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EXPERIMENTAL INVESTIGATION OF QUENCH PHENOMENA AND TWO-PHASE FLOW BEHAVIOR FOR HOT HORIZONTAL TUBES WELL ABOVE THE LIMITING TEMPERATURE FOR SOLID–LIQUID CONTACT

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Abstract

Quench cooling of a hot dry surface involves the rapid decrease in surface temperature by a sudden contact with a coolant. Situations involving quenching are encountered in a number of postulated accidents in Canada Deuterium Uranium (CANDU) reactors, such as quenching of a hot calandria tube in certain Loss of Coolant Accidents (LOCA). In this study, an experimental setup has been built and a series of experiments were conducted to investigate quenching of hot horizontal tubes by a water multi-jet system. The effects of key role parameters on the re-wetting delay time, the re-wetting front velocity and the quench and re-wetting temperatures were investigated. These variables were found to be strongly dependent on water subcooling. The effects of initial surface temperature, jet velocity and surface curvature were also investigated.

Keywords: Quenching heat transfer, Re-wetting, horizontal tubes, CANDU, LOCA.

Introduction

Quench heat transfer of a hot dry surface involves the rapid decrease in surface temperature resulting from bringing the hot surface into sudden contact with a liquid at a lower temperature. Quench temperature is the surface temperature at the onset of the rapid decrease and corresponds to the onset of destabilization of a vapor film that exists between the hot surface and the liquid. After quenching occurs the liquid re-establishes contact with the surface at the so-called re-wetting temperature. Situations involving quench heat transfer are encountered in a number of postulated accidents in CANDU reactors, such as quenching of hot fuel elements experiencing post – dryout conditions during a loss of flow accident and quenching of a hot calandria tube in a critical break LOCA which can lead to the progression to a severe accident.

The core of a CANDU reactor contains horizontal fuel channels surrounded by heavy water moderator. Each fuel channel consists of an inner tube (pressure tube) and an outer tube (calandria tube). The pressure tube contains fuel bundles. The calandria tube is approximately 130 mm in diameter. In a critical break LOCA the coolant flow in a fuel channel can become very low for a sustained period of time. During this period of low coolant flow the fuel heats up causing the pressure to increase sufficiently resulting in ballooning deformation of the pressure tube into contact with its calandria tube. Contact between the hot pressure tube and the cold calandria tube results in high heat transfer between the two contacting tubes. In turn, this results in high heat transfer from the calandria tube to the surrounding moderator liquid. This can cause the calandria tube surface to experience dry out and a subsequent escalation in the temperature of the calandria tube [1, 2]. If the calandria tube temperature is not reduced by initiation of quench heat transfer, a subsequent fuel channel failure may occur.

The time period from applying the coolant to the establishment of re-wetting is called the re-wetting delay time. If the re-wetting is established at a location on the hot surface, a wet patch is formed at that location and starts to spread to cover and cool the entire surface. The outer edge of the wet patch, called the re-wetting front, can proceed only if the surface ahead of it cools down to the re-wetting temperature. At the front itself, transition and nucleate boiling co-exist. Surface re-wetting is a very complex heat transfer process. All types of boiling heat transfer as well as single phase convection can exist simultaneously at different spatial locations on the surface. Figure 1 shows a typical image of re-wetting a hot tube by a jet of water.

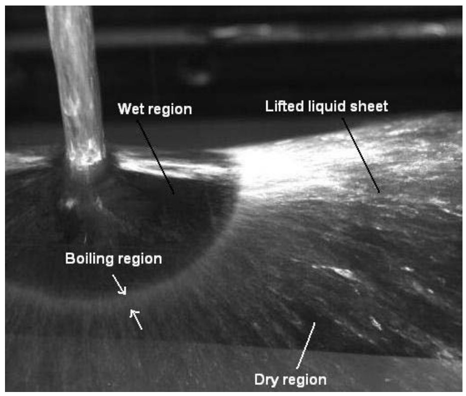


Figure 1: Typical image of re-wetting a hot tube by a jet of water.

1. Determination of the quench and the re-wetting temperatures

The determination of the quench and re-wetting temperatures in the reactor is very important for limiting the extent of core damage during the early stages of severe accidents. All theoretical models of quench cooling require knowledge of either temperature and incorrectly assumed values of these temperatures could lead to enormous errors in the final analysis of the problem [3]. In literature, there is no unique definition of these temperatures. Some researchers used both terms to describe the same phenomenon [4, 5]. Some researchers defined the re-wetting temperature as the Leidenfrost temperature [6, 7] and others considered it equal to the minimum film boiling temperature [8]. F. Gunnerson [9] defined re-wetting as the establishment of a liquid-solid-vapor triple interface and distinguished between the re-wetting temperature and the Leidenfrost temperature. Barnea [10] defined the re-wetting temperature as the highest temperature at which the slope of the cooling profile exceeds an arbitrary value of 500^{o}C/sec. Others [1, 2, 3, 9, 11, 12] defined the quench temperature as the onset of the rapid decrease in surface temperature and the re-wetting temperature as the temperature at which the direct solid-liquid contact occurs. This later definition has been adopted in this study. A typical cooling profile during quenching is shown in Figure 2. The quench temperature can be estimated as the intersection point between the tangent line drawn to the cooling profile before the rapid decrease and the tangent line drawn at the point where the profile's slope is steepest. The re-wetting temperature is determined by observing the interface along with the temperature measurement. The location of the re-wetting temperature is approximated in Figure 2 [9].

