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Investigation on temperature distribution of flash evaporation of LiCl droplets released into vacuum

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ABSTRACT

A new method of regenerating dehumidification solution is developed, which releases the dilute solution into vacuum to improve water evaporation instead of the traditional methods. Experiments on the temperature distribution in the lithium chloride solution droplets were carried out on the basis of the theoretical analysis. The experimental results indicate that both the surface temperature and center temperature declined sharply in the beginning stage of flash evaporation, then recover slowly, even though sometimes one is higher than the other in the whole process; pressure is the core factor of evaporation rate, the lower the pressure, the more intense flash; droplets with higher initial temperature only strengthen the intensity of the flash evaporation at the beginning. Radiant heat can significantly promote the strength of the flash evaporation which cannot be neglected especially for single droplet. The contrast between the experimental results and the numerical results prove that droplet flash evaporation model can be applied to the process without radiation, and the numerical results should be amended when used on the radiation condition.

1. Introduction

Liquid desiccant air conditioning, derived by waste heat, solar energy, etc., has seen rapid development in recent years, which is necessary because of the worldwide energy crisis. The regenerator is one of the core pieces of equipment for recycling the solution in a dehumidification system, whose heat and mass transfer performance is directly related to the dehumidification capacity of the entire system and running security. Improving the regeneration performance is one of the priorities of the current study.

Adiabatic regenerators, which have relatively higher efficiencies, have been focused on for many years. Elsarrag and Abdalla [1] tested a packed regenerator using random polypropylene and structured pickings. Experiments showed that the evaporation rate was 130–300% greater in the randomly packed bed than the structured packing bed. Jain et al. [2]. conducted experimental and theoretical studies of regeneration of aqueous lithium bromide solution in a falling film plate regenerator suitable for a desiccant augmented cooling system. In this study, the heating of the desiccant solution was achieved by circulating oil heated in a tank by immersion heaters. Oberg and Goswami [3] developed two new types of liquid desiccant systems in 1998. Compared with experimental results, the predicted value errors are within 15%; Yin and Zhang [4], in 2010, proposed a regenerator which was middle heated. Test results showed that the heat, offered in the process of regeneration, not only improved the mass transfer efficiency, but also improved the heat transfer efficiency.

Research mentioned above, and some other published papers [5,6] on regeneration, were all carried out under atmospheric pressure. By taking different measurements, efficiencies of heat and mass transfer have been improved to a certain extent. Here an alternative approach is introduced to regenerate dilute solution

vacuum flash evaporation, which is completely different from the previous approach. When the condition is suddenly changed to a very lower pressure, the water at the surface of a droplet of dilute solution, at approximately 90 °C, reaches a state of overheating, then dramatically evaporates. The vacuum pressure gradually increases with continuous evaporation, and then the cooling water, at 32 °C, is used to cool the moisture through the cooling coil. Thus water is separated from the solution. The vacuum pump is only used to reduce the initial pressure in the first step of the whole

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Nomenclature

a	radius of the model (m)
C	specific heat capacity (J/kg K)
D	diffusion rate (m^2/s)
h	latent heat (J/kg)
p	pressure (Pa)
M	molar mass of water vapor (g/mol)
$\dot{m}$	mass change rate of droplet (kg/s)
q	heat transfer (W)
R	universal gas constant, 8.31451J/(mol K)
T	steam temperature (K)
ρ	vapor density around droplets (kgm^{-3})
ρ_p	droplet density (kg/m^3)
λ	thermal conductivity of water vapor (W/(m K))

Subscripts

p	constant pressure
L	liquid
V	vapor of water
w	water
s	surface of droplet
a	$r = a$
∞	$r = \infty$

process. The driving force of the flash regeneration is the temperature difference between the solution and the cooling water.

Flashing characteristics of the droplets play a very important role in the entire evaporation process. Some research findings have been published in other research fields, such as desalination of sea water, biological pharmacy, etc. Some of their results concerning droplet evaporation, which can be refer to the research in this paper, are as follows.

