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EXPERIMENTAL INVESTIGATION OF RE-WETTING OF HOT HORIZONTAL TUBES

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ABSTRACT

Re-wetting of a hot dry surface is the establishment of direct contact between the surface and a liquid at a lower temperature. Re-wetting heat transfer is characterized by a large increase in heat transfer from the surface and occurs when a vapor film existing between the dry surface and the liquid is destabilized. Study of re-wetting heat transfer is very important in nuclear reactor safety for limiting the extent of core damage during the early stages of severe accidents after loss of coolant accidents LOCA and is essential for predicting the rate at which the coolant cools an overheated core. Surface re-wetting is established by the formation of a wet patch on the hot dry surface which then grows in size to cover the entire surface. The leading edge of the wet patch is called the re-wetting front and consists of transition and nucleate boiling heat transfer regions. The aim of this study is to introduce and study two important variables related to the re-wetting front as it moves on hot horizontal tubes cooled by water jet impingement. These variables are: the rebound phenomenon of the re-wetting front and the width of the re-wetting front. Experimental observations of this study showed that the re-wetting front could rebound a small distance just after the formation of the wet patch due to rapid heat conduction in the solid towards the wet patch. The rebound distance was found to increase by decreasing water temperature and the velocity of the jet. The width of the re-wetting front was found to increase by increasing water temperature and decreasing the initial surface temperature. As the solid thermal conductivity increases, this width was found to increase.

INTRODUCTION

The core of the Canada Deuterium Uranium (CANDU) reactor contains horizontal fuel channels surrounded by heavy water moderator. Each fuel channel consists of an inner tube called the pressure tube which contains fuel bundles and an outer tube called the calandria tube. In an accident referred to as a critical break LOCA the coolant flow in a fuel channel can become very low for a sustained period of time. This can cause both tubes to heat up and the outer surface of the calandria tube to experience dryout. If the calandria tube temperature is not reduced by re-establishing a wet contact with the moderator failure of the fuel channel may occur which can lead to the progression to a severe accident. Re-wetting heat transfer is initiated by de-superheating a vapor film that separates the surface from the liquid [1, 2].

When re-wetting occurs, a wet patch is established on the surface which spreads to cover and cool the entire surface. The leading edge of the wet patch (the re-wetting front) can proceed only if the surface ahead of it cools down to a certain temperature called the re-wetting temperature. Re-wetting consists of two simultaneous processes: rapid transition from film boiling to nucleate boiling and rapid heat conduction within the solid towards the wet patch.

Upstream of the re-wetting front, single-phase convection exists and film boiling prevails downstream [3]. The film boiling region is characterized by slow cooling rate. The surface-liquid contact drastically increases the cooling rate by nucleate boiling. At the re-wetting front itself, vigorous transition and nucleate boiling co-exist and liquid drops of several sizes are ejected from the surface and a cloud of steam is usually observed.

NOMENCULATURE

t_d	[sec]	Re-wetting delay time
T_{in}	[^{o}C]	Initial surface temperature
T_{water}	[^{o}C]	Water temperature
V_{jet}	[m/sec]	Jet velocity

Subscripts

in	Initial
water	Water

Abbreviations

CANDU	Canada Deuterium Uranium
DAQ	Data Acquisition System
fps	Frames per second
LOCA	Loss of Coolant Accident
NB	Nucleate Boiling

TB	Transition Boiling
WQF	Water Quench Facility

In this study, two characteristics of the re-wetting front are introduced and investigated during jet impingement cooling of hot horizontal tubes: the rebound phenomenon and the width of the re-wetting front. The re-wetting front moves on the surface as a region which has a certain width. This region is referred to as the "boiling region" [4, 5, 6]. This width usually ranges from fraction of a millimeter to few millimeters and is important to study because the heat flux tends to be higher in this narrow moving region. Also, any theoretical modeling of the re-wetting process should take into consideration the re-wetting temperature which can not be determined without determining the location of the re-wetting front. The re-wetting temperature at a certain location on the hot dry surface is usually determined with visual observation of the re-wetting front at that location combined with temperature measurement at the same location. This front represents a boundary where direct surface-liquid contact starts to take place.

