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Liquid dehumidification-assisted evaporative supercooling method for ice slurry production

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Abstract: Due to the fact that the conventional ice slurry production system using supercooled water suffers from ice block and depends heavily on electric power, a novel ice slurry production system is proposed. The new system consists of two major parts: the evaporative supercooling process and the liquid dehumidification process. The classical diffusion-control equation is improved by introducing an impact factor into the simulation analysis in the evaporative supercooling process. Meanwhile, experiments are carried out by adopting the particle analyzer to detect the radii and the velocities of the droplets, and an infrared camera to examine the temperature profile of the physical process. It is found that the theoretical conclusion agrees well with the experimental results. Compared with the conventional system, the new system can alleviate the burden on electric power and raise efficiency. These improvements are essentially attributed to the reutilization of the inner waste heat generated from the system itself.

Key words: ice slurry; liquid dehumidification; evaporation

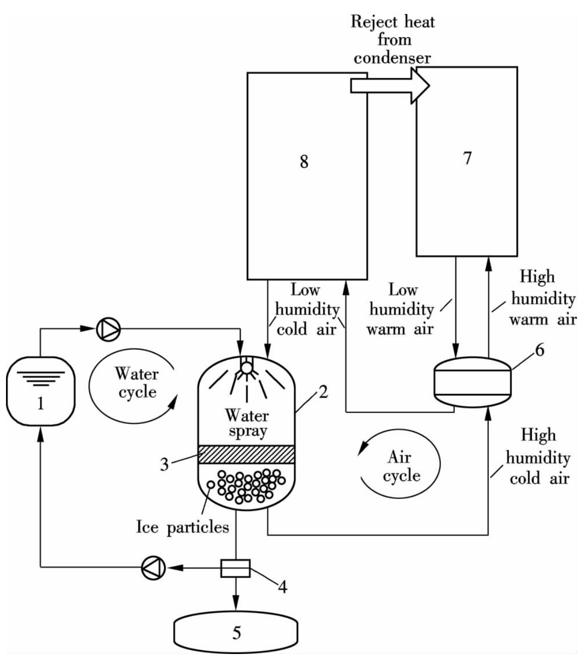
Ice has been widely used in today's life, such as in food preserving, industrial cooling and air conditioning. Particularly, ice storage is an effective and meaningful measure for the energy saving of refrigerations and air conditionings, which places a heavy burden on the energy supply system. Ice slurry, the mixture of ice particles and a liquid solution, is considered as an ideal material for ice storage due to its good thermal properties and flowing characteristics. The present ice slurry production methods can be generally divided into three kinds [1]. The most widely used method is the scraper type system, the main disadvantage of which is the high amount of the extra mechanical work required by the scraper, decreasing the global energy efficiency of the whole system. Another method is the dynamic supercooled water method, which is a research hotspot in this field. As described in Ref. [2], the water is first cooled to a supercooled region and then comes in contact with the supercooled water releaser, where the supercooled state is broken and the ice forms. However, this technology may bear the troubles of ice block in that the supercooled water may freeze inside the tube before it comes in contact with the supercooled water releaser. The third method is the evaporative-freezing method. Its principle is as follows: Water will evaporate as long as the saturation vapour pressure of its layer is higher than that of the surrounding atmosphere. The saturation pressure of the layer corresponds to the water temperature. If the vapour pressure of the atmosphere is below 611 Pa (the vapour pressure is around 611 Pa at 0 ℃), the water will keep on evaporating until a vapour pressure balance is achieved between its layer and the surrounding atmosphere. Meanwhile, the water temperature will fall below 0 ℃ [3-4]. In other words, the water has been super-cooled[5-6]. The evaporative-freezing method can avoid the instability appearing in the supercooled water method, because the water is supercooled and turns into ice outside the tube. However, the mechanical vacuum process has a side effect in that it implies high volume flows and also depends heavily on electric power.

Actually, it is not necessary to vacuum for obtaining low water vapour pressure. The low water vapour pressure can be obtained by decreasing the humidity to a sufficient degree. So a novel ice slurry production system is proposed. Liquid dehumidification is used to reduce the vapour pressure and water is evaporated to its supercooling state, through which the ice slurry is finally obtained. The processes are theoretically and experimentally analyzed. It shows that the theoretical conclusion agrees well with the experimental results. Besides, ice particles are formed in the experiments for testing the feasibility of this new method.

1 Materials and Methods

1.1 System description

As shown in Fig. 1, the water (above 0 ℃) is pumped from



1—Water tank; 2—Ice-producing chamber; 3—Supercooled water releaser; 4—Ice-water separator; 5—Ice storage tank; 6—Heat exchanger; 7—Liquid dehumidification cycle; 8—Refrigeration cycle

Fig. 1 Sketch of the novel system

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a water tank to the “ice-producing chamber” and then sprayed there; meanwhile, low humidity air is introduced to this chamber, which produces an appropriate environment where the wet bulb temperature is below 0 ℃.

