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Experimental study on temperature variation patterns and deterioration of spray cooling with R21

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ABSTRACT

The transient heat transfer performance of spray cooling with R21 is studied experimentally. Three variation patterns of surface temperature depending on the initial surface temperature are observed. There is only one rapid temperature drop at lower initial surface temperature and two drops with a shoulder transition at higher initial surface temperature. Further increasing the initial surface temperature will deteriorate heat transfer. Based on the pool boiling heat transfer curve and one-dimensional transient heat conduction model, the temperature variation patterns and processes are discussed which relate to nucleate boiling, transition boiling and film boiling, respectively. The experimental results reveal that the deterioration temperature decreases with increase of the heating flux and nozzle-to-heater distance, while increases with the spray flow rate. Based on the experimental results a region map of temperature variation patterns in transient spray cooling is given.

1. Introduction

With the development of increasing integration density and reducing size of electronic devices, heat dissipation requirement may exceed the ability of traditional air cooling techniques [1]. Many cooling techniques were proposed and investigated, such as single phase micro-channel [2–4], flow boiling [5–7] and jet impingement cooling [8,9]. Spray cooling is one of the high-efficiency heat dissipation techniques [10–12]. It attracts researchers' attention because it has much better heat transfer performance than pool boiling [13]. Due to its high heat dissipating capability, spray cooling may have a great application potential in cooling electronic devices [10,14].

Spray cooling can be divided into two heat transfer regions according to whether or not phase change occurs, i.e., single-phase convection and boiling heat transfer [10]. It is a complicated process with lots of influential factors, including spray flow rate, spray distance of nozzle-to-heater, spray angle, droplet diameter, surface temperature, orientation of heater surface, electric force, etc. [15–23].

Estes and Mudawar [24] investigated the influence of spray volumetric flux and subcooling on spray cooling and the results showed that the critical heat flux (CHF) increased with the spray volumetric flux and subcooling. Chen et al. [19] found that the droplet velocity had the largest effect on CHF, followed by droplet flux. The influence of the Sauter mean diameter was negligible. The CHF they obtained with water using nozzle Bete#3 was 945.7 W/cm^2. Lin and Ponnapan [25] investigated the spray cooling performance of FC-72, FC-87, methanol and water. The critical heat fluxes were 83.5 W/cm^2, 90 W/cm^2, 490 W/cm^2 and above 500 W/cm^2, respectively. Abbasi and Kim [26] found that the CHF depended primarily on the local normal pressure and subcooling.

Experimental study on spray cooling with micro-structured silicon surfaces (characteristic size: 25–200 μm) by Zhang et al. [27] revealed that micro-structured surfaces had better heat transfer performance than smooth surface in the thin film and partial dry out regions, but no superiority in flooded region. Yang et al. [28] obtained the maximum heat flux of 451 W/cm^2 using ammonia as coolant with microcavity surfaces.

Rini et al. [13] used a high-speed camera to determine the bubble density in spray cooling with FC-72. The results showed that the nucleation sites density was 3500/cm^2 for spray cooling with heat flux of 60 W/cm^2, while the density was 900/cm^2 for pool boiling with heat flux of 10 W/cm^2 at similar surface temperature. Sodtke et al. [29] examined the relationship between the three phase contact line and heat flux. The results showed that the heat flux and contact line length had a significant positive correlation. Horacek et al. [30] also found that the heat flux correlated well with contact line length.

Zhao et al. proposed a theoretical model to simulate heat and mass transfer in spray cooling [31]. The deviation with experimental results was below 10%. Xie et al. also developed a theoretical

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model to predict the film thickness and heat transfer performance, which showed good agreement with the experimental data [32].

Mohapatra et al. [33] studied spray cooling with high initial surface temperature but they didn't investigate the influence of initial surface temperature. Bhatt et al. [34] conducted spray cooling experiment that investigated the role of water temperature at different initial surface temperatures. The initial surface temperatures at 300 °C, 500 °C and 800 °C were used. The results showed that the initial heat flux was higher at 800 °C than that at 300 °C and 500 °C. Milke et al. [35] investigated the effect of dissolved gases on spray cooling at different initial surface temperature. They found that for low ratio of the temperature change to a reference temperature the dissolved gases enhance the cooling process by reducing the incoming radiant input.

Most of the studies on spray cooling were concerned with the influences of spray flow rate, nozzle-to-surface distance and heat flux, etc., but no report about the influence of initial surface temperature of the heater on the variation pattern of surface temperature was noticed by the authors.

In the present work, the dependence of the variation patterns of heater surface temperature on its initial temperature is investigated with R21 as coolant. The mechanisms of temperature variation patterns and deterioration are discussed. The influences of heating flux, spray flow rate and nozzle-to-heater distance on heat transfer deterioration are investigated. Furthermore, a region map of temperature variation patterns in transient spray cooling is proposed, which could help the design of spray cooling. The influences of spray flow rate, nozzle-to-heater distance on heat flux in quasi-steady state are also studied.

