AN EXPERIMENTAL STUDY ON THE QUENCH FRONT VELOCITY AND TEMPERATURE DURING REWETTING OF A HOT VERTICAL ROD

N. Lymperea, A. Nikoglou and E.P. Hinis
Department of Nuclear Engineering
National Technical University of Athens
Zografos Campus, 9 Heroon Polytechniou, 15780 Athens, Greece
Corresponding Address
nlymper@mail.ntua.gr; anikog@mail.ntua.gr; ehinis@nuclear.ntua.gr

ABSTRACT

This study presents experimental work upon the rewetting mechanism of bottom flooding of a vertical annular channel enclosing a concentrically heated rod. A one loop experimental rig with two phase water flow was used to simulate the dry out and the rewetting process at atmospheric conditions. Experiments have been conducted for water mass flow-rate within the range of 8.33 $g \cdot s^{-1}$ to 50.01 $g \cdot s^{-1}$, inlet water sub-cooling up to 25°C and initial surface temperature of the rod up to 550°C. Beyond the generic remark that the quench velocity increases with increasing inlet sub-cooling, increasing liquid mass flow-rate and decreasing initial wall temperature an investigation is conducted on the effect of the geometry of the annulus upon the quench velocity and the rewetting mechanisms by comparing the present data with data from previous experimental works. The comparison is carried out by employing the thermal properties and the geometrical characteristics of the rod via the dimensionless Peclet number and a modified Biot number. In addition, the effect of the experimental conditions on the quench temperature is examined and contrasted to previous top rewetting experiments. An empirical correlation for the prediction of the quench temperature with respect to the physical properties of the heated surface along with the experimental conditions is introduced.

KEYWORDS
Bottom flooding, quench front, rewetting

1. INTRODUCTION

Surface rewetting is the establishment of liquid and solid contact when the initial temperature of the solid is higher than the quench temperature. Studies of hot surface rewetting are of fundamental importance to the understanding of the physical mechanisms that take place after a Loss Of Coolant Accident (LOCA) in a Light Water Reactor.

Many experimental studies have been performed on the study of rewetting mechanisms [1-4]. The final analysis of every rewetting process involves the knowledge of the velocity and temperature of the quench front [5-9].

This work presents experimental results upon the rewetting mechanisms that occur during bottom flooding experiments and carries out an investigation on the parameters that may affect the quench front propagation such as initial wall temperature, coolant inlet temperature and coolant mass flow-rate. The effect of each parameter on the quench velocity and temperature along with an empirical correlation with the quench temperature is also reported.

2. EXPERIMENTAL FACILITY

The experimental rig and the instrumentation employed in the present work have already been accurately reported in previous works [10,11]. A simple schematic diagram of the experimental set-up employed in the present work for bottom flooding rewetting is shown in Figure 1. The experimental loop consists of the heating tank, the holding tank, the test section and the relevant instrumentation that allows measuring and controlling of all the experimental critical parameters such as pressure, temperature and flow-rate. Liquid flows from the bottom of the heating tank and enters the bottom of the test section. After re-flooding the test section the liquid along with the steam condensate are accumulated in the holding tank.

The test section is composed of a stainless steel heated rod enclosed concentrically in a vertical annular channel made of borosilicate glass. The outer diameter of the rod is 15.875 mm while the inner diameter of the channel is 50 mm. The overall heated length of the rod is 1016 mm. In the cladding of the rod a 4.5 kW heater tape that simulates fission heat is adjusted along with twelve iron-constantan thermocouples (TC) embedded in almost equally spaced positions as shown in Figure 1.

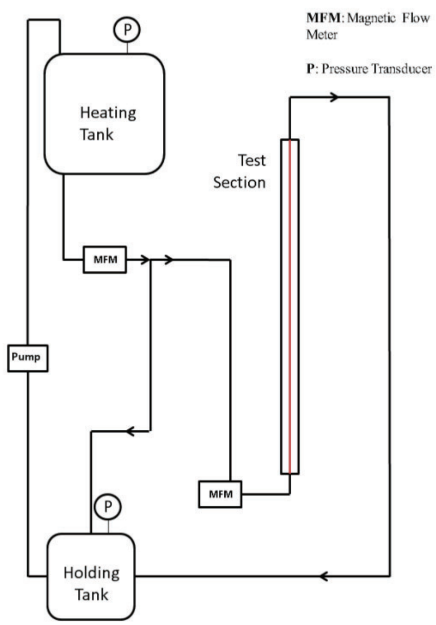

Figure 1. Schematic diagram of the test facility.