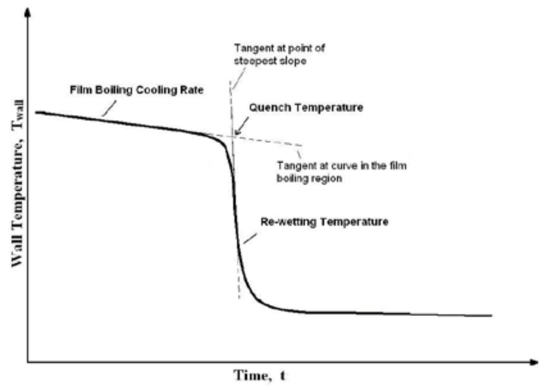


Figure 2: Typical cooling profile.

2. Objectives

Very limited knowledge of quench of hot curved surfaces is available in literature. The aim of this study is to investigate this relatively unexplored field. The objectives in specific are to: (1) Experimentally measure the surface temperature of hot horizontal cylindrical tubes during jet impingement quench cooling. The effects of key role parameters are to be investigated. (2) Visualize the two-phase flow behavior simultaneously with the temperature measurement. The results of this study provide novel information and an experimental database for mechanistic modeling of quench heat transfer on hot tube surfaces that experience film boiling. This mechanistic modeling can, with futher effort and appropriate qualification, be used to support safety analysis methodology that has been developed to demonstrate fuel channel integrity during LOCAs in CANDU reactors [2].

3. Literature review

The authors in another work [13] studied the effects of water subcooling and initial surface temperature on the re-wetting front propagation along the circumferential direction on a 2.54 cm horizontal brass tube. The tube initial surface temperature was varied between 300-700^{o}C and was cooled using a circular water jet with 3 m/s jet velocity. It was found that the re-wetting front slows down as the temperature difference between the hot tube and the jet decreases. The prediction of the re-wetting front velocity on flat surfaces has been the main goal of many researchers. On curved surfaces, however, M. Akmal et al. [14] studied re-wetting of a 2.54 cm hot horizontal steel tube using circular water jet. The re-wetting velocity was correlated with a power law function of time and was found to be strongly dependent on water temperature. At low water temperatures and high jet velocities the re-wetting front was found to grow fast.

J. Luxat [2] developed a mechanistic model to describe the heat transfer and thermal-mechanical processes associated with the deformation of a pressure tube into contact with its calandria tube in the CANDU reactor. It was stated that the extent and duration of film boiling heat transfer on the outer surface of the calandria tube is dependent on the heat flux from the pressure tube and the subcooling of the water surrounding the calandria tube. The model was validated by comparison with experimental data and the minimum film boiling temperature was estimated from a number of contact boiling tests and compared with several correlations available from the literature. Jiang et al. [1] developed and validated a mechanistic model of convection film pool boiling on the outer surface of a hot horizontal tube cooled by water. The tube diameter was relevant to the CANDU calandria tube. The effects of coolant subcooling and surface temperature on the vapor film thickness were investigated.

Investigating quench of spherical objects is advantageous in studying the quench of cylindrical tubes as both objects are curved surfaces. C. Liu [15] investigated the film boiling on spheres immersed in a bath of flowing water. Brass spheres had a little lower quench temperatures compared to those of steel. J. Stevens [16] found that the minimum film boiling temperature of a copper sphere moving through subcooled water is not affected by the velocity of the sphere.

4. Experimental setup and procedure

An experimental setup, “Water Quench Facility (WQF), has been designed and constructed as part of this study. An image of the facility is shown in Figure 3.

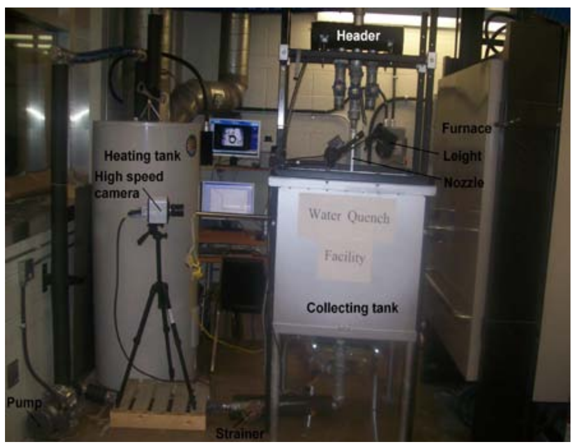


Figure 3: Image of the Water Quench Facility (WQF).

