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

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ABSTRACT

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

1. Introduction

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

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

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

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Nomenclature

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

Subscript and abbreviation

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

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

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

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

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

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

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

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

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

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

Wallis [40] proposed the following correlation:

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

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

A very limited published work was presented on the interaction between rewetting and flooding during the quenching of hot vertical tubes by a falling liquid film in the presence of rising hot gases Guerrero and Lowe [15] showed experimentally that the vapor generated during the rewetting of a hot vertical tube can produce countercurrent flow rate which exceeds the flooding limit and delay the rewetting process. In their experiments, water was introduced into a high temperature vertical tube and the generated vapor was constrained to vent either from the top of the tube or from the top and the bottom together. Later, Chan and Grolmes (1975) [5] presented a theoretical study for transient cooling of a hot vertical tube by a falling liquid film to check if the vapor generated during the quenching of the tube is sufficient to reach onset of flooding or not. Also Block and Wallies [4], presented a theoretical study on rewetting of vertical surfaces limited by flooding caused by the generated vapor Duffey et al. [9] showed the 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 rod and the tube. Recently, Patil et al. [29] 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 counter current flow of steam–water mixture has an adverse effect on cooling. More recently, Nada et al. [25] conducted detailed experimental work of quenching of very hot vertical tubes by a falling liquid film with different directions for venting the generated steam during the quenching process and its effect on the rewetting behavior. They showed that in case of venting the steam generated from the top of the tubes, the onset of flooding limit was reached and this adversely affect the rewetting of the tube.

The purpose of the present study is to investigate the interaction between the flooding and rewetting phenomena during cooling of very hot vertical tubes by a falling liquid film in the presence of rising hot gases. The effect of adding the upward flow of rising non condensable gases to the generated steam during quenching of the tube on the flooding limits and on the rewetting rate of the tube is the main aim of this study.

2. Experimental setup and procedure

2.1. Test loop

A schematic of the test loop is shown in Fig. 1. The loop consists 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 thermocouples embedded on the outer surface of the tube at five axial TS1-TS5 (see Fig. 1). The thermocouples axial locations TS1, TS3 and TS5 (see Fig. 1) at the top, middle and bottom of the tubes contain two thermocouples at 180°. Each of thermocouples axial location TS2 and TS4 contains only one thermocouple. The thermocouples 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 {Elliott and Rose [8,13]; Lee et al. (1983), Ueda and Inoue [22], Lee and Chen [39] Saxena et al. [33] and Nada et al. [25]}. 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. The tube was thermally insulated by 2 inch glass wall insulation pipe. A pressure transducer was connected across the two ends of the tube to measure the pressure drop.

In the air circulating system, the air coming from the air line was passed through a pressure regulator to reduce the air pressure to a value sufficient to circulate it inside the loop. Pressure, temperature and flow rate of the air were measured downstream the pressure regulator by a pressure transducer, thermocouple probe and venturi meter, respectively. The air was then heated electrically in an air heater. The heated air was injected into the test section through the lower plenum to heat the test section to the required temperature. Pressure and temperature of the air were measured at the inlet of the test section by a pressure transducer and thermocouple probe. After the test section was reached to the required temperature, the air flow rate was adjusted to the required value 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. 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 inters the test section through these fine matrices of holes in the form of a liquid film. The test section was supplied From CANDU research center as a standard straight tube. Precautions were taken during shipping to assure complete straightness of the tube. Straightness/wrapping of the tube was