2. Experimental setup and procedure

2.1. Experimental setup

The spray cooling system setup is shown in Fig. 1. The coolant, R21, is pumped out from the reservoir tank by a magnetically driven gear pump. A bucket filled with ice-water mixture is used to subcool the coolant to prevent vaporization in the pump. The coolant temperature at the inlet of the nozzle (Spraying Systems, TG SS 0.3) is measured by a sheathed T-type thermocouple. The orifice of the nozzle is 0.51 mm. An electric heater and a temperature controller are used to control the coolant temperature. A pressure transmitter is used to measure the nozzle inlet pressure. The temperature and pressure signals are acquired by using NI 9203 and 9205 acquisition cards.

The absolute pressure of the spray chamber is 1 atm and the ambient temperature is about 20.0 °C. The properties of R21 under 100 kPa are shown in Table 1.

Fig. 2 shows the heating component structure that consists of copper block, cartridge heaters, and thermal insulation material. The heat conduction block is made of a cylindrical copper with thermal conductivity of 396 ± 5 W/(m·K) according to Ref. [36]. The diameter of the heater surface is 15.0 mm. Five cartridge heaters, each with a resistance of 220 Ω, are inserted into the block. The block is well insulated by perlite. Three layers of T-type thermocouples are arranged at Sections B, C and D, as shown in Fig. 2. The spacing between adjacent sections is 10.0 mm and the spacing between Surface A and Section B is 5.0 mm. Three thermocouples with different distance (0.0 mm, 2.0 mm, and 4.0 mm) to the block center are inserted into each section and the angle between each thermocouple is 120°. Since the thermal conductivity of copper is much higher than the perlite, the radial heat conduction can be ignored and the axial heat conduction is considered as one-dimensional Fourier conduction.

2.2. Experimental procedure

Before spray, the heater surface is heated to a certain temperature at constant heating power. The typical variation curve of surface temperature is shown in Fig. 3, where the coolant spray flow rate is 13.7 L/h, the nozzle-to-heater distance is 6.0 mm and the coolant temperature is 21.9 °C. The temperature rises continuously before the spray starts. Once the spray starts, the surface temperature drops rapidly to a quasi-steady state. It will take a long time to reach a steady state. Analysis indicates that the heat flux difference between the quasi-steady state and the steady state is less than 1.6% in our experiment. To save time and coolant, the quasi-steady state is used to calculate the heat flux.

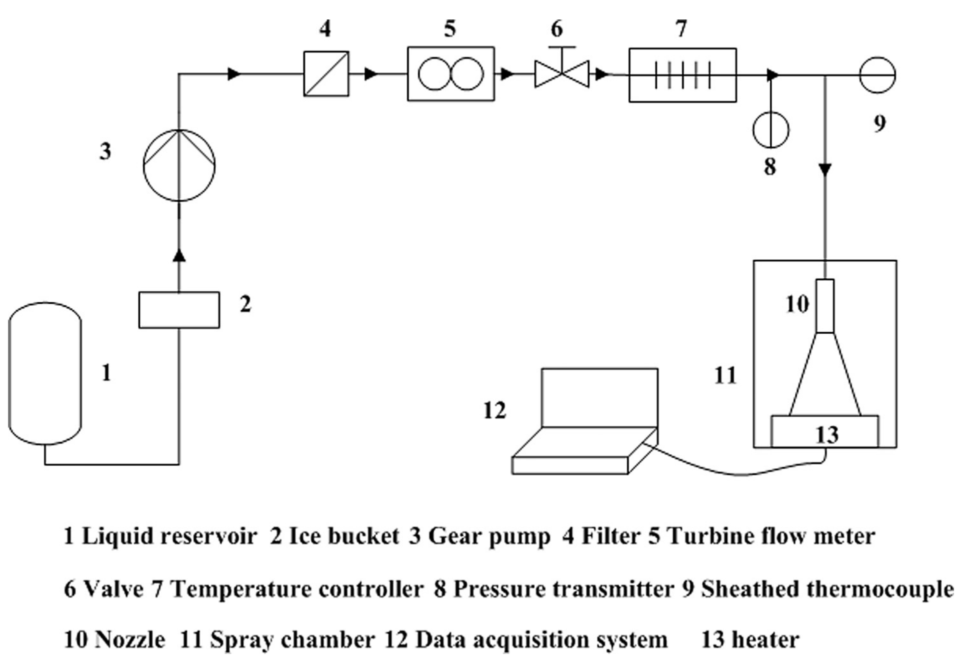

Fig. 1. The spray cooling system.