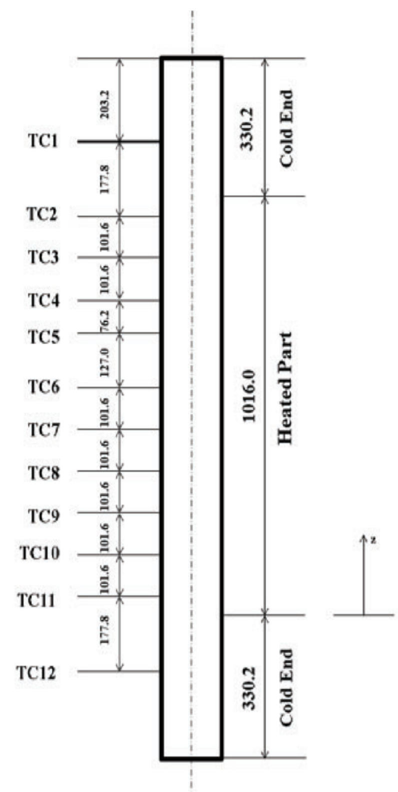

Figure 2. Schematic diagram of the heated rod with thermocouple positions in mm.

The experimental procedure followed to simulate LOCA and the rewetting phenomena breaks down to three main steps. These steps have already been thoroughly analysed and reported in earlier publications of experiments conducted in the same test facility [10,11]. The essential difference between the present and the previous experimental works is the way the water enters the test section during the rewetting step, which in the present work is from the bottom of the test section.

In the present work bottom rewetting experiments have been performed at atmospheric conditions for initial rod temperatures in the range of 300 to 550°C using a 5°C step, water flow-rate within the range of 8.33 to 50.01 $g \cdot s^{-1}$ and inlet sub-cooling up to 25°C. Using a 5°C step for initial rod surface temperature in every experimental series with constant cooling water properties one is led to approximately 50 experimental evaluations of the rewetting velocity versus the initial rod temperature.

3. EXPERIMENTAL RESULTS

3.1 Introduction

Throughout the experiments, two different cases of rewetting depending mainly on the water flow-rate have been observed. The first case deals with the experiments at low mass flow-rates up to 25.01 $g \cdot s^{-1}$ where an easily identified quench front is observed moving upwards along the heated rod and three boiling regimes are clearly separated from one another. The first regime is upstream the quench front and defines the wetted region of the heated surface. The second regime is at the quench front and the third regime is downstream the quench front and defines the non-wetted region of the rod.

On the other hand, the experiments at high mass flow-rates from 33.34 to 50.01 $g \cdot s^{-1}$, belong to the second case in which the quench front cannot clearly be observed due to the faster re-flooding rate. In this case four regimes are observed. Similar to the first case, the first regime is the wetted region upstream the quench front. The second regime is at the approximate region of the quench front where there is a great deal of droplet formation and the water is blown upward. This regime is called transition boiling regime. The third regime is directly downstream the quench front and is characterized by the vapour gap that is formed between the heated surface and the liquid. This regime is called film boiling regime. The last well-identified regime, which is called dispersed flow regime, is observed at the upper part of the rod where some water droplets are carried away by a vapour current. The rewetting behaviour of each case is illustrated using the temperature profile plots of the thermocouple station number 6 (TC6) in Figures 3 and 4 for the present study.

At this point it should be noted that the differentiation of the magnitude of mass flow-rate at low and high rates refers exclusively to the current bottom flooding experiments.

The different regimes which have been observed based on the extent of mass flow-rate, have also been reported in previous works [12,13]. In addition, the current experimental observations are in agreement with experimental observations that were made after studying the quenching cooling process of fuel rods from the bottom in big scale projects such as the PWR-FLECHT experiments [14,15].

