig.2 Meshes for the simulation

3. RESULTS AND DISCUSSION

3.1 Temperature field analysis

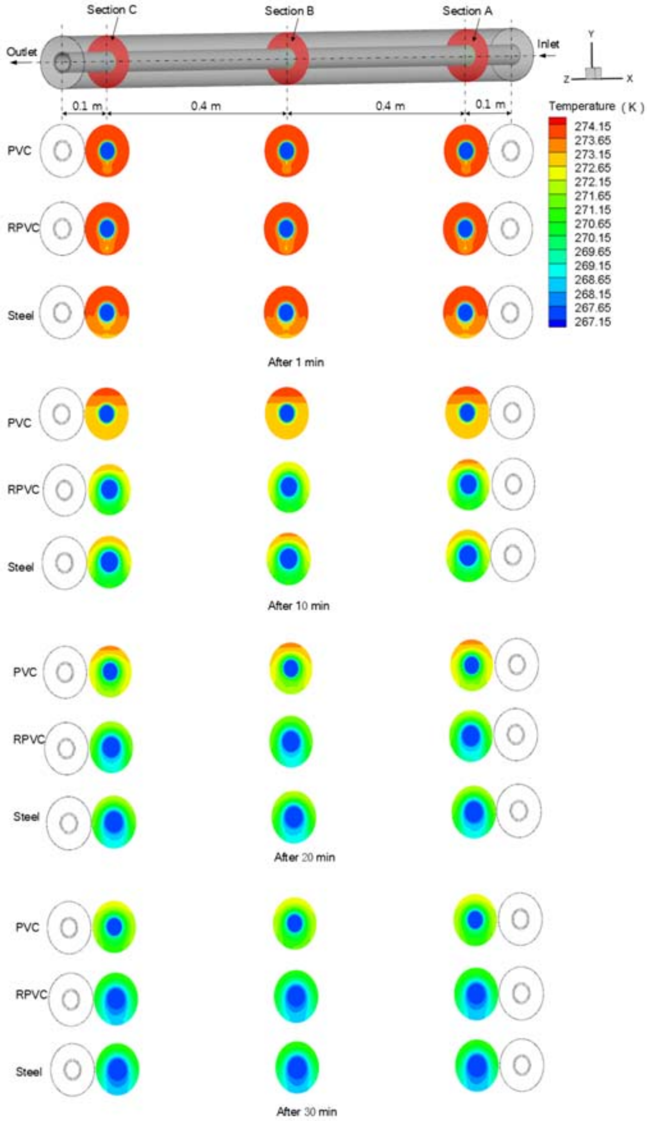

Fig.3 Temperature distributions on the cross sections over time

Fig.3 shows the temperature field on three representative sections of coils of different materials at a specific time in the icing process. It can be seen from the figure that the temperature of each section gradually decreases with time. In each section, the lowest temperature of water appears near the coil and below the coil. In the sections near the inlet and outlet, the difference of water temperature distribution is not obvious, indicating that there is little difference in icing speed outside the 1m long coil. At the same time, the water temperature of steel coil is lower than that in PRVC, and both are lower than that in PVC coil, which is due to the influence of thermal conductivity of coil material on heat transfer performance. However, when the water temperature is lower than 273.15k, the gradual difference between steel coil and RPV C coil becomes smaller. This is because after the water outside the coil begins to freeze, the thermal resistance of ice gradually becomes the main factor affecting heat exchange. However, the difference of PVC is still obvious due to its very low thermal conductivity. This phenomenon can also be verified from Fig.4.

