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Cooling of very hot vertical tubes by falling liquid film in presence of countercurrent flow of rising gases

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ABSTRACT

An experimental investigation of cooling a very hot vertical tube by sudden introduction of a falling liquid film in the presence of a countercurrent flow of rising hot gases air is presented. Experiments were carried out for different rising air flow rates, flow rates of falling liquid film, initial tube temperatures and subcooling of the liquid film. Experiments showed that vapor generated during quenching of the tube can produce a countercurrent vapor velocity which exceeds the onset of flooding limit and any addition of rising air can move the situation to be more closer to zero liquid penetration limit. The results showed that the rewetting velocity (velocity of axial rewetting of the tube hot surface with the falling liquid film) increases with the decrease of initial tube temperature and decreases with the increase of air flow rate until zero quenching rate was obtained. However, the rewetting velocity slightly increased with the increase of the liquid film flow rate and liquid subcooling in case of rewetting without rising air, the presence of rising air finishes the effect of inlet liquid film flow rate and liquid subcooling on rewetting velocity. Air flow rate at which the tube cannot be totally rewetted was determined and compared with that obtained during adiabatic flooding test for the same test section and test conditions. Results were compared with previous ones and good agreement was found.

1. Introduction

Cooling of very hot vertical surfaces by sudden introduction of highly subcooled liquid is encountered in many applications. In case of using downward flow of cooling liquid, the vapor formed due to surface quenching may form countercurrent flow and adversely affect the cooling process. Moreover, the presence of rising extra vapor from other sources, and possibly non-condensable gases may strongly adversely affect the cooling process, particularly if the flooding limit is reached. In the process industries, this phenomenon is encountered in nuclear engineering, cryogenic engineering, metallurgical processes, heat pipes, boiler tubes and other industrial applications of multiphase flow. This cooling process is very relevant to CANDU (Canadian Nuclear Reactor; stand for CANada Deuterium Uranium) technology. In some sever accidents, vapor mixed with non-condensable gases may rise through the feeders against the downward flow of the emergency core cooling water injected in the headers. So the present work aims to study the effect of the addition of countercurrent flow of possibly non condensable gases to the steam generated during tubes quenching on the tube cooling and quenching process. These countercurrent flow of non condensable gases may moves the phenomena from the onset of flooding limit to complete flooding limit which constitute very critical situation and may lead to sever accident.

This process of cooling includes mainly two physical phenomena: Rewetting of hot surfaces and hydrodynamics of the liquid film in gas-water two-phase countercurrent flow. Review of literature on these two physical phenomena indicated that while an enormous amount of published information on each of the two phenomena exist, data on the rewetting of hot surfaces in the presence of countercurrent flow of rising gases are very limited.

In the area of rewetting of vertical surface, several experimental and theoretical studies were done to find the rate of rewetting of a hot surface and the effects of different parameters on this rate. In the theoretical studies, the rewetting process of a vertical hot surface was considered as conduction controlled process. Some of the previous investigators {Yamanouchi [11], Sun et al. [36,37],Elias and Yadigaroglu [42] and Olek and Zvirin [28]} considered the problem as one-dimensional conduction controlled. For high liquid flow rate, other investigators {Duffey and Porthouse [7], Coney [8], Tien and Yao [38] and Olek [27]} considered the problem as two-

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Nomenclature

D_i	tube inner diameter, m
g	gravity acceleration, m/s^2
J	superficial velocity, m/s
$\overset{*}{J}$	dimensionless superficial velocity
k	thermal conductivity, W/(m K)
$\dot{m}$	mass flow rate, kg/s
ρ	density, kg/m^3

Subscript and abbreviation

CANDU	CANada Deuterium Uranium
G	gas
L	liquid
K	G or L

dimensional conduction controlled. Starodubtseva et al. [34] carried out a numerical investigation and experimental verification of the dynamic behavior of rewetting of hot vertical surfaces by cryogenic fluid. It was shown that local motion velocity of the wetting front is not constant. Recently, Sahu et al. [31] in a comprehensive review of rewetting of hot surface, concluded that most of the studies adopt a conduction controlled approach to analyze the phenomena of rewetting. The difference among these various investigations stems from the assumed variation of heat transfer coefficient and number of heat transfer regions considered in the wall. In these studies, the hydrodynamic effect of the steam generated during the quenching process and any preexisting rising gases on the propagation of the liquid front have not considered. These may be true in bottom flooding but the case is different in cooling the tube by a falling liquid film, where the liquid film drains downwards inside the tube while the vapor moves counter currently upward. This countercurrent flow of vapor and others rising gases can cause flooding to the liquid film and delay the cooling process and in this case the rewetting velocity predicted by the conduction controlled model becomes invalid.