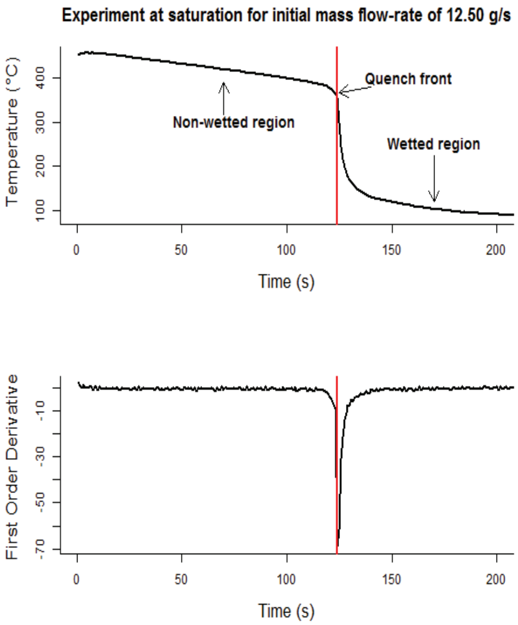

Figure 3. Temperature history and first order derivative of thermocouple number 6 at a low mass flow-rate.

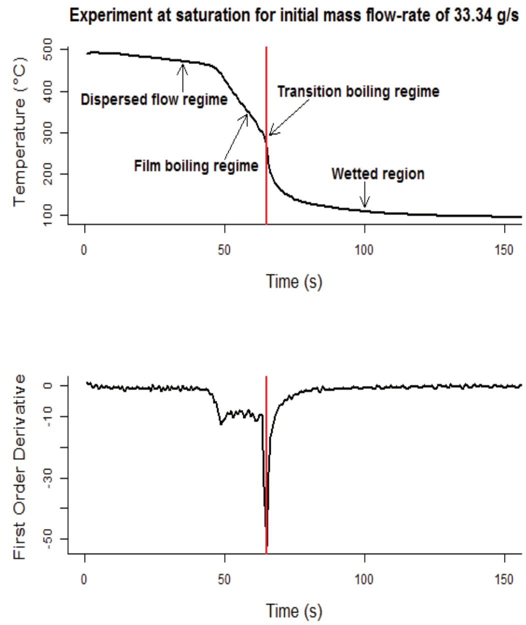

Figure 4. Temperature history and first order derivative of thermocouple number 6 at a high mass flow-rate.

3.2 Data processing

The initial wall temperature (T_w) is estimated as the average value of the indications of the thermocouple stations TC11 and TC4 located within the rod of the test section and downstream of the wet front. The rewetting velocity indicates the ability of the coolant to effectively remove the heat from the rod. The rewetting velocity is defined on the steady-state assumption as the distance of the thermocouple stations TC4 and TC11 (711.2 mm) divided by the time needed for the wet front to travel between them. The arrival of the quench front is represented through the sudden change in curve inclination [5,16] of the temperature history plots of each thermocouple station. The numerical way to determine the position of the quench front at a thermocouple station is by calculating the minimum of the temperature first order derivative as shown in Figures 3 and 4.

Figure 5 depicts the distance between the thermocouple stations TC11 to TC4 from the inlet of the test section versus the time of arrival of the quench front at each station along with the estimated regression line. The linear correlation coefficient equals 0.9725 and thus the steady state assumption is confirmed.

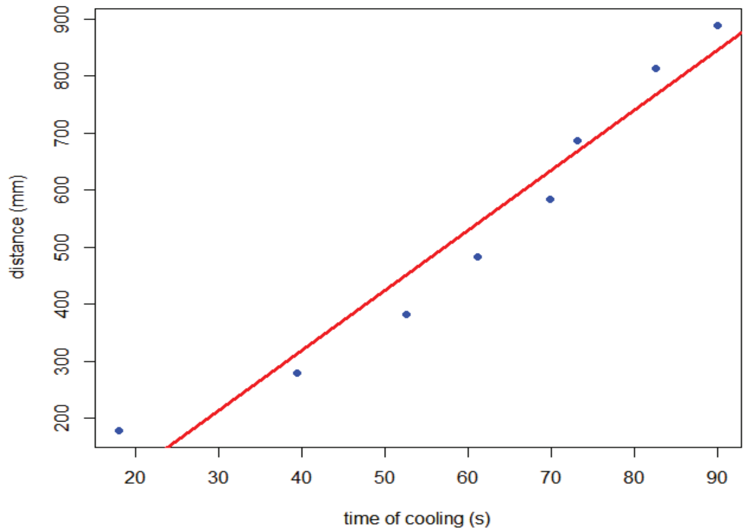

Figure 5. Distance and time of rewetting for thermocouple stations TC11 to TC4 at conditions of saturation for coolant mass flow-rate of 16.67 g·s^{-1} and initial wall temperature at 550 °C.

