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Research Paper

Investigation into the ice generator with double supercooled heat exchangers

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HIGHLIGHTS

- An ice generator with double heat exchangers is proposed for continuous ice-making.
- The ice is melted by the hot compress gas without extra heater.
- The ice generator is compact, high-performance and low-cost.

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ABSTRACT

A novel ice generator with double supercooled heat exchangers is introduced for continuous ice generation using supercooled water. When the ice blockage happens in one of the supercooled heat exhcangers, the ice generator can continue to work by switching to another one instead of stopping work, assuring the continuous ice making. The outstanding highlight of this ice generator is that the ice blockage that happened in one of the supercooled heat exchangers can be melted by the hot refrigerant gas without extra heater. In this paper, the flow and heat transfer characteristics of the heat exchanger are simulated by providing guidance for experimental studies. Based on the results of simulation and the theoretical studies, a series of experiments are conducted. Although the ice blockage cannot be thoroughly resolved, the results show that it is a practical and efficient method of ice generation system. This work provides theoretical and experimental basis and is practical for the improvement of ice generator using supercooled water; in addition, the ice blockage is retarded, improving the ice production.

1. Introduction

Energy consumption is always a serious problem for human beings. At present, the energy becomes less and less, and the requirement for environmental protection is increasingly urgent. As an environment-friendly medium of ice thermal storage, ice slurries can improve energy efficiency and reduce building energy consumption, thanks to the latent heat of ice crystals and its good fluidity. Ice slurries exploit the latent heat of the ice, making them have more efficient heat carries than single-phase fluids. Nowadays, ice slurry has received increasing attention due to their outstanding features [1–6]. Their large thermal capacity and lower operating thermal temperature allow large temperature difference to be maintained, providing desirable heat characteristics [7–12]. Ice slurry refers to a homogenous mixture of small ice particles and carrier liquid [13]. Ice slurries are used widely for cooling although their applications have spread to other fields [14–17], some of which are given by Kauffeld [18] and Leiper [19].

Using supercooled water is one promising method for ice generation because of its high efficiency and energy conservation. The known method of supercooled concept is that a stream of water flowing into an evaporator is cooled by a few degrees below normal freezing point without crystallizing; after or before leaving the evaporator, the supercooled water flow is physically disturbed in order to generate ice crystals [20]. The key problem in this kind of generator is the ice blockage that happened in the supercooled heat exchanger which reduces the efficiency of the ice generation system. A great deal of endeavor has been made to avoid ice blockage, categorized into three groups: adding additives, interfering externally and improving surface conditions [21–24].

However, the satisfactory methods to solve the problem of ice blockage have not been found up to now. A compact and convenient ice generator with double plate supercooled heat exchangers was present in this paper. The objective of this work is to find an effective method for continuous ice generation using supercooled water.

2. Investigation into the supercooled heat exchanger

The supercooled heat exchanger is a main part of the ice generation system, and is then the place where the water is cooled down

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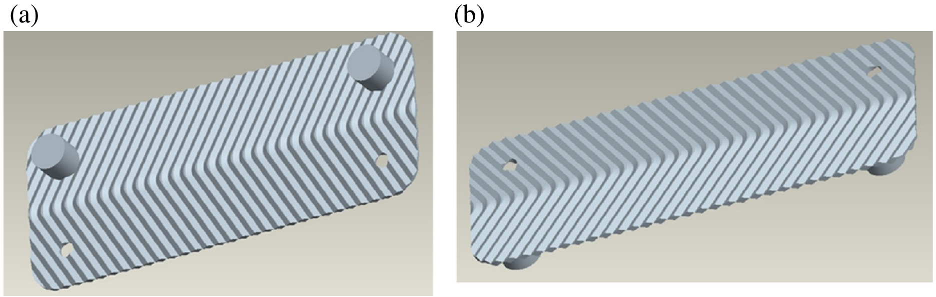

Fig. 1. (a) Front of the model. (b) Back of the model.

to the supercooling state. In this ice generator, the two supercooled heat exchangers are same two plate heat exchangers. Prior to the experiments, the flow and heat transfer characteristics in the supercooled heat exchanger are simulated by Fluent at the proper temperature and velocity in the experiment.

2.1. *The physical model*

According to the material object, the 3D model is established, as seen in Fig. 1. Two same plates are welded together to form channels, which are composed of the corrugations on the two same plates with different flow directions. The water and the refrigerant flow using the separate channels.

