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

A R T I C L E I N F O

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

Keywords:
Quench front propagation
Rewetting velocity
Countercurrent flow
Flooding limits

A B S T R A C T

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

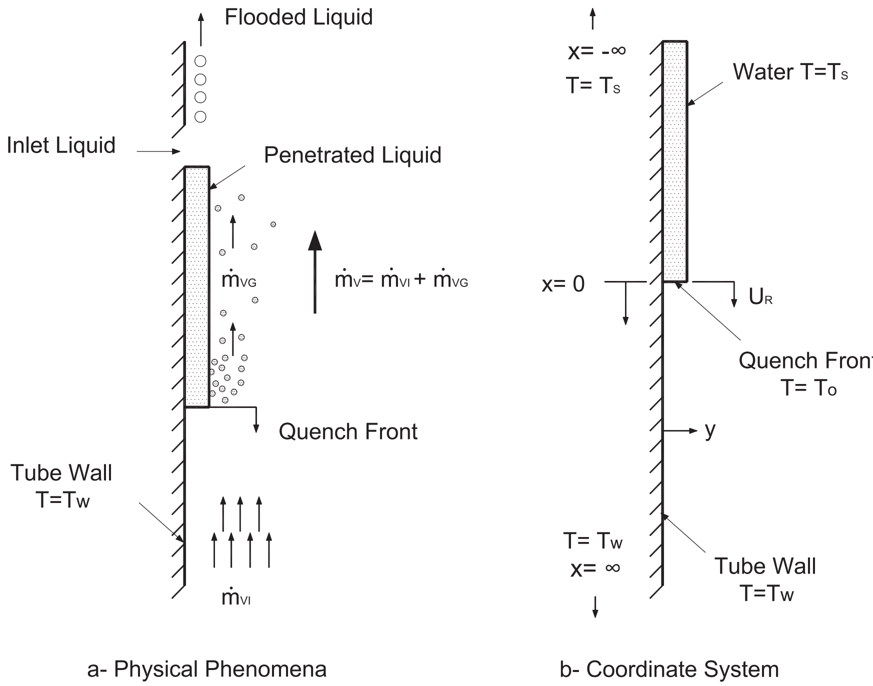

Fig. 1. Physical model of rewetting of vertical tube by falling liquid film in presence of countercurrent flow of rising vapors.

rewetting temperature at which the tube surface begins to rewet. The vapor generated during the quenching process constitute a part of the rising hot vapors where the other part is a vapor coming at the bottom of the tube from other sources. The countercurrent flow of rising vapors slow down liquid front propagation and may reach to a value that can reverse some of the injected liquid. To simplify the analysis of this complex process, the following assumptions are employed.

- Cooling of the tube occurs by axial conduction in upward direction from $x = 0$ to $x = -\infty$ (see Fig. 1).
- laminar liquid film flow.
- Liquid film thickness is uniform and very small as compared to the tube diameter,
- The penetrated liquid film is at saturation temperature.
- The thickness of the wall is small enough to give low Biot number ($Bi = h\ \delta/k$) so that the temperature gradient in the tube thickness is neglected as compared to the axial direction (i.e. $Bi/T_W((T_W - T_R)/(T_W - T_s)) \leq 1$) and the assumption of one dimensional heat conduction can be accurately considered in the analysis [32].
- The physical properties of the liquid film and the tube wall are constant
- The inertia of the falling liquid film and the pressure gradient are small compared to the gravity force.
- Quench front velocity is constant along the tube.

3. Mathematical analysis and governing equation

In liquid–gas countercurrent flow in vertical tube, the momentum equation can be written in the form:

$$\mu_L \frac{d^2U}{dy^2} = -\rho_L g \tag{1}$$

The boundary conditions of Eq. (1) are

$$U = 0 \quad \text{at} \quad y = 0,$$

$$\mu_L \frac{dU}{dy} = \tau_i, \quad \text{at} \quad y = \delta$$

where $\tau_i = 1/2\rho_V(U_V - U)^2 f_i$ is the interfacial shear stress between the falling liquid film and the rising gases which can be further simplified by neglecting the liquid film velocity U with respect to the gas velocity U_V

$$\tau_i = -\frac{1}{2}\rho_V U_V^2 f_i \tag{2}$$

Solving Eq. (1) under the given boundary conditions, the liquid film velocity can be obtained in terms of the rising gas velocity and the liquid film thickness as follows:

$$U(y) = -\frac{1}{2}\frac{g\delta^2\rho_L}{\mu_L}\left[\left(\frac{y}{\delta}\right)^2 - 2\left(\frac{y}{\delta}\right)\right] - \frac{1}{2}\frac{\rho_V U_V^2 f_i}{\mu_L} y \tag{3}$$

The average velocity of the liquid film across the liquid film thickness can be obtained by:

$$\overline{U} = \frac{1}{\delta}\int_0^\delta U(y)dy = \frac{g\delta^2\rho_L}{3\mu_L}\left\{1 - 0.75\rho_V U_V^2 f_i/(\rho_L g\delta)\right\} \tag{4}$$

The mass flow rate of the falling liquid film can be calculated from:

$$M_P = \pi D\delta\rho_L\overline{U}, \quad \text{therefore}$$

$$\delta = \frac{M_P}{\pi D\rho_L\overline{U}} \tag{5}$$

Substituting by Eq. (5) in Eq. (4) and rearrange, one can get

$$\overline{U} = \left(\frac{gM_P^2}{3\mu_L\rho_L(\pi D)^2}\right)^{1/3}\left(1 - 0.75\rho_V U_V^2 f_i\left(\frac{\pi D}{gM_P}\right)\overline{U}\right)^{1/3} \tag{6}$$

where the first term $(gM_P^2/3\rho_L\mu_L\pi^2D^2)^{1/3}$ represents the velocity of a free falling liquid film (i.e. at $U_V = 0$) and will be denoted by U_0. Therefore, Eq. (6) becomes

$$\overline{U} = U_o\left(1 - 0.75\rho_V U_V^2 f_i\left(\frac{\pi D}{gM_P}\right)\overline{U}\right)^{1/3} \tag{7}$$

The first term in the R.H.S of Eq. (7) represents the free falling film velocity (U_0) while the second term represents the effect of the rising gas flow on the falling film velocity. Eq. (7) is valid for tubes of moderate temperatures ($T_W < T_R$), where, T_W and T_R are the initial tube wall temperature and the rewetting temperature (tube wall Temperature at which the liquid start to rewet it).