3.3 Study on the Quench Velocity

One of the objectives of the current study is to identify the interdependence of the rewetting velocity and the initial experimental conditions.

The generic and obvious remark that the quench velocity increases with increasing coolant flow-rate, increasing inlet sub-cooling and decreasing initial wall temperature, which has already been multi-verified by other researchers [17-19] is also observed during the experiments. However, concerning the current bottom flooding experiments, it is deduced that at low mass flow-rates (8.33–16.67 g·s^{-1}) rewetting velocity is weakly dependent upon initial wall temperature in contrast with the significant dependence of rewetting velocity upon initial wall temperature at higher mass flow-rates above 25.01 g·s^{-1}. The reason for this discrepancy appears to be attributed to the geometry of the annular channel of the test section and it will be thoroughly discussed in the next section.

Moreover, the estimated rewetting velocity stemming from the current experiments is compared to the cold re-flooding velocity at the same mass flow-rate, as indicated in Figure 6. Figure 6 depicts the experimental data at initial wall temperatures 300°C, 400°C, 450°C and 500°C using saturated water at atmospheric conditions with coolant mass flow-rate in the range of 8.33 to 41.68 g·s^{-1}. Cold re-flooding velocity is defined as the velocity of water in the annulus when the test section rod is not heated. As shown in Figure 6 at low initial wall temperature, approximately 300°C, the rewetting rate is very close to the cold re-flooding rate for all the mass flow range applied in this work. In this case the dominant heat transfer mechanism is convection. However, as the thermodynamic effect becomes more dominant for initial surface temperature greater than 400°C, the deviations in rewetting velocity from the cold re-flooding velocity seem to be significant. These deviations are maximized as the mass flow-rate increases at a constant initial wall temperature.

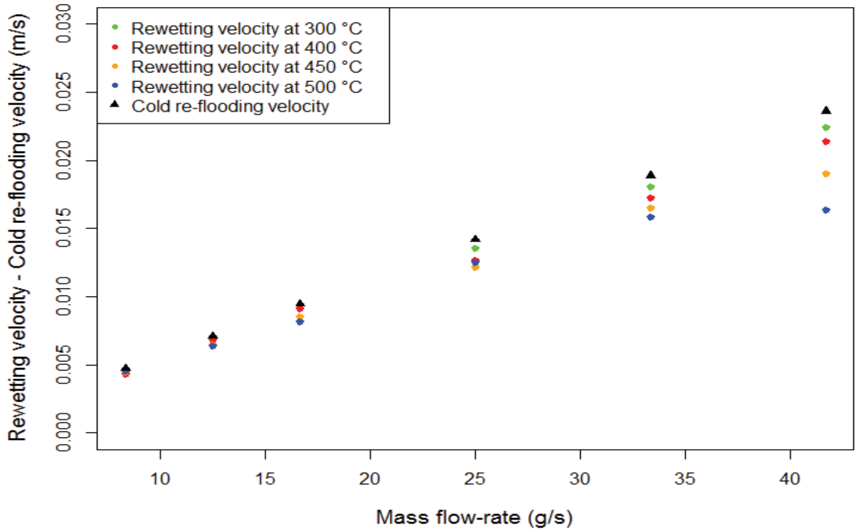

Figure 6. Rewetting velocity and cold re-flooding velocity against mass flow-rate with saturated coolant water.

The current experimental observations along with the analysis above lead to the conclusion that a quench test occurs when the initial wall temperature is greater than 400°C. This deduction has also been made by other researchers in the past concerning rewetting experiments on a stainless steel heated surface [20,21]. Thus, it is suggested that the experimental tests conducted at the initial wall temperatures lower than 400°C do not represent a quench test but a rapid cooling of the surface. Finally, Figure 7 summarizes only the experimental data collected in this study for the initial wall temperatures above 400°C at different mass flow-rates.