The boiling region has a white appearance due to the vigorous boiling. Locating the re-wetting front is not an easy task as the large generation of vapour at the front prevents the clear visibility [7]. Figure 1 shows a typical image of the boiling region as observed in this study during jet impingement cooling of a hot horizontal tube.

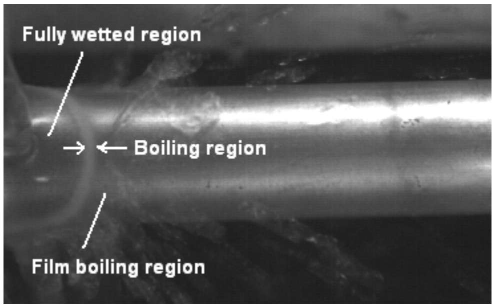

Figure 1 Typical image of surface re-wetting with the boiling region shown

LITERATURE REVIEW

The rebound phenomenon of the re-wetting front has not been found in literature and it is first reported in this study. Also, there are very few studies on the width of the boiling region. Analysis of the boiling region on curved surfaces has not been found.

In a recent study, P. Woodfield et al. [6] investigated the flow behavior and the boiling region size during water jet cooling of a high temperature cylindrical block 94 mm in diameter and 59 mm height. In their experimental work, a 2-mm diameter circular water jet was directed upward towards the flat bottom of the cylinder. Three blocks made of copper, brass and steel were used with initial surface temperature varied between 250-600^{o}C. Water subcooling was varied between 5-45^{o}C with two jet velocities of 3 and 5 m/sec. The size of the boiling region was found to increase with material thermal conductivity and to decrease with water subcooling and jet velocity. The boiling region was found to shrink with increasing initial surface temperature.

A. Mozumder [8] experimentally investigated the boiling region size using the above experimental setup with water subcooling varied between 5-80^{o}C and jet velocity between 3-15 m/sec. He reported an increase in the boiling region width with increasing the radial position during the propagation of the re-wetting front. The boiling width was greatly influenced by the radial temperature gradient: the higher the radial gradient, smaller was the boiling width.

M. Akmal [9] studied re-wetting of hot horizontal 2.54 cm steel tube using a 3-mm impinging water jet. It was reported that the width of the boiling region was affected by the initial surface temperature, water temperature and jet velocity. For initial surface temperature of 500^{o}C the boiling region width varied from less than 0.5 mm to a maximum of 5 mm.

M. Mitsutake et al. [5] considered the decrease in the boiling region width with increasing water subcooling to be governed by the heat removal by the liquid combined with the heat transferred in the solid by conduction. They reported that the maximum heat flux at a certain position on the surface takes place when nucleate boiling occurs there.

OBJECTIVES

A significant number of studies examine the re-wetting front location and velocity. Due to some confusion in literature in determining the location of the maximum heat flux and the location of the re-wetting temperature with respect to the re-wetting front (whether they coincide with the leading or the inner edge), it is advantageous to study the boiling region. An increasing number of researchers are referring to the importance of the boiling region size in understanding some key variables in re-wetting heat transfer.

The objective of this study is to contribute to the understanding of re-wetting heat transfer of curved surfaces by investigating jet impingement cooling of hot dry cylindrical tubes. In specific, the objective is to visualize the two-phase flow behavior around the tubes and to:

1. Study the rebound phenomenon of the re-wetting front and study the effects of water temperature and jet velocity on the rebound distance.

2. Experimentally measure the size of the boiling region and study the effects of initial surface temperature, water temperature and solid material.

EXPERIMENTAL SETUP AND PROCEDURE

The Water Quench Facility, which was designed and constructed as part of this study, was used to collect the experimental data. A schematic of the facility showing the major parts is shown in Figure 2. A brief description of the facility is summarized in the following paragraphs. The facility consists of the following major parts:
(1) Specimens and Motorized Motion System. (2) Water Circulation System. (3) High Speed Imaging and Data Acquisition Systems.