The facility consists of the following main parts:

4.1 Specimens and motorized motion system

A schematic of one of the heated tubes is shown in Figure 4. This is a 1-ft long cylindrical tube. The tube was prepared from two 1-ft tubes (one half from each tube) milled through the axis with accuracy of ± 0.0005 mm. Eighteen 1-mm K-type thermocouples with maximum deviation of -0.8^{o}C at 650^{o}C were mounted by silver soldering in the inner wall of each half in the hole locations shown in Figure 4. A 2-in diameter stainless steel specimen was also prepared.

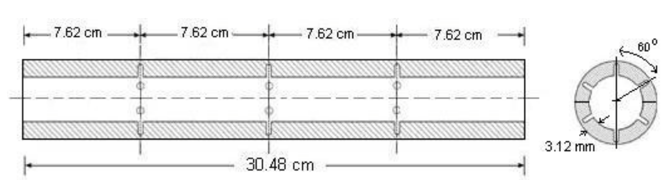


Figure 4: Heated tube and thermocouple locations.

Silver soldering can perfectly mount the thermocouple which is very important in quench experiments. The two tube halves were then welded to each other. The tube is heated in a box furnace. A specimen holding system was designed to move the specimen quickly, precisely and gently to the prescribed cooling location. A motorized linear motion system is used to move the tube. A specimen guard is loaded on a spring which is automatically released when the hot tube is moved to the cooling location and a proximity switch sensor sends a measurement signal when the guard just starts to move. This assembly is shown in Figure 5.

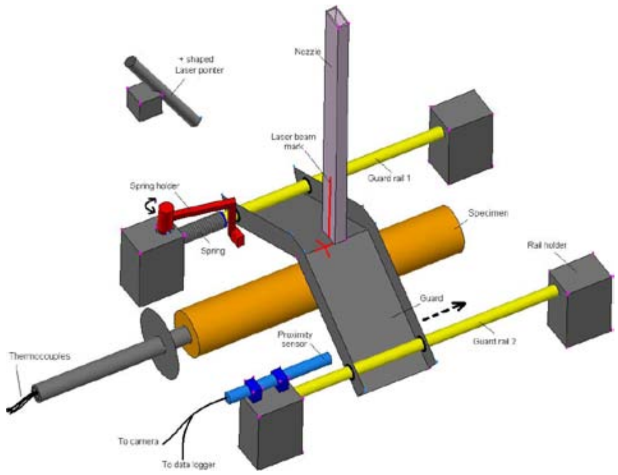


Figure 5: Specimen guard, loaded spring assembly and proximity sensor.

4.2 Water circulation system

The water used in the cooling process is pumped from a heating tank to a head tank from where it flows to a three-outlet cylindrical flow distribution header located above a collecting tank. The header outlets connect to long rectangular slots to provide rectangular water jets. Each header outlet has a valve to control the flow rate through the nozzles which have a length sufficient to ensure fully developed flow. The slot opening is 1× 1/2 in. One jet has been used in this paper.

4.3 High speed imaging and data acquisition system

A FASTCAM-X PCI 1024 high-speed camera has been used. It 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. The temperatures were recorded by NI SCXI-1000 data acquisition system DAQ with maximum sampling rate of 500 kSample/s. Both measurements start simultaneously when receiving the signal from the proximity switch sensor.

4.4 Experimental procedure

The following procedure was followed to obtain the experimental data:

1. The outer surface of the tube was polished by Emery paper of 200 Grit before each test to remove the surface oxidation following a period of film boiling, thereby facilitating test repeatability.

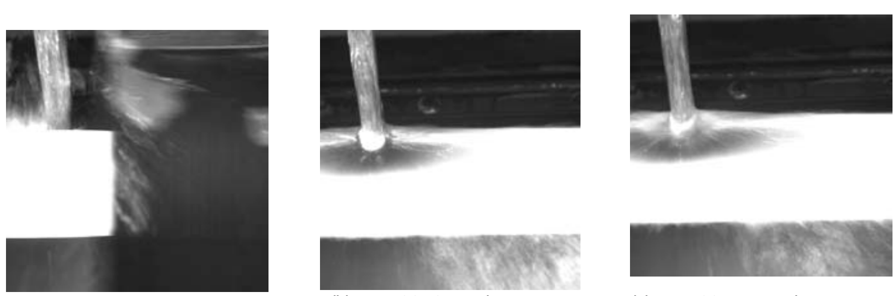
2. The water in the heating tank was heated to the required water temperature. The heated water was pumped through the water circulation system at the required velocity until steady state conditions of jet temperature and jet velocity were reached.

