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Rewetting of hot vertical tubes by a falling liquid film with different directions of venting the generated steam

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ABSTRACT

An experimental study of quenching of a hot vertical tube by sudden introduction of a falling liquid film was investigated under different methods of venting the generated steam. The steam generated during the quenching process may form a countercurrent vapor velocity which exceeds the onset of flooding limit causing flooding of the liquid film and resisting the propagation of the quench front delaying the rewetting process. To study the effect of this steam countercurrent flow, experiments were carried out in three stages. In the first stage, the tube was closed from top to force the steam generated to be vented from bottom. In the second stage, both ends of the tube were opened to allow venting of the steam from both ends. In the third stage, the tube was closed at bottom and the steam was vented from top. The results showed that, the rewetting velocity in case of bottom steam-venting is higher than that in case of top and bottom steam-venting which in turn is higher than that in case of top steam-venting. For the three methods of steam venting, the quenching velocity decreases with increasing the initial tube temperature and the inlet liquid temperature and decreasing the liquid flow rate. Experimental correlations for rewetting velocities were deduced from experimental data for different cases of steam venting directions. Predictions of equations were compared with the present and previous experimental data and good agreement was found.

1. Introduction

Cooling of a very hot vertical surface by sudden introduction of highly subcooled liquid is encountered in many engineering applications. If the hot surface is cooled by downward flow of cold liquid, the vapor formed due to surface quenching may form countercurrently upward flow. This countercurrent upward flow may adversely affect the rewetting (quenching) and the refilling process, particularly if the flooding limit is reached. The relevance of the work for practical situation is encountered in nuclear engineering, heat pipes, boiler tubes and other industrial applications of multiphase flow. The process is very relevant to nuclear reactors technology, whereas in case of postulated loss of coolant accident, the reactor is shut off and the vapor inside the pressure tubes becomes highly superheated. This vapor raises the temperature of the feeder pipes. At the same time, the emergency cooling water is injected into the headers and reaches the core through the feeder pipes. The cooling water moves downwards in the feeders and quenches their surfaces under the resistance of the steam generated during the quenching process.

This process of cooling involves, in interaction shape, both hydrodynamics of the liquid film in vapor-water two-phase countercurrent flow and the thermal phenomena involved in the quenching process. Review of the literature on these two physical phenomena, rewetting of hot surfaces and countercurrent flow, indicated that while an enormous amount of published information on each of the two phenomena exists, data on the interaction between the two phenomena are very limited.

In the area of rewetting of hot surfaces, numerous theoretical and experimental investigations were undertaken to find the rate of rewetting of a hot surface and the effects of the different parameters on it. In the theoretical studies, the rewetting process of vertical surfaces was considered as conduction controlled process. Some of the previous investigators [31,26,27,8,19] considered the problem as one-dimensional conduction controlled. For high liquid flow rates, others investigators [5,6,28,18] considered the problem as two dimensional conduction controlled. The difference among these various investigation stems from the assumed variation of the heat transfer coefficient and the number of heat transfer regions considered in the wall. Lists of the heat transfer coefficients and the

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number of regions used by the previous investigators were given by Ref. [9]. Ref. [25] 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, Ref. [22] 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. In view of this, various analytical and semi-analytical techniques have been used to solve the conduction equation.

Several experimental studies [6,10,14,15,29,23] have been done to investigate the rewetting process and to show the dependence of the quench front velocity on the system variables, including initial wall temperature, mass flow rate of the liquid film, subcooling of the liquid film, heat capacity of the wall, surface finish of the wall and pressure of the system. These studies showed a complicated dependence of the quench front velocity on these system variables. In these experimental studies, the steam generated during the quenching process is forced to move concurrently with the liquid film.

Ref. [11] showed experimentally that the vapor generated during the rewetting of a hot vertical pipe can produce countercurrent flow which exceeds the flooding limit and delay the rewetting process. Ref. [4] presented a theoretical study to check if the vapor generated during the quenching of a hot vertical tube is sufficient to reach onset of flooding or not. Ref. [3] presented a theoretical study to find the rate of heat flux applied on a vertical oriented internal flow which is necessary to generate steam to cause flooding. Ref. [7] showed the retardation of the propagation of the quench front during the rewetting of a hot vertical rod placed in a glass tube with the increase of the countercurrent flow of rising air which was injected in the annulus between the rode and the tube. Ref. [24] 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. The study showed that rewetting velocity increases with an increase in flow rate of water and it decreases with an increase in the initial surface temperature and the rewetting velocity was higher in the case of rewetting under bottom flooding conditions as compared to that in the case of rewetting under top flow conditions. These conclusions agree with the conclusions reported in the earlier literature. Ref. [30] conducted a study to physically explain micro-scale high frequency sputtering during rewetting of PWR fuel cladding during post-LOCA reflood. Later Ref. [21], 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. Ref. [16] carried out an experimental study on the rewetting of heated vertical surfaces during top/bottom reflooding. The existence of a cyclic bursting phenomenon at the quench front has been observed. Temperature measurements indicate that the metal surface temperature at the rewetting front is close to the homogeneous nucleation temperature. More recently Ref. [20], observed experimentally that a large volume of steam generated during cooling process and comes out through the top of the test section expelling a significant amount of the coolant. This countercurrent flow of steam–water mixture has an adverse effect on cooling.

Above literature reveals that in most of the theoretical and experimental studies, the hydrodynamic effect of the countercurrent flow of steam, which is generated during the quenching process, on the propagation of the liquid film front is not considered. This may be true in bottom flooding but not in cooling by a falling liquid film, where the liquid film drains down the tube while the vapor moves countercurrently upward. This countercurrent flow of vapor can cause flooding to some of the injected liquid film and in the same time resists the propagation of the penetrated liquid film resulting in delaying the cooling process. In this case the rewetting velocity predicted by the conduction-controlled model becomes invalid.

The purpose of the present study is to investigate, experimentally, the effect of the hydrodynamics of the steam generated during the quenching process on the rewetting velocity. Also the effects of initial tube temperature, inlet liquid flow rate and inlet liquid temperature on the rewetting velocity were investigated under different methods of venting the generated steam.

