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Experimental Investigation to Boiling Heat Transfer on a Heated Surface with Multiple Impinging Jets

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Abstract. On the condition of water multiple jet impingements, a steady-state experimental study had been conducted for boiling heat transfer in an atmospheric pressure. The jet velocity was 0.95~1.59m/s and the sub-cooling degrees of jet fluid were 30~83℃.The results revealed that increasing either jet velocity or sub-cooling degrees would promote the heat flux through heated surface, and the effect was more pronounced in partial boiling regime than fully-developed boiling regime. The heat transfer with multiple jets is enhanced due to disturbance of different impingements. With modification of the factor which related to flow distance of fluid on heated surface, correlation which is applicable to one single impinging jet boiling, can also be used to calculate critical heat flux(CHF) in boiling heat transfer with multiple impinging jets.

Introduction

As a new, highly efficient cooling method ,the liquid jets boiling cooling has been widely used in the steel industry, nuclear industry, aerospace industry, microelectronic device production process, and the thermal control process. However, because the surface with high temperature most covered by a layer of stream, it has much more difficult to strengthen boiling heat transfer on hot surface. Jet fluid with sub- cooled is able to break through the stream layer and get to the heated surface. It will highly increase the heat flux through heat wall in transition boiling zone, enlarge transition boiling zone, and make boiling curve more flat in this zone. Currently, researches of boiling heat transfer with one single jet extensively carry out. Among the papers about jet velocity effects on boiling heat transfer, Katsuta[1] and Wolf[2] reported jet velocity has little effect on fully developed jet nucleate boiling with saturated water on free surface. The work of Qiu Yuhao[3] indicated that to reach the same heat flux, higher jet velocity conduced higher temperature on heated surface. Zhao Yaohua[4] prepared an experiment on transient boiling heat transfer, and concluded that cooling efficiency increased with the jet velocity. For the effect of sub-cooling to boiling heat transfer, most researches obtained the same result, sub-cooling had little effect on critical heat flux (CHF).

Satish [5] pointed out that cooling effect with one single jet was not balanced, it was impossible to achieve uniform cooling; the entire heated surface would appear large temperature gradient and boiling mode changed from upstream to downstream. Therefore, cooling with multiple jets impingement is necessary. An experimental study of boiling heat transfer with multiple jets was conducted in this paper, liquid of jets blended on heated plane, make heat transfer on heated surface even and intense. On the basis of the empirical correlation for one single jet boiling, summarized correlation for multiple jets boiling heat transfer.

1. Experimental Apparatus and Method

1.1. Experimental Apparatus. Fig.1 shows the experimental apparatus. Cooling fluid flow from the reservoir, pass through centrifuge pump, pulsation damper, filter, mass flow control valve and flow meter, get into work tank and ejected from the pinholes on the tank, the fluid jets strike surface of copper block. The distance between the pinholes and the heated copper surface is fixed on 5cm.

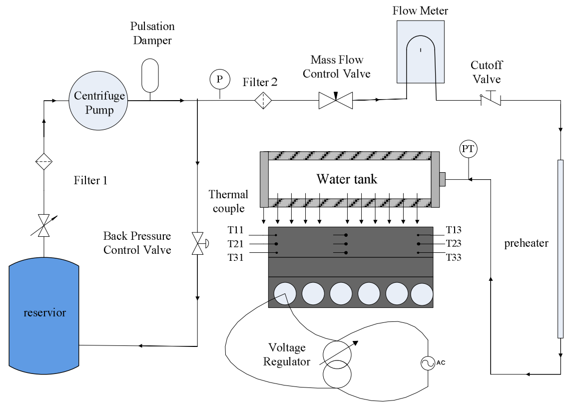

Fig.1 Schematic of the experimental apparatus

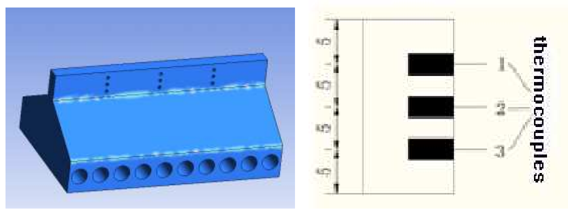

Fig.2 Copper block and thermocouples

The heated body is a cast industrial copper block, which has similar thermal conductivity with pure copper. The block upper part size-reduced, and the top surface is a horizontal narrow smooth plane for the heat transfer. Nine thermocouples were installed in the upper part of copper, three ones in a horizontal plane, and three ones in a vertical plane, as shown in Fig.2.