The sprayed water droplets keep on evaporating due to the water vapour pressure difference between its saturation layer and the surrounding atmosphere. Soon, the droplet temperature approaches the wet bulb temperature of the air (below 0 ℃). This indicates that the water has been supercooled. According to the present research, −2 ℃ is a reliable supercooled degree for ice slurry production[2]. So if the wet bulb temperature is below −2 ℃, the supercooled degree of the water can also be reduced below −2 ℃. Then, the supercooled state is released with a supercooled water releaser. Some water droplets will change to ice while some will not. An ice-water separator is adopted to separate the water and the ice. Excessive water is reused; ice is stored or made into ice slurry. The humidity of the air leaving the chamber is enhanced and its bulb temperature may rise.

The temperature and humidity are raised for the air leaving the chamber. To continue the cycle, a liquid dehumidification cycle and a refrigeration cycle are required. The air leaving the chamber is first dehumidified and then sent to the evaporator of the refrigeration cycle for cooling. It should be noted that the air temperature may rise during the dehumidification process because the air temperature may be lower than that of the liquid desiccant (The air directly comes in contact with the liquid desiccant). In this case, a heat exchanger takes on the task of counter-current heat exchange between the air leaving the chamber and the air leaving the dehumidifier. In an ideal situation of complete heat exchanging, the temperature of the air leaving the chamber will rise to that of the air just leaving the dehumidifier; the temperature of the air leaving the dehumidifier will drop to that of the air just leaving the chamber. In this way, the temperature fluctuation of the air can be eliminated or at least reduced. There is great flexibility in the refrigeration cycle since it can be a vapour compression cycle driven by electric power, an absorption cycle driven by solar energy, or an adsorption system driven by waste heat.

In the liquid dehumidification process, the strong desiccant solution absorbs the moisture from the air and becomes weak solution. This weak solution must be recovered to maintain the cycle. Thus, a regenerator, which calls for driven energy, is needed. Since the temperature threshold is only 60 to 80 ℃ for a heat source to drive the liquid dehumidification cycle[7], the rejected heat from the condenser of the refrigeration cycle can be reutilized to do this work. This implies that the rejected heat of the system itself has been reutilized, which can improve the performance of the whole system.

1.2 Analysis of the evaporative supercooling process

To theoretically analyze the evaporating supercooling process of water droplets, a simulation calculation is carried out based on the diffusion-controlled evaporation model[8]:

$$\frac{\mathrm{d}T}{\mathrm{d}t}=\frac{3\left[\frac{h_{\mathrm{m}}l_{\mathrm{w}}M}{\bar{R}}\left(\frac{P_{\mathrm{a}}}{T_{\mathrm{a}}}-\frac{P_{\infty}}{T_{\infty}}\right)-k_{\mathrm{g}}(T_{\infty}-T_{\mathrm{a}})\right]}{r^{2}\rho C_{\mathrm{w}}} \quad (1)$$

where $\mathrm{d}T/\mathrm{d}t$ is the temperature variation; r is the droplet radius; C_{w} is the specific heat of the water while ρ is the density; T is the Kelvin temperature; P is the pressure difference; l_{w} is the latent heat of vaporization; h_{m} and k_{g} are the mass and heat transfer coefficients, respectively; M stands for the molecular weight of the water and $\bar{R}$ is the universal gas constant. The subscripts a and ∞ symbolize the droplet surface and the surrounding environment.

Experiments are conducted to investigate the evaporation supercooling process and examine the mathematical model. A nozzle is employed to sprinkle water droplets in a chamber where the dry and wet bulb temperatures are controlled. The flow rate and the pressure of the water are maintained unchanged to ensure a stable spray. There are three important parameters that must be collected: the average diameters and velocities of the droplets and the dynamic droplet temperature profile. The average diameters and velocities of the droplets are measured by particle dynamics analysis (PDA). Its measurable droplet size range is 0.5 to 13 000 mm with an accuracy of 0.5%. Its velocity measurement accuracy is 0.5%. The experimental image is displayed in Figs. 2 (a) and (b). The droplets are so small and sensitive that a contact temperature measurement method (such as thermocouple) can change the real droplet temperature. Therefore, VisIR Ti 200, an infrared camera, is employed to detect the dynamic temperature profile. Its temperature sensitivity is 75 μK at 30 ℃, which symbolizes the accuracy of the temperature difference detection.

It should be noticed that Eq. (1) is developed in the case of a single droplet. Nevertheless, the experimental fact is different. The spray consists of numerous droplets and these droplets have an impact on one other. The interaction of the droplets should be taken into consideration. Therefore, an impact factor X is introduced to Eq. (1) to make some improvements. The value of this factor can be determined by analyzing the experimental data, and Eq. (1) can be rewritten as

$$\frac{\mathrm{d}T}{\mathrm{d}t}=\frac{3\left[\frac{h_{\mathrm{w}}l_{\mathrm{w}}M_{\mathrm{w}}}{\bar{R}}\left(\frac{P_{\mathrm{a}}}{T_{\mathrm{a}}}-\frac{P_{\infty}}{T_{\infty}}\right)-k_{\mathrm{g}}(T_{\infty}-T_{\mathrm{a}})\right]}{r^{2}\rho C_{\mathrm{w}}}X \quad (2)$$

(a) (b)