2. Experimental arrangements

2.1. Experimental facility

A schematic of the test loop is presented in Fig. 1. The loop consisted mainly of three parts: test section, air circulating system and liquid circulating system. The test section was a vertical Stainless-Steel (SUS 304) tube having 2000 mm length, 25.4 mm outside diameter and 1.5 mm wall thickness. The tube was fitted with 8 k-type thermocouples of 0.5 mm diameter embedded on the outer surface of the tube at five axial locations (TS1–TS5) as shown in Fig. 2. The thermocouple junctions passed to the mid thickness of the tube before adhesion. The junctions sense the arrival of water front inside the tube at its axial location through dramatically decrease in junctions temperatures. Thermal diffusivity of tube section is small so the relative time lag of sensing the liquid front arrival by thermocouple response is negligible. This procedure is supported by literature work of rewetting surfaces [6,10,14,29,15,24]. A heating tape was wrapped around the tube to accelerate the process of heating and improve the uniformity of temperature along the surface of the tube. In the air circulating system, the air coming from the air line at 7 bar was passed through a pressure regulator to reduce the air pressure to a value sufficient to circulate the air inside the loop. Pressure, temperature and flow rate of the air were measured downstream the pressure regulator by a pressure transducer, thermocouple and venturi meter, respectively. The air was then heated electrically in an air heater. The outlet hot air from the heater was injected into the test section through the lower plenum to heat the test section to the required temperature. After the test section reached the required temperature, the air flow was bypassed across the test section and the heating tape was switched off.

The liquid circulating system consisted of main tank, circulating pump, filter, piping system, valves and sinter section. The water inside the main tank was heated electrically by an immersed heater to the desired temperature. Then the water was pumped, filtered, metered and passed to the test section or returned to the main tank through the bypass line. Firstly, the water was passed through the bypass line until the required conditions were accomplished, then the water was injected to the test section through a sinter section. The water flow rate and water temperature at the inlet of the test section were measured by a turbine flow meter and a thermocouple probe, respectively. A sinter section was used to supply the water to the test section in the form of a liquid film. The inner tube of the sinter section was an extension of the test section tube and had 350 holes of 1 mm diameter each. Water enters the test section through these fine matrix of holes in the form of a liquid film.

2.2. Experimental procedure

The experimental procedure during each run was as follows: The required water flow rate and water temperature were first set up during the flow of the water through the bypass line. The air heater and the heating tape were switched on. The heated air was

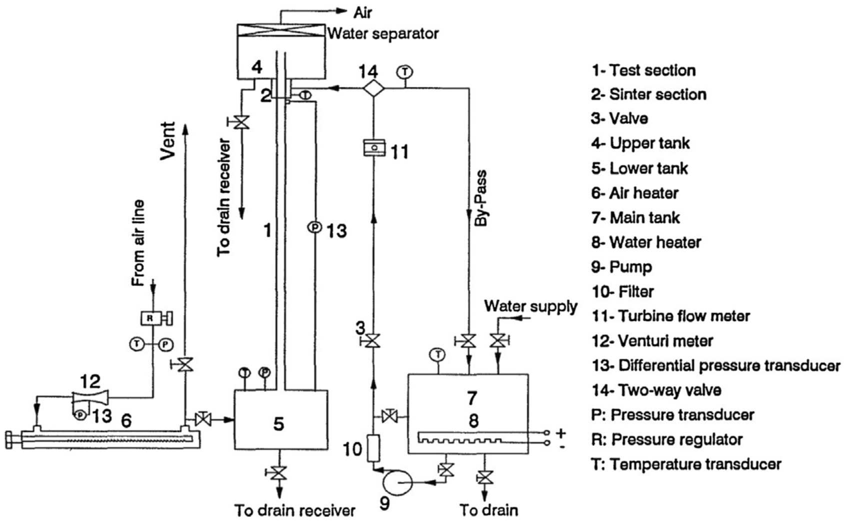

Fig. 1. Schematic of experimental facility.

passed through the test section to heat it to the desired initial tube temperature. When the desired initial tube temperature was reached, the air supply was bypassed across the test section and the heating tape was turned off and then the direction of steam venting was set by opening or closing the valves at the two ends of the test section. At this time, the scanning program was set and water was injected to the test section by turning the bypass valve. The scanning program was continued until the tube was totally rewetted. The measurements taken by the data acquisition system during the scanning process were the transient readings of the thermocouples on the surface of the test section, the reading of the thermocouples at the inlet of feed water and the inlet water flow rate. The water carried up by the generated steam to the upper tank was also collected and measured. Rate of water carried up (L/min) was estimated by measuring time of water collecting and amount of water collected.

All thermocouples were calibrated in a constant temperature path and a measurement accuracy of ± 0.2 °C was obtained. The turbine flow meter used for measuring inlet water flow rate was calibrated and a measuring accuracy of 98.5% was obtained. Accuracy of measuring tube diameter, tube thickness and axial distance along tube length were 0.0001 m and 0.001 m, respectively. Accuracy of time measurement by data acquisition system through lab View software was 0.1 s. The uncertainty in rewetting velocity (axial length on the tube/time consumed by the quench front to travel this length) was estimated based on the procedure of [12] and the uncertainty range was within 1.2–4.7%.

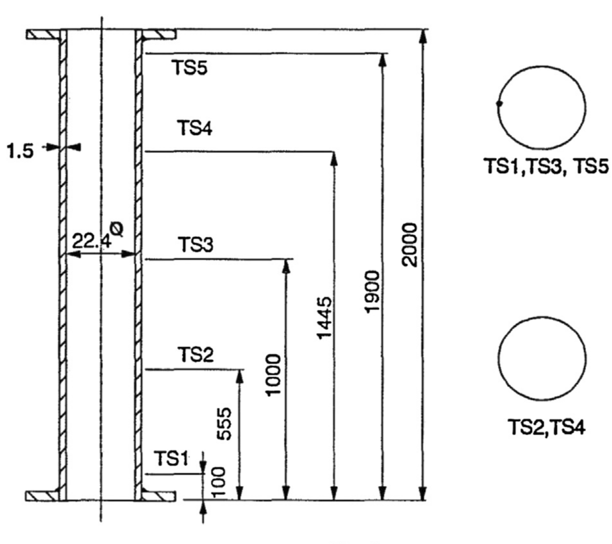

Fig. 2. Thermocouples stations along test section.