In case of a very hot tube ($T_W > T_R$), the physical mechanism of moving the liquid film on the tube will be different. The heat conduction along the tube controls the propagation of the liquid film on the surface and the liquid film velocity is further retarded by the need to cool down the quench front zone to the rewetting temperature. In this case the free falling liquid film velocity U_0 in Eq. (7) is retarded to the conduction controlled rewetting velocity U_R. Furthermore the vapor generated during tube quenching will be added to the preexisted countercurrent vapor and adversely affect the quench front propagation. According to this physical mechanism and by analogy to Eq. (7), the expression for the quench front propagation velocity in cooling very hot vertical tube ($T_W > T_R$) in the presence of rising hot vapor can be written in the following form:

$$\overline{U} = U_R\left(1 - 0.75\rho_V U_V^2 f_i\left(\frac{\pi D}{gM_P}\right)\overline{U}\right)^{1/3} \tag{8}$$

where U_V is the counter current vapor velocity of the mixture of the preexisted vapor and the vapor generated during tube quenching.

Literature review reveals that a lot of work have been conducted on the subject of rewetting of hot surfaces by free falling liquid film to estimate U_R. It is generally accepted that the experimental data can be reasonably well described by means of conduction models which assumes that the quench front velocity is determined by the rate at which heat can be conducted from the hot dry surface through the metal to the wetted area. Considering the physical model of this study, vertical hot surface with coolant supply from above as shown in Fig. 1-b, the heat conduction equation inside the tube wall thickness can be written in the form:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{1}{\alpha_W}\frac{\partial T}{\partial t} \tag{9}$$

Considering the assumptions of constant rewetting velocity with respect to time [6,33,34] and, consequently, if a moving x coordinate coincides with the wetting front was considered, the following rate equation can be written:

$$U_R\frac{\partial T}{\partial x} = -\frac{\partial T}{\partial t} \tag{10}$$

Substituting Eq. (10) in Eq. (9), one can get

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{U_R}{\alpha_W}\frac{\partial T}{\partial x} = 0 \tag{11}$$

The boundary conditions of Eq. (11) are

$T = T_R$ at $x = 0$

$T = T_s$ at $x = -\infty$

$T = T_W$ at $x = \infty$

For a thin wall and one-dimensional heat conduction assumption, Eq. (11) have been initially solved by Yamanouchi [3] to give the rewetting velocity U_R in terms of the initial tube temperature T_W, the rewetting temperature T_R and the heat transfer coefficient h at the quench front as follows:

$$U_R = \frac{1}{\rho_W C_W}\left(\frac{hk_W}{\varepsilon_W}\right)^{1/2}\frac{T_R - T_s}{(T_W - T_s)^{1/2}(T_W - T_R)^{1/2}} \tag{12}$$

In the last equation the rewetting temperature T_R and the heat transfer coefficient h at the quench front are unknown. The heat transfer coefficient in quench front wetted area h is variable and depends on the local wall temperature in the vicinity of the quench front as well as the liquid penetration rate. In previous work either a simplified linearized heat transfer coefficient in a certain range of temperature variation near the front in the wetted zone is considered or estimating the value for the heat transfer coefficient so that the experimental results of the rewetting velocity may be predicted by the model. In this semi analytical study, the common practice of the second technique is used. One of the well-known correlation for the heat transfer coefficient is that of Yamanouchi [3] which obtained from the experimental data as a function of the water flow rate in the form:

$$h = 8.4 \times 10^6 \quad M_P^{0.5} \tag{13}$$

where h is in W/m.k and M_P is in kg/s. Literature review of the subject of rewetting temperature reveals that an average value of rewetting temperature of 260 °C is consistent with the finding of the experimental measurements [1,2,12,13], so this value is considered in the present work.

Eqs. (6)–(8) and (12) contains the falling liquid penetration rate M_P. The falling liquid penetration rate is equal to the injected liquid rate in case that rising gases rate is not sufficient to achieve the onset of flooding limit. In case of achieving onset of flooding limit, part of the injected liquid will be reversed and flooded at tube top and the other part will be penetrated downwards. In this situation, the downward penetration rate of the liquid is limited by the onset of flooding phenomenon. After the onset of flooding limit, the liquid penetration rate can be obtained using available correlations and models developed for two-phase countercurrent flow limitation (CCFL). It is typically a function of the rising gas flow rate, tube diameter, thermophysical properties of the two phases and the geometry of the gas entrance at the bottom of the test section. Countercurrent flow limitation (CCFL) has been studied extensively because of its relevance to many industrial applications. The most popular way of correlating the onset of flooding data is in the form suggested by Wallis [34],

$$\overset{*}{J}_V{}^{1/2} + m\overset{*}{J}_V{}^{1/2} = C \tag{14}$$

where m and C are empirical constants which are dependent on the characteristics of the test section. They are typically in the range $0.4 < m < 1.0$ and $0.7 < C < 1.0$. The dimensionless velocity of phase K (K = G for gas (vapor) and K = L for liquid) is the ratio between the inertia and buoyancy forces,

$$\overset{*}{J}_K = J_K\left(\frac{\rho_K}{gD(\rho_L - \rho_V)}\right)^{1/2} \tag{15}$$

where J_K is the phase superficial velocity, defined by $J_K = \dot{m}_k/\pi(D^2/4)\rho_k$. If the flooding characteristics of the test section is known, i.e. m and C, one can calculate the liquid penetration rate $M_P = (\pi/4)D^2\rho_L J_L$ from Eq. (15) for a given upward gas/vapor

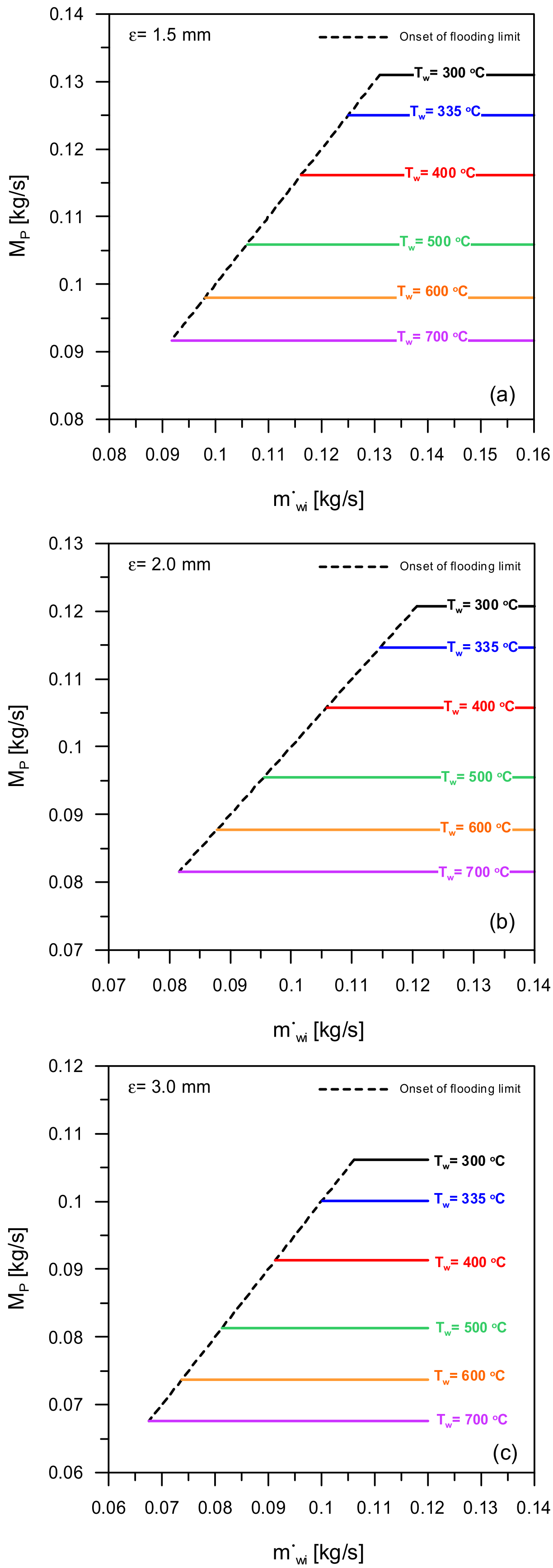

Fig. 2. Variation of liquid penetration rate with water injection rate.

