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On the size of the boiling region in jet impingement quenching

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ABSTRACT

Experimental investigations of jet impingement quenching for three different cylindrical blocks made of copper, brass and steel have been conducted with block initial temperature from 250 to 600 °C. Visible observations during the quench show that the wetted area can be divided into two regions – a central region with no apparent boiling and the outer annular region where the liquid boils vigorously. The width of the boiling region is of interest since there is a coupling between high heat transfer rates and the observed boiling pattern. Boiling width increases with material conductivity and decreases with jet subcooling and velocity. Boiling width is also influenced by the initial temperature of the solid.

1. Introduction

Quenching by jet impingement is one of the most effective cooling processes used in industry. It has important applications in metallurgy and emergency cooling systems for nuclear reactors. The quenching phenomenon itself progresses in a number of stages [1–3]. Shortly after the jet first impinges on the surface, a small wetted patch appears which may not change in size for a considerable period of time. Then suddenly the wetted area starts to enlarge until the entire surface becomes covered with liquid. Previously the authors of this paper developed an empirical correlation for the resident time [1], which is defined as the time from when the jet first impinged on the surface to when the wetted patch began to grow quickly. Based on Monde et al.'s relation for critical heat flux [4], Mozumder et al. [2] also developed a relation for the maximum heat flux during jet impingement quenching. Concerning the propagation velocity of the maximum heat flux point during growth of the wetted region, Mozumder et al. [3] considered the effects of liquid subcooling, jet velocity, initial solid temperature and solid material.

These studies have contributed towards our understanding of quenching with the view to developing models for jet impingement quenching. The present study provides a continuation on this theme but with the focus being on the size of the boiling region within the wetted area. The size of the boiling region is important because the heat flux tends to be higher in this region and we should expect a strong coupling between the surface temperatures, heat flux and boiling phenomena occurring on the surface. Another important consideration is that the accuracy of the method used to measure the maximum heat flux in the previous studies [1,2] may diminish if the boiling region becomes too narrow due to space resolution issues with the inverse solution [5]. The present paper offers insight into why for some conditions the data reported in [1,2] and showed considerable scatter.

Investigation of jet impingement quenching also has been performed by a number of other researchers and scientists [6–12]. Filipovic et al. [10] conducted transient boiling experiments using a large, preheated test specimen exposed to a water wall jet on its top surface. They observed a 'bell' shaped transition boiling zone of several centimeters long at the leading area of the moving quench front. Their study reported that the location of maximum heat flux was coincident with the leading edge of this bell shaped zone. They found that the width of the bell shaped zone elongated as the rear end of the boiling surface was approached. According to their study, that behavior was due to a decrease in the downstream surface temperature caused by film boiling heat transfer in the precursory zone downstream of the moving front. They described the width of the bell shaped zone as the gap which is physically bounded by temperatures corresponding to the critical heat flux, T_{CHF} and rewetting temperature, T_R. They reported that with increasing time during quenching, the temperature gradient decreases and the width of the 'bell' shaped transition boiling region increases. Upstream of the critical heat flux (CHF) location, nucleate boiling occurs, and in regions where the surface temperature is lower than the saturation temperature, conditions are characterized by single-phase forced convection.

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Nomenclature

dT_w/dr	surface radial temperature gradient (°C/mm)	T_b	initial block temperature (°C)
q_w	surface heat flux (MW/m^2)	T_w	surface temperature (°C)
r_s	radial position at which boiling appears to stop (mm)	ΔT_{sub}	liquid subcooling (K)
t	time (counted from the impingement of jet) (s)	u	jet velocity (m/s)
t^*	resident time at which wetting front starts moving (s)	W	width of the boiling region (mm)

Definitions for the surface rewetting have been given by some researchers. Dua and Tien [11] performed experimental study for rewetting of a copper tube by a falling film of liquid nitrogen. According to their definition, surface rewetting refers to the establishing of liquid contact with a solid surface whose initial temperature is higher than the sputtering temperature, the temperature up to which a surface may wet. They observed that the rewetting temperature at the wet front corresponds to neither of the two temperatures at which the maximum (or critical) or the minimum heat fluxes of the pool boiling exist. The rewetting temperature instead lies in the region of transition boiling which is indicative of the state of boiling at the location of the wet front.