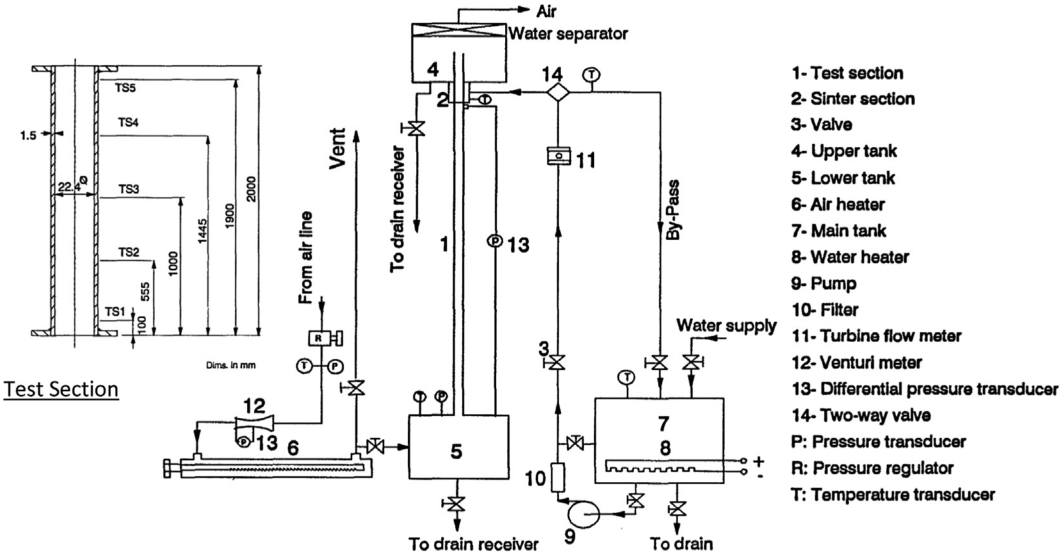


Fig. 1. Schematic of experimental facility.

checked during installation using scaled water level indicators. The test section with the sinter section is vertically aligned with the help of water level indicator and a string with hanged weight technique.

An adiabatic test with transparent test section similar to the heated one was firstly done. The aim of the adiabatic tests is a) to ensure that the sinter section provide the liquid as a liquid film as well as to ensure the uniformity of the liquid film on the tube inner section, and (b) to compare the results of the very hot test section with the adiabatic tests results.

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 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 adjusted to the required value and the heating tape was turned off. At this time, the scanning program was set and water was injected to the test section by switching the bypass water valve. The scanning program was continued until the tube was totally rewetted. In the case of complete flooding, the test section is never completely rewetted, and the scanning program was stopped after a reasonable period of time. The measurements taken by the data acquisition system during the scanning process were air flow rate, air pressure and temperature downstream venture meter and at inlet of the test section, water injection flow rate, water temperature at inlet of the test section, pressure drop across test section and the transient readings of thermocouples on the surface of the test section. The water flooded to the upper tank was collected and measured.

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 Holman and Gajda [17] and the uncertainty range was within 1.25–5%.

2.3. Test matrix

Initial tube surface temperature	250 °C–335 °C
Inlet water flow rate	0.32–5 L/min (0.0053–0.083 L/s)
Inlet water temperature	22 °C–80 °C
Air flow rate	0–6 L/s
Test Pressure	1 atms