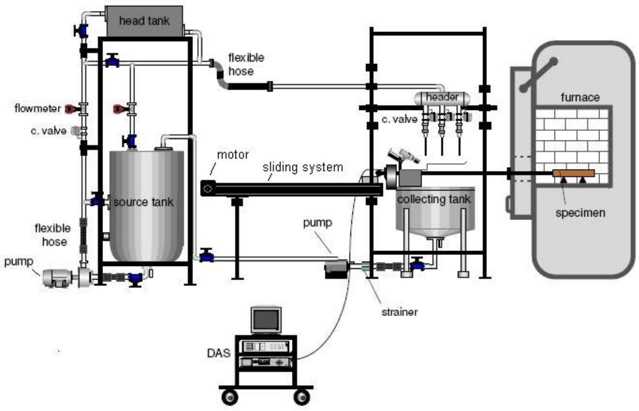

Figure 2 Schematic of the Water Quench Facility (WQF)

1. Specimens and Motorized Motion System

Cylindrical brass and steel tubes were used in this study. The tubes were machined from two 1-ft tubes (one half from each tube) cut through the axis. K-type thermocouples were inserted in holes drilled in the inner wall of the tube before welding the two parts to each other.

The tubes were heated in a box furnace. A specimen holding system was designed to hold the specimen while in the furnace and to move it quickly, precisely and gently to the prescribed cooling location. A linear motorized motion system was used to move the hot tubes.

An Aluminum sheet is positioned coaxially 2 inches above the heated tube to act as a guard. Upon cooling, the guard is rapidly moved axially by automatically releasing a spring to let the jet cool the surface. A "+" shaped laser pointer is used to point at the stagnation point at the tube center point. This assembly is shown in Figure 3.

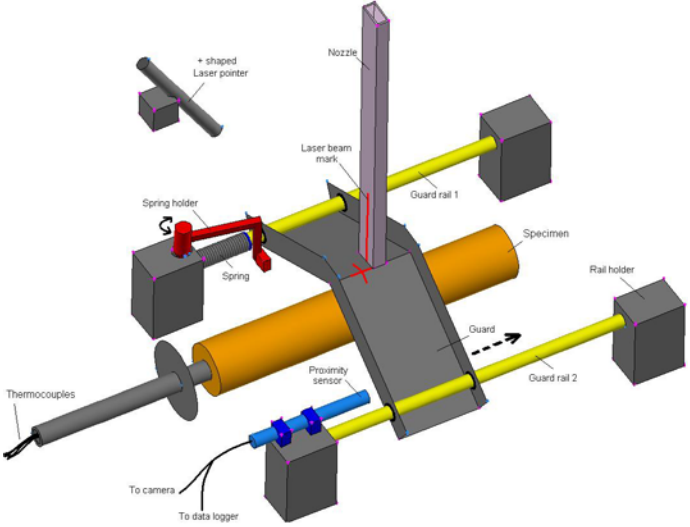

Figure 3 Heated tube, tube guard and loaded spring assembly

2. Water Circulation System

The water used in the cooling process passes through a circuit that includes a heating tank, flow pump, distribution flow header and a collecting tank. Water is pumped from a 45 kW heating tank to a three-outlet cylindrical header located above the collecting tank. The header outlets connect to long rectangular nozzles (slot opening 1×1/2 in.) to provide rectangular water jets.

3. High Speed Imaging and Data Acquisition System

The two-phase flow behavior around the tubes when re-wetted was visualized and recorded by a FASTCAM-X PCI 1024 high-speed camera. The camera provides maximum of 1000 frames/sec at a resolution of 1024×1024 pixels and up to 109,500 frames/sec at a reduced resolution of 128×16 pixels. Two special lights were used for illumination. The temperature at the thermocouple locations in the tubes were recorded by NI SCXI-1000 data acquisition system DAQ that provides a maximum sampling rate of 500 kSample/s. More details on the experimental setup are available in reference [12].