3. The tube was inserted into the furnace and heated to the desired initial surface temperature. The tube was then rapidly moved into position beneath the specimen guard which was then moved away quickly. The measurements were recorded until the tube's surface temperature reached that of the jet.

4. Most of the tests were repeated at least three times to ensure test repeatability.

5. Results and discussion

Figure 6 shows the process of re-wetting a 2-in steel tube and the development of the wet patch. The hot tube was bright red in color when moved out of the furnace as shown in image (a). After the jet strikes the tube, the area surrounding the stagnation point starts to darken as shown in image (b). The temperature measurement showed that this image corresponds to the quench temperature. Immediately after that, the vapor film completely collapses as indicated by observing a rapid rupture in the liquid sheet due to rapid vaporization resulting from transition boiling as shown in image (c). Then, a darker wet zone starts to develop and grow in size as shown in image (d). This zone is the wet patch where the water fully wets the surface. Image (e) shows the wet patch at a later time and in image (f) the two re-wetting fronts moving in the circumferential direction meet at the tube bottom point. The re-wetting front continues to move in the axial direction until the tube becomes fully wetted. The temperatures at which these images were captured are marked on the temperature profiles in Figure 7. A sketch of the tube being re-wetted is also shown. N.B and T.B denote nucleate and transition boiling; respectively.



(a) t=0: Jet strikes the surface.
(b) t=5.133: Quench starts at stagnation.
(c) t=5.733: Re-wetting starts at stagnation.

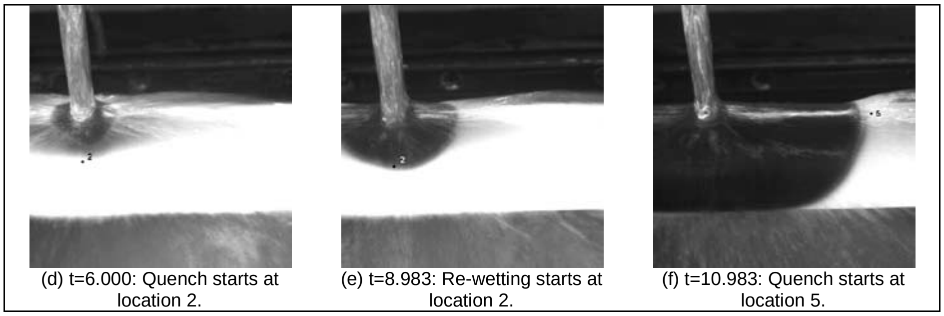


Figure 6: Typical images of re-wetting a 2-in steel tube, T_{in} = 650°C, T_{water} = 82°C and V_{jet} = 0.7 m/sec.

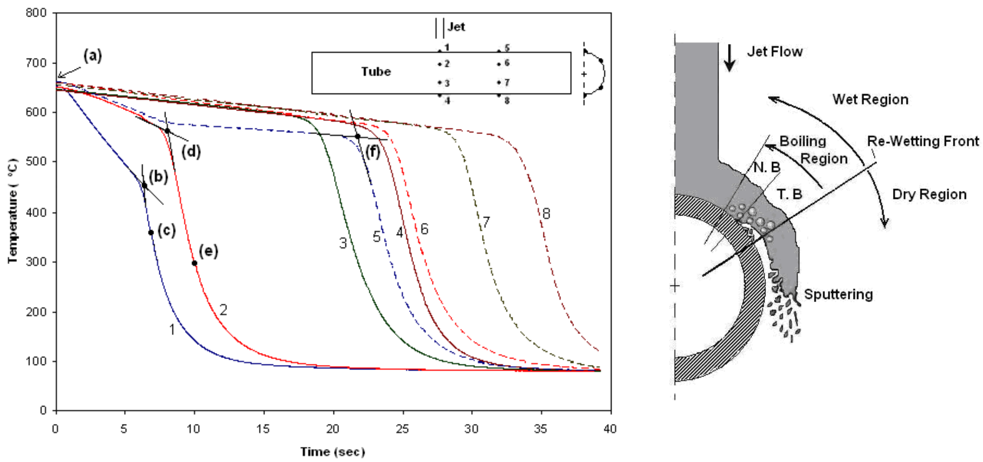


Figure 7: Typical cooling profiles during cooling of a 2-in steel tube, T_{in} = 650°C, T_{water} = 82°C, V_{jet} = 0.7 m/sec with observations shown in Figure 6. Sketch is not to scale.

5.1 Correlation for the re-wetting delay time

The re-wetting delay time was found to depend on water temperature, jet velocity, initial surface temperature, solid material and tube diameter. It is assumed that the water does not initially wet the surface because the heat transfer by conduction in the solid q_{solid}, is higher than the heat convected to the liquid. The heat conduction in the solid is generally proportional to $\sqrt{\frac{\rho C k}{t}}$ [11].