Shepherd and Sturtevant [7] and Avedisian [8] indicated that by suspending a droplet in the immiscible fluid, the image of the internal boiling process can be seen entirely and clearly with a wide range of superheated temperatures. Owen and Jali [9] observed the shape changes of droplets hanging in the thermocouple with the absolute pressure of approximately 850 Pa, and presented the basic characteristics in the different phases of the process. Yang and Wong [10] have studied the effects of heat conduction into the droplets through the fiber and the liquid-phase absorption of the radiation from the furnace wall on the evaporation rate of droplets at micro-gravity condition. They found that without considering these effects, there is a large discrepancy between their theoretical results and the experimental data of Nomura et al. Liu et al. [11] experimentally investigated the flash evaporation process of salt-water droplets released into vacuum, and found that component and solution concentration has great influence on the evaporation process. Zhang et al. [12] studied different flash speed in experiments by adding orifice plate with different orifice diameters between flash and vacuum chamber. The results suggested that shrinking orifice diameter from 80 to 5 mm can reduce flash speed for about one or two orders of magnitudes.

Simultaneously, various theoretical models were proposed to predict the values of evaporation. For example, Shin et al. [13] obtained the characteristics of the changes from the droplets to the ice by using the diffusion-controlled evaporation model. Isao et al. [14] developed a theoretical model which can predict the variation in droplet temperature when the pressure is suddenly dropped.

Some results of the above research can be adopted in the present study on single solution droplet evaporation. The objectives of this paper are: to achieve the temperature distribution variation both in the center and at the surface of a static solution droplet; to discuss the factors that have influence on the flash intensity and temperature change; and to analyze the differences between the calculated values and the experimental values. The results will lay the foundation for further study of the mechanism of spray vacuum flash.

2. Mathematical model and its adaptability

2.1. physical considerations

To reduce the complexity and highlight the basic characteristics of the solution droplet flash evaporation, assumptions are made to simplify the analysis based on the quasi-equilibrium theory:

(1) A droplet remains spherical in the flash process.
(2) The droplet is considered to have a uniform temperature, ignoring the internal thermal resistance.
(3) The air and water vapor are considered ideal gases.
(4) Evaporation occurs only on the outer surface.
(5) Pressure and temperature in the flash chamber are kept constant.
(6) Radiation heat transfer between chamber wall and droplets is neglected.

2.2. Governing equations

Fig. 1 shows the schematic of the liquid flash model, where a is the droplet radius, ranging from 0 to ∞; ρ is the vapor density around droplet; D_v is the diffusion rate of water vapor. The inner solid line represents the boundary of the droplet, and the outer dashed line is the virtual boundary of the model.

There are two main factors that cause the temperature changes in solution droplet when its volume is small enough and the surrounding space is infinite. One is the latent heat due to the vaporization of the liquid droplet itself, and the other is heat transfer between the droplet surface and the environment, which is caused by the temperature difference between them.

According to our assumptions, when the droplet diameter is smaller enough, the natural convection and heat transfer resistance in the droplets are ignored, and the droplet is considered as a whole, the heat transfer occurs only in the surface. In this case, the heat and mass transfer equations can be established as follows.

When the droplet temperature is lower than the ambient temperature, the heat absorption (q') from the environment can be expressed in the following equation.

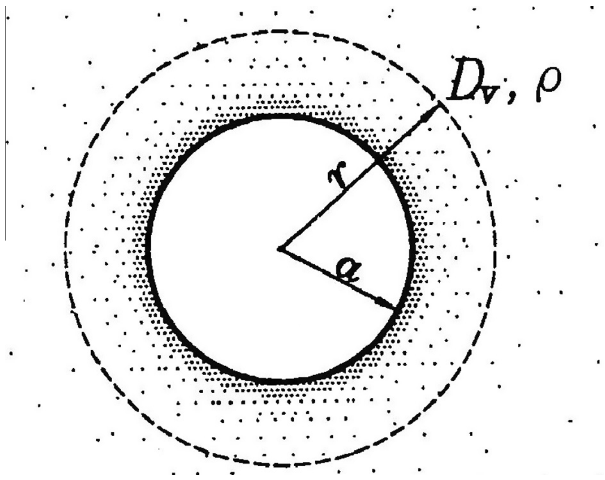

Fig. 1. Liquid flash evaporation model.