International Journal of Thermal Sciences 99 (2016) 85–95

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Semi analytical parametric study of rewetting/quenching of hot vertical tube by a falling liquid film in the presence of countercurrent flow of rising vapors

S.A. Nada*, H.F. Elattar

Department of Mechanical Engineering, Benha Faculty of Engineering, Benha University, Benha, 13511 Qalyubia, Egypt

ARTICLE INFO

Article history:
Received 1 February 2015
Received in revised form
13 June 2015
Accepted 12 August 2015
Available online 9 September 2015

Keywords:
Quench front propagation
Rewetting velocity
Countercurrent flow
Flooding limits

ABSTRACT

Vapor generated during rewetting/quenching of hot vertical surfaces/tubes by a falling liquid film forms countercurrent flow to the quench front propagation. This vapor in addition to the possibly rising vapors from other sources resist the downward propagation of the quench front and may cause partially or complete flooding of the injected liquid. The present work develops a semi analytical model to parametrically study the rewetting/quenching rate of a hot vertical tube by a falling liquid film in terms of initial tube temperature, flow rate of rising vapors, tube thickness and cooling water injection and penetration rates. Momentum, energy and conduction-controlled equations are used to find the model governing equations. Correlations for liquid penetration rate and interfacial friction factor driven from experimental data were incorporated in the model. The resulting governing equations were solved iteratively to study the effects of the controlling parameters on the quench front propagation velocity. Conditions of onset of flooding and complete flooding in terms of the controlling parameters are deduced and discussed. Results are compared with available experimental results and good agreement was obtained.

1. Introduction

Rewetting/Quenching of hot vertical surfaces by a falling liquid film is encountered in many industrial applications like nuclear reactors and cryogenic systems. Vapors generated during quenching have to be vent countercurrently upward resulting in slow down the quench front propagation and limit the liquid film penetration rate. Moreover, the presence of rising vapors from other sources adversely affect the problem. This cooling process is particularly relevant to CANDU technology where in some postulated accidents in CANDU reactors vapor generated during cooling process, mixed with vapor from other sources, may rise through the feeders against the downward flow of the emergency core cooling water injected into the headers and adversely affect quench front propagation.

Literature review indicated that while an enormous amount of experimental and analytical studies of quenching/rewetting of hot vertical surface have been conducted, data on quenching of hot surfaces in the presence of countercurrent flow of rising vapors are very limited. Recently, Nada et al. [1] and Nada [2] conducted experimental investigations to study the effect of vapor generated from rewetting process and possibly gases from other sources on the rewetting rate of a vertical tubes by a falling liquid film. These studies were conducted for a specific geometric, operating and controlling parameters such as tube temperature and liquid film rates. The literature review show that no analytical works take the effect of the countercurrent flow of rising vapor on the rewetting process. The unavailability of such analytical works and the limitations of the applicability of the results of Nada et al. [1] and Nada [2] for specific geometric and operating parameters motivate the necessary of the present work. Therefore, the present work aims to analytically generalize the problem and parametrically study the phenomena for a wide range of the controlling parameters: tube dimensions, tube surface temperature, liquid injection rate and rate of countercurrent flow of rising vapors.

Most of previous analytical studies [3–11] have not considered the hydrodynamic effects of the vapor generated during the quenching process and the possibility of simultaneous countercurrent flow of vapors and other gases. Some of these studies [3–7]

---

* Corresponding author. Tel.: +20 1066611381.
E-mail address: samehnadar@yahoo.com (S.A. Nada).