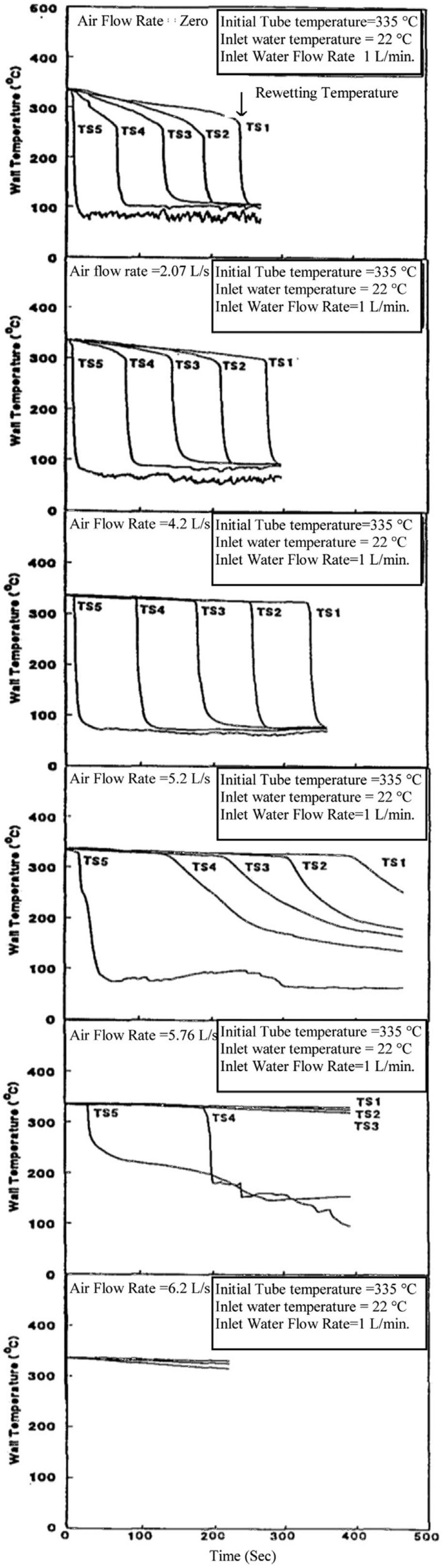


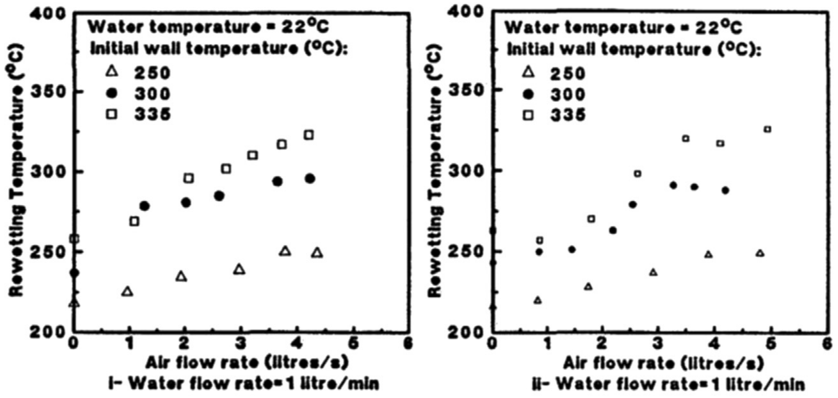
Fig. 2. Transient tube wall temperatures.

3. Results

3.1. Transient tube wall temperature

Tube wall transient temperature curves at different axial locations of the test section are shown in Fig. 2 for different rising air flow rates. As shown in the figure, the time required to totally rewet the test section increased with the increase of air flow rate until the air flow rate reaches a value at which the test section cannot be totally rewetted. Such behavior may be attributed to the following reasons: a) the steam generated during the quenching of the tube, even without air injection, was higher than the gas flow rate necessary to cause onset of flooding. So any increase of the injected air flow rate will reduce liquid penetration rate and at the same time resists the motion of the penetrated water and, accordingly, decreases the quench front propagation rate. Further increase in the air flow rate resulted in approaching complete flooding conditions where the injected water was held up by the air-steam mixture and fails to rewet the tube completely, and b) injecting hot air at the bottom of the test section tends to reduce the pre cooling of the dry lower part of the test section. This reduction in pre cooling retards the propagation of the quench front according to the conduction controlled model.

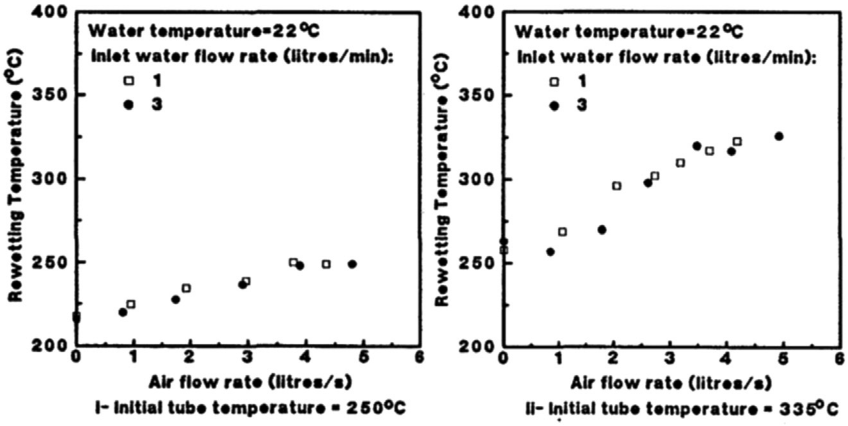
It appears from Fig. 2 that, with the exception of the first thermocouple station TS5), the apparent rewetting (quench) temperature is almost constant independent on the location. The apparent quench temperature for the first axial thermocouple station is higher than those at downstream locations. The high apparent temperature of the first axial thermocouple could be caused by long precursory cooling period at downstream locations; this pre cooling 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.



i- Water flow rate=1 litre/min

ii- Water flow rate=1 litre/min

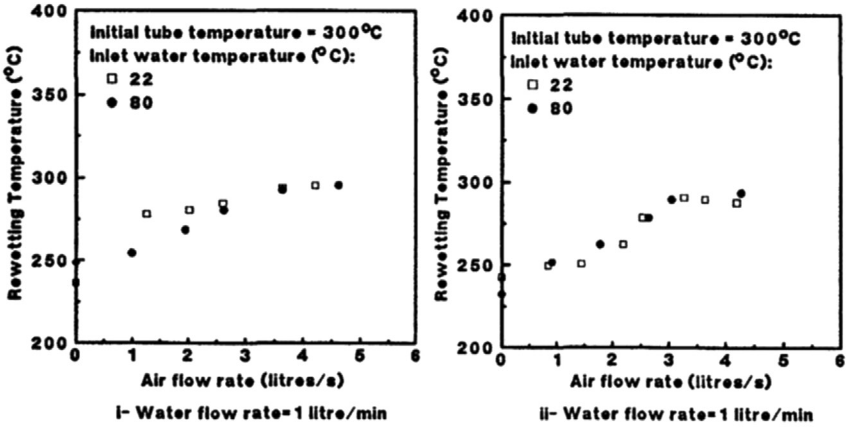
a- Effect of initial tube temperature



i- Initial tube temperature = 250°C

ii- Initial tube temperature = 335°C

b- Effect of inlet water flow rate



i- Water flow rate=1 litre/min

ii- Water flow rate=1 litre/min

c- Effect of inlet water temperature

Fig. 3. Effect of different parameters on rewetting temperature.