Experimental Procedure

The experimental data was collected by the following procedure:

1. The outer surface of the tubes was polished by Emery paper of 200 Grit before each test.

2. The water in the heating tank was heated to the desired water temperature and the tube was inserted into the furnace and heated to the desired initial surface temperature.

3. The heated water was pumped through the water circulation system at the required water jet velocity.

4. The tube was rapidly moved into position beneath the tube guard which was then moved away quickly allowing the water jets to impinge on the heated tube. The measurements were simultaneously recorded using the high speed camera and the DAQ by receiving a signal from a proximity switch sensor as shown in Figure 3.

5. The initial surface temperature was varied by controlling the furnace temperature, jet velocity by controlling a valve opening at the header outlet and water temperature by controlling the heating tank electric power.

Table 1 below shows the measurement uncertainty of the devices used.

Table 1 Measurement uncertainty

Measured variable	Uncertainty
Temperature	- 0.8 ^{o}C at 650^{o}C.
Flow rate	± 1% of reading.
Water temperature	± 0.2 ^{o}C.
Time (for imaging)	± (1/fps*).
Time (for thermocouple)	± (1/sampling rate).
Specimen location beneath the jet	± 1 mm.

* fps: frames per second.

RESULTS AND DISCUSSION

1. Rebound of the Re-Wetting Front

Figure 4 shows the rebound phenomenon of the re-wetting front during cooling of a 1-in brass tube initially at 800°C with jet velocity of 0.22 m/sec and water temperature of 21°C. The rebound occurs just after the initiation of the wet patch on the surface. The establishment of a wet patch creates a high temperature gradient in the solid and forms a deriving force for rapid heat conduction towards the wet region. The rapid heat conduction causes the region of the surface surrounding the wet patch to re-dry which causes the re-wetting front to rebound.

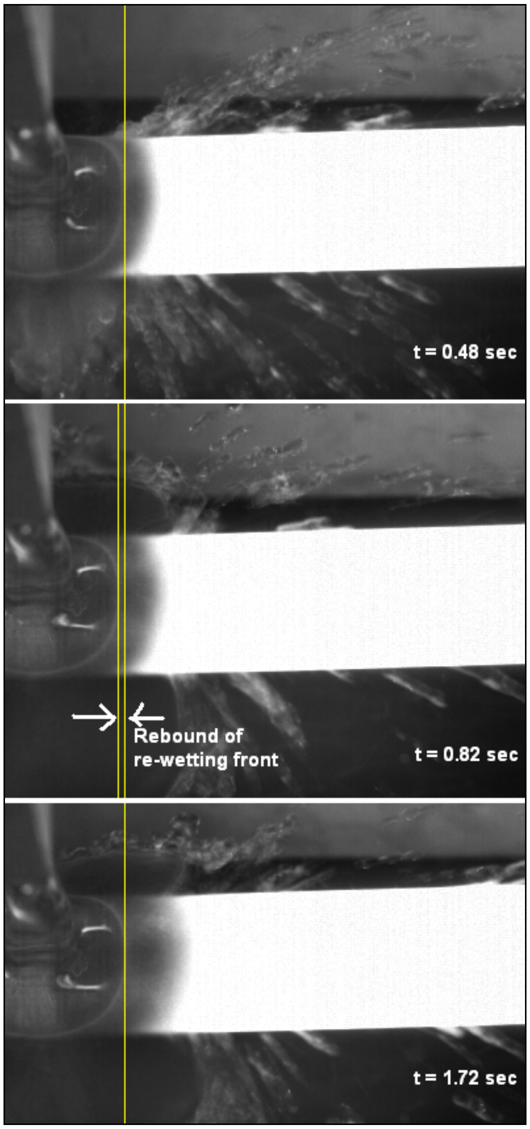

Figure 4 Rebound of the re-wetting front during cooling of a 1-in diameter brass tube, $T_{in} = 800^{o}C$, $V_{jet} = 0.22$ m/sec and $T_{water} = 21^{o}C$