Therefore:

$$q_{solid} = -k\frac{\Delta T}{\Delta x} = -k\frac{(T_{in} - T(t))}{\Delta x} = \gamma\sqrt{\frac{\rho C k}{t}}(T_{in} - T(t))$$

Where γ is a constant, T_{in} is the initial surface temperature and (T_{in}-T(t)) is the temperature deriving force for the heat conduction. At the moment of re-wetting this is assumed to be equal to the heat transferred to the liquid. The heat transfer coefficient is generally a function of jet velocity and the temperature difference (T(t) – T_{water}), which may be related to (T_{in} – T_{water}) and (T_{sat} – T_{water}) [11, 17]. Also, according to the observations of this study, the delay time, t_d, is related to tube diameter d. Using the experimental data collected, the following correlation was obtained by the least mean square method:

$$\sqrt{\frac{\rho Ck}{t_d}} = 4.12\times10^3 V_{jet}^{\ 0.44}(T_{in} - T_{water})^{2.53}(\Delta T_{sub})^{-2.04} d^{-2.53}$$

Figure 8 shows a plot of the correlation. The ranges of the operating conditions used to obtain the correlation are: V_{jet} = 0.22 – 1.43 m/sec, ΔT_{sub} = 15-80°C, T_{in} = 400-740°C, d = 2.54 and 5.08 cm (1 and 2 in.) and solid material: steel, brass and Alumina.

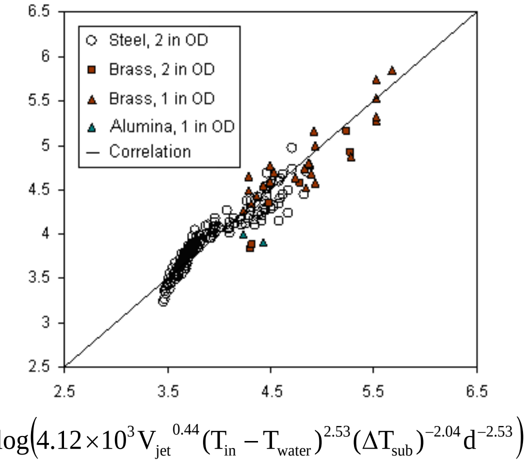


Figure 8: Data of delay time with correlation prediction.

5.1.1 Effect of surface curvature

Figure 9 shows the delay time for four brass surfaces with the same amount of solid material but with different surface curvatures. Three of the surfaces have the same wall thickness of 3.2 mm and the fourth surface has a wall thickness of 1.5 mm. The delay time increases by increasing the surface curvature. This behavior could be due to the ability of the tube to supply heat from the lower part (where there is no liquid around the surface) to the upper part where the jet interacts with the surface.

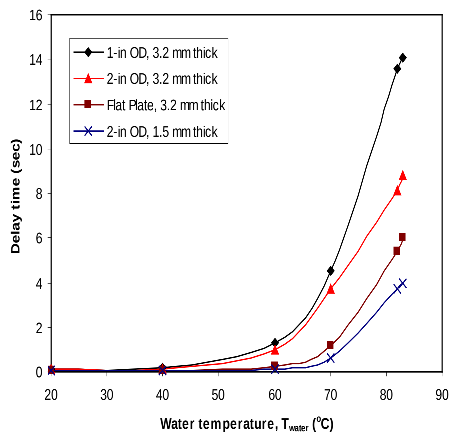


Figure 9: Effect of surface curvature on the re-wetting delay time, brass surfaces, T_{in} = 600°C, T_{water} = 83°C and V_{jet} = 0.6 m/sec.

5.2 Re-wetting front velocity

The re-wetting front velocity was calculated by dividing the distance between two locations at the tube surface in the axial direction by the time required for the re-wetting front to move between the two locations. This was done for several locations at the surface. Almost all of the tests showed that the re-wetting velocity tends to be constant after the rapid initiation of the wet patch. It is common to correlate the re-wetting front velocity to the product of the velocity and the subcooling of the coolant. This product describes parameters from the coolant side only and gives indication of the ability of the liquid to cool the surface. Figure 10 shows this relation for four initial surface temperatures.

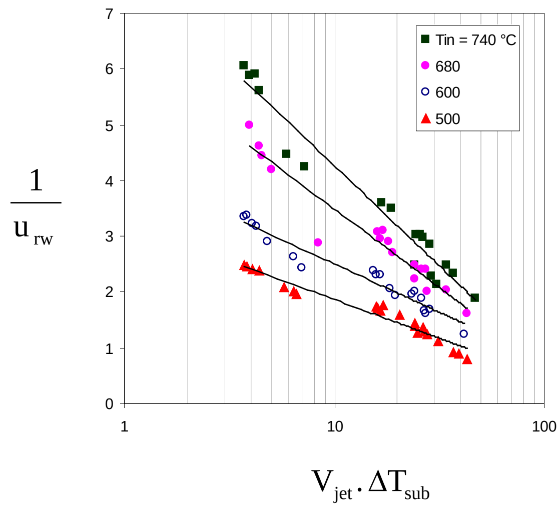


Figure 10: Data of the re-wetting front velocity for a 2-in steel tube.