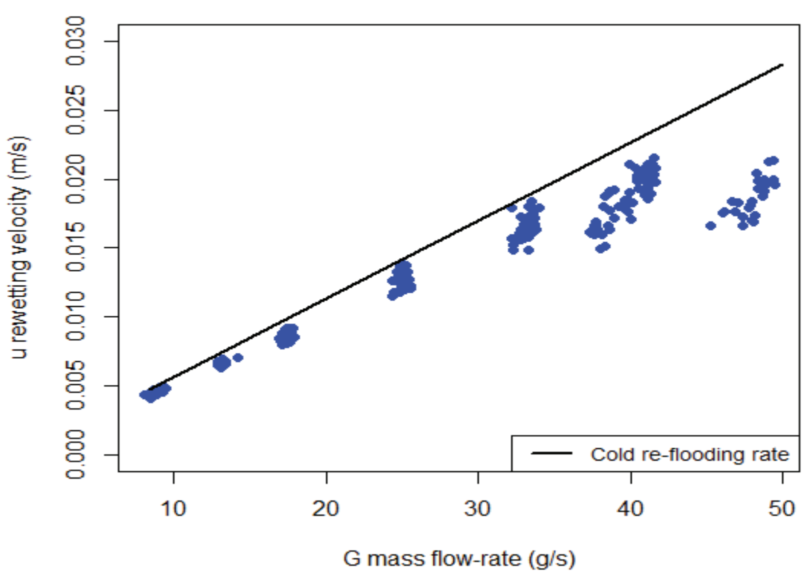

Figure 7. Rewetting velocities versus coolant mass flow-rate at various initial wall temperatures within the range 400°C to 550 °C approximately.

3.4 Study on the effect of Geometry

To corroborate the effect of the geometry of the annular channel on the rewetting velocity, a number of quench experiments have been conducted at initial wall temperature of 400 to 550°C using saturated water at atmospheric conditions and water mass flow-rate in the range of 8.33 to 50.01 $g \cdot s^{-1}$. Furthermore, a comparison has been carried out between the present data and the data from previous experimental works.

It has been suggested by Duffey and Porthouse [8] that the quenching mechanisms depend on the heated perimeter of the rod and not on the surface area of the annular channel. Following this approach, we express the thermal properties and the geometrical characteristics of the heated rod via the dimensionless Peclet number and the modified Biot number respectively. Peclet number is defined as the dimensionless rewetting velocity and is calculated by the following expression:

$$Pe = \frac{\rho c \varepsilon u}{k} \tag{1}$$

The Biot number is identified as a criterion of the relativity of conduction and convection regarding heat transfer mechanisms. It also depends on the thermal properties of the surface and is proportional to the convection heat transfer coefficient. Duffey et al. [8] have suggested that convection heat transfer coefficient is a function of the mass flow-rate per unit perimeter of the rod, so a modified Biot number is employed and calculated by the following expression:

$$Bi_{mod} = \left(\frac{G}{2\pi R}\right)\left(\frac{\varepsilon}{k}\right) \tag{2}$$

Table I summarizes the test sections and conditions of the present work as well as of other experimental studies for atmospheric bottom flooding experiments [8, 9, 22]. It should be noted that Duffey et al. [8,22] have used two test sections with hydraulic diameters (D_h) equal to 2.394 mm and 4.000 mm while Saxena et al. [9] have used an experimental apparatus which consists of a test section with a hydraulic diameter equal to 1.600 mm. Respectively, the hydraulic diameter of the experimental rig of the current study is larger and equals 8.598 mm. Nevertheless, the results of the present work seem to be in agreement with the results of the other researchers as shown in Figures 8 and 9. Applying regression analysis using the least squares approach on all the experimental data for constant initial wall temperature, two correlations have been evaluated and are shown in Table II.

Table I. Atmospheric bottom flooding experimental data

Author(s)	Rod/tube description	Initial wall temperatures for comparison (°C)	Mass flow-rate range (g s^{-1})
Duffey and Porthouse [8]	stainless rod 0.085 cm thick magnesia fill 1.25 cm o.d[1]	400-500	0.3-10
	stainless rod 0.085 cm thick magnesia fill 1.25 cm o.d	400-500	0.1-37
Saxena and Venkat Raj and Govardhana Rao [9]	stainless tube 0.03 cm thick 1.5 cm o.d	400-500	16.67-121.7
Current work	stainless rod 0.03 cm thick magnesia fill 1.5875 cm o.d.	400-500	8.33-50.01