2.3. Test matrix

The conditions tested during the experiments were in the ranges:

Direction of steam venting	Down, down and up and up
Initial tube surface temperature	250–335 °C
Inlet water flow rate	0.32–5 L/min
Inlet water temperature	22–80 °C

3. Results

3.1. Transient tube wall temperature

The transient wall temperature curves at the different axial locations of the test section for the three different methods of steam venting are shown in Fig. 3(1). As shown in the figure, the time required to totally rewet the test section with bottom steam-venting is much smaller than that with both top and bottom steam-venting. Also, the rewetting time of the test section in the case of top and bottom steam-venting is smaller than that in the case of top steam-venting. This was observed for all the experiments. This is attributed to the amount of steam vented from the top of the test section. This amount of steam in case of top venting is larger than that in the case of top and bottom steam-venting. This steam vented from the top of the test section forms a countercurrent flow to the falling liquid film and resists its motion. Also, this countercurrent steam flow could cause flooding and reduce the rate of water penetration and, accordingly, increase the time required by the quench front to totally rewet the test section. No steam is vented from the top of the test section in case of bottom venting and all the injected water is penetrated downward and quenches

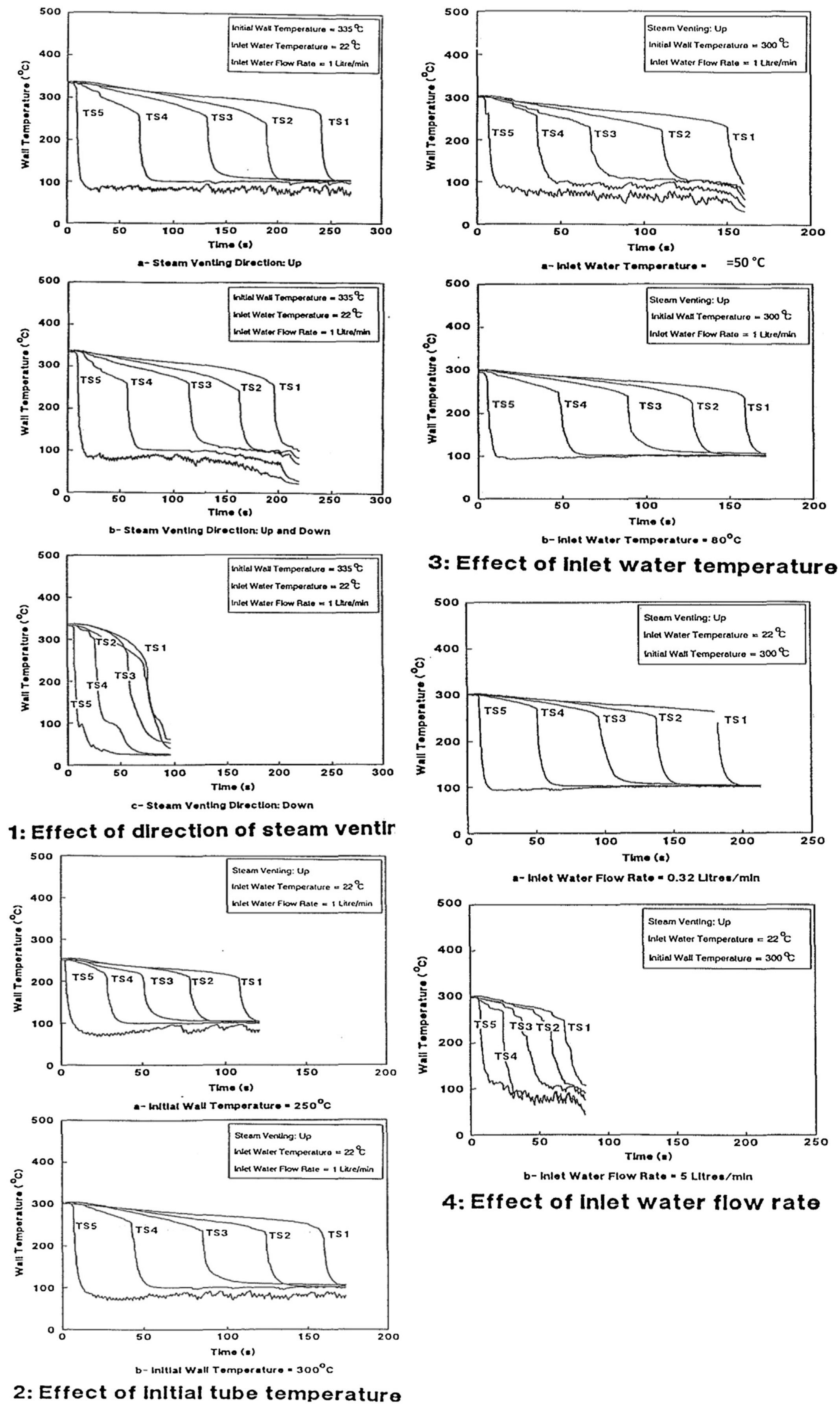

Fig. 3. Effect of different parameters on transient wall temperature.

the test section, and this makes the rewetting time very small as compared with the other two cases.

It appears from Fig. 3 that, with the exception of the first thermocouple station (TS5), the apparent rewetting (quench) temperature is almost constant independent on the location. The apparent quench temperature for the first axial thermocouple station is higher than those at downstream locations. This could be caused by: a – High local water subcooling at the first locations; the decrease in the liquid subcooling increases the time period of film boiling before the quenching process. b – Long precursory cooling period at downstream locations; this precooling is due to heat loss from the test section to the surroundings and, also, due to the sputtering of the liquid film which occurs at the quench front during its movement along the test section. Sometimes this sputtering of the liquid film, especially in the case of bottom steam-venting, causes disorder in the transient response of any thermocouple, like that of TS2 in Fig. 3(1-c).

Moreover, Fig. 3 shows that, after complete quenching of the test section, the temperature near the top of test section remains lower than those of lower thermocouple stations which are approximately at the saturation temperature. This may be attributed to high local subcooling of liquid film at the upper thermocouple station of the test section. Afterward, the liquid film becomes saturated due to heat gained from wall of the test section.

The effects of different parameters such as initial tube temperature, inlet water temperature and inlet water flow rate on the temperature transient at different axial locations of the test section are shown in Fig. 3(2)–(4), respectively. As shown in these figures, the rewetting time of the test section increases with the increase of initial tube temperature and inlet water temperature and decreases with the increase of inlet water flow rate.

3.2. Characteristics of flooding phenomenon during quenching process

In all experiments of the third stage of the experimental work (rewetting with bottom steam venting), the test section was closed from the top and the generated steam was forced to move downward along the test section. Accordingly, there was no possibility of flooding to occur.

In the first and second stages of experiments with top and top and bottom steam-venting, all or part of the generated steam moves upward and forms a countercurrent flow to the falling liquid film. If the flow rate of this upward steam is larger than the countercurrent gas flow rate at the onset of flooding corresponding to this injected water flow rate, some of the injected water will be flooded to the upper tank, and this reduces the rate of water penetration through the test section which, in turn, results in slowing down the quench front propagation along the test section.