Effect of Water Temperature

Figure 5 shows the rebound distance during cooling of a steel tube initially at 600°C versus water temperature for different jet velocities. As the figure shows, the rebound distance increases by decreasing jet velocity and by decreasing water temperature. As the jet velocity increases, the jet hydrodynamics form higher resistance for the re-wetting front to rebound. Also, as the water temperature decreases, the surface cools faster and the deriving force of heat conduction increases. The effect of water temperature tends to be stronger as water temperature increases. For water temperatures higher than 81°C the rebound distance seems to depend only on the water temperature with weak dependence on the jet velocity. This occurs for a range of water subcooling called the critical water subcooling range as will be shown in the following subsection.

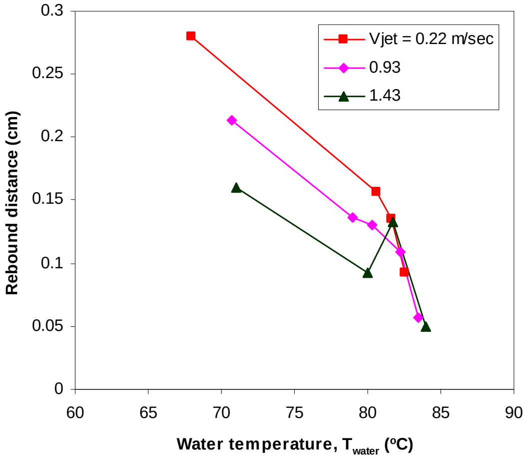

Figure 5 Effect of water temperature on the re-wetting front rebound distance during cooling of a 2-in diameter stainless steel tube for various jet velocities, $T_{in} = 600^{o}C$

Effect of Jet Velocity

Figure 6 shows the rebound distance against jet velocity where linear relation is observed for several water temperatures. The effect of jet velocity is stronger (steeper slope) as water temperature decreases.

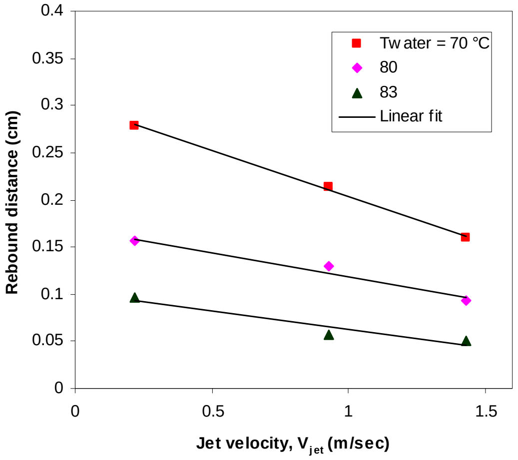

Figure 6 Effect of jet velocity on the re-wetting front rebound distance during cooling of a 2-in diameter steel tube for various water temperatures, $T_{in} = 600^{o}C$

Observations of this study showed that, for certain combinations of surface and water temperatures, there is a possibility of the vapor film to re-appear after collapsing. The re-appearance of the vapor film can be looked at as a strong rebound of the re-wetting front. It is advantageous to look at the surface temperature at the stagnation point under such conditions. Figure 7 shows three cooling profiles (a), (b) and (c) obtained for brass tube and measured at the stagnation point. Brass has a high thermal conductivity which allows heat to be easily conducted to balance the heat flux demand by the jet and to maintain a high surface temperature [8]. In profile (a) initially rapid and then slow cooling occurs followed by another rapid cooling. Such a profile was obtained for high water subcoolings combined with low jet velocity. Profile (b) shows an initial very rapid decrease in surface temperature for a very short time followed by a slow decrease indicating the re-appearance of the vapor film. This profile was obtained for initial surface temperatures above 500°C and for a range of water subcoolings where any small change in water temperature was found to have a strong effect on the re-wetting delay time: the time interval from when the water jet strikes the surface to the moment when the re-wetting is established. This subcooling range is called the "critical subcooling range" and will be discussed in another study. Profile (c) shows a "shoulder" of slow cooling period noticed for low water subcoolings combined with very low jet velocity; like 0.15 m/sec.