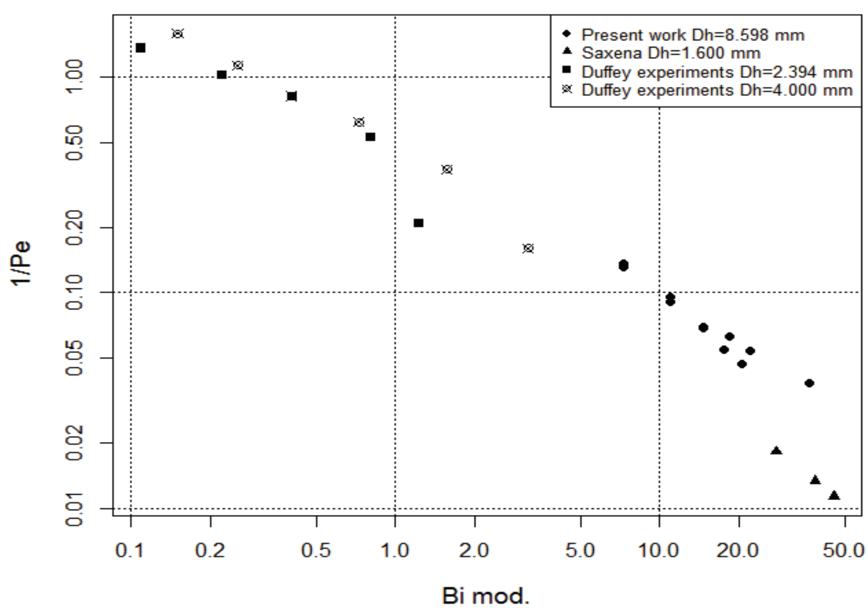

Figure 8. Log-log plots of experimental values of reverse Peclet number against modified Biot number at initial wall temperatures of 400°C.

[1] o.d. stands for the outer diameter of the rod/tube

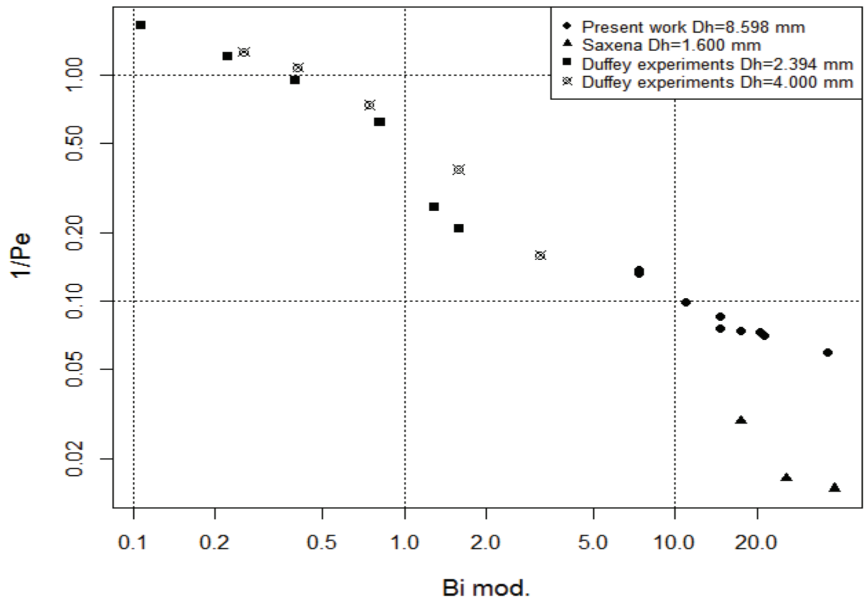

Figure 9. Log-log plots of experimental values of reverse Peclet number against modified Biot number at initial wall temperatures of 500°C.

Table II. Final correlations

Initial wall Temp. (°C)	Linear correlations	R-squared	Transformed correlation
400	$\log\left(\frac{1}{Pe}\right)$=-0.909-0.732 $\log(Bi_{mod})$	R^2 =0.946	$Pe=10^{0.909}Bi_{mod}^{0.732}$
500	$\log\left(\frac{1}{Pe}\right)$=-0.801-0.724 $\log(Bi_{mod})$	R^2 =0.918	$Pe=10^{0.801}Bi_{mod}^{0.724}$

From the previous analysis, it can be concluded that the rewetting mechanisms of the bottom rewetting process occur in the approximate region of the heated surface and strongly depend on its geometrical characteristics and material properties regardless of the dimensions of the annulus in which the surface is included. The presented correlations can be extended to a general model which in its final form will include the initial wall temperature parameter.