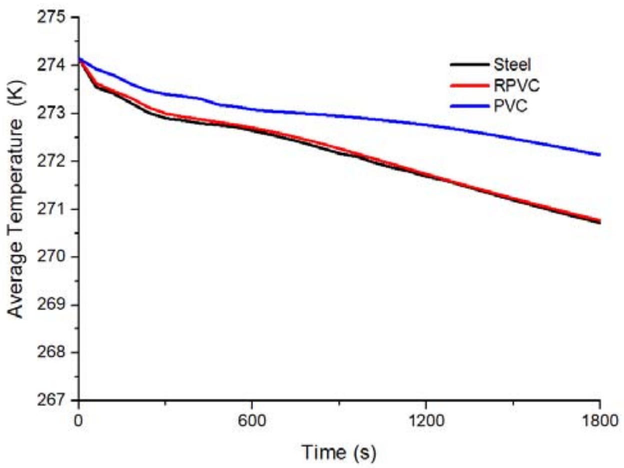

Fig.4 Average temperature of the ring near wall over time on section C

3.1 Liquid phase rate analysis

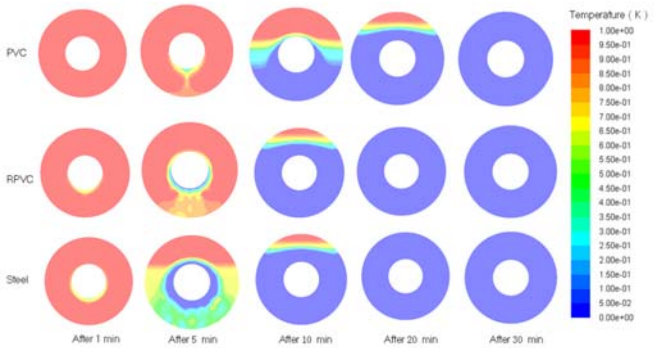

Fig.5 Liquid phase ratio of water on section C

Fig.5 shows the change of liquid phase rate of water over time at section C. It can be clearly seen that the liquid phase rate of water outside the steel coil decreases faster than RPVC, and both of them are faster than PVC. The ice layer first forms below the coil and gradually wraps the coil. Temperature stratification always exists in the liquid phase area. The water outside the steel coil and RPVC coil can completely freeze within 20 minutes, and the water outside the PV coil needs 30 minutes to completely freeze. The freezing time of the coil of the three materials is much lower than that of the ice coil in the actual ice storage project. This is because in this case, the research domain is very small, but in the actual project, the liquid water in the ice storage tank will have a continuous and large heat exchange impact on the freezing process outside the coil, which greatly increases the time required for ice freezing.

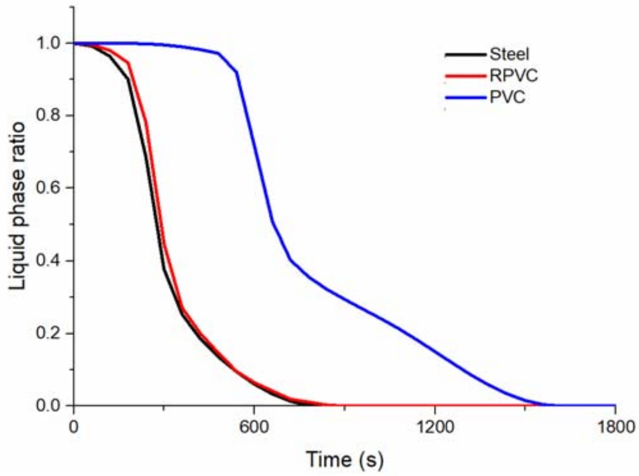

Fig.6 Average liquid phase ratio of water on section C

This phenomenon can also be confirmed from Fig. 6. It can also be seen from Figure 6 that in the initial cooling stage, the change of liquid phase rate is relatively gentle. After 200s, the liquid phase rate of water outside the steel coil and RPV C coil decreases sharply, and then the liquid phase tends to zero at 800s. The change of liquid phase rate of water outside PVC coil has a similar trend, but the whole process lags about 400s. The sudden drop is just due to the influence of water latent heat. The initial stage of cooling is only the release of sensible heat of water. For steel coil and RPVC coil, this process is only 200s. Then the water begins to release latent heat, which lasts for about 600s. When the latent heat was completely released, the liquid water quickly turns into solid ice. The change of water liquid phase rate outside PVC coil lasts for a long time because the low thermal conductivity of the material is the main factor affecting heat transfer. The thermal conductivity of RPVC is only 2.3 W/(m·K) higher than that of PVC, but the time required for water outside the coil to completely freeze is reduced by 46%. The thermal conductivity of steel is 37.5 W/(m·K) higher than that of RPVC, but the time required for water outside the coil to completely freeze is only reduced by 7%.

4. CONCLUSIONS

The ice storage process of single coil with different materials is studied in this paper. The temperature field and liquid phase rate of typical sections during the cooling process are analyzed, and the following conclusions are drawn.

1) The thermal conductivity of ice coil material has an effect on the icing process. Especially when the thermal conductivity of coil material is lower than that of ice, the lower the thermal conductivity, the longer the time required for icing.

2) When the thermal conductivity of coil material is higher than that of ice, the improvement of thermal conductivity of coil material has little effect on the time required for icing. The thermal conductivity of RPVC is only 2.3 W/(m·K) higher than that of PVC, but the time required for water outside the coil to completely freeze is reduced by 46%. The thermal conductivity of steel is 37.5 W/(m·K) higher than that of RPVC, but the time required for water outside the coil to completely freeze is only reduced by 7%. In terms of the time required for icing, RPVC is expected to replace steel.

3) The natural convection of water has an effect on the icing outside the coil. The ice layer first appears on the lower and outer side of the coil and gradually wraps all the outer wall of the coil.

Due to different calculation domains, the conclusion of this case is obviously different from the actual project. The next step is to expand the calculation domain and compare it with the actual project.

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