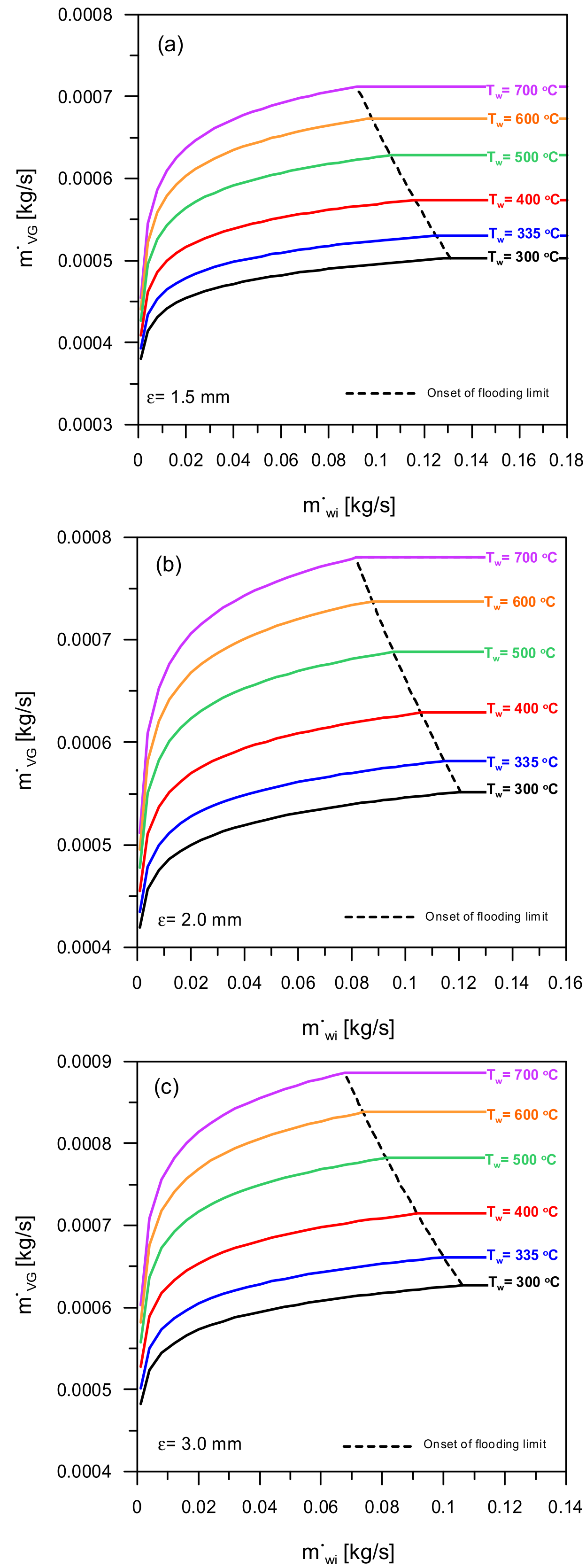

Fig. 3. Variation of vapor generation rate with water injection rate.

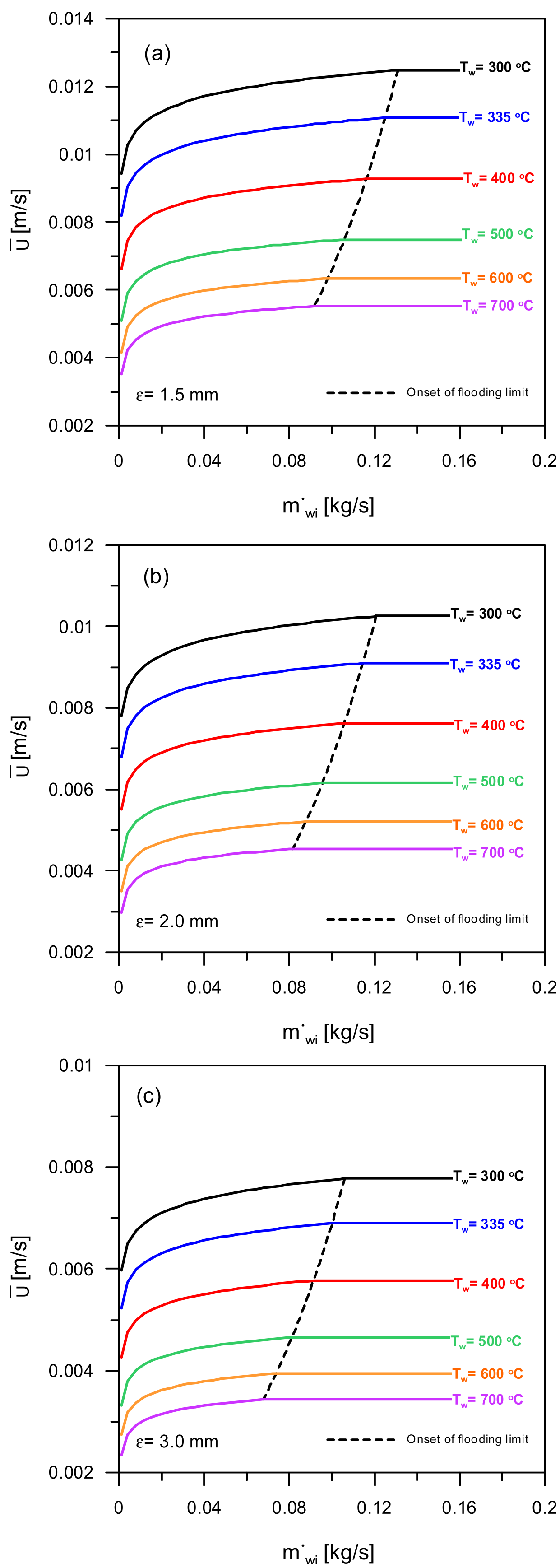

Fig. 4. Variation of quench front propagation velocity with water injection rate.

mixture flow rate. Nada [2] performed adiabatic countercurrent gas–liquid flow in 22 mm diameter pipe and was able to correlate his data with Eq. (14) in which m = 0.46 and C = 0.738.