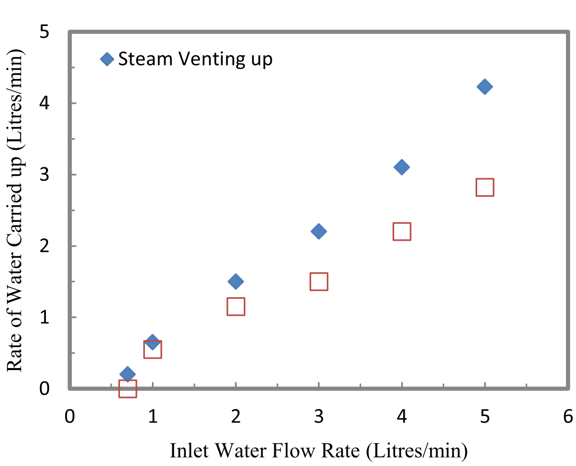

Fig. 4. Variation of average rate of water carried up with inlet water flow rate.

In all experiments of this phase, except only one series of experiments (low inlet water flow rate and low initial tube temperature), it was found that the upward flow rate of steam generated, even with top and bottom venting, was sufficient to reach and pass the limit of onset of flooding. This was indicated by the water flooded to the upper tank. Fig. 4 shows the average rate of water carried up to the upper tank during the quenching process for two cases of steam venting, namely top venting and top and bottom venting. This figure shows clearly that, allowing the steam to vent at the top results in higher flooding rate. Moreover, the difference between flooding rates of the two cases increases with the increase of water injection rate.

The only two tests in which the onset of flooding limit was not reached were those with the following conditions:

Initial tube temperature	250 °C
Inlet water flow rate	0.32 L/min
Inlet water temperature	22 °C
Condition of steam venting	Up, up + down

In such tests, the rate of steam generated was not sufficient to cause onset of flooding for this inlet flow rate. This may be attributed to low thermal energy stored in test section and, also, due to low flow rate of injected water. It can be seen from adiabatic flooding tests which was carried out for the same test section (see Ref. [17]) that as the injected water flow rate decreases, the rate of countercurrent gas flow necessary to cause onset of flooding increases. On the other hand, as the heat capacity of the test section decreases, the rate of steam generation decreases. These results contradicted with that obtained by Ref. [11] which showed that, for top steam-venting and top and bottom steam-venting, the test section cannot be quenched, due to reaching complete flooding limit, specially, for low water injection rate. The contradictory between the two results can be attributed to the heat stored in the test section during the experiments of [11]. This stored heat may be was sufficient to evaporate all of the liquid film and so complete quenching of the test section was not obtained.

3.3. Rewetting velocity

The rewetting velocity is normally calculated from the transient wall temperature curves by calculating the time difference between the sharp drops in wall temperature at different axial locations. The rewetting velocity considered in this study is the average rewetting velocity along the test section. It was calculated by measuring the difference in time between the sharp drop in wall temperature at the top of the test section (first thermocouple station) and that at the bottom of the test section (last thermocouple station), see Fig. 3. The rewetting velocity was then calculated by dividing the distance between these two sections by the corresponding time difference. Illustrating sketch for evaluating the rewetting velocity by this procedure can be found in Ref. [21].

In the following sections, the effects of different parameters, countercurrent flow of ·generated steam, initial wall temperature, inlet liquid flow rate and inlet liquid temperature, on the rewetting velocity were investigated.

3.3.1. Effect of countercurrent flow of generated steam

Fig. 5 shows the effect of the direction of venting the generated steam on the rewetting velocity at different conditions of inlet

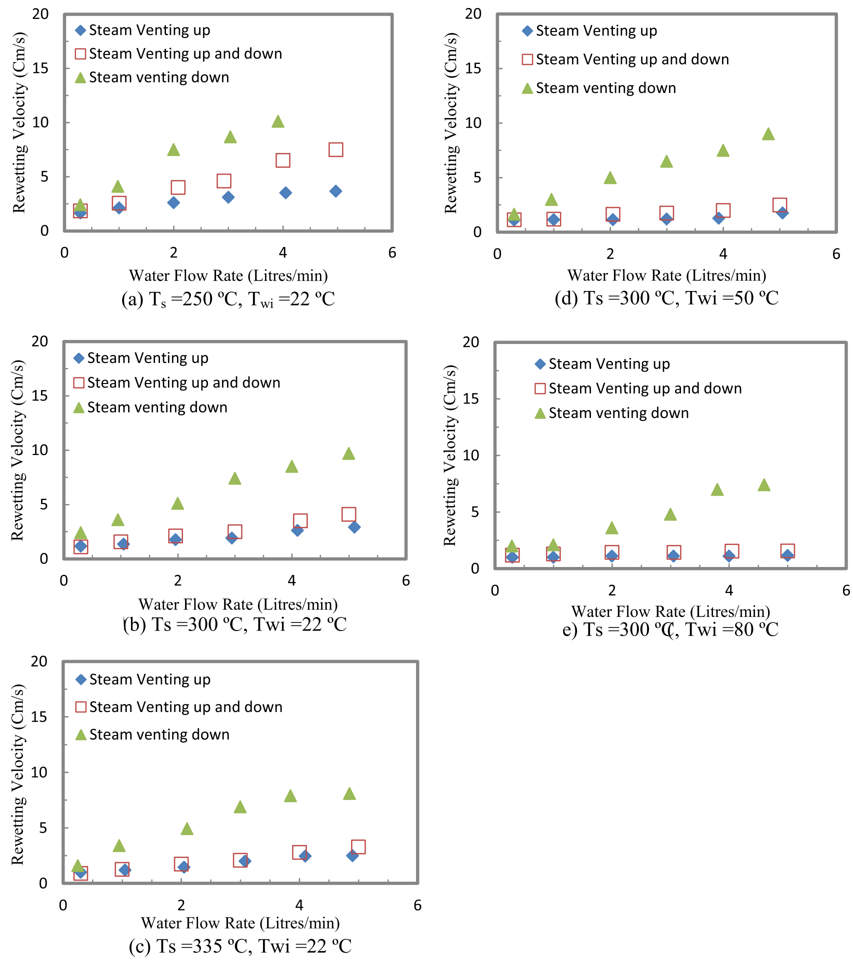

Fig. 5. Effect of direction of steam venting on rewetting velocity.

water flow rate, initial tube temperature and inlet liquid subcooling. As shown in the figure, the rewetting velocity in case of bottom venting is higher than that in case of top and bottom venting. Also, the rewetting velocity in case of top and bottom venting is higher than that in case of top venting. This is attributed to the effect of the rate of the countercurrent flow of steam. As the velocity of the countercurrent flow of steam increases: a) the interfacial shear stress between the rising steam and the falling liquid film increases and this retards the advance of the quench front, and b) the amount of the liquid flooded to the upper tank increases (see Fig. 4) and so the amount of the liquid penetrated to quench the tube decreases and this will decrease the rewetting velocity as discussed in the next section.

