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Measurement and analysis of the re-wetting front velocity during quench cooling of hot horizontal tubes

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HIGHLIGHTS

- Two phase flow & re-wetting front velocity were studied for quench of hot tubes.
- The velocity decreased as temperature difference between tube and coolant decreased.
- Increasing surface curvature was found to decrease the re-wetting front velocity.
- Increasing tube thermal conductivity decreased the velocity.
- Correlations were developed to predict the front velocity.

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ABSTRACT

When a liquid is put into contact with a hot dry surface, there exists a maximum temperature called the re-wetting temperature below which the liquid is in actual contact with the surface. Re-wetting occurs after destabilization of a vapor film that exists between the hot surface and the liquid. If re-wetting is established at a location on the hot surface, a wet patch appears at that location and starts to spread to cover and cool the entire surface. The outer edge of the wet patch is called the re-wetting front and can proceed only if the surface ahead of it cools down to the re-wetting temperature. 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. One of the important parameters in re-wetting cooling is the velocity at which the re-wetting front moves on the surface. In this study, experimental tests were carried out to investigate the re-wetting front velocity on hot horizontal cylindrical tubes being cooled by a vertical rectangular water multi-jet system. Effects of initial surface temperature in the range 400–740 °C, water subcooling in the range 15–80 °C and jet velocity in the range 0.17–1.43 m/s on the re-wetting front velocity were investigated. The two-phase flow behavior was observed by using a high-speed camera. The re-wetting front velocity was found to increase by increasing water subcooling, decreasing initial surface temperature and decreasing jet velocity. Effects of surface curvature, solid material, tube wall thickness, jet orientation, number of jets and number of tubes were also investigated. Empirical correlations for the re-wetting front velocity have been developed and provided good prediction of experimental data.

1. Introduction

The core of a CANDU reactor is contained within a large horizontal cylindrical tank called the calandria vessel. The core contains horizontal fuel channels surrounded by heavy water moderator. Each fuel channel consists of an inner tube (pressure tube) which contains the fuel, and an outer tube (calandria tube). In a critical break LOCA dryout of the outer surface of the calandria tube and a subsequent escalation in the tube temperature may occur (Jiang and Luxat, 2008; Luxat, 2002). This can lead to fuel channel failure if the tube is not re-wetted.

Other situations involving re-wetting heat transfer include hardening of metals in metallurgical industries, start-up of liquid natural gas pipe lines, microelectronic device production and filling of cryogenic vessels.

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Nomenclature

t_d	re-wetting delay time (s)
T_{in}	initial surface temperature measured at the stagnation point (°C)
T_{water}	water temperature (°C)
V_{jet}	jet velocity (m/s)
u_{rw}	re-wetting front velocity (m/s)
ΔT_{sub}	degree of liquid subcooling (°C)
a	constant in re-wetting front velocity correlation (cm/s $^\circ C^b$)
b	constant in re-wetting front velocity correlation (–)
B	constant in re-wetting front velocity correlation (s/cm)
n	constant in re-wetting front velocity correlation (s/cm)

Abbreviations

LOCA	loss of coolant accident
CANDU	Canada Deuterium Uranium
WQF	Water Quench Facility
DAQ	Data Acquisition System
fps	frames per second
NB	nucleate boiling
TB	transition boiling

Subscripts

in	initial
sub	subcooling

When a liquid is put into contact with a hot dry surface, like exposing the surface to an impinging jet of evaporable liquid, there exists a maximum temperature called the re-wetting temperature below which the liquid is in actual contact with the surface. Re-wetting occurs after destabilization of a vapor film that exists between the hot surface and the liquid. If re-wetting is established at a location on the hot surface, a wet patch appears 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. During the motion of the wet patch front, heat is removed by transition and nucleate boiling at the front and by conduction within the surface from the dry to the wet region. Due to its practical applications, the prediction of the re-wetting front velocity has been the main goal of many researchers.