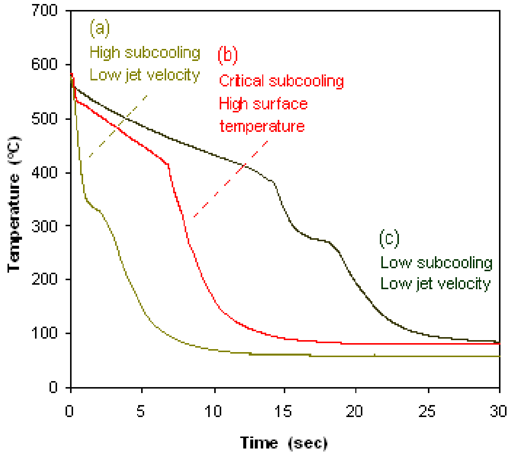

Figure 7 Cooling profiles at stagnation point for a 1-in brass tube showing the effect of the rebound of the re-wetting front

2. Boiling Region Width

After the re-wetting front rebounds, it starts to move ahead on the surface. The wetted area can be divided into two regions: fully wetted central region with no apparent boiling but with only single phase liquid convection and an outer thin annular region with vigorous nucleate and transition boiling. The inner edge of this region represents the boundary between the single-phase liquid convection region and the combined nucleate and transition boiling region. The term "stop boiling position" was used by Hammad [7, 10] and Mozumder [8] to refer to this edge. The outer edge represents the re-wetting front line where the surface-liquid contact starts to take place.

The boiling width was measured from the captured digital frames. For better vision of the boiling region boundaries the images were processed by the ImageJ software using the "edge finder" tool. A typical curve showing the boiling region width is shown in Figure 8. The figure also shows that the boiling region starts to move on the surface only after the re-wetting delay time period.

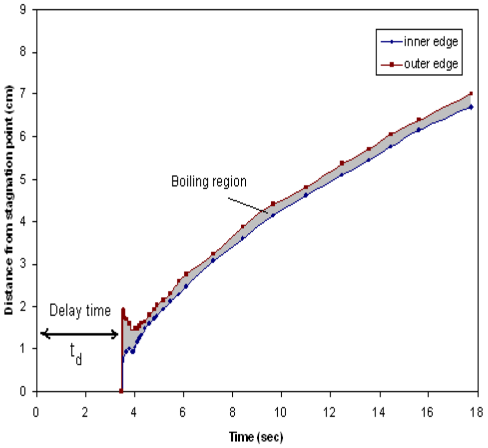

Figure 8 Re-wetting front location and boiling region size versus time during cooling of a 2-in diameter steel tube, T_{in} = 500°C, T_{water} = 83°C and V_{jet} = 0.37 m/sec

Figure 9 shows a sketch of a hot horizontal tube being re-wetted by a water jet. N.B and T.B denote nucleate boiling and transition boiling; respectively. The boiling region was observed to stay almost constant in size as the re-wetting front progresses towards the end of the tube. The sputtering droplets are moved downstream by the rapidly generated vapor.