5.2.2 Effect of surface curvature

Figure 11 shows the re-wetting velocity for three hot brass surfaces initially at 600°C and with different curvatures. As the surface curvature increases, more liquid slips down on the surface which decreases the re-wetting front velocity in the axial direction.

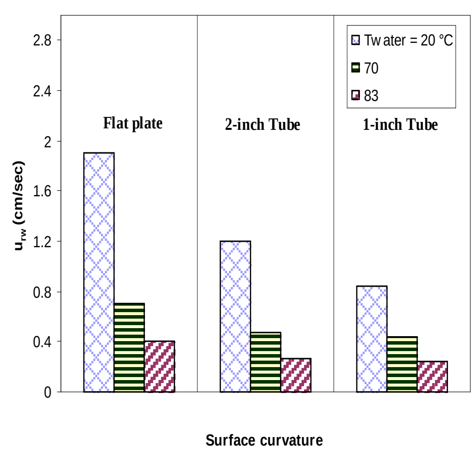


Figure 11: Effect of surface curvature on the re-wetting velocity for brass surfaces, T_{in}=600°C and V_{jet}=0.6 m/sec.

5.3 Quench temperature

5.3.1 Effect of water subcooling and initial surface temperature

Figure 12 (A) shows the quench temperature at the stagnation point during cooling of a 2-in steel tube. The quench temperature increases with increasing water subcooling. When the water gets cooler, thinner vapor film is expected which collapses faster. The quench temperature shows a strong dependence on water temperature for water temperatures higher than those of the circled points. For water temperatures less than the circled points, the quench occurs very rapidly in fraction of a second. The range in which the quench temperature strongly depends on water temperature will be referred to as the "critical water subcooling" range. Any small change in the water subcooling in this range; like 0.50°C, was found to have a considerable effect on the quench temperature and the delay time. For water temperatures above around 81°C, the quench temperature was found to tend to almost a constant value in the range 450-470°C.

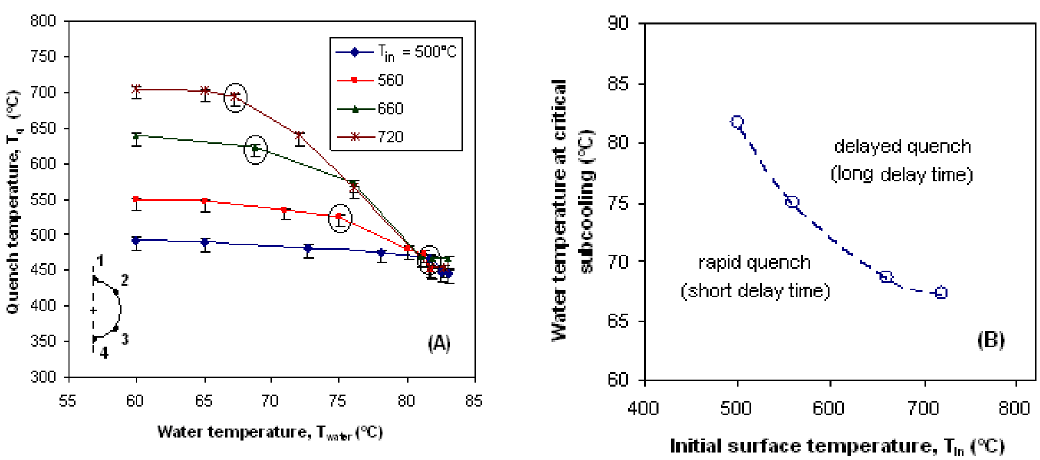


Figure 12: (A) Quench temperature at location 1 and (B) Water temperature at critical subcooling versus initial surface temperature during cooling of a 2-in steel tube for V_{jet} = 1.43 m/sec.

In Figure 12 (B) the water temperatures of the circled points are plotted against the initial surface temperature. The resulting line forms a boundary between the region of rapid quench and the region of delayed quench (relatively long delay times: arbitrarily 2 seconds and more). If, initially, the conditions for vapor film destabilization are not achieved due to high heat conduction in the solid towards the stagnation region then the whole solid must cool down by vapor film boiling before the film starts to destabilize. This results in a much longer delay time.