Lienhard et al. [12] investigated splattering and heat transfer for un-submerged, circular, fully turbulent impinging liquid jets. They observed that splattering occurs within a narrow radial band, rather than being distributed at all radii in the liquid sheet. The region where vigorous boiling occurs is the most effective cooling zone among the entire heat transfer area on the hot surface. With the movement of the wetting front (i.e. the visible leading edge of the moving liquid over the surface), this most effective cooling zone also moves to the circumference region. The main objectives of this paper are to investigate the characteristics of the visible width for the vigorous boiling region and the temperature distribution of this region. The dominating parameters for the expansion of the boiling region such as jet velocity, jet subcooling, solid initial temperature and solid material properties are also explored.

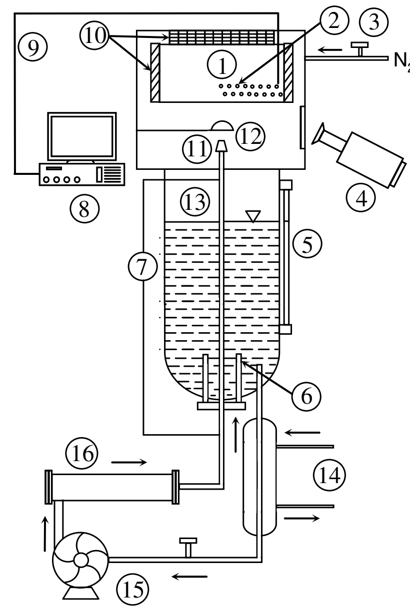

Fig. 1. Schematic diagram of the experimental set-up. 1 – tested block, 2 – thermocouple positions, 3 – nitrogen gas valve, 4 – high-speed video camera, 5 – level gauge, 6 – main heater, 7 – dynamic strain meter (for measuring jet velocity), 8 – data acquisition system, 9 – thermocouple wire, 10 – block heaters, 11 – nozzle, 12 – rotary shutter, 13 – liquid tank, 14 – cooler, 15 – pump, and 16 – auxiliary heater.

2. Experiment

2.1. Experimental set-up

The desired temperature for the liquid is first obtained by heating with electric heaters (6 and 16) as shown in Fig. 1 or by cooling with a cooler (14). The test section (1) is heated with three electric heaters (10) mounted on the top and around the block. The test section is of cylindrical shape with 94 mm diameter and 59 mm height. Sixteen thermocouples (0.1 mm wire diameter and 1 mm sheath diameter of CA type) have been inserted at two different depths (eight at each depth), 1.9 mm and 5 mm from the surface of the block. For protecting the test surface from oxidation, it was plated with a thin gold layer of 5 μm thickness, which has a good oxidation resistance and thermal conductivity of 317 W/mK. The surface roughness is 5–18 μm. Nitrogen gas is charged on the test surface during the experiment to maintain an inert atmosphere for minimizing the oxidation effect of the surface at elevated temperatures. When all the desired conditions of the experiment are obtained, the liquid is allowed to impinge on the test surface through a 2 mm diameter nozzle (11) which is centrally located 44 mm from the test surface. Jet velocity is estimated from differential pressure measured by a strain meter (7) which is attached at two points on the flow line before the nozzle. All the experiments are conducted at atmospheric pressure. A high-speed video camera (4) with a maximum resolution of 1280 × 1024 pixels and a maximum rate of 10,000 frames/s was employed for capturing the visual phenomena on the test surface during quenching. The estimated time lag of the thermocouple response is less than 0.1 s. The thermocouples' signals are scanned by a data acquisition system (8) sequentially at 0.05 s intervals. The uncertainty for the placement of the thermocouples is estimated to be ±0.1 mm and the uncertainty for the measurement of temperature is ±0.1 °C. At the beginning of the experiment, the liquid temperature was controlled within ±1 °C and for some conditions where the duration of the experiment was long it was sometimes noticed ±2 °C variation from the initial temperature. The uncertainty of the jet velocity was ±0.1 m/s. The block initial temperature was maintained ±2 °C from the desired value. A detailed description of the experimental apparatus is given elsewhere [13].