At air flow rate near or equal to that required to cause complete flooding, some spots of the test section are rewetted and other spots are not as shown in Fig. 2. This is because at the point of complete flooding or very close to it, a very thin liquid film may be penetrated. This liquid film may be intermittent and not uniform around the circumference of the test section.

Moreover, Fig. 2 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. Afterwards, the liquid film becomes saturated due to heat gained from wall of the test section.

3.2. Rewetting temperature

A universally accepted definition of rewetting temperature often referred to also as sputtering, quenching, knee, minimum film boiling or Leidenfrost temperature, does not exist. Several authors {Yamanouchi [42] Lee et al. [21] and Kim and Lee [18]} have referred to the knee of the typical temperature transient curve obtained during the rewetting experiments as the rewetting temperature. Recently, Yadigaroglu et al. [41] reported that if 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 precooling took place. 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; see Fig. 2). Fig. 3 shows the effect of the air flow rate on this apparent rewetting temperature. As shown in the figure as the air flow rate increases the rewetting temperature increases. This may be attributed to the decrease of the precooling with the increase of the air flow rate as shown in Fig. 2. Fig. 3a shows the increase of the rewetting temperature with the increase of the initial tube temperature. This variation of the rewetting temperature with the initial tube temperature was noticed by previous investigators for rewetting of horizontal tube {Ahluwalia et al. [2] and Abdul-Razzak [1]} and rewetting of vertical tube by bottom flooding and falling liquid film {Kern and Lee [18] Lee et al. [21]}. Fig. 3b and c show no effect of inlet water flow rate and inlet water temperature on the rewetting temperature. This can be attributed to the flooding occurred to the most of the inlet water. This flooding made the penetrated liquid flow rate is constant and very small whatever the inlet liquid flow rate reaching to the saturation temperature at advanced stage of the tube.

The effects of the different parameters on the rewetting temperature obtained in the current study supports the previous investigation of Yadigaroglu et al. [41] which reported that the knee 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 and the only explanation for the sudden wall temperature drop is the arrival of the quench front at that location.

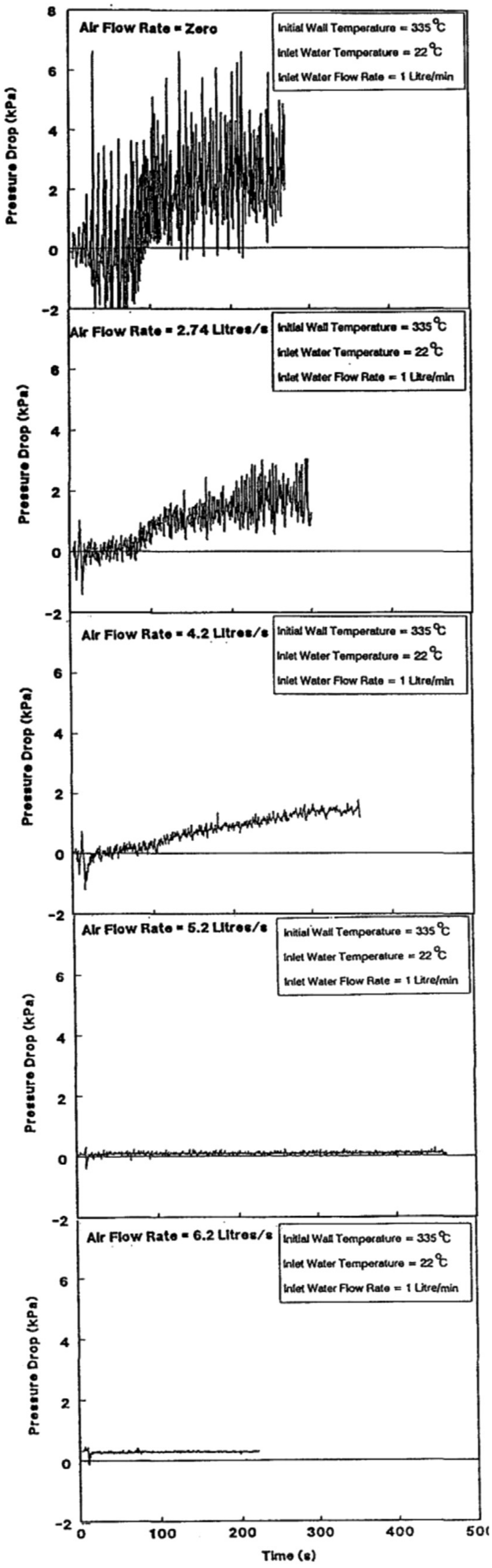


Fig. 4. Transient pressure drop.