As shown in Fig. 5, the retardation of the rewetting velocity due to the countercurrent flow of the generated steam increases with the increase of the liquid flow rate. This may be attributed to: a) the increase of the rate of steam generation with the increase of the liquid flow rate; as the liquid flow rate increases, the rewetting velocity increases and the time required to remove the heat capacity of the tube decreases and, hence, the rate of steam generated increases, and b) the increase of interfacial shear stress with the increase of liquid film thickness.

Fig. 5 also shows that the difference between the rewetting velocity in the case of top steam-venting and that in case of top and bottom steam-venting decreases with the decrease of inlet water flow rate. This may be investigated with the aid of Fig. 4. As shown in this figure, the difference between the rate of water carried up with the generated steam in case of top venting and that in case of top and bottom venting decreases with the decrease of the inlet water flow rate. This means that the rate of water penetration in case of top steam-venting becomes closer to that in case of top and bottom steam-venting with the decrease of inlet water flow rate and this causes the decrease in the difference of the rewetting velocity between these two cases of steam venting with the decrease of inlet water flow rate. Also, Fig. 5 shows that the rewetting velocities in these two methods of steam-venting, top venting and top and bottom venting, become closer to each other with increasing the initial wall temperature and decreasing the inlet water subcooling.

3.3.2. *Effect of initial tube temperature*

Fig. 6 shows the effect of initial tube temperature on the rewetting rate for the different cases of steam venting. A decrease in the rewetting velocity was always observed as the initial wall temperature was increased for any liquid flow rate in all cases of steam venting. This may be attributed to the following reasons: a) a higher initial wall temperature means more thermal energy stored in the tube and this means that more time is required to remove the stored thermal energy from the wall; hence, the rewetting velocity will be lower, and b) for the cases of top steam-venting and top and bottom steam-venting, the amount of the steam generated due to the quenching process increases with the increase of initial tube temperature and this increases the velocity of the countercurrent steam which results in further reduction of the rewetting velocity.

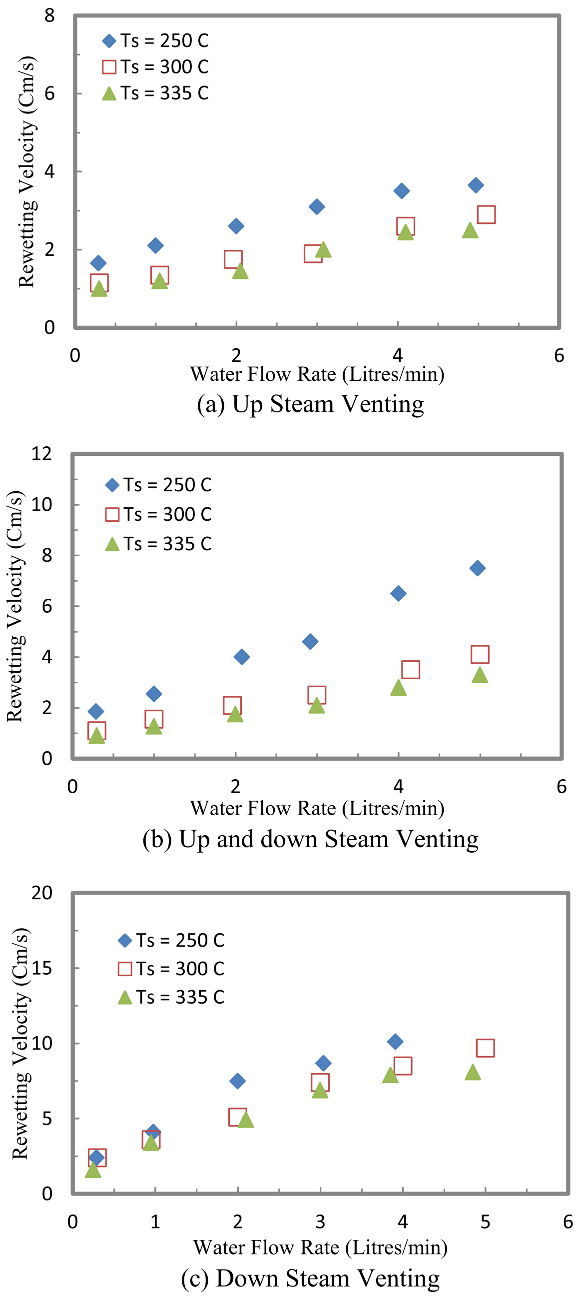

Fig. 6. Effect of initial tube temperature on rewetting velocity.

3.3.3. *Effect of liquid subcooling*

Fig. 7 shows the variation of rewetting velocity with liquid temperature at inlet of the test section. As shown in the figure, the rewetting velocity increases with the increase of liquid subcooling. The increase of the rewetting velocity with liquid subcooling is smaller for low liquid flow rates and increases with the increase of liquid flow rate. The increase of the rewetting velocity with increasing liquid subcooling is caused by the increase of the cooling capability of the liquid film. This improves the axial conduction heat transfer along the tube permitting a further increase in the rewetting velocity. Also, for the cases of top steam-venting and top and bottom steam venting, increasing the inlet liquid temperature increases the rate of steam generated specially at high liquid flow rates. The increase of steam generated increases the countercurrent steam velocity which decreases the rewetting velocity.

3.3.4. *Effect of water flow rate*

Figs. 5–7 show the effect of water flow rate on the rewetting velocity. All figures indicate that an increase in the liquid flow rate always results in a higher rewetting velocity at given conditions. This is true for all cases of steam venting. The reasons may be explained as follows: a) increasing the liquid flow rate increases the heat transfer coefficient in the wet and sputtering regions and this improves the rate of axial heat conduction along the tube, and b) increasing the liquid flow rate improves the precooling which reduces the quench temperature and, hence, increases the rewetting velocity. The previous theoretical studies support this trend where the theoretical rewetting velocity increases with the increase of the heat transfer coefficient and the decrease of the quench temperature.