2.2. Data analysis

The purpose of inserting thermocouples is to estimate the surface temperature and heat flux. However, it is very difficult to measure directly the surface thermal parameters by thermocouples. The thermocouples are inserted beneath the test surface and they are used to estimate the surface temperature and heat flux with the help of an inverse solution to the heat conduction problem. The inverse solution was adopted from Monde et al. [14] and Woodfield et al. [5]. The detailed mathematical derivation of the inverse solution and its estimation accuracy are described in these references.

3. Results and discussion

3.1. Effect of radial position on boiling width

Fig. 2 represents the variation of the width of the boiling region with radial position for three different times (713.5 s, 717.1 s and 720.8 s from when the jet first impinged on the surface). Radial temperature and heat flux distribution are also shown in this figure. For each of the cases, the wetted area can be divided into two regions – a shiny region near the center and a dark region of vigorous boiling. Quite clearly the width of the boiling region increases in size as the wetting front progresses towards the circumference of the test piece. A similar observation was made by Hammad et al. [13].

It is interesting to notice the relationship between the surface temperature and the size of the boiling zone in each of the cases in Fig. 2. A general observation is that a steeper maximum radial temperature gradient corresponds to a narrower boiling region. For example, for the case where $r_s = 8.5$ mm, the maximum temperature gradient is 8.4 °C/mm and the boiling width is 21.7 mm. In the second frame where $r_s = 11.6$ mm, the maximum temperature gradient has decreased to 5.5 °C/mm and the boiling width has increased to 15.7 mm. This inverse relationship is depicted graphically at the bottom of the figure. A similar general qualitative correspondence between the radial temperature gradient and the width of the boiling region could be observed for most cases considered in this study. The physical reason for this correlation between the radial temperature gradient and the width of the boiling region may simply be that if the radial temperature gradient is large then the range of temperatures where boiling is likely occupies a smaller radial width on the surface. The trend is only qualitative because the surface temperature is not the only factor that influences the presence or absence of vigorous boiling.

Also notice that the outer boundary to the visible boiling region in Fig. 2 is not simply a constant temperature. For the case where $r_s = 8.5$ mm, the temperature at the wetting front is about 220 °C while for the case with the wetting front nearer the circumference ($r_s = 15$ mm), the surface temperature is about 160 °C. The reason for this variation in the apparent Leidenfrost temperature with radial position is not clear and should be the subject of further studies. The surface temperature of about 125 °C at the position where boiling is observed to stop, r_s, is reasonably consistent among the three cases. Some further observations from Fig. 2 concern the heat flux distribution. The maximum heat flux point for all three cases is within the boiling region. However, towards the outer edge of the boiling region the heat flux is surprisingly low, particularly for $20 < r < 24$ mm in the case where $r_s = 8.5$ mm. This suggests a