3.3. Pressure drop along the test section

Fig. 4 shows the transient pressure drop along the test section for different air flow rates. The figure indicates that for low air flow rates (0, 2.74 and 4.2 L/s) the pressure drop fluctuates with time. These fluctuations are due to the waves formed on the liquid film. The figure shows that for those air flow rates, the pressure drop increases with time during the experiment. This is due to the increase of steam generation and the increase of the length of liquid film along the test section. Moreover, the figure shows that the fluctuation and the increase of the pressure drop decreases with the increase of air flow rate; see curves for air flow rates of 5.2 and 6.2 L/s. This is attributed to the decrease of the liquid film thickness and the associated decrease in surface waves roughness.

Fig. 5 shows the variation of average pressure drop through the test section with air flow rate. As shown in the figure, the average pressure drop decreases with the increase of air flow rate. Comparing this curve with the pressure drop curve obtained by Nada [24] during the adiabatic flooding tests, one can be sure that the current experiments lies in the range between onset of flooding and complete flooding.

3.4. 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). The rewetting velocity was then calculated by dividing the distance between these two sections by the corresponding time difference. At higher air flow rates, some parts of the test section are rewetted and other parts are not. In this situation, the rewetting velocity is taken to be zero and this condition is considered to be the condition of totally unquenched test section.

In the following sections, the effects of different parameters such as countercurrent flow rate of rising hot air, initial wall temperature, inlet liquid flow rate and inlet liquid temperature, on the rewetting velocity are investigated.

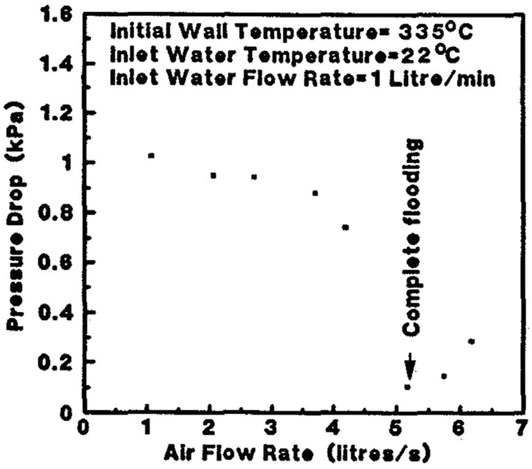


Fig. 5. Variation of average pressure drop with air flow rate.

3.4.1. Effect of countercurrent air flow rate

Fig. 6 shows the effect of countercurrent air flow rate on the rewetting rate for different values of inlet water flow rates, inlet tube temperatures and inlet water subcooling. The figure shows clearly the retardation of the falling liquid (decrease of rewetting