The work tank is made of stainless steel tube, the shape of cavity in tube is a cylinder of 30mm, there are 25 pinholes on the wall of tank, and diameters of pinholes are uniform 0.4mm. The locations which jets striking on heated surface are shown in Fig.3. On the condition of steady-state experiment, fluid ejected from the tank is much less than the fluid in the tank, so velocities of jets are almost uniform.

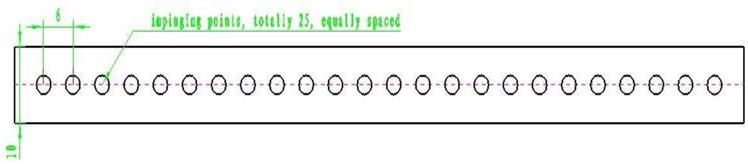

Fig.3 Impinging points on heated surface

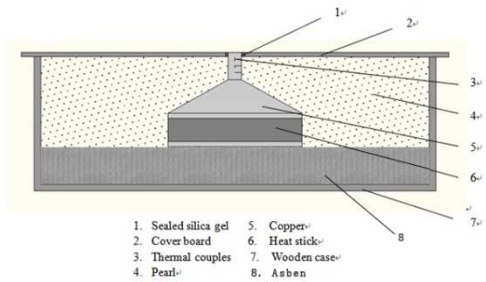

Fig.4 Schematic diagram of copper block set in box

1.2 Experimental Method. This experiment conducted at atmospheric pressure, selected distilled water as cooling fluid. In the lower part of copper part, there were 10 electric heat sticks, total heating power was 6KW. To make sure the top plane was the only surface with heat transfer, the copper block was placed in a wooden box, there was sheet made of insulating material (Aspen) under the bottom of copper block, pellets of perlite filled the space around copper block. Top of the box was covered by a flat plane with a rectangle-shaped hole in the middle. The hole was just fit for top surface of copper block, gap between them was filled by high-temperature-setting glue. The interior structure of box is shown in Fig.4.

Katsuta[1] proved that if three thermocouples which in a horizontal plane measured the same temperature, the cubical copper block was in one-dimensional heat conduction condition. In these experiments, the temperature values measured by thermocouples in one horizontal plane were always approximate. Therefore, we measured the difference between temperature values of thermocouples in different horizontal planes, to obtain the temperature on the top surface and heat flux through the surface. In order to reduce measurement errors, we chose two thermocouples relatively far apart to calculate.

2. Experimental Result and Discussion

Experiments about boiling heat transfer with multiple jets carried out, studied the velocity and sub-cooling effect on boiling curve and critical heat flux. Choose the saturation temperature of drilled water at atmospheric pressure as reference temperature, sub-cooling degrees of fluid and excess temperature of heated surface were the difference between measured temperatures and reference temperature.

2.1 Jet Velocity effect on nucleate boiling heat transfer. In the experiments which studied the effect of jet velocity, sub-cooling degree was fixed at 83℃ . In Fig.5, nucleate boiling curves are plotted with heat flux through heated surface as ordinate against excess temperature ΔT_{SAT} as abscissa, the velocity of jet was 0.95~1.59m/s.

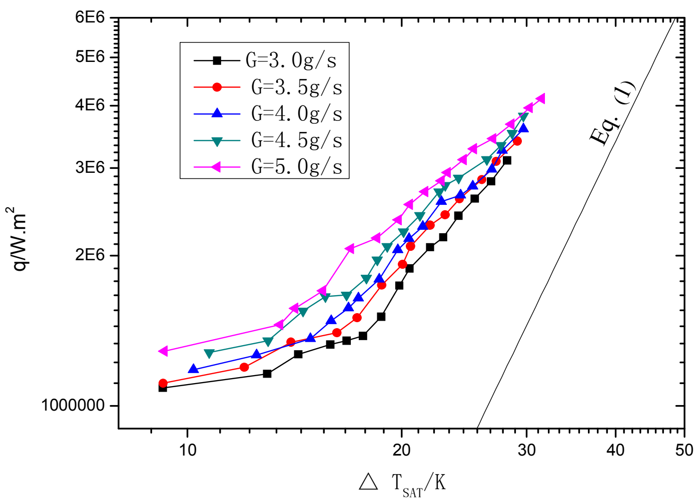

Fig 5 Boiling heat transfer curves with different jet velocity

The results reveal that jet velocity has great effect on boiling heat transfer in nucleate boiling zone, as the jet velocity increase, the boiling curve overall ascend. The curve can be divided into two areas: partially developed nucleate boiling, fully developed nucleate boiling. When the excess temperature below 20K, bubbles grow on the surface of heat transfer are isolated from each other, few mutual interference between them, it is partially developed nucleate boiling. When the excess temperature greater 20K, there are more and more bubbles grow on the surface, intensive bubbles mix with each other, and enhance the heat transfer of heated surface, it is fully developed nucleate boiling.