In Eqs. (2)–(8), (14), (15) the upward vapor flow ($\dot{m}_V$), upward gas velocity (U_V) and the upward gas superficial velocity (J_G) should be calculated based on the summation of the inlet vapor flow rate ($\dot{m}_{VI}$) and the vapor generation rate ($\dot{m}_{VG}$). The inlet vapor flow rate ($\dot{m}_{VI}$) simulate all possible vapors that may come from sources other than the generated vapor during tube quenching. Accordingly the upward gas superficial velocity and the upward gas velocity takes the following form:

$$J_G = \frac{4}{\rho_g \pi D^2}(\dot{m}_{VI} + \dot{m}_{VG}) \tag{16}$$

$$U_V = \frac{4}{\pi \rho_V (D-2\delta)^2}(\dot{m}_{VI} + \dot{m}_{VG}) \cong \frac{4}{\pi \rho_V D^2}(\dot{m}_{VI} + \dot{m}_{VG}) \quad (\text{Neglecting } \delta \text{ w.r.t } D) \tag{17}$$

where ρ_V is the density of the vapor.

Estimation of the vapor production rate $\dot{m}_{VG}$ during the quenching process is necessary to calculate the total upward gas velocity. Referring to Fig. 1, the energy balance of the falling liquid film gives:

$$q_{Lf} = q_W \tag{18}$$

where,

$q_{Lf} = \dot{m}_{VG}\overline{h}_{fg}$ (heat gained by the liquid film and utilized in vapor generation)
$q =$ (heat released from the tube by the liquid film) $= \pi D \varepsilon \rho_W c_W \overline{U}(T_W - T_s)$

Therefore,

$$\dot{m}_{VG} = \frac{\pi D (T_W - T_s)\rho_W c_W \varepsilon \overline{U}}{\overline{h}_{fg}}, \tag{19}$$

As shown in Eq. (19), the rate of vapor generation is a function of the unknown rewetting velocity $\overline{U}$. The process of deriving Eq. (19) implicitly use the transformation co-ordinates from time to axial

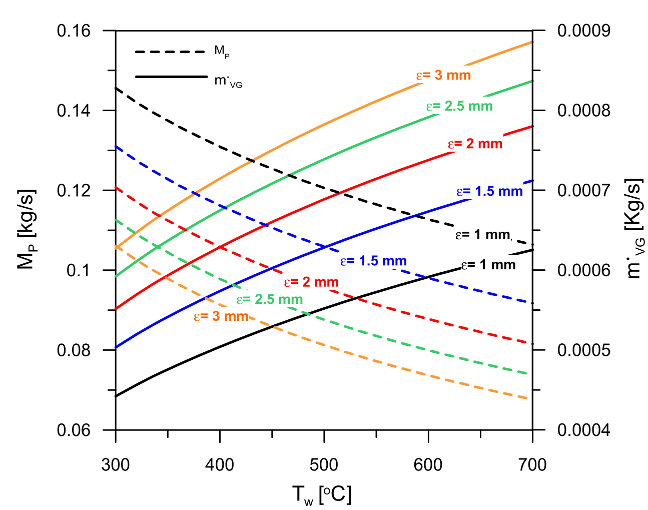

Fig. 5. Variation of vapor generated rate with initial tube temperature and tube thickness.

direction via rewet velocity. This has already reported in a lot of literature such as Duffy–Porthouse [8].

Considerable research has been carried out to determine the interfacial friction coefficient between a falling liquid film and rising gas. Wallis [36] and Bharathan [37] used the momentum equation with the help of experimental data to develop correlations for f_i in case of adiabatic air–water countercurrent flow. Grolmose et al. [38] used the momentum equation and the onset of flooding data to obtain a correlation for the interfacial friction factor. Duffey et al. [29] suggested that the value of the interfacial friction factor be 300 times the friction factor for gas flow in dry tube. All of these correlations were obtained on the basis of adiabatic data and their applicability in the present case may not be appropriate. The experimental results of Nada [39] on the rewetting of hot tubes by falling liquid film in the presence of countercurrent flow of rising gases together with the film momentum equation and the quench front propagation equations are used to develop a correlation for the interfacial friction factor between the falling liquid film and rising vapors on the form;

$$f_i = 104 \times 10^6 (\delta/D)^{2.52} \quad (20)$$

4. Results

The above equations were solved iteratively to yield the rewetting velocity of the falling film in terms of the initial wall temperature, tube thickness, countercurrent vapor flow rate and injected water flow rate. The ranges of the studied parameters were as follows:

Initial tube temperature (T_W)	300–700 °C.
Inlet vapor flow rate ($\dot{m}_{VI}$)	0–0.002 kg/s.
Tube wall thickness (ε)	0.5–3 mm.
Injected water flow rate ($\dot{m}_{WI}$)	0.01–0.2 kg/s.

Two cases will be studied; in the first case countercurrent flow of only the vapor generated during quenching process is considered and no additionally vapor from other sources are considered. In the second case, countercurrent flow of a combination of the vapor generated during quenching process and possibly vapors from

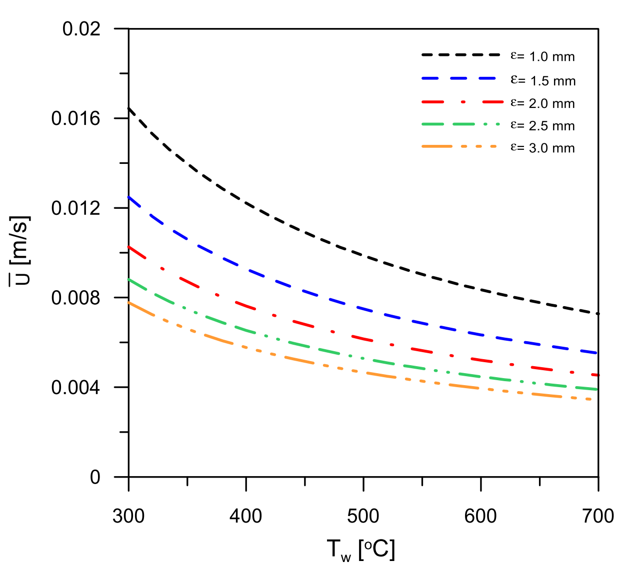

Fig. 6. Variation of quench front propagation velocity with initial tube temperature and tube thickness.