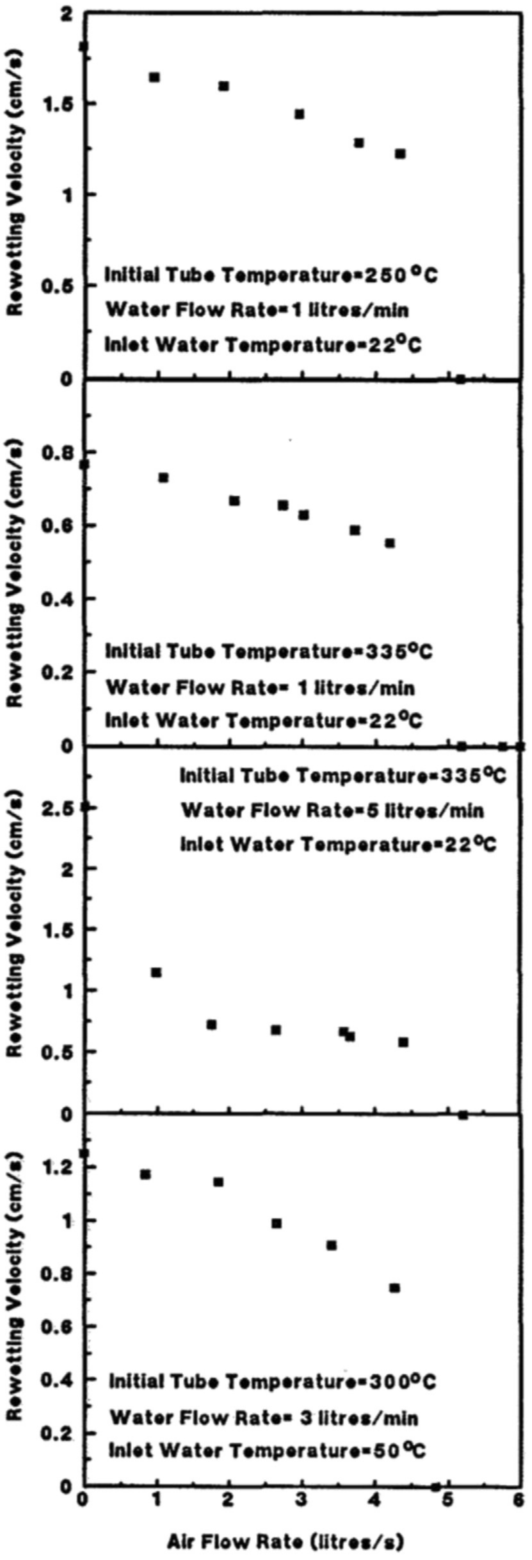


Fig. 6. Effect of air flow rate on rewetting velocity.

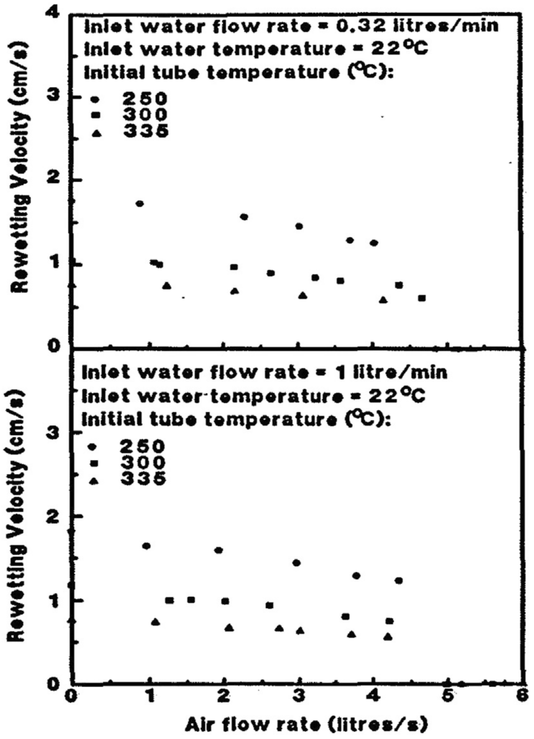


Fig. 7. Effect of initial tube temperature on rewetting velocity.

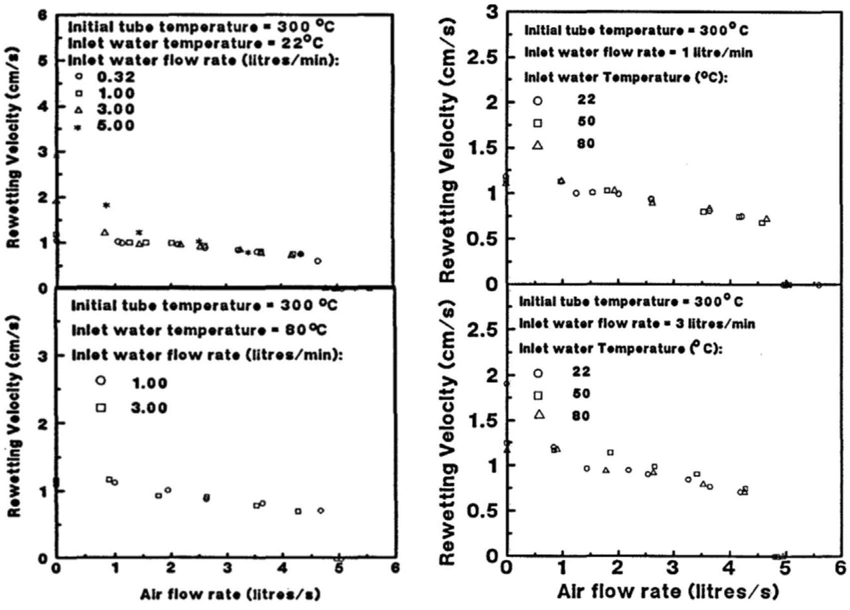
velocity) with the increase of countercurrent air flow rate, until a certain countercurrent air flow rate is reached (about 5 L/s) at which the liquid film ceases to move downwards and the wall cannot be completely quenched. This variation of rewetting velocity with countercurrent air flow rate may be attributed to the following reasons: a) as the countercurrent air flow rate increases, the situation moves away from the onset of flooding condition and becomes closer to the complete flooding point and this means the decrease of the liquid penetration rate to the test section. This decrease in the liquid penetration rate leads to lower rewetting velocity, b) as the countercurrent air flow rate increases, the interfacial shear stress between the rising air and the penetrated falling liquid film increases and this retards the advance of the quench front, and c) as the air flow rate increases, the precooling of the test section decreases and this reduces the rewetting velocity.