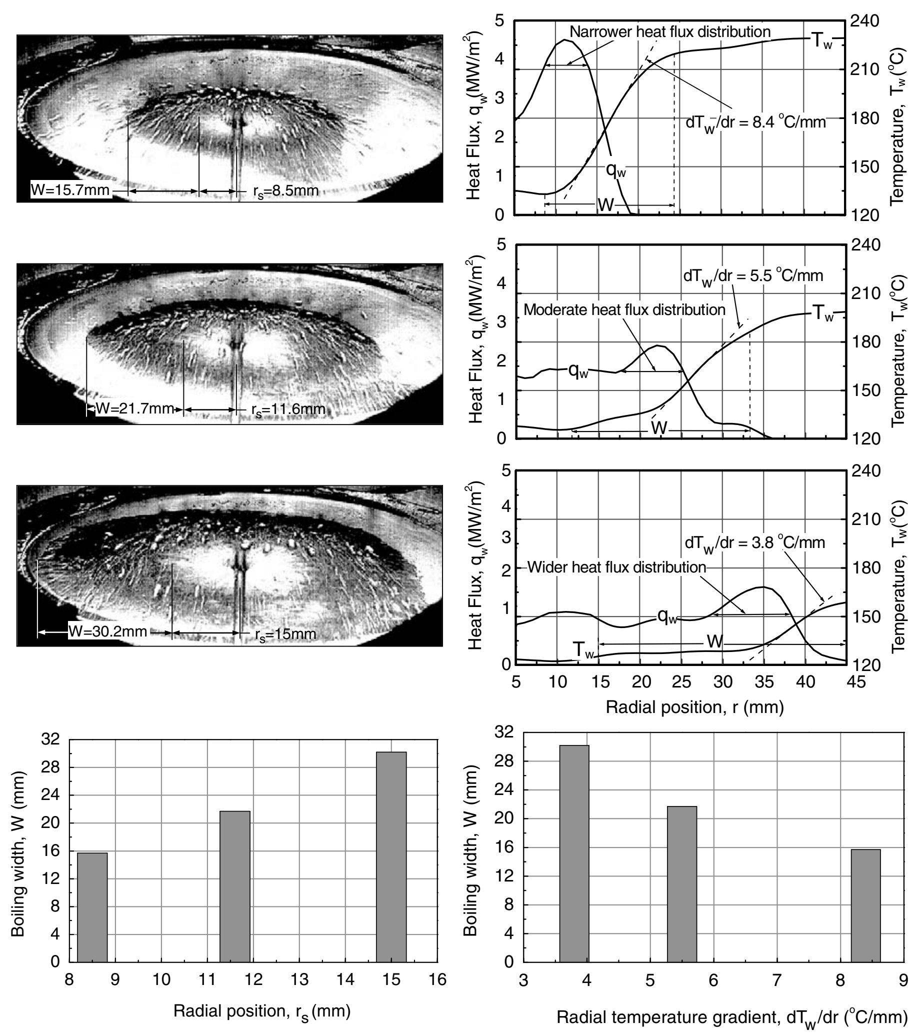

Fig. 2. Variation of boiling width together with heat flux distribution during wetting front movement (material: copper, $T_b = 400$ °C, $\Delta T_{sub} = 5$ K, $u = 3$ m/s).

region where film boiling effects may be dominating. However, this feature was not observed for many other flow conditions where the jet velocity and subcooling were greater than the example in Fig. 2.

It is also worth pointing out that the heat flux in the shiny region near the center is quite high in spite of the fact that vigorous boiling cannot be observed. The region is shiny because the surface of the liquid is smooth and light from the halogen lamp used to illuminate the surface is reflected well. Vigorous boiling causes the surface to ripple so that the light is scattered and the region appears dark to the camera. The shiny central region with no apparent boiling in Fig. 2 is not completely unexpected. An important characteristic of two-phase flows is that if the convection heat transfer contribution is large enough, then sufficient heat can be removed to suppress the phase change. Monde et al. [4] also observed a single-phase region in subcooled critical heat flux experiments using a heater which maintained a constant heat flux over the whole surface. Consistent with their findings, the present results show that the absence of visible boiling does not necessarily mean the heat flux is low.

3.2. Effect of liquid subcooling and jet velocity

Fig. 3 represents the effect of subcooling on the width of the boiling region with four different video clips where the corresponding surface temperature distributions are also depicted. The radial temperature gradient within the visible boiling region for each condition is also given. All of the cases have been selected so that the radial position where the boiling appears to stop, r_s, is always at 20 mm. Clearly, the boiling width decreases sharply with subcooling especially when the subcooling values are smaller, whereas the boiling width drops gradually when the liquid subcooling is high. The correspondence between the boiling width and the radial surface temperature gradient is not quite as clear in Fig. 3 when compared with Fig. 2. However, it is interesting that the temperature at the point of r_s changes significantly with the