http://dx.doi.org/10.1016/j.ijthermalsci.2015.08.007
1290-0729/

Nomenclature

C	specific heat J/(kg K)
D	tube inside diameter, m
f	interfacial friction factor
g	acceleration of gravity, m/s^2
h	heat transfer coefficient, W/(m^2 K)
h_{fg}	latent heat of vaporization, J/kg
h_i	interfacial heat transfer coefficient, W/(m^2 K)
J_V	vapor superficial velocity, m/s
J_V^*	dimensionless vapor superficial velocity
k	thermal conductivity, W/(m K)
M_P	liquid penetration rate, kg/s
$\dot{m}$	mass flow rate, kg/s
Pr	Prandtl number
q	heat flux, W/m^2
$\overline{U}$	quench front propagation velocity in presence of countercurrent flow of vapor, m/s
U_R	rewetting velocity in the absence of vapor countercurrent flow, m/s
U_V	countercurrent vapor velocity, m/s
Re	Reynolds number, dimensionless
T	temperature, °C
t	time, s
x	coordinate along the axis of the tube, m
y	coordinate normal to the axis of the tube, m

Greek symbol

α	thermal diffusivity, m^2/s
δ	liquid film thickness, m
ε	wall thickness, m
ξ	mass fraction of vapor in vapor-gas mixture
μ	dynamic viscosity, kg/(m s)
ρ	density, kg/m^3
τ	shear stress, N/m^2

Subscribt

G, g	gas
ff	free falling film
i	interfacial
L	liquid
Lf	liquid film
o	free falling film
R	rewetting
s	saturation
q	quench front
V	vapor
VI	inlet vapor
VG	generated vapor
Wi	injected water
w	wall

proposed one-dimensional conduction controlled models to predict the rewetting rate, while others [8–12] used two-dimensional conduction controlled models. Recently, Sahu et al. [13], 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. Lists of heat transfer coefficients and number of regions used by previous investigators were given by Elias and Yadigaroglu [14]. Starodubtseva et al. [15] and Pavlenko et al. [16] carried out numerical investigations and experimental verification of the dynamic behavior of rewetting of hot vertical surfaces by cryogenic fluid. The effects of the liquid flow rate and the tube temperature on the dynamic behavior was presented. It was shown that local motion velocity of the wetting front is not constant.

On the other side, several experimental studies [17–27] 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 liquid film, heat capacity of the wall, direction of flooding, surface finish of the wall, pressure of the system and gravity on the rewetting phenomenon and rewetting rat rate. 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 been 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 countercurrently upward. Countercurrent flow of rising gases represents additional hydrodynamic resistance to the propagation of the liquid film along the hot surface leading to the possible onset of flooding and ultimately delaying the cooling process. Guerrero and Low [28] showed experimentally that the vapor generated during the rewetting of a vertical pipe can produce countercurrent flow of vapor which exceeds the onset flooding limit (vapor upward velocity at which it can carry part of the downward falling liquid with it) and delay the rewetting process. Duffey et al. [29] obtained experimental data which showed that the propagation of the quench front during the rewetting of a hot vertical rod placed inside a glass tube was decreased with the increase of the countercurrent flow of air injected in the annulus between the rod and the tube. Later, Chan and Grolmes [30] and Block and Wallis [31] presented theoretical studies to examine whether the vapor generated during the quenching of a hot vertical tube is sufficient to reach the onset of flooding or not. Recently Nada et al. [1] and Nada [2] published experimental investigations to study the effect of vapor generated from rewetting process and possibly air from other sources on the rate of rewetting of a vertical tubes by a falling liquid film. The studies showed that the countercurrent flow of generated vapors and rising air adversely affect the rewetting rate. The study revealed that the vapor generated during the tube quenching can exceed the onset of flooding and limit the penetration of the liquid film. The present work aims to analytically treat the problem to parametrically study the phenomena for a wide range of the controlling parameters; tube dimensions, tube surface temperature, liquid injection rate and rate of countercurrent flow of rising vapors. Data of Nada [1] were utilized to identify the falling liquid/upward vapor interfacial parameters needed by the analytical model.

2. Physical model and assumptions

The physical model, as shown in Fig. 1, is a hot vertical tube in which a rising vapor flows upward and a liquid film is injected the top of the tube to quench it. The tube is initially at a temperature higher than the rewetting temperature. The liquid film advances downwards under the resistance of the countercurrent flow of the rising vapors. The liquid film is firstly cool down the tube to the