Fig. 2 Experiments of evaporative supercooling process

2 Results and Discussion

In the conventional supercooled water method, the water is supercooled to about −2 ℃ and then turns to ice by releasing its supercooled state. In the proposed method, the supercooled water is also changed to ice by a supercooled state releaser. The difference is that the water is supercooled through spraying and evaporation. The ice-block phenomenon can be eliminated because there is no supercooled water flowing inside a tube. The mission of the refrigeration cycle in this new method is different from that in the conventional one. It not only affords the cooling load for maintaining the dry bulb temperature of the air, but also provides the rejected heat for fuelling the regeneration process of the liquid dehumidification units. In the conventional method, only the cooling capability of the refrigeration cycle is utilized for supercooling water. Thus, the refrigeration cycle in this new method has a double effect, which makes the ice production process more efficient.

Experiments are conducted aiming at examining the new method. With PDA measurements, we obtain that the average droplet diameter is 265 μm and the average initial velocity (vertical) is 10.9 m/s. The dry bulb temperature of the environment is 1 ℃ while the wet bulb temperature is −3 ℃. By analyzing part of the experimental data, it is found that the impact factor X in Eq. (2) is 0.3. For theoretical simulation, the values of some important parameters are listed in Tab. 1. Fig. 3(a) presents the temperature profile captured by the infrared camera and Fig. 3 (b) shows the comparison between the experimental results and the theoretical results calculated by Eq. (2). It can be found that the simulation results agree well with the experimental results, which proves that the adjustment of the impact factor is fairly effective in reflecting the true evaporative supercooling process. Finally, tiny ice particles are formed in the experiments as shown in Figs. 4(a) and (b).

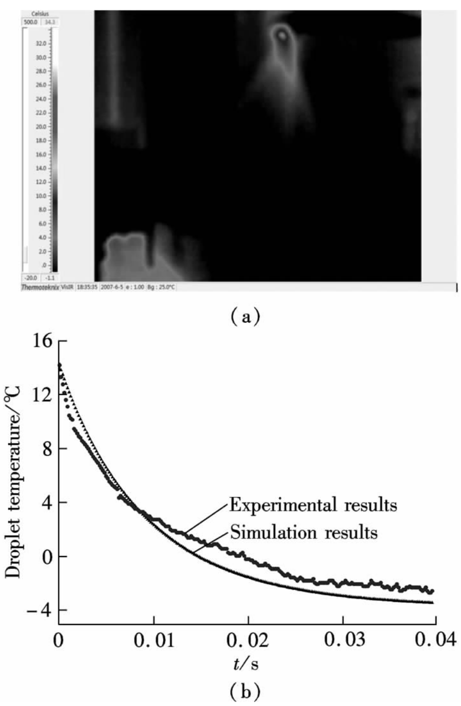

Fig. 3 Comparison between experimental and theoretical results. (a) Temperature profile; (b) Temperature curves

Tab. 1 Parameters for simulation

Parameters	Value
$C_w/(kJ\cdot(kg\cdot K)^{-1})$	4.2
$h_m/(m\cdot s^{-1})$	0.025[8]
$k_g/(kW\cdot(m^2\cdot K)^{-1})$	2.2×10^{-5} [8]
$l_w/(kJ\cdot(kg\cdot K)^{-1})$	2 500
$M/(kg\cdot kmol^{-1})$	18

Fig. 4 The formed ice particles. (a) Ice particles; (b) Formed ice

3 Conclusion

Water is supercooled by evaporating and turns into ice in this novel ice-slurry production method, so the trouble of ice block is put aside and the ice slurry production process is more reliable. Liquid dehumidification is capable for producing an appropriate environment of very low humidity for evaporative supercooling.

The refrigeration cycle not only offers the cooling load but also contributes the normally waste heat from the condenser for producing ice slurry. It is an important improvement because this double effect alleviates the burden of electric power and the whole performance is improved.

The improved model for the evaporative supercooling process agrees well with the experimental results, but it still needs further testing with different experimental parameters such as humidity, air temperature, water droplet diameter and water temperature. Besides, the mechanism of the phase change from supercooled water to ice needs more research work. Also, more attention should be paid to the sustainability and reliability of the new ice slurry production method.

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溶液除湿辅助的蒸发过冷式流态冰制取方法

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摘要：针对目前过冷水制取流态冰的方法常会碰到冰堵并且极度依赖电能的问题，提出了一种新的流态冰制取方法. 新方法主要包括 2 个部分：蒸发式过冷过程和溶液除湿过程. 对蒸发式过冷过程进行了理论研究，通过影响因子的引入改进了经典的扩散–控制模型；同时，对蒸发式过冷过程进行了实验研究，用粒子分析仪测量水滴的粒径与速度，用红外热像仪测量蒸发过冷过程的温度场. 研究结果表明：改进的理论模型所得出的结果与实验结果吻合得很好. 另外，通过与传统过冷水制取流态冰方法的比较发现，新方法可以回收利用自身排出的废热，降低了对电能的依赖，提高了制流态冰的效率，从而使系统的整体性能得到改善.

关键词：流态冰；溶液除湿；蒸发

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