3.4.2. *Effect of initial tube temperature*

Fig. 7 shows the effect of initial tube temperature on the rewetting velocity for different inlet liquid flow rates and countercurrent air flow rates. As shown in the figures, for any inlet liquid flow rate and any countercurrent air flow rate, the rewetting velocity decreases with the increase of initial tube temperature. This may be attributed to the increase of the thermal energy stored in the test section with the increase of initial tube temperature, and this means that more time is required by the penetrating water to remove this energy. Hence, the rewetting velocity will be lower.

3.4.3. *Effect of inlet liquid flow rate*

The effect of inlet liquid flow rate on the rewetting velocity is shown in Fig. 8(a). As discussed in Nada [24]; in the absence of rising air, the rewetting velocity is dependent on the inlet water flow rate; it increases with increasing inlet water flow rate except for conditions of relatively high initial tube temperature and/or inlet water temperature where high vapor generation rates associated with these conditions may cause onset of flooding. This trend is clear in Fig. 8(a) at zero air flow rate. Fig. 8(a), however, shows that even for low initial wall temperature and inlet water temperature, the effect of the inlet water flow rate on the rewetting velocity diminishes as the countercurrent air flow rate is introduced. This can be explained in terms of the liquid penetration curve obtained in the adiabatic flooding tests (Tests with replacing the hot stainless tube, Test section, with adiabatic transparent tube with cold countercurrent air and water flow for possible visualization of the onset flooding and complete flooding limits) as shown in Fig. 9. The figure shows that, once the onset of flooding is reached, the



(a) Effect of inlet water flow rate (b) Effect of inlet water temperature

Fig. 8. Effect of inlet water flow rate and inlet water temperature on rewetting velocity.

liquid penetration rate becomes a unique function of the air flow rate, independent of the inlet water flow rate until complete flooding is reached. The present results showed that onset of flooding is reached even without the introduction of air, i.e. the rising generated steam is sufficient to cause the onset of flooding. As such the data shown suggest that once the air is introduced, the rewetting velocity becomes independent of the inlet water flow rate and dependent on the air flow rate. Further increase in the upward air flow causes complete flooding and the rewetting velocity is reduced to zero.

3.4.4. *Effect of liquid subcooling*

Fig. 8(b) shows the effect of liquid subcooling on the rewetting velocity for two different inlet liquid flow rates. As shown in the figures, for the present range of water subcoling and tube thermal capacity, the subcooling of inlet liquid has essentially no effect on rewetting rate of hot vertical tube in the presence of rising hot air within the range of conditions presented. As discussed above, this appears to be due to reaching the onset of flooding limit and the decrease of the liquid penetration rate. For low liquid penetration rate, the liquid film thickness is expected to be very thin and so it may become saturated (due to heat transfer from the rising hot air and the test section to the liquid film) before rewetting the test section. These findings are consistent with the data obtained by Nada [24] for rewetting of vertical tube without the injection of rising hot air, where no effect of liquid subcooling on the rewetting rate was indicated for low inlet liquid flow rates. However, as shown in Fig. 8(b), only in the absence of air flow, the data show a higher rewetting velocity for the low inlet water temperature (22 °c) and high inlet liquid flow rate. This is consistent with the above understanding as the vapor generation rate is expected to be low and the onset of flooding may not be reached in earlier stage of the rewetting process.

3.5. *Condition of unquenching of test section*

This condition exists when the rewetting velocity becomes zero due to the fact that the liquid propagation ceases and part of the tube is completely bare of the liquid and the other part is covered by stagnant liquid film. In fact, it is difficult to determine, precisely, the air flow rate at which the test section can not be totally quenched. It lies somewhere in the range between the two successive air flow rates at which the test section is completely rewetted and not. This range is plotted versus inlet liquid flow rate in Fig. 10 for different initial tube temperatures in a dimensionless form $(J^*_G - J^*_L)$ plane. Also, the results obtained from the adiabatic flooding tests (Fig. 9) are plotted on the same figure. As shown in the figure, the superficial air velocity J^*_G at which the test section cannot be totally quenched is insensitive to the initial wall temperature and does not depend on the inlet liquid flow rate. The independence on the inlet liquid flow rate is supported by the results obtained from the adiabatic flooding tests. The independence on the initial tube temperature may be attributed to the vanishing of the steam generation rate near and at complete flooding conditions. As shown in the figure, the superficial air velocity at which the test section cannot be quenched is close to that obtained from the adiabatic flooding tests. The results showed that the critical superficial gas velocity at which the rewetting of the tube cannot be attained is approximated by: $J^*_{G\,\text{critical}} = 0.6$. The agreement between the critical air velocities obtained in the adiabatic and diabetic tests can be attributed to the fact that in the rewetting tests, prior to complete flow reversal, the liquid film thickness is particularly thin. Under such condition, the rate of steam generation is