Upstream of the re-wetting front, single-phase forced convection exists with absence of boiling whereas film boiling prevails downstream (Dhir, 2002). At the front itself, transition and nucleate boiling co-exist and liquid drops of several sizes are ejected from the surface and a cloud of steam is generated due to vigorous boiling. The re-wetting front is actually a thin region and usually called the "boiling region". The vigorous boiling at the re-wetting front causes the coolant to be lifted as a thin sheet from the hot surface. This lifting is most likely due to rapid vapor generation at the outer boundary of the re-wetting front. Due to surface tension, the sheet breaks down to a large number of droplets further downstream (Woodfield et al., 2005). Fig. 1 shows a typical image of re-wetting a hot tube by jet impingement. In literature, there is still confusion in determining the location of the re-wetting front edge. Locating the re-wetting edge is not an easy task as the high generation of vapor at the re-wetting front prevents clear visibility (Hammad, 2004).

Surface re-wetting is a very complex heat transfer process. Re-wetting consists of two simultaneous processes: the first process is rapid transition from film boiling to nucleate boiling heat transfer through a transition boiling region. All these modes of heat transfer can exist simultaneously at different spatial locations on the surface. The second process is rapid heat conduction within the solid.

Many studies of re-wetting of flat surfaces and vertical tubes are found in literature. Very few researchers studied re-wetting of horizontal tubes. The determination of the re-wetting front velocity on the overheated reactor core tubes is very important for predicting the rate at which the coolant can re-wet the core after a severe accident. The objective of this study is to contribute to the understanding of heat transfer during re-wetting of curved surfaces by investigating the velocity at which the re-wetting front moves on horizontal cylindrical tubes cooled by jet impingement. The detailed objectives are listed in Section 3 below. The test parameters with ranges are summarized in Table 1.

2. Literature review

Akmal et al. (2008) studied re-wetting of hot horizontal tube using impinging circular water jet. 2.54 cm outer diameter stainless steel tube was used. Effects of jet velocity, jet diameter, water temperature and initial surface temperature on the re-wetting front velocity in the axial direction were investigated. The initial surface temperature was varied between 250 and 800 °C, water temperature between 20 and 80 °C and jet velocity between 5

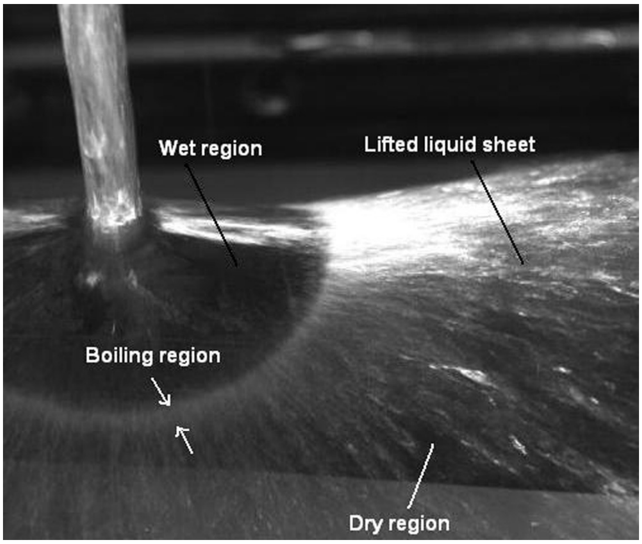

Fig. 1. Typical image of jet impingement on a hot tube.

Table 1
Test parameters and ranges.

Test parameter	Range	Unit
Initial surface temperature	400–740	°C
Water subcooling	15–80	°C
Water jet velocity	0.17–1.43	m/s
Tube diameter	25.4–5.08 (1–2)	mm (in.)
Tube thickness	1.5–3.2	mm
Tube thermal conductivity	6–109	W/m K
Number of tubes	1, 2	–
Number of jets	1, 2, 3	–