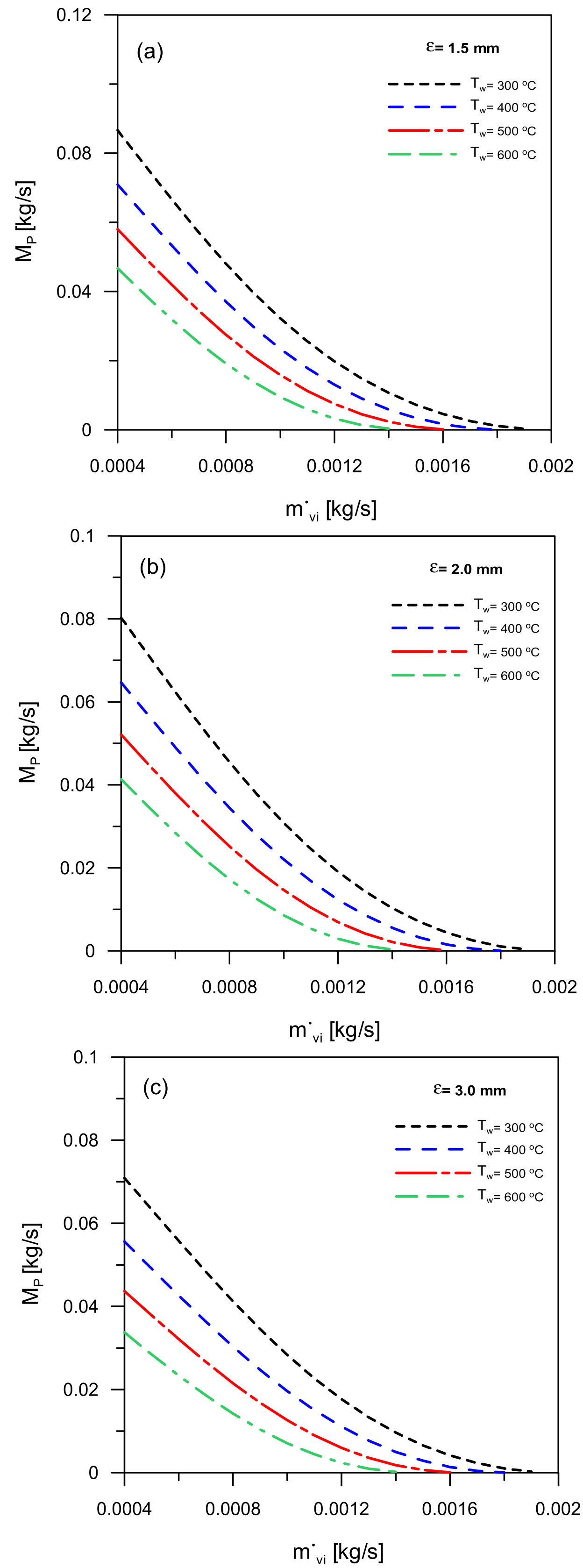

Fig. 7. Variation of liquid penetration rate with vapor rate from other sources.

other sources are considered. In both cases the effects of the controlling parameters on rewetting and flooding process are investigated and analyzed. The onset of flooding and complete flooding conditions are also investigated. The model predictions were compared with the available experimental data.

4.1. Vapor generated rate and water penetration rate

Vapor generated during tube quenching moves upward and forms a countercurrent flow to the falling liquid film. The rate of vapor generated depends on tube initial temperature, heat capacity and tube wall thickness, rewetting velocity and liquid penetration rate. These parameters affect each other in a complex form. If the vapor generated rate is higher than the countercurrent gas flow rate at the onset of flooding of the injected water flow rate ($\dot{m}_{WI}$), some of the injected water will be flooded upward, and this reduces the amount of water penetrated resulting in slowing down the quench front propagation along the test section.

Figs. 2–4 show the variation of the liquid penetration rate, vapor generation rate and quench front propagation velocity with the injected water flow rate at different initial tube temperatures and tube thickness. At certain initial tube temperature, Fig. 2 shows that at low inlet water flow rate, all the injected water penetrates downwards in the tube (dash line in Fig. 2) until the inlet water flow rate reaches a certain value at which the vapor countercurrent flow $\dot{m}_{VG}$, which increase with $\dot{m}_{wi}$ as shown in Fig. 3, reaches a value sufficient to cause onset of flooding limit after which the penetrated water flow rate remains constant whatever the increase of the inlet water flow rate. Fig. 2 shows that the onset of flooding limit and the liquid penetration rate decreases with the increase of the initial tube temperature and the tube thickness and this can be attributed to the increase of the vapor generated rate due to the increase of stored thermal energy in the tube that released during tube quenching.

For a specific initial tube temperature, Fig. 3 shows the increase of the vapor generated rate with the increase of the injected water flow rate until it reaches a certain limit (onset of flooding limit), the vapor generated rate becomes constant whatever the injected water flow rate. This can be attributed to the increase of the quench front propagation velocity with the increase of the liquid penetration rate (see Fig. 4) before the onset of flooding limit and the constantan of the penetrated water flow rate after the onset of flooding limit (see Fig. 2) which leads to constant propagation velocity of the quench front (see Fig. 4). Fig. 3 also shows the increase of the vapor generation rate with the increase of the initial tube temperature and the tube thickness and this can be attributed to two contradictory effects for vapor generation. One is to the decrease of the rewetting velocity which leads the reduction of $\dot{m}_{VG}$ and the second is to the increase of the heat stored in the tube that released during tube quenching. The effect of the increase of the heat stored is more dominant.

For a specific initial tube temperature, Fig. 4 shows the increase of the quench front propagation velocity with the increase of the injected water flow rate until the flooding limit is reached, the quench front velocity becomes constant. This can be attributed to two contradictory effects for quench front velocity. One is the increase of the heat transfer coefficient at the quench front region with the increase of the liquid penetration rate (see Eqs. (8) and (12)) and the second is the increases of the vapor generated rate (see Fig. 4) which leads to the decreases of the quench front propagation velocity as per Eq. (8). The effect of the increase of the heat transfer coefficient is more dominant. Fig. 4 also shows the increase of the quench front propagation velocity with the decrease of the initial tube temperature. This can be attributed to the