Heat flux increase with jet velocity, nucleate boiling heat transfer could be enhanced by increasing jet velocity. The experimental result is in line with the Qiu Yuhao[3] conclusion. In Fig.5, compare the result with Eq.1. The correlation was obtained by Wolf[2] in fully developed nucleate boiling regime with one jet.

$$q = 63.7 \Delta T_{SAT}^{2.95} \tag{1}$$

Fig.5 shows when the heated surfaces have the same excess temperature, heat flux on the surface cooled by multiple jets is much higher than the one cooled by one jet. And heat flux still effect by the jet velocity in the fully developed nucleate boiling regime. According to the mechanism of nucleate boiling, higher jet velocity can disturb the bubbles on the heated surface much more pronounced, accelerate bubbles leaving heated surface, and increase heat transfer coefficient. Mutual interference between jets also accelerates bubbles leaving, and enhances heat transfer further.

2.2 Sub-cooling degrees effect on nucleate boiling heat transfer. In the experiments which studied the effect of sub-cooling, jet velocity was fixed at 1.27m/s. In Fig.6, nucleate boiling curves are plotted with heat flux through heated surface as ordinate against sub-cooling as abscissa.

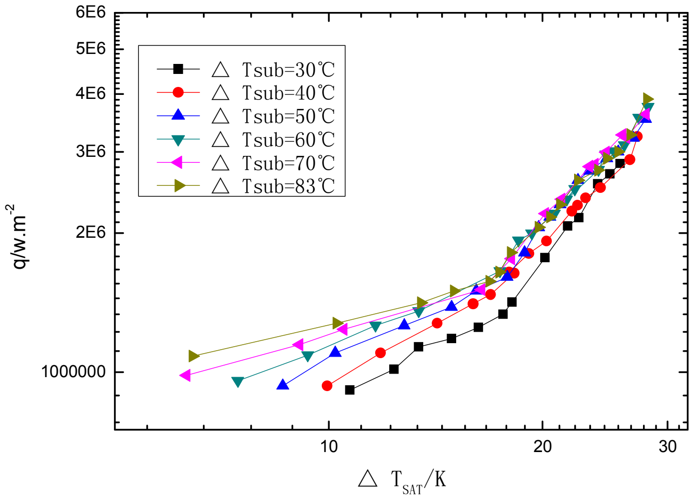

Fig.6 Boiling heat transfer curves with different sub-cooling degree

Sub-cooling has greater effect on the boiling heat transfer in the partially developed regime. At the same excess temperature, higher sub-cooling degrees correspond to greater heat flux. In fully developed nucleate boiling regime, sub-cooling of fluid almost do not have effect on boiling curve, the result is in line with the result obtained through boiling heat transfer experiment[7] with single jet.

According to the result, interference between jets and sub-cooling of the fluid are two independent factors for boiling heat transfer. When heated surface is at low excess temperature, impinging high sub-cooling fluid can pronounced decrease the temperature of fluid on heated surface and accelerate bubbles leaving heated surface; When heated surface is at high excess temperature, impinging high sub-cooling fluid cannot decrease the temperature of fluid on heated surface, so it do not has great effect on heat transfer. Sub-cooling effect on boiling heat transfer with multiple jets can refer to the effect with one single jet.

3. Fitting Critical Heat Flux Empirical Correlation

When the excess temperature of heated surface is greater than a certain value, heat flux decrease as the excess temperature increase, nucleate boiling change to film boiling, the peak value q_{MAX} of heat flux define as critical heat flux (CHF). In all of the correlations of CHF, the correlation Monde[6] summarized is the most universal one, form is as follows:

$$\frac{q_{MAX}}{\rho_g H_{fg} V_n} = 0.221\left(\frac{\rho_f}{\rho_g}\right)^{0.645}\left[\frac{2\sigma}{\rho_f V_n^2 (2r-d)}\right]^{0.343}\left(1+\frac{2r}{d}\right)^{-0.364} \tag{2}$$