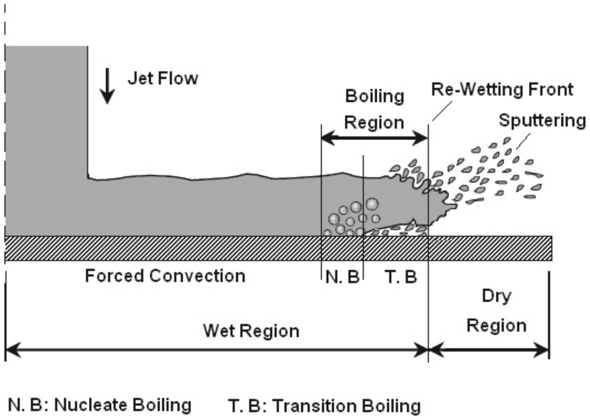

Figure 9 Axial view sketch of re-wetting of a hot horizontal tube

Effect of Initial Surface Temperature and Water Subcooling

Figure 10 shows the effect of initial surface temperature on the boiling region size for several water temperatures. The boiling region size increases with decreasing the initial surface temperature. Under this condition the transition and nucleate boiling are preferable more than the film boiling and thus the boiling region size increases. Linear relationship is observed between the boiling region size and the initial surface temperature. The figure also shows that the boiling region size increases by increasing the water temperature. However, for high initial surface temperatures, like 700°C, the boiling region size tends to a constant value regardless of the water temperature. For such high initial surface temperature, the water temperature increases rapidly and approaches the saturation temperature as the water moves on the surface.

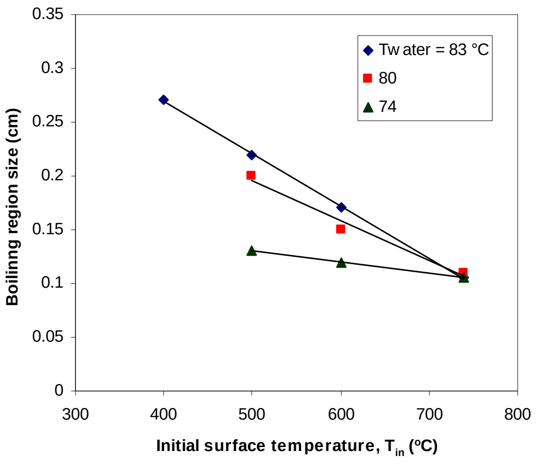

Figure 10 Effect of initial surface temperature on the boiling region size in axial direction during cooling of a 2-in diameter steel tube for various water temperatures, $V_{jet} = 0.93$ m/sec

Effect of Solid Material

Figure 11 shows the effect of solid material type on the boiling region size. As it is shown, for particular experimental conditions and for a certain location on the surface, the boiling region size on a brass tube is higher than that on a steel tube. Therefore, as the thermal conductivity of the material increases, the boiling region size increases. Mitsutake [5] also reported an increase in the size of the boiling region as the thermal conductivity increases. The material with higher thermal conductivity shows longer delay times and hence lower temperatures at which the vapor film starts to destabilize. Lower surface temperature conditions cause the boiling region size to increase.

Effect of Number of Jets

Heat and flow behavior in multiple-jet re-wetting might be more complicated than single-jet re-wetting due to interactions between flows from the adjoining jets [11]. The boiling region was observed to slightly increase in size as the number of jets increases. This is due to the higher cooling rate provided by the multiple jets; conditions where transition and nucleate boiling are preferable more than film boiling.

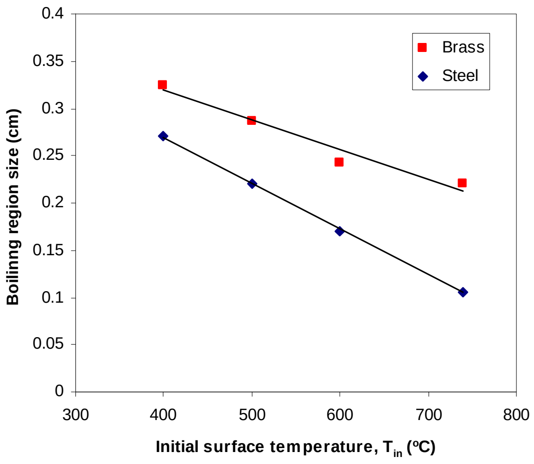

Figure 11 Effect of solid material type on the boiling region size during cooling of 2-in diameter tubes, $T_{water} = 83^{o}$C and $V_{jet} = 0.6$ m/sec

CONCLUSIONS

The rebound phenomenon of the re-wetting front and the size of the boiling region were studied. Visual observations showed that the re-wetting front could rebound just after the formation of a wet patch on a hot dry surface. The rebound distance was found to increase by decreasing water temperature and jet velocity. The boiling region size was found to increase with water temperature and with decreasing initial surface temperature. As the solid thermal conductivity increases, the boiling region size was found to increase.

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