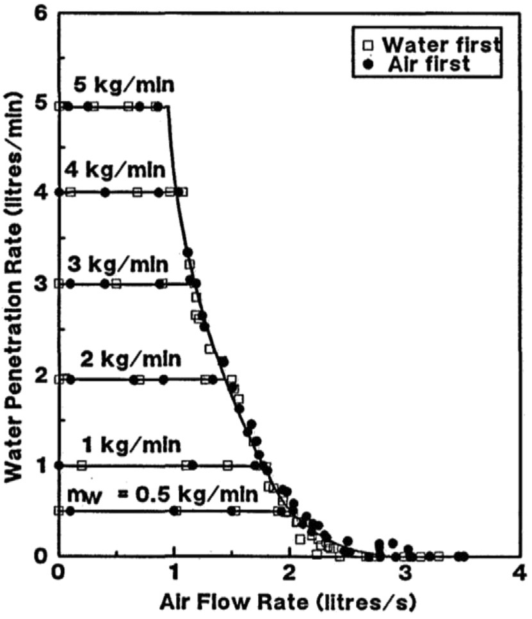


Fig. 9. Water penetration curve for adiabatic flooding tests.

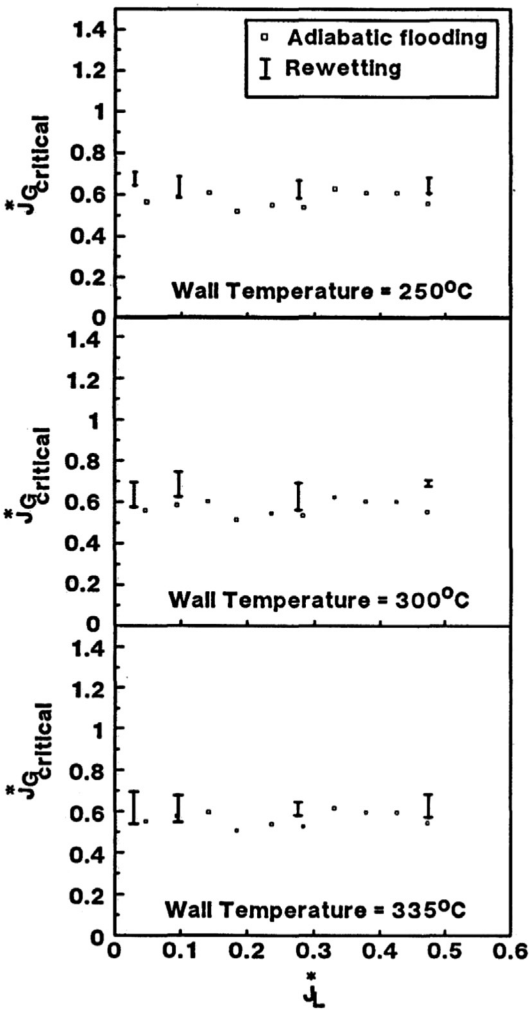


Fig. 10. Conditions of unquenching of test section.

negligibly small such that the flow reversal phenomenon is completely controlled by the air flow similar to the adiabatic case.

4. Conclusions

Detailed experimental data on rewetting of hot vertical tube by a falling liquid film in the presence of countercurrent flow of rising hot air were obtained. It was found that, the steam generated during the quenching process can reach the onset of flooding limit and any addition of injected rising air moves the situation to be much closer to the zero liquid penetration limit. The data showed the decrease of the rewetting velocity with the increase of the countercurrent air flow rate until the air flow rate reaches a higher value at which the tube cannot be totally rewetted. The value of the air flow rate at which the test section cannot be totally rewetted was constant and did not depend on the inlet liquid flow rate or the initial tube temperature. This value was compared with the air flow rate at zero liquid penetration rate obtained during the adiabatic flooding test and it was very close to it. For the same air flow rate, it was found that the rewetting velocity decreases with the increase of initial tube temperature. However, for the tested liquid flow rate and liquid subcooling, the rewetting velocity was not affected by inlet liquid flow rate or inlet liquid temperature. The transient wall temperature curves at different axial locations was obtained for different air flow rates. The apparent rewetting temperature was deduced from these curves and the effects of different parameters on it were investigated.

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