Several experimental studies {Duffey and Porthouse [8], Elliott and Rose [13]; Lee et al. (1978) [21], Ueda and Inoue [39], and Lee and Chen [22], Shibamoto et al. [32]} have been done to investigate the effects of the system variables, including initial wall temperature, mass flow rate of the liquid film, inlet subcooling of the liquid film, heat capacity of the wall, surface finish of the wall and pressure of the system on the rewetting rate. In these studies no rising gases was introduced and the steam generated during the quenching process was forced to move cocurrently with the liquid film Saxena et al. [33] conducted experimental studies to study the rewetting behavior of a hot vertical annular channel, with hot inner tube, for bottom flooding and top flow rewetting conditions. Walker et al. (2012) [43] conducted a study to physical explain micro-scale high frequency sputtering during rewetting of PWR fuel cladding during post − LOCA reflood. Later Sahu et al. [30], conducted an experimental investigation on rewetting by injecting water from the top of a hot vertical heater to study effect of several coolant injection systems on the hydrodynamics of rewetting Muhammad et al. [23] carried out an experimental study on the rewetting of heated vertical surfaces during top/bottom reflooding.

Countercurrent gas–liquid two phase flow in which liquid flow downwards in the inner surface of the tube and gas flows upward in the core of the tube is often encountered in many important applications in the power and process industries. In gas liquid countercurrent flow in a vertical pipes two important hydrodynamic limitations exist. For a given liquid feed rate and low upward flow of gas all the liquid feed is able to penetrate the tube downwardly. As the upward flow of gas increases, the first hydrodynamic limit is reached when for a given upward gas flow, the liquid down flow at the bottom of the tube cannot be increased by further increasing liquid supply at the top. This limitation is called the onset of flooding limitation. Beyond the onset of flooding, the supply liquid is split into two parts, one part penetrates downwards and the second part is carried up by the rising gases. By further increase upward gas flow, the downward flow of liquid is decreased until the second hydrodynamic limitation is reached when the liquid penetration rate at the bottom of the tube reached zero. This second limitation is called zero liquid penetration limit or complete carry up limit. Due to the lack of complete understanding of the physical mechanisms responsible for initiating flooding, dimensional scaling parameters were suggested for correlating experimental data. One of the most commonly used correlations for the onset of flooding was suggested by Wallis [40] in the form,

$$\overset{*}{J}_G^{1/2} + m\overset{*}{J}_L^{1/2} = C \tag{1}$$

where the dimensionless superficial velocity $\overset{*}{J}_K$($K = G$ for gas phase and $K = L$ for liquid phase) represents the ratio between the inertia and buoyancy forces and defined by:

$$\overset{*}{J}_K = J_K\left\{\frac{\rho_K}{gD(\rho_L - \rho_G)}\right\}^{1/2} \tag{2}$$

asnd J is the superficial velocity, defined by: $J_K = \dot{m}_k/\pi(D^2/4)\rho_k$. The constants m and C were found by many investigators to be in the ranges $0.5 < m < 1.0$ and $0.7 < C < 1.0$ depending on the test section geometry. Many investigators, such as Hewitt and Wallis [6], Clift et al. [10], Dukler and Smith [16], Shoukri et al. [35] and Noel et al. [26] have correlated their flooding data according to Eq. (1).

In theory, Wallis' type correlation can predict liquid penetration rate through partial flooding up to the point of zero-liquid penetration. The critical gas flow required to zero-liquid penetration can be obtained from Eq. (1) by setting $J_L = 0$ giving

$$\overset{*}{J}_{G\ \text{critical}} = C^2 = \text{Cons}. \tag{3}$$

Wallis [40] proposed the following correlation:

$$\overset{*}{J}_{G\ \text{critical}} = 0.5 \tag{4}$$

Shoukri et al. [35] correlated their data according to Eq. (3) to obtain $C^2 = 1.02$ and $C^2 = 0.78$ for increasing gas flow and decreasing gas flow test procedures, respectively.

A very limited published work was presented on the interaction between rewetting and flooding during the quenching of hot vertical tubes by a falling liquid film in the presence of rising hot gases Guerrero and Lowe [15] showed experimentally that the vapor generated during the rewetting of a hot vertical tube can produce countercurrent flow rate which exceeds the flooding limit and delay the rewetting process. In their experiments, water was introduced into a high temperature vertical tube and the generated vapor was constrained to vent either from the top of the tube or from the top and the bottom together. Later, Chan and Grolmes (1975) [5] presented a theoretical study for transient cooling of a hot vertical tube by a falling liquid film to check if the vapor generated during the quenching of the tube is sufficient to reach onset of flooding or not. Also Block and Wallies [4], presented a theoretical study on rewetting of vertical surfaces limited by flooding caused by the generated vapor Duffey et al. [9] showed the