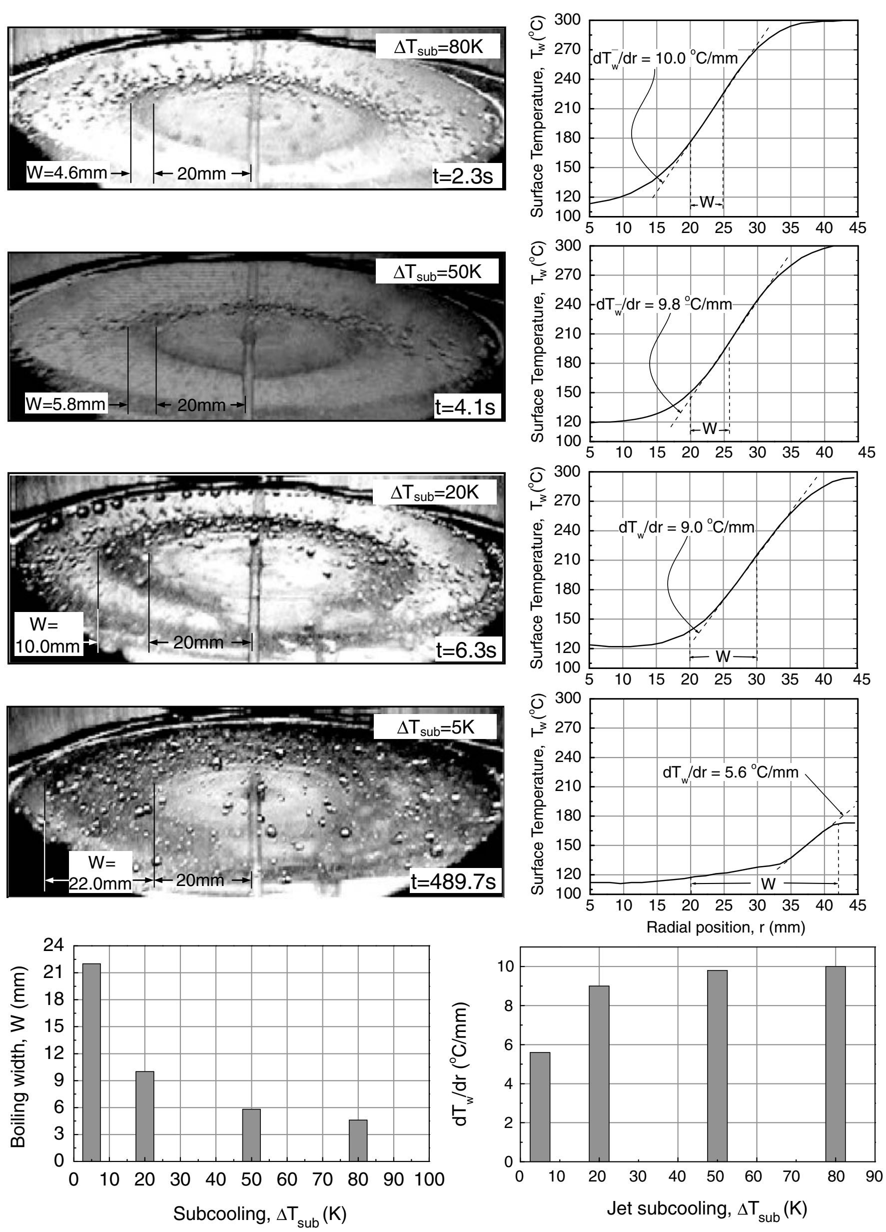

Fig. 3. Variation of boiling width with subcooling (material: brass, T_b = 300 °C, u = 5 m/s).

decrease in subcooling. For the subcooling case of 80 K, the temperature at r_s is about 170 °C while for a subcooling of 5 K it is only about 120 °C. It is quite probable that the boiling does not actually stop at 170 °C but rather the strong subcooling results in the formation and collapse of tiny bubbles that cannot be observed with the present visualization system. Iida et al. [15] observed such tiny bubbles on a micro-heater with a microscope.

Increasing the jet velocity had a very similar effect to increasing the subcooling so for the sake of conciseness no figure is shown. The similarity of the effect of increasing subcooling and increasing velocity indicates that the greater cooling potential of the jet is responsible for the steep radial temperature gradients and narrower boiling region. Mozumder et al.[1] already pointed out that a parameter, $u\Delta T_{sub}$, plays an important role in determining the characteristics of resident time and surface temperature at the resident time.

