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Assessment of the process of boiling heat transfer during rewetting of a vertical tube bottom flooded by alumina nanofluid

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ABSTRACT

The present investigation focusses on the rewetting of a vertical tube bottom flooded by alumina dispersed water nanofluids. Emphasis is on the estimation of the apparent rewetting temperature and most importantly the construction of boiling curve from the temperature–time responses recorded during the rewetting phenomenon. The boiling curves provide an insight into the different regimes of boiling under flow conditions. Rewetting in nanofluids takes place faster than water. Rewetting in general, depends on coolant inlet velocity, initial wall temperature and axial location of the tube from the inlet. For nanofluids, it also depends on the concentration of nanoparticles. An earlier rewetting and an enhanced maximum heat flux exhibited by nanofluids can be attributed to the deposition of nanoparticles which results in the formation of several micro-cavities. This in turn alters the surface wettability and roughness, thereby inducing an enhanced rate of heat transfer and an earlier collapse of vapor film. The deposition of nanoparticles and its morphology, confirmed from microscopic and spectroscopic analysis, supports this conjecture.

1. Introduction

The phenomenon of rapid cooling of a dry and sufficiently hot solid is often known as quenching. However, when the temperature of the solid is much above the saturation temperature of the liquid coolant, formation of a vapor film over the surface of the solid inhibits the liquid contacting it. With time, the vapor layer collapses and the liquid wets the solid which drastically increases the rate of heat transfer. This phenomenon of re-establishment of the solid–liquid contact is known as rewetting. One of the most crucial applications of rewetting phenomenon is envisaged in nuclear reactors during the emergency core cooling after a loss of coolant accident (LOCA). The LOCA in water cooled reactors occurs when the primary cooling system becomes non-functional. The emergency core cooling system (ECCS) serves as a secondary cooling system where the coolant floods in and removes the excess heat from the nuclear reactor core. Similar occurrence of the phenomenon include cooling of superconducting magnets, LPG pipeline, cryogenic pipeline and different metallurgical processes.

Rewetting is characterized by a highly transient heat transfer process. In a closed system, rewetted by the injection of a liquid coolant, flow boiling occurs. Downstream of the quench front, the generation of an enormous quantity of vapor results in a flowing vapor–liquid mixture. The entire propagating front experiences a number of different types of flow regimes in course of wetting the solid. The rewetting phenomenon is strongly affected by the flow condition of the coolant and the orientation of the channel. Depending on this, the phenomenon is associated with a number of complexities, some of which are discussed below. When the coolant enters a sufficiently hot vertical channel from the bottom (known as bottom flooding), due to the formation of vapor film, the advancing liquid occupies only the central region of the channel, the tip of which is known as the reflooding front (shown as X in Fig. 1a). The location at every instant where the solid–liquid contact takes place is known as the rewetting front (depicted by Y in Fig. 1a) which in all cases follow the reflooding front. The generation of vapor within the channel in some events is so high that it creates a back-pressure on the advancing quench front. As a result, some oscillations are observed during the propagation of the rewetting front. In another case, when the coolant is flooded from the top (known as top flooding), the vapor generated can flow in the upward direction thereby obstructing the downward moving coolant and retarding the rate of heat transfer [1]. Additionally,

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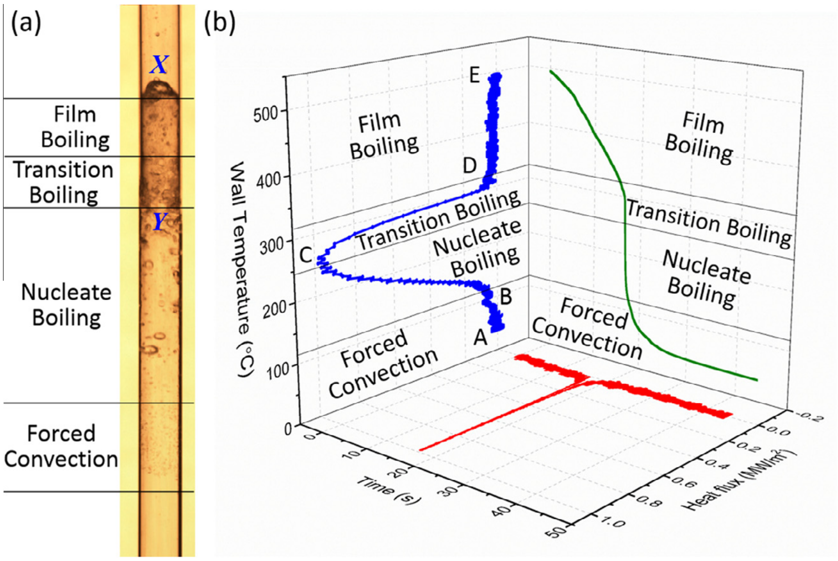

Fig. 1. (a) Photographic and (b) graphical representation of the different boiling regimes during rewetting by bottom flooding. The reflooding and rewetting fronts are marked as X and Y, respectively in (a).

the propagation of the quench front is accompanied by several instabilities downstream, such as wave generation in the inverted annular film boiling regime, fragmentation of the liquid core and formation of droplets and their further breakup [2,3].