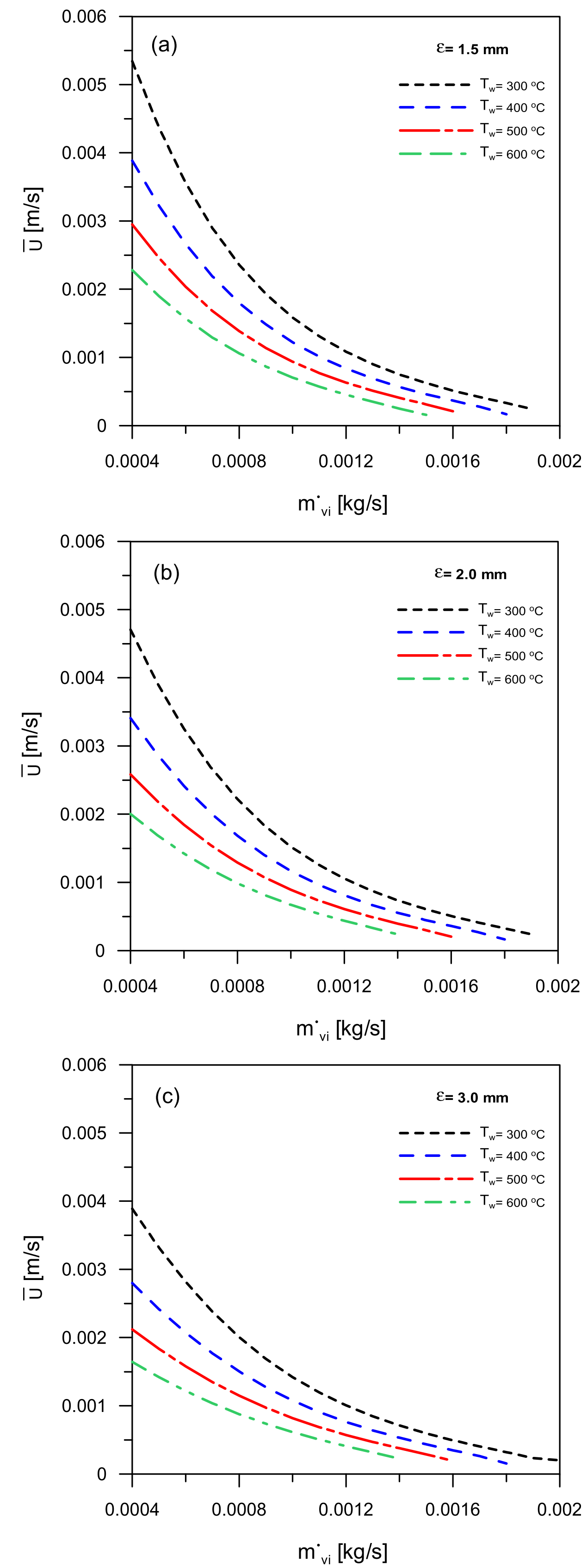

Fig. 8. Variation of quench front propagation velocity with vapor rate from other sources with T_w as a parameter.

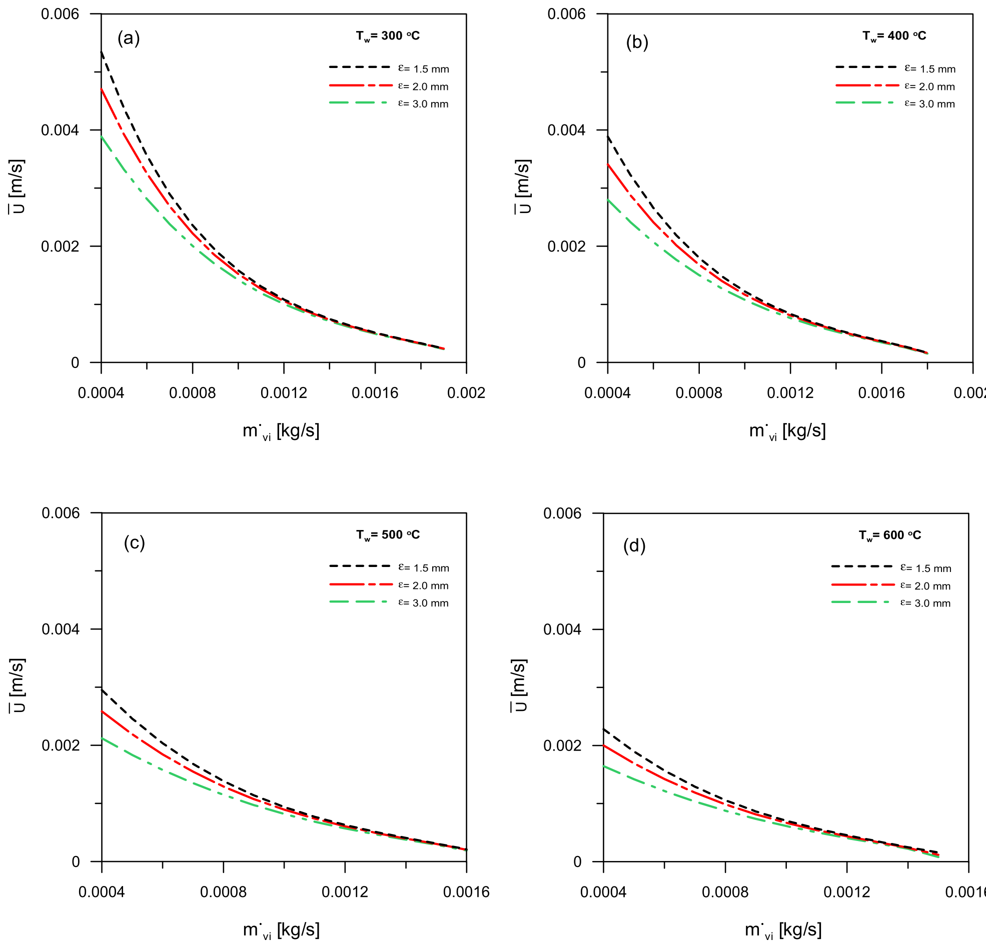

Fig. 9. Variation of quench front propagation velocity with vapor rate from other sources with ε as a parameter.

increase of U_R and the decrease of the vapor generated rate with the decrease of the initial tube temperature (see Eq. (12)).

Figs. 3 and 4 also show that the onset of flooding limit occurs much faster (i.e. at low injected water flow rate) with the increase of the initial tube temperature and the tube thickness and this is attributed to the increase of the vapor generated rate which accelerate the occurrence of the flooding limit.

4.2. *Effects of tube temperature and tube thickness at high injected water rates*

It is clear from the discussion of the previous section that to increase the quench front propagation rate, the water should be injected at a rate higher than the flooding limit to maximize the liquid penetration rate which will equal to the water flow rate at the flooding limit. Providing that the injected water flow rate is higher than the flooding, Figs. 5–6 show the variation of vapor generated and liquid penetration rates and quench front propagation velocity with initial tube temperature and tube thickness. As shown in Fig. 5, the vapor generation rate increases and the liquid penetration rate decreases with the increase of the initial tube temperature and the tube thickness. This can be attributed to the increase of the thermal energy stored in the tube that released during the tube quenching. Increasing the released thermal energy stored increases the vapor generation rate and consequently decreases the liquid penetration rate. The decrease of liquid penetration rate with the increase of vapor generation rate is supported by Eq. (14) and the results of Wallis [35].

The variation of quench front propagation velocity with the initial tube temperature and the tube thickness is shown in Fig. 6. The figure shows the decrease of the quench front propagation velocity with the increase of the initial tube temperature and the tube thickness. This can be attributed to the increase of the thermal storage in the tube with the increase of the initial tube temperature and the tube thickness. As per Eq. (12) increasing tube thermal storage by increasing T_w and ε decrease U_R and increases vapor generated rate and both decreases quench front propagation velocity U as per Eqn. (8). Moreover, increasing the initial tube temperature and tube thickness decreases liquid penetration rate (see Fig. 5) and this decreases quench front propagation velocity.