Figs. 5–7 show that for the cases of top venting and top and bottom venting, the dependence of the rewetting velocity on the inlet liquid flow rate decreases with increasing initial tube

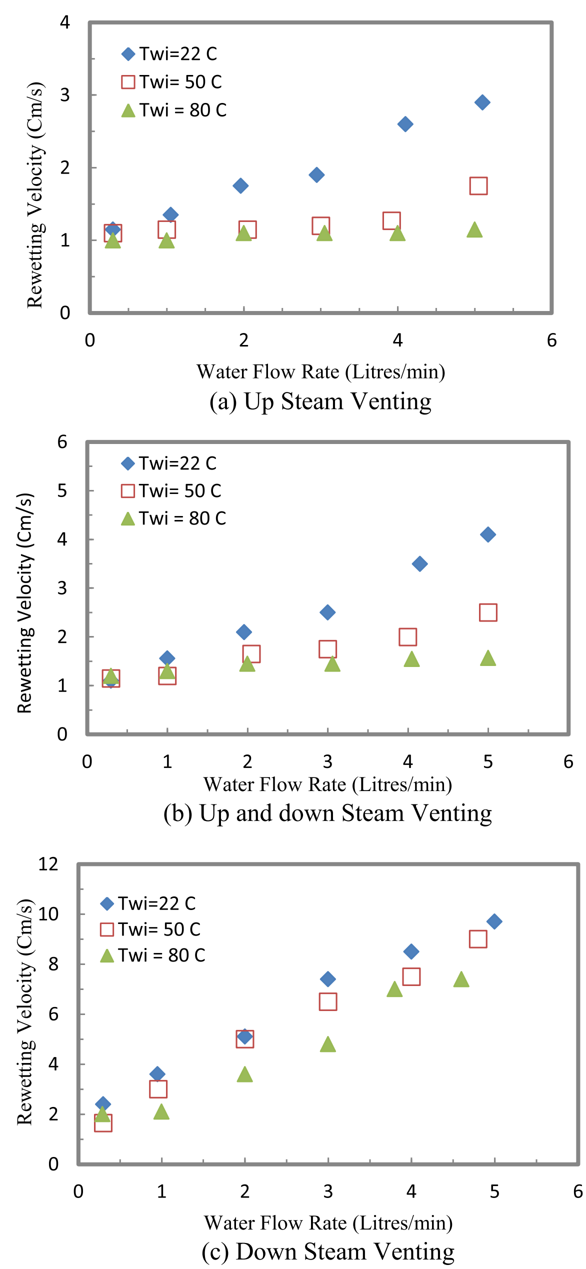

Fig. 7. Effect of inlet water temperature on rewetting velocity.

temperature and decreasing inlet liquid subcooling. This is attributed to the increase of the amount of steam generated with increasing initial tube temperature and decreasing inlet liquid subcooling. This steam generation may be sufficient to allow a constant water penetration rate whatever the inlet liquid flow rate and this causes the independence of the rewetting velocity on the inlet liquid flow rate.

3.4. Experimental correlations

A lot of previous semi analytical and experimental studies [6]; Piggott and Porthouse (1975) and Ref. [21] correlated their results for rewetting velocity in the form:

$$U = \frac{K}{\rho C \varphi^m}\left(\frac{Q}{2\pi r}\right)^n, \quad \varphi = \frac{T_s - T_{sat}}{T_r - T_{sat}} \tag{1}$$

where U is the rewetting velocity, Q is inlet water flow rate, ρ is density of tube material, C is specific heat of tube material, r tube inner radius, φ is dimensionless temperature, T_s is tube surface temperature, T_{sat} is saturation temperature, T_r is rewetting temperature and K, m and n are constants.

Present experimental results are correlated using least square methods to find the constants K, m and n of Eq. (1) to give correlations of rewetting velocities in terms of the different parameters affect the rewetting phenomenon. Table 1 gives the constants K, m and n of Eq. (1) for the different directions of venting the steam generated during the quenching process.

The predictions of Eq. (1) are plotted against the experimental data in Fig. 8 for the different directions of steam venting. As shown in the figure, the correlations can predict all experimental data within accuracies ±18% whatever the steam venting directions. The accuracy of prediction for each case of steam venting direction is given in Fig. 8.

3.5. Comparison with previous experimental work

3.5.1. Down steam-venting

A considerable number of previous experimental works was conducted in the field of rewetting of hot surface by a falling liquid film. Different ranges of initial tube temperature, inlet water temperature, water flow rate and surface dimensions and geometries were tested. The work of Ref. [33] is one of the previous experimental works where rewetting of a vertical tube by a falling liquid film with down steam-venting was tested under conditions similar to the conditions of the present work (initial tube temperature = 300 °C, and inlet water temperature = room temperature). Fig. 9 shows the variation of rewetting velocity with mass flow rate of the water film per unit length of tube perimeter for the present results compared with that of [33]. The figure also shows the prediction of Eq. (1). The present results show reasonable agreement with the results of Ref. [33].

Also, the present results are in qualitative agreement with the results of other researchers (e.g. Refs. [6,10,15,29,21]). The comparison shows a good agreement of the effects of different parameters (initial tube temperature, inlet water temperature and inlet water flow rate) on the rewetting velocity. However, direct quantitative comparisons of their results with the present results cannot be made because of the significant differences in the test conditions used.

Table 1
Constants K, m, and n in Eq. (1) for different direction of steam venting.

Venting direction	K	m	n
Venting up	10,840	4.55	0.32
Venting up and down	8800	4.55	4.5
Venting down	4320	5.33	0.65

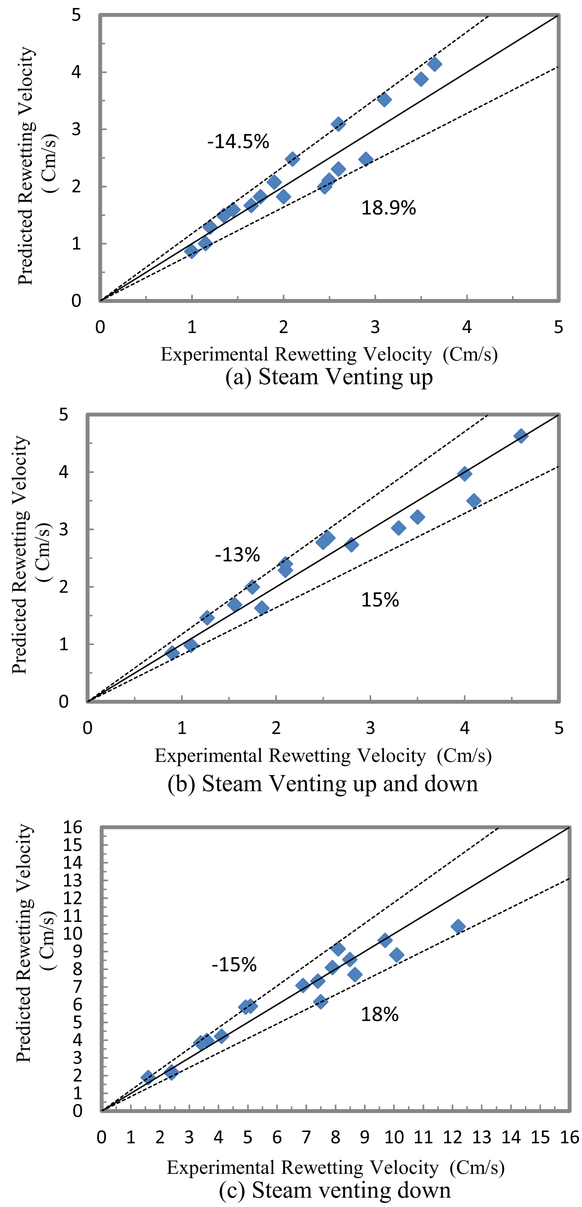

Fig. 8. Comparison of correlations predictions with experimental data.