5.3.2 Effect of spatial location

Figure 13 shows the quench temperature at four locations at the tube surface versus water temperature for T_{in} = 720°C and V_{jet} = 1.43 m/sec. TC denotes the Thermocouple location. The quench temperature decreases as moving from location 2 towards location 4 at the tube bottom point. This is because the tube lower part cools by conduction to the upper part as it is quenched. The stagnation point is excluded from this behavior as the water temperature there is lower.

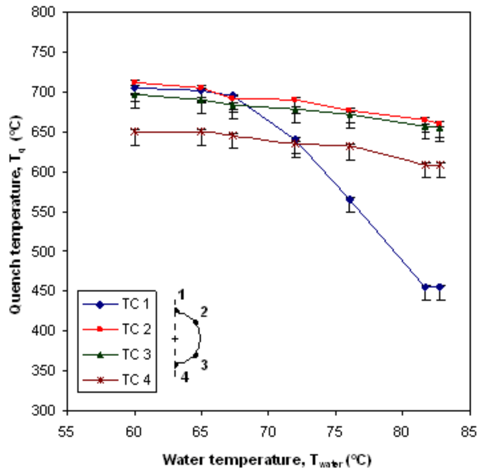


Figure 13: Quench temperature at locations 1-4 during cooling of a 2-in steel tube for T_{in} = 720°C and V_{jet} = 1.43 m/sec.

5.3.3 Correlations for the quench and the re-wetting temperatures

For better understanding of the quench and the re-wetting temperatures, the two temperatures are plotted in Figure 14 versus water temperature for T_{in} = 580°C and V_{jet} = 0.93 m/sec. Also, shown in the figure are the quench and the re-wetting delay times. The quench delay time was determined from the cooling profile at the quench temperature.

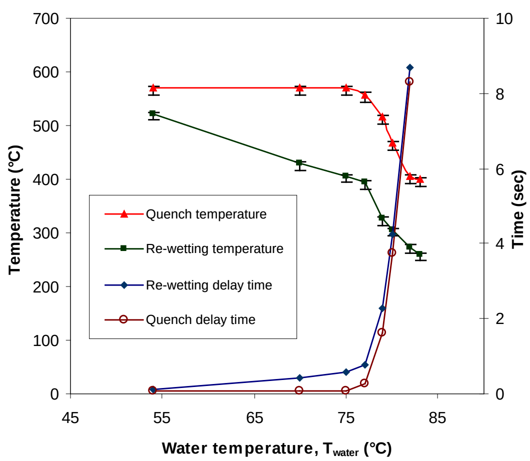


Figure 14: The Quench and re-wetting temperatures at the stagnation point and the delay times during cooling of a 1-in brass tube for T_{in} = 580°C and V_{jet} = 0.93 m/sec.

For the delayed quench tests, the quench temperature at the stagnation point was found to relate linearly with water subcooling as follows:

$$T_q(^{o}C) = 12.18\Delta T_{sub} + 246.4 \qquad (1)$$

The re-wetting temperature was determined at the moment when the liquid sheet was ruptured. The re-wetting temperature was found to relate linearly with water subcooling as follows:

$$T_{rw}(^{o}C) = 7.91\Delta T_{sub} + 223.2 \qquad (2)$$

Figure 15 shows plots of the two correlations. The correlations were obtained using the following ranges of operating conditions: V_{jet} = 0.22-1.43 m/sec, T_{in} = 500-720^{o}C, T_{water} = 72-84^{o}C and using the 2-in diameter steel tube. Other correlations were obtained for the brass tube. The correlations are shown in Table 1.

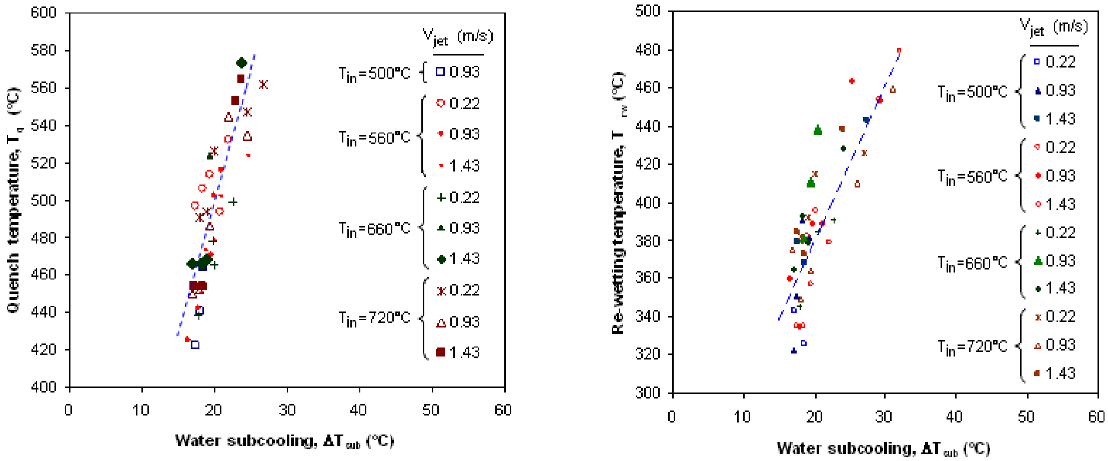


Figure 15: Correlations for the quench and re-wetting temperatures during cooling of a 2-in steel tube.