4.3. *Effect of possible countercurrent flow of vapor from other sources*

The possibility of presence vapor from other sources increases the countercurrent flow of the rising vapor. If the countercurrent flow of the rising vapor increases to a certain limit complete flooding may occurs and no liquid will penetrated to quench/cool down the tube. Fig. 7 shows the effect of the mass flow rate of the other source vapor ($\dot{m}_{VI}$) on the liquid penetration rate with the initial tube temperature as a parameter. As shown in the figure increasing ($\dot{m}_{VI}$) dramatically decreases the liquid penetration rate until complete flooding is reached (liquid penetration rate = 0). The figure also shows that the complete flooding point occurs at lower ($\dot{m}_{VI}$) with increasing initial tube temperature and the tube thickness due to the increase of the vapor generated.

Figs. 8 and 9 show the variation of the quench front propagation velocity with $\dot{m}_{VI}$ for different initial tube temperatures and tube thicknesses. Increasing $\dot{m}_{VI}$ decreases the quench front propagation velocity until it reaches zero at the complete flooding point. This can be attributed to the decrease of the liquid penetration rate and the increase of the interfacial shear stress between the rising vapor and the falling liquid film and both decrease the quench front propagation velocity. Figs. 8 and 9 also show the decrease of the quench front propagation velocity with the increase of the initial tube temperature and the tube thickness due to the increase of the released heat stored in the tube which leads to more vapor generation rate. Fig. 9 shows the convergence of the effect of the tube thickness with the increase of $\dot{m}_{VI}$. This can be attributed to that at higher ($\dot{m}_{VI}$) the liquid penetration rate is very limited (see Fig. 7) and the quench front propagation velocity becomes very low and both limit the rate of release of the thermal energy stored in the tube and the vapor generation rate whatever the tube thickness.

The value of $\dot{m}_{VI}$ at complete flooding conditions $(\dot{m}_{VI})_{C.F}$ can be obtained from Fig. 9 by extending the curve until intersect the horizontal axis. Fig. 10 shows the variation of $(\dot{m}_{VI})_{C.F}$ in a dimensionless form $(J^*_{VI})_{C.F}$ with the initial tube temperature. As shown on the figure the value of $(J^*_{VI})_{C.F}$ decreases with the increase of the initial tube temperature. This can be attributed to the increase of the vapor generation rate with the increase of the initial tube temperature and this means that a smaller value of ($\dot{m}_{VI}$) will be sufficient to reach the flooding limit.

4.4. Model verification and comparison with previous experimental work

For the model verification, the predictions of the model is compared with the results of Nada et al. (2014) in Fig. 11 for the case of quenching without possible rising vapors from other sources. As per the literature review no data are available to compare with it for the case of quenching in the presence of rising vapors from other sources. As shown in Fig. 11, the model is capable of predicting the data trends correctly and is in good general agreement with the measured rewetting velocity. Fig. 11 shows that the deviation between the model predictions and the experimental data of Nada et al. (2014) are within ±15%.

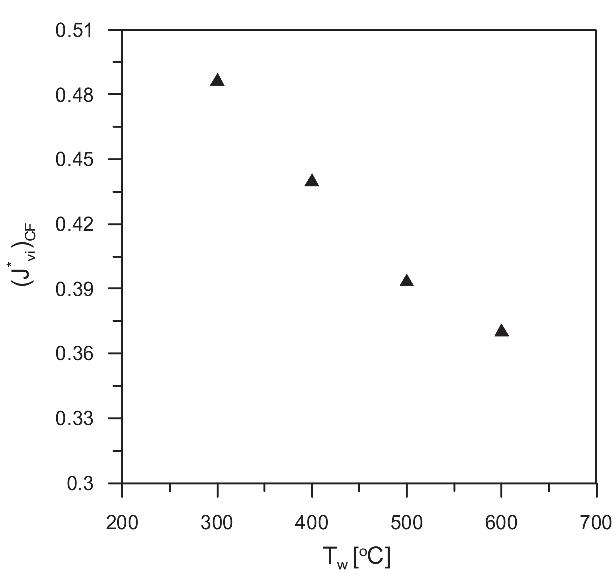

Fig. 10. Variation of dimensionless inlet vapor flow rate at complete flooding conditions with the initial tube temperature.

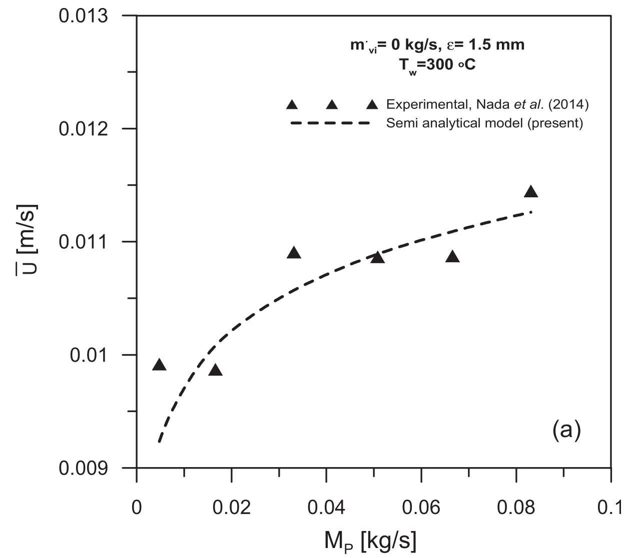

Fig. 11. Comparisons of present model prediction with previous experimental work.

5. Conclusions

The conclusion of the present study can be summarized in the following points:

- A semi analytical model, with appropriate set of correlations deduced from relevant experimental work, can successfully predict the rewetting rate in the presence of countercurrent flow of rising vapor in terms of the controlling parameters.
- The model is capable to predict onset of flooding and complete flooding limits.
- The results show the decrease of the quench front propagation velocity with increasing initial tube temperature and tube thickness and decreasing liquid penetration rate.
- The onset of flooding limit and the liquid penetration rate decreases and the vapor generation rate increases with increasing initial tube temperature and tube thickness.
- Increasing rate of vapor from other sources dramatically decreasing the liquid penetration rate and the quench front until complete flooding is reached
- Occurrence of complete of flooding point is accelerated with increasing initial tube temperature and the tube thickness.

References

[1] S.A. Nada, M. Shoukri, A.F. El-Dib, A.S. Huzayyin, Rewetting of hot vertical tube by a falling liquid film with different directions of venting the generated steam, Int. J. Therm. Sci. 85 (2014) 62–72.
[2] S.A. Nada, Cooling of very hot vertical tubes by falling liquid film in presence of countercurrent flow of rising gases, Int. J. Therm. Sci. 88 (2015) 228–237.
[3] A. Yamanouchi, Effect of core spray cooling in transient state after loss of coolant accident, J. Nucl. Sci. Technol. 5 (1968) 547–558.
[4] K.H. Sun, G.E. Dix, C.L. Tien, Cooling of a very hot surface by a falling liquid film, ASME J. Heat. Transf. (1974) 126–131.
[5] K.H. Sun, G.E. Dix, C.L. Tien, Effect of precursory cooling on a falling-film rewetting, ASME J. Heat. Transf. (1975) 360–365.
[6] E. Elias, G. Yadigaroglu, A general one-dimensional model for conduction control rewetting of a surface, Nucl. Eng. Des. 42 (1977) 185–194.
[7] S. Olek, Y. Zvirin, The effect of temperature dependent properties on the rewetting velocity, Int. J. Multiph. Flow. 11 (1985) 577–581.
[8] R.B. Duffey, D.T.C. Porthouse, The physics of rewetting in water reactor emergency core cooling, Nucl. Eng. Des. 25 (1973) 379–394.
[9] M.W.E. Coney, Calculations on the rewetting of hot surfaces, Nucl. Eng. Des. 31 (1974) 246–259.
[10] C.L. Tien, L.S. Yao, Analysis of conduction-controlled rewetting of a vertical surface, ASME Trans. J. Heat Transf. (1975) 161–165.