Depending on the process parameters, different regimes of boiling, – nucleate, transition and film boiling (inverted annular flow) are observed during rewetting as shown in Fig. 1. As the process is temperature controlled, the temperature–time data is utilized to estimate the dependence of surface heat flux on time (shown in Fig. 1b) by applying a transient energy balance model (discussed in details in Section 3.4). The rewetting zone identified by the sharp fall in temperature corresponds to the peak of the heat flux–time relationship. As depicted in Fig. 1b, the heat flux does not categorically vary with time other than the region where the peak is observed. The cooling in the regions where the heat flux remains fairly constant takes place either by the superheated vapor (during the initial stages of quenching) and or by the subcooled liquid (during the later stages of quenching) both of which correspond to single phase cooling. During rewetting the two-phase cooling gives rise to a high heat flux that generates a spike or a delta function in the heat flux–time relationship. Following this, the heat flux–time relationship is mapped to a corresponding wall temperature versus surface heat flux, which is conventionally known as the boiling curve (shown in Fig. 1b) for all the three prominent regimes of boiling.

To assess the heat removal process during rewetting it is necessary to explore the different regimes of boiling by analyzing the typical boiling curves. Traditionally, the process of heat transfer may be assessed from boiling curves constructed from the experimental data of pool boiling [4,5]. In case of forced convective rewetting, the mechanism of heat transfer is markedly different compared to pool boiling due to various reasons, namely, non-uniformity of temperature of the rewetting surface, axial conduction, forced convection of coolant and the presence of different two-phase flow regimes as well as instabilities downstream of the rewetting front. Hence efforts have been made to construct the boiling curves specifically for the rewetting phenomenon [6–9]. Commonly, during rewetting the time–temperature response at a specific location is recorded. The heat flux is then predicted from the temperature history by implementing the transient heat transfer equation either analytically [7] or numerically [6]. The various parameters affecting the heat flux during rewetting are coolant flow rate, coolant inlet sub cooling, initial wall temperature, wall thickness and wall material [8,9].

During rewetting, the heat removal process from the two distinct regions, namely the dry region (film boiling) and wetted region (transition and nucleate boiling) play a crucial role. The temperature at which the transition between the two regions takes place is called the rewetting temperature. The determination of the rewetting temperature is complicated but crucial for the basic understanding of the mechanism of rewetting. Different terminology, namely minimum film boiling temperature, film boiling collapse temperature, quench front temperature and sputtering temperature have been used to describe the rewetting temperature in literature. Several parameters have been observed to influence the rewetting temperature and the advancing quench front like the coolant injection velocity, liquid sub-cooling [10], initial wall temperature [11], surface roughness of the substrate [7] and type of coolant [12,13]. Table 1 gives an overview of some of some of the correlations developed to predict the rewetting temperature. A state of the art review on rewetting temperature has been compiled by [14].

A rapid rate of cooling is often desirable particularly for applications in nuclear engineering. In recent times, researchers have been investigating the capabilities of nanofluids as an alternative heat transfer fluid with phase change. Nanofluids are a class of unique fluids that can be more precisely defined as the colloidal suspension of nanoparticles (preferably less than 100 nm in size) dispersed in a small quantity (preferably <1 vol.%) in liquids that brings in a substantial change in the property of the base fluid. The enhancement of thermal transport in nucleate boiling and a rise in the CHF for nanofluids in comparison to that of base fluid serves as a motivation for using them as an alternate boiling medium [22,23]. It is important to note that although steady state boiling and convective heat transfer of nanofluids has been widely researched for various configurations, the study of rewetting phenomenon in vertical tubes under flow boiling conditions is limited. In the recent past a group of researchers have conducted rewetting tests of a vertical tube using nanofluids [12,24–26]. After a LOCA, rapid rewetting of the reactor core is always desirable to meet the safety requirements. The enhanced rate of boiling heat transfer of nanofluids may be explored in this respect. Earlier it has been