Several correlations for the minimum film boiling temperature T_{mfb} are available from literature. Some of these correlations are shown in Table 1. Figure 16 shows a comparison between these correlations. The correlations developed in this work are consistent with the other correlations.

Table 1: Correlations for minimum film boiling temperature and correlations of this work.

Study	**Correlation**	**Liquid/Solid**
Lauer and Hufschmidt (L-H) [4]	$\Delta T_{mfb} = 5.893\ \Delta T_{sub} + 228.6$	water/steel cylinder and sphere
Adler [4]	$\Delta T_{mfb} = 6\ \Delta T_{sub} + 130$	distilled water/steel sphere
	$\Delta T_{mfb} = 7\ \Delta T_{sub} + 175$	de-ionized water/steel sphere
Bradfield [2]	$\Delta T_{mfb} = 6.15\ \Delta T_{sub} + 200$	water/copper sphere
Groneveld and Stewart (G-S) [18]	$T_{mfb} = 6.3\ \Delta T_{sub} + 289$	water/Inconle tube
Ohnishi [2]	$\Delta T_{mfb} = 5.1\ \Delta T_{sub} + 350$	
This work	$T_q = 12.18\ \Delta T_{sub} + 246.4$	water/steel tube
This work	$T_{rw} = 7.91\ \Delta T_{sub} + 223.2$	water/steel tube
This work	$T_q = 20.91\ \Delta T_{sub} + 36.7$	water/brass tube
This work	$T_{rw} = 6.04\ \Delta T_{sub} + 256.3$	water/brass tube

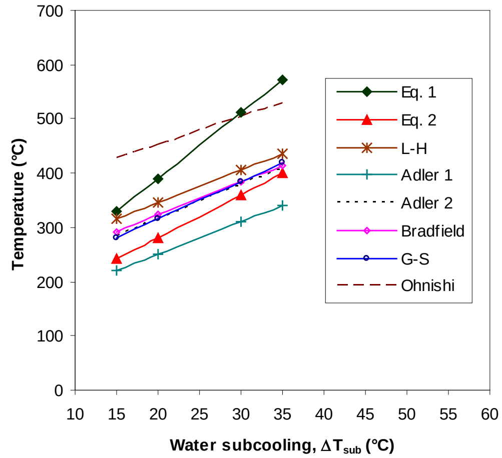


Figure 16: Comparison of Equation 1 and Equation 2 with the correlations shown in Table 1.

5.3.4 Effect of surface curvature and solid material

The quench temperature of the brass tube was found to be slightly lower than that of the steel tube as the correlations shown in Table 1 assume. This result is consistent with the findings of C. Liu [15] for quench of brass and steel spheres. However, the two tubes show almost the same re-wetting temperature. This is consistent with the findings of J. Hammad [11] on jet quenching of high temperature blocks made of brass and steel and the findings of A. Mozumder [19] for brass, steel and other flat surfaces.

6. Conclusions

The effects of several parameters which play a key role in quench cooling have been investigated during quench of hot horizontal tubes. There exists a range of water subcooling in which any small change in water temperature greatly affects the re-wetting delay time and the quench and the re-wetting temperatures. Surface curvature has a considerable effect on the re-wetting delay time and the re-wetting front velocity.

Empirical correlations and associated uncertainties have been developed for the phenomena studied and agree with correlations developed by othe researchers. These correlations clearly separate the quench region (region in which the vapor layer at the hot metal surface becomes destabilized with a resultant increase in heat trnafer coefficient) from the rewet region (region in which a liquid film is progressively resestablished on the hot metal surface and nucleate boiling is reestablished). Because quench is a phenomenon that is distinct from rewet, it is important to separate the two phenomena in order to appropriately represent them in nuclear safety analysis models and adequately quantify the reestablishment of cooling on heated surfaces that have experienced degraded cooling conditions.

7. Acknowledgement

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8. References

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Nomenclature

Symbol	**Unit**	**Description**
T_{in}	^oC	Initial surface temperature
T_{water}	^oC	Water temperature
T_{mfb}	^oC	Minimum film boiling temperature
T_{rw}	^oC	Re-wetting temperature
T_q	^oC	Quench temperature
V_{jet}	m/sec	Jet velocity
ΔT_{sub}	^oC	Degree of liquid subcooling

Abbreviations

LOCA	Loss of Coolant Accident
CANDU	Canada Deuterium Uranium
WQF	Water Quench Facility
DAQ	Data Acquisition System
TC	Thermocouple