Of which, σ is the gas-liquid surface tension; ρ_f and ρ_g are vapor and liquid density respectively; H_{fg} is latent heat of evaporation; V_n is jet velocity; r is maximum distance of cooling fluid flowing on the heated surface; d is the diameter of pinhole. On the basis of Eq.2, Nonn[7] obtain the empirical correlation which is applicable for boiling heat transfer with sub-cooled fluid:

$$\frac{q_{MAX,SUB}}{q_{MAX,SAT}} = 1 + 0.952\left(\frac{\rho_f}{\rho_g}\right)^{0.18}\frac{C_p \Delta T_{SUB}}{H_{fg}} \tag{3}$$

Of which, C_p is specific heat capacity of fluid. Summarized Eq.2 and Eq.3:

$$q_{MAX,SUB} = C_1 V_n^{0.314} f(r)(1 + C_2 \Delta T_{SUB}^{1.414}) \tag{4}$$

Of which $f(r)=\frac{(1+2r/d)^{-0.364}}{(2r-d)^{0.343}}$, $C_1=0.2803\rho_f^{0.302}\rho_g^{0.355}H_{fg}\sigma^{0.343}$, $C_2=0.952\frac{(\rho_f/\rho_g)^{0.118}C_p^{1.414}}{H_{fg}^{1.414}}$

All physical parameters are integrated into C_1 and C_2, there is only f(r) has relevance to the size of boiling regime on heated surface in Eq.4, define as dimension factor. Make Eq.4 applicable to boiling transfer with multiple jets through modifying dimension factor. In Eq.4, C_2 represent the effect of sub-cooling, according to the property of cooling fluid in this experiment $C_2=0.000317$, so sub-cooling has little effect on the critical heat flux.

In Fig.7, make f(r) =62.3, compare experimental results with Eq.4, curves are plotted with heat flux through heated surface as ordinate against sub-cooling temperature ΔT_{SAT} as abscissa.

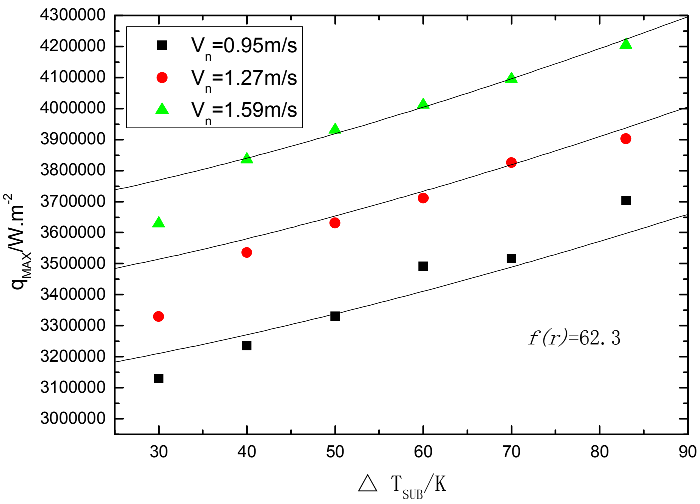

Fig.7 Experimental Data of Critical Heat Flux Compared with Eq.4

Monde[8] proved by experiments, for boiling heat transfer with multiple jets but there was regime cooling fluid did not blend, Eq.4 was still applicable. In Fig.7, in different jet velocities, experiment results and Eq.4 correspond very well. So, if modify f(r) properly, Eq.4 is applicable to the boiling heat transfer with multiple interference jets.

For the boiling heat transfer with multiple jets, interference of jets has great effect on heat transfer. So, the modification of f(r) must contain items associated with distance of pinholes, specific forms of these items need for further experiments.

3. Conclusions

From experiments of jet velocity from 0.95 m/s to 1.59 m/s, sub-cooling degrees from 30℃ to 83℃, obtained conclusions:

1) Jet velocity has great effect on nucleate boiling heat transfer, nucleate boiling curves overall ascend. Compared with boiling with one jet, at the same excess temperature, heat flux with multiple jets is much higher, and CHF is much higher too.
2) Sub-cooling degree has effect on partially developed nucleate boiling, heat flux increase as sub-cooling degree of fluid, but in the regime of fully developed nucleate boiling, sub-cooling degree has little effect on it. The results are consistent with conclusions obtained from one jet impinging boiling experiment.
3) Modify the dimension factor *f(r)* in correlation of calculating CHF with a jet; it could be applied to boiling heat transfer with multiple jets.

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