2.2. *The numerical model*

According to the practical situations, some hypotheses are made: (1) the fluid is an incompressible Newtonian fluid; (2) ignore the effect of gravity and buoyancy; (3) ignore the thermal effect from the viscosity; (4) no phase transition.

The governing equations are as follows:

The continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

where u is the velocity component of the x direction; v is the velocity component of the y direction; w is the velocity component for the z direction.

$$\frac{\partial U_i}{\partial x}+v\frac{\partial U_i}{\partial y}+w\frac{\partial U_i}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+\nu\left(\frac{\partial^2 U_i}{\partial x^2}+\frac{\partial^2 U_i}{\partial y^2}+\frac{\partial^2 U_i}{\partial z^2}\right) \tag{2}$$

where U_i is the velocity component for the i direction; ρ is the density; ν is the viscosity, P is the pressure.

The energy equation:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=a\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{3}$$

where a is the diffusion coefficient.

Based on the analysis, the RNG $k-\varepsilon$turbulent model can make a good simulation for the flow characteristics in the plate heat exchanger. The equations are shown as:

$$\frac{\partial}{\partial t}(\rho\kappa)+\frac{\partial}{\partial x_i}(\rho\kappa u_i)=\frac{\partial}{\partial x_j}\left(\alpha_\kappa\mu_{eff}\frac{\partial\kappa}{\partial x_j}\right)+G_\kappa+G_b-\rho\varepsilon \tag{4}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left(\alpha_\varepsilon\mu_{eff}\frac{\partial\varepsilon}{\partial x_j}\right)+C_{1\varepsilon}\frac{\varepsilon}{\kappa}(G_\kappa+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{\kappa}-R_\varepsilon+S_\varepsilon \tag{5}$$

where G_κ is the turbulence kinetic energy caused by velocity gradient; G_b is the turbulence kinetic energy caused by buoyancy; $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are two constants, $C_{1\varepsilon}=1.42$, $C_{2\varepsilon}=1.68$; α_κ and α_ε are prandtl numbers; S_κ and S_ε are defined by user.

2.3. *Simulation results*

Ideally, the temperature in the storage tank is 0 °C, the temperature at the inlet of the heat exchanger is set as 0.2 °C with the consideration of cold loss. As seen in Fig. 2, the supercooled degree increases with the increasing velocities due to the improvement of heat transfer. It also shows that: the lower the wall temperature is, the bigger supercooled degree can be reached.

It is very likely to cause ice blockage when the supercooled water has too large supercooled degree, while the too small supercooled degree is not proper for ice generation. Based on the previous experimental results, the supercooled degree $T=-0.5$ °C is perfect. Fig. 3 shows a significant positive correlation between the velocity and the wall temperature: the wall temperature of the heat exchanger decreases along with the increasing velocities at the supercooled degree of –0.5 °C.

The temperature distribution and velocity vector distribution are also simulated respectively at the supercooled degree of –0.5 °C and the inlet velocity of 0.15 m/s. The results are shown in Figs. 4 and 5. In general, the temperature and the velocity vector are well-distributed aside from some local places with too large supercooled degree, such as the inlet, the outlet and the peripheries. The results indicate that it is much better to choose lower velocity and lower wall temperature in the ice making experiment.

3. Investigation on the ice generation system

3.1. *Experimental set up*

A schematic of the ice generation system is shown in Fig. 6. The test plant includes two cycles, i.e. the cooling cycle and the supercooled water cycle. The cooling one is composed of a compressor 1, an air cooled condenser 2, a liquid receiver 3, a filter drier 4, expansion valves 5a and 5b, two evaporators (plate heat exchangers) 8a and 8b, pressure regulating valve 14, and some valves. The second cycle (the lower part) is the supercooled water cycle. As flowing through the supercooled heat exchanger, the water is gradually cooled down to the freezing point. Thanks to the pump 12 and gravity, the storage tank 13 receives the supercooled water from the supercooled heat exchangers 8a/8b. The ice slurries are produced when proper operating conditions are met, and stored into the tank 13. The ice blockage that happened in the supercooled heat exchanger results in the discontinuous ice generation. Therefore, avoiding the ice blockage is a foremost and hard work. In this work, the outstanding highlight is the ice generator with double heat exchangers for avoiding/retarding ice blockage (see Fig. 6).