3.3. Effect of initial block temperature

The effect of the initial block temperature on the size of the boiling zone was not as dramatic as the effects of liquid subcooling and jet velocity. Therefore, we have not included a figure in this communication. Nonetheless, it is interesting that if the resident time was long (as in the case of a high initial temperature) then the boiling width tended to be greater for the same jet velocity and subcooling.

3.4. Effect of material

Fig. 4 compares the flow pattern observed for three different materials, copper, brass and steel where the jet temperature and velocity are constant. Quite clearly material properties have a large effect on the quenching phenomenon. For the same value of r_s, the boiling width for copper is 20 mm while for steel it is only 6.1 mm. Without doubt this is related to the fact that the thermal conductivity for copper is about three times that of brass and about 10 times that of steel. The higher thermal conductivity results in a tendency to even out steep temperature gradients. Thus, the maximum radial temperature gradient in Fig. 4 is 2.0 °C/mm for copper and 9.8 °C/mm for steel. Again there is a very clear inverse correlation between the boiling width and the radial temperature gradient. Another interesting feature of Fig. 4 is that the flow pattern

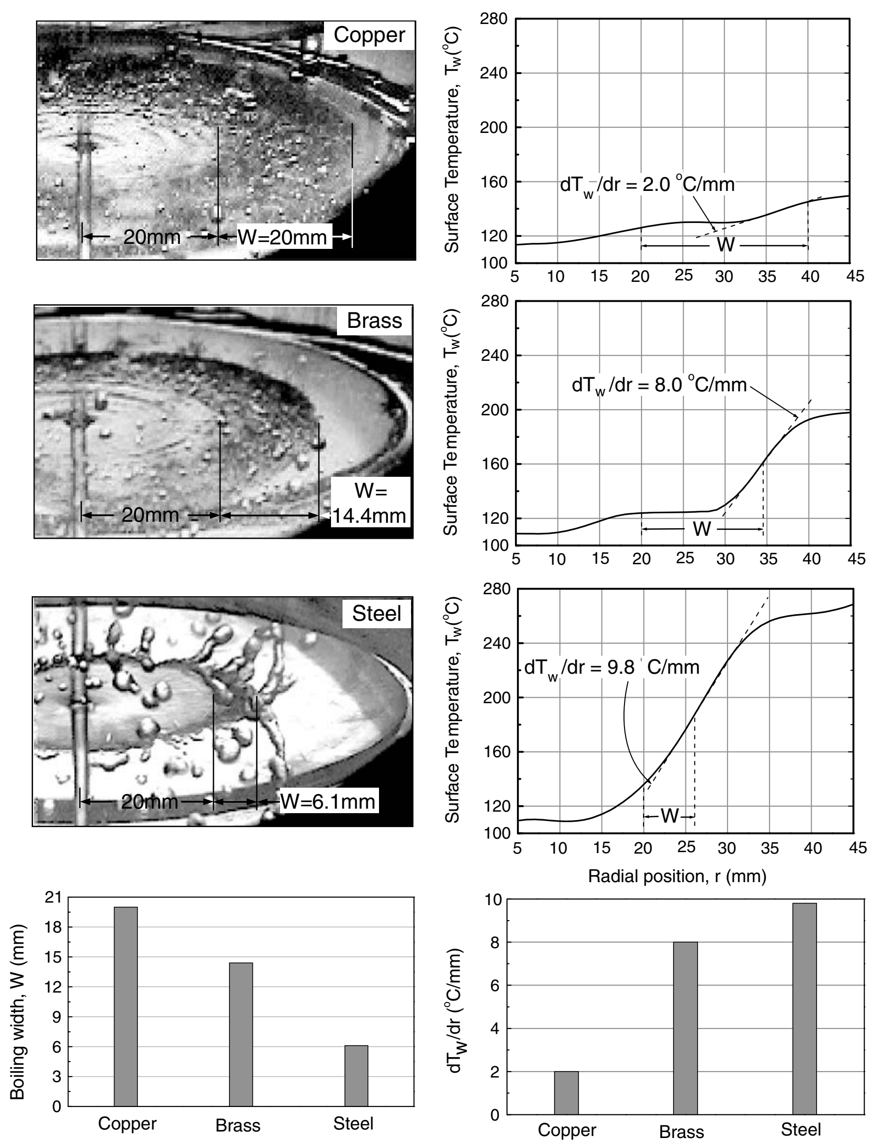

Fig. 4. Effect of material on boiling width (T_b = 300 °C, ΔT_{sub} = 20 K, u = 3 m/s).

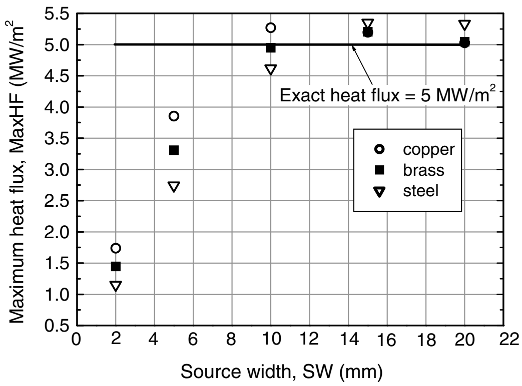

Fig. 5. Simulation results showing effect of source width on heat flux distribution for three different materials (sensor spacing: 5 mm for all the conditions).

for steel is quite different to that of brass or copper. In the case of steel, large droplets of liquid are issuing from the edge of the wetted region, while in the cases of copper and brass small droplets are issuing from many different radial positions within the boiling region. The differences in the observed boiling phenomena among the materials are also related to the ability of the solid to supply heat to the boiling region. Since steel has a thermal conductivity of about one-tenth that of copper, localized surface cooling occurs more readily on the steel surface than on the copper surface under conditions of high heat flux. Finally, it may be worth mentioning that heat flux transferred from a semi-finite solid is proportional to $\sqrt{\rho c \lambda}$.

3.5. Effect of boiling width on accuracy of heat flux estimation