3.5.2. Top and top and down steam-venting

To the author's knowledge, no experimental data for rewetting of hot vertical tube by a falling liquid film with top steam-venting or top and bottom steam-venting under the same conditions of the present work are found. Moreover, only one previous work [11] carried out at different conditions (initial tube temperature = 815 °C) exists. The results of the present work were qualitatively compared with this work and a good agreement is found where both of works show that the quenching time for top steam-venting is larger than that for top and bottom steam venting.

3.6. Rewetting temperature

Several authors [14,31,13] have referred to the knee of the typical temperature transient curve obtained during the rewetting experiments as the rewetting temperature. Ref. [32] reported that if

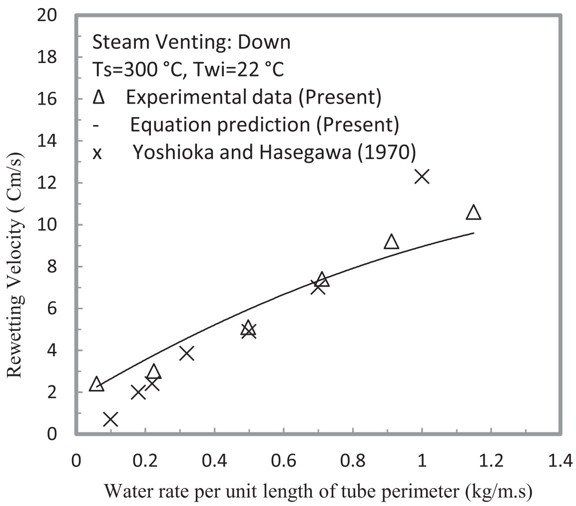

Fig. 9. Comparison of present results with previous work.

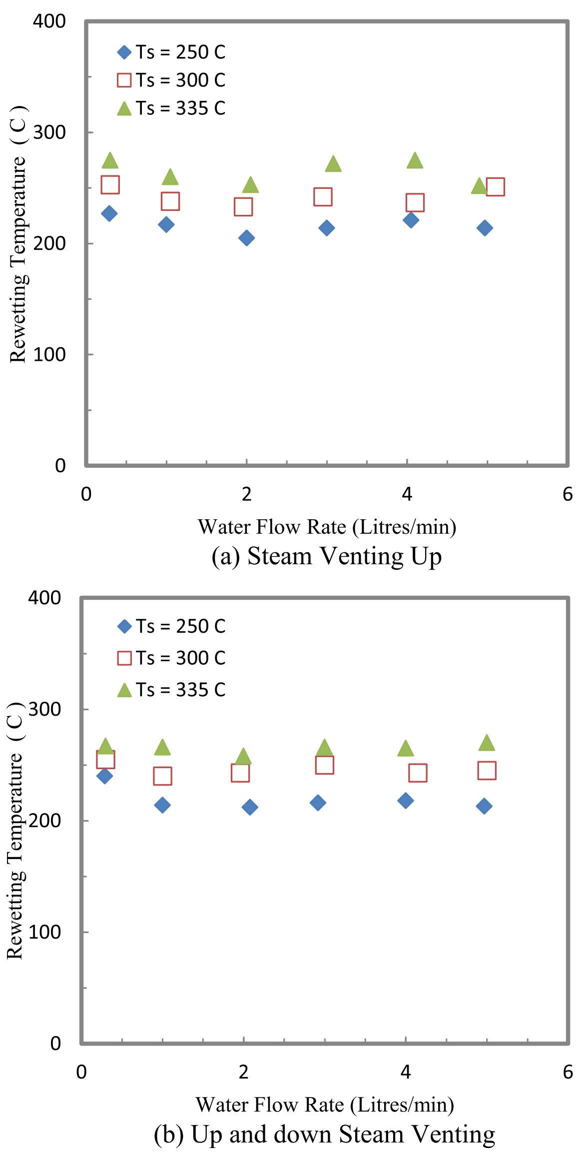

Fig. 10. Effect of initial tube temperature on rewetting temperature.

one considers the advance of the quench front, and the simultaneous slow cooling of the wall ahead of it by pre-quenching heat transfer, it becomes evident that this temperature happens to be the instantaneous value of the wall temperature (as determined by its cooling history from the beginning of the rewetting) at the time at which that particular point is reached by the advancing quench front. Also, Yadigaroglu reported that there are experimental temperature traces, mainly for bottom reflooding at low flow rate or dispersed flow cooling from the top, where no significant pre-cooling took place and no change in the fluid quality or velocity was observed just prior to quenching. They reported that the only explanation for the sudden wall temperature drop in these cases is the arrival of the quench front at that location.

In the present study, the rewetting temperature was taken as the wall temperature at which the dramatic change in the cooling rate of the surface occurs (knee point). Fig. 10 shows the effect of the initial tube temperature on the rewetting temperature for different methods of steam venting. As shown in the figure, as the initial tube temperature increases the rewetting temperature increases. This variation of the rewetting temperature with the initial tube temperature was noticed by previous investigators for rewetting of horizontal tube [2,1] and rewetting of vertical tube by bottom flooding and falling liquid film (Kern and Lee (1979), Ref. [14]).