[11] S. Olek, The effect of precursory cooling on rewetting of a slab, Nucl. Eng. Des. 108 (1988) 323–330.
[12] Y. Sibamoto, Y. Maruyama, T. Yonomoto, Rewetting front propagation under anticipated operational occurrences for boiling water reactors – development of two-dimensional analytical model, J. Nucl. Sci. Technol. 50 (2) (2013) 148–159.
[13] S.K. Sahu, P.K. Das, S. Bhattacharyya, Analytical and semi-analytical models of conduction controlled rewetting: a state of the art review, Therm. Sci. Online First (2013), 10.2298/TSCI121231125S.
[14] E. Elias, G. Yadigaroglu, The reflooding phase of the LOCA in PWRs, part II. Rewetting and liquid entrainment, Nucl. Saf. 19 (1978) 160–175.
[15] I.P. Starodubtseva, A.N. Pavlenko, O.A. Volodin, A.S. Surteav, The features of rewetting dynamics of overheated surface by a falling film of cryogenic liquid, Thermophys. Aeromech. 19 (2) (2012) 307–316.
[16] A.N. Pavlenko, A.S. Surtaev, A.N. Tsoi, I.P. Starodubtseva, V.S. Serdyukov, Dynamics of superheated surface rewetting with a falling liquid film, High. Temp. 52 (6) (2014) 861–868.
[17] D.F. Elliott, P.W. Rose, The quenching of a heated zircaloy surface by a film of water in a steam environment at pressure up to 53 bar, React. Dev. Div. AEE Winfrrith (1971).
[18] Y. Lee, W.J. Chen, D.C. Groeneveld, Rewetting of a very hot vertical and horizontal channels by flooding, in: 6th International Heat Transfer Conference, Canada, 1978, pp. 95–100.
[19] Y. Lee, W.Q. Chen, Effect of surface roughness on the rewetting process, Int. J. Multiph. Flow. 13 (1987) 857–861.
[20] T. Ueda, M. Inoue, Y. Iwata, Y. Sogawa, Rewetting of hot surfaces by a falling liquid film, Int. J. Heat. Mass Transf. 26 (1983) 401–410.
[21] Yasuteru Shibamoto, Yu Maruyama, Hideo Nakamura, Measurement and analysis for rewetting velocity under post-BT conditions during anticipated operational occurrence of BWR, J. Eng. Gas. Turbines Power 132 (10) (2010).
[22] A.K. Saxena, V.V. Raj, V.G. Rao, Experimental studies on rewetting of hot vertical channel, Nucl. Eng. Des. 208 (2001) 283–303.
[23] S.P. Walker, M. Ilyas, G.F. Hewitt, The rewetting of PWR fuel cladding during post-LOCA reflood: a proposed physical explanation for the micro-scale highfrequency sputtering observed, Proc. Inst. Mech. Eng. Part A J. Power Energy 226 (3) (2012) 384–397.
[24] S.K. Sahu, P.K. Das, S. Bhattacharyya, An experimental investigation on the quenching of a hot vertical heater by water injection at high flow rate, Nucl. Eng. Des. 240 (2010) 1558–1568.
[25] I. Muhammad, A. Masroor, P.H. Colin, S.P. Walker, G.F. Hewitt, Rewetting process during top/bottom re-flooding of heated vertical surfaces, in: ASME/JSME 2011 8th Thermal Engineering Joint Conference, 2011. T10187-T10187-9.
[26] Y. Mitsutake, M. Monde, R. Kawabe, Transient heat transfer during quenching of a vertical hot surface with bottom flooding, in: J. Padet, F. Arinc (Eds.), Proc. Intern. Symp. on Transient Convective Heat and Mass Transfer in Single and Two Phase Flows, Begell House, 2003, pp. 257–266.
[27] B. Verthier, G.P. Celata, G. Zummo, C. Colin, J. Follet, Effect of gravity on film boiling heat transfer and rewetting temperature during quenching, Microgravity Sci. Technol. 21 (1) (2009) 185–191.
[28] H.N. Guerrero, P.A. Lowe, Exploratory single-tube top flooding gravity-feed heat transfer tests, ANS Trans. 18 (1974) 234.
[29] R.B. Duffey, M.C. Ackerman, B.D.G. Piggott, S.A. Fairbairn, The effect of countercurrent single and two-phase flows on the quenching rate of hot surfaces, Int. J. Multiph. Flow. 4 (1978) 117–140.
[30] S.H. Chan, M.A. Grolmes, Hydrodynamically-controlled rewetting, Nucl. Eng. Des. 34 (1975) 307–316.
[31] J.A. Block, G.B. Wallis, Heat transfer and fluid flows limited by flooding, AICHE Symp. Ser. (1978) 73–82.
[32] M.E. Mosaad, Rewetting of hot vertical surfaces by a falling liquid film, Heat Transfer-Asian Res. (4 APR 2015), http://dx.doi.org/10.1002/htj.21178. Article first published online.
[33] R.A. Nelson, Forced-convection post-CHF heat transfer and quenching, Trans. ASME 104 (1982) 48–54.
[34] G. Yadigaroglu, R.A. Nelson, V. Teschendorff, Y. Murao, J. Kelly, D. Bestion, Modeling of reflooding, Nucl. Eng. Des. 145 (1993) 1–35.
[35] F.P. Incropera, D.P. DeWitt, Introduction to Heat Transfer, John Wiley & Sons Inc., New York, 1990.
[36] G.B. Wallis, One Dimensional Two Phase Flow, McGraw-Hill, New York, 1969.
[37] D. Bharathan, Air-water Countercurrent Annular Flow in Vertical Tubes, Electrical Power Institute Report, 1978. EPRI NP-786.
[38] M.A. Grolmes, G.A. Lambert, H.K. Fauske, Flooding in vertical tubes, Symposium on Multi-Phase Systems, University of Strathclyde, Glasco, Scotland.
[39] S.A. Nada, Quenching of Hot Vertical Tube by a Falling Liquid Film in the Presence of Rising Hot Gases (Ph. D thesis), Faculty of Engineering, Cairo University, Egypt, 1997.