In our previous studies [1,2], we observed that if the jet velocity or subcooling was high, the radial position is low or if the material was steel rather than copper then the scatter in the data for resident time and maximum heat flux was invariably great. From the results shown above, all of these conditions correspond to a narrow boiling width. It may be reasonable to suppose that space resolution issues for our measuring system, which includes the inverse solution technique, contribute to the scatter when the phenomenon on the surface changes abruptly. Fig. 5 gives results from a simulation used to verify the inverse solution for the present application. An analytical solution for a moving heat sink of constant width and a heat flux of 5 MW/m^2 was used to generate temperature readings for similar positions in the solid to the thermocouples used in the experiment. The inverse solution was then applied and comparison with the exact result for the maximum heat flux could then be made. Fig. 5 gives the result for different sink widths. Quite clearly, the inverse solution gives reasonable estimates if the width of the sink is 10 mm or greater but an underestimate if it is smaller. From this, we expect that if the width of the boiling region is too much less than 10 mm, we will likely have space resolution issues with our data for maximum heat flux. Noting Fig. 4, this problem is of particular concern for steel and may contribute towards explaining why we were unable to arrive at a satisfactory correlation for the steel data in our previous reports [1,2].

4. Conclusions

Jet impingement quenching is a complicated phenomenon. This paper contributes some background information regarding the width of the vigorous boiling region. At the moment the fundamental accomplishments are as follows:

1. When the value of the bulk temperature and the radial temperature gradient of the solid are high, the width of the boiling region shrinks. Smaller bulk temperature and smaller radial temperature gradient favors further expansion of the boiling width.
2. Boiling width decreases with increasing jet subcooling and velocity when the other remaining experimental conditions are same.
3. Among three materials, copper, brass and steel, relatively more local cooling takes place for steel due to its smaller conductivity which results in narrower width of the boiling region.
4. Space resolution of the maximum heat flux will be a problem if the width of the boiling region is small.

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