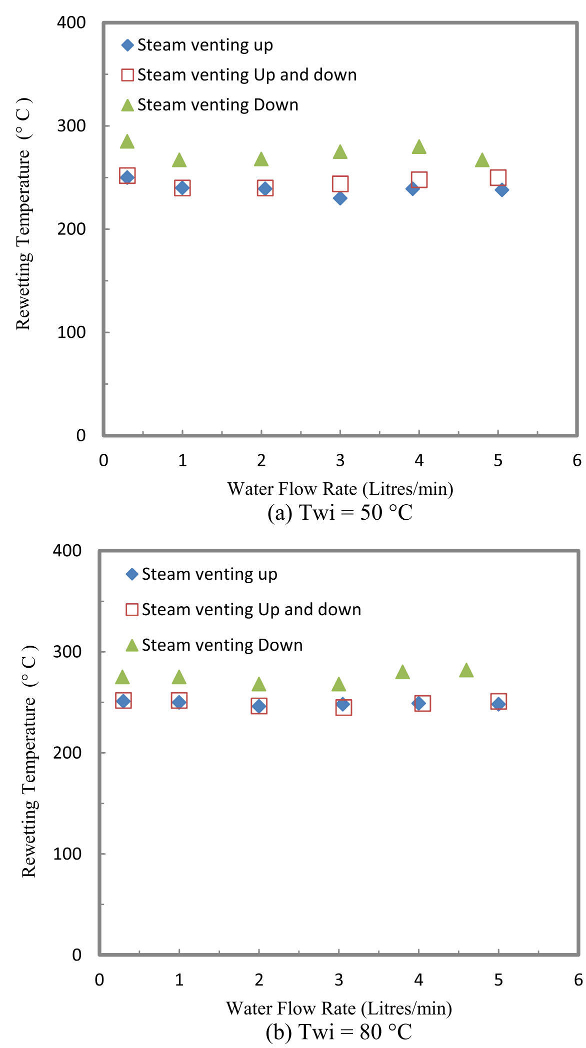

Fig. 11. Effect of steam venting direction on rewetting temperature.

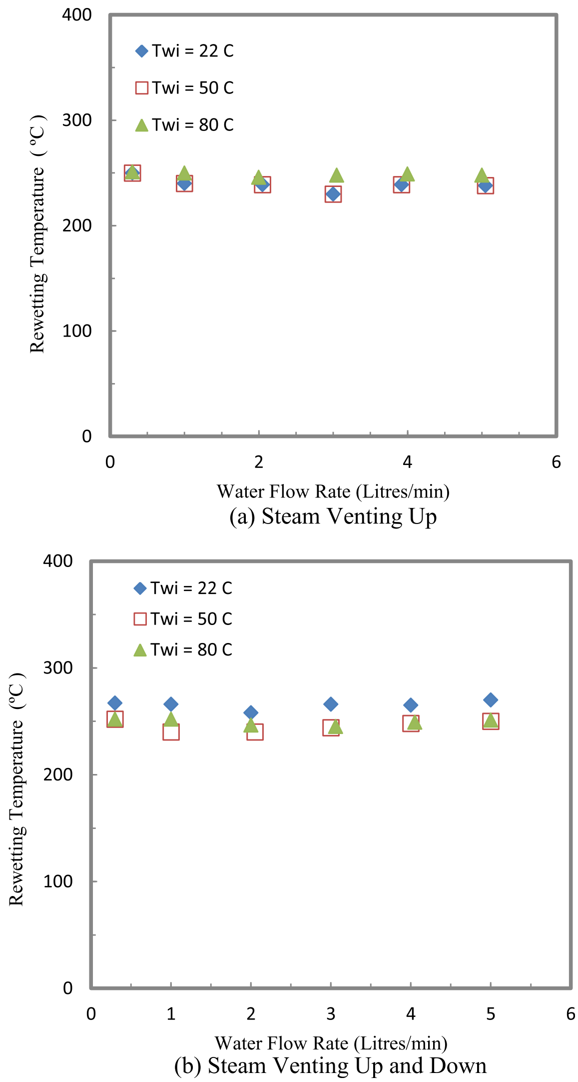

Fig. 12. Effect of water temperature on rewetting temperature.

Fig. 11 shows the effect of the direction of venting of the steam generated during the quenching process on the rewetting temperature. As shown in the figure, the rewetting temperature in case of bottom steam-venting is higher than that in cases of top steam-venting and top and bottom steam-venting. This may be attributed to the hydrodynamic effect of the steam generated, when it moves countercurrently to the falling liquid film, which cause delaying to the rewetting process. This allows more precooling to the surface to occur before the arrival of the quench front. This supports the above arguments of Ref. [32] about the knee temperature.

Fig. 12 shows the effect of the inlet liquid temperature on the rewetting temperature. As shown in the figure, the inlet liquid temperature has no effect on the rewetting temperature. This contradicts with the previous investigators who found an increase in the rewetting temperature with the decrease of the inlet liquid temperature. This may be due to the low range of initial tube temperature (250–335 °C) at which the present data were obtained.

4. Conclusions

New experimental data on the rewetting of hot vertical tube by a falling liquid film for different directions of venting the steam generated during the quenching process were obtained. It was found that, the steam generated during the quenching process can cause flooding to some of the injected water delaying the quenching process. The possibility of this flooding decreases with the decrease of both of the initial tube temperature and inlet water flow rate.

The effects of various parameters (direction of venting the steam generated during the quenching process, initial tube temperature, inlet water flow rate and inlet water temperature) on the rewetting velocity were investigated. In particular, the rewetting velocity in the case of top steam-venting was lower than that for top and bottom-steam venting which was lower than that in the case of bottom steam venting. For the three methods of steam venting, it was found that the rewetting velocity decreases with the increase of initial tube temperature and increases with the increase of inlet liquid flow rate and the decrease of inlet water temperature. For top steam-venting and top and bottom steam-venting, the effect of water flow rate on the rewetting velocity decreases with the increase of initial tube temperature and inlet water temperature. The effects of the different parameters on the rewetting velocity agreed well with those reported in previous investigations. Experimental correlations for the rewetting velocities for the different directions of steam venting were deduced from the experimental results in terms of effective parameters. Prediction of equations was compared with the present and previous experimental data and good agreement was found.

The effect of the different parameters on the knee point (apparent rewetting temperature) of the temperature transient curve was studied for low range of initial tube temperature. It was found that, the apparent rewetting temperature increases with the increase of the initial tube temperature. The rewetting temperature in the case of bottom steam-venting was higher than those in the case of top venting and top and bottom venting. For this range of initial tube temperature both of the water flow rate and water temperature had no effect on the rewetting temperature.

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Nomenclature

C: specific thermal capacity of tube material (kJ/kg^{-1} K^{-1})
K: constant (Eq. (1))
m: constant (Eq. (1))
n: constant (Eq. (1))
Q: volumetric flow rate of water (L/min)
r: tube inner radius (m)
T: temperature (°C)
T_r: rewetting temperature (°C)
T_s: tube surface temperature (°C)
T_{sat}: saturation temperature (°C)
T_{wi}: inlet water temperature (°C)
U: rewetting velocity (cm/min)
ρ: density of tube material (kg/m^3)
φ: dimensionless temperature ($\varphi = T_s - T_{\mathrm{sat}}/T_{\mathrm{r}} - T_{\mathrm{sat}}$)