3.5 Study on the Quench Temperature

Quench temperature is defined as the maximum temperature of a heated solid surface when a liquid re-establishes contact with the surface. In the present work, the quench temperature is calculated directly from the thermocouples' temperature history, as shown in Figure 3 and 4, the moment that the liquid re-establishes contact with the rod surface at each and every thermocouple station (from TC11 to TC4) embedded in the test section heated rod. As previously mentioned, the moment that the liquid re-establishes contact with the rod surface is defined by the minimum of the temperature first order derivative. It is understood that by using this method we realize that the calculated quench temperature depends on the initial wall temperature and due to precursory cooling effect each thermocouple station downstream has lower quench temperature than the previous one. As a result and for purpose of the current study, the experimental mean quench temperature at steady state conditions is expressed by the mean value of the eight thermocouple stations.

The present study thoroughly examines the effect of the coolant water mass flow-rate and the coolant inlet temperature on the quench temperature. In Figure 10 the experimental values of the mean quench temperature are presented with reference to the values of the initial wall temperature that have been obtained from the present bottom flooding experiments at atmospheric conditions and initial wall temperatures greater than 400°C. The plots in the top row refer to six sets of experimental data for water mass flow-rates within the range of 8.33 to 50.01 $g{\cdot}s^{-1}$ and water inlet sub-cooling of 25 °C. The plots in the bottom row refer to experimental data with saturated coolant for the same water mass flow-rate and initial wall temperature range.

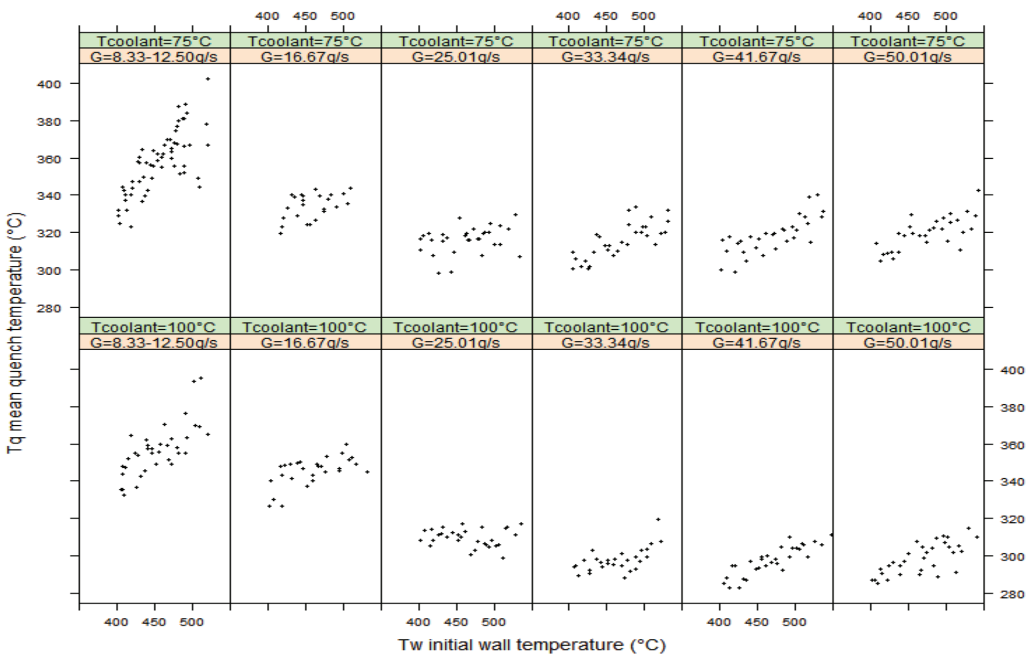

Figure 10. Effect of initial wall temperature, coolant mass flow-rate and coolant inlet temperature on the quench temperature at bottom flooding experiments.

The experimental measurements presented in Figure 10, show that at low mass flow-rate experiments the standard deviation and the range of the measured quench temperature values are greater than the ones at higher mass flow-rate experiments. In addition to this, at low mass flow-rate a strong linear correlation between the quench temperature and the initial wall temperature is observed while at higher mass flow-rate the linear correlation becomes less significant. For instance, for the experiments at 8.33 – 12.50 $g{\cdot}s^{-1}$ mass flow-rate and liquid temperature near saturation (bottom-left corner plot) the standard deviation of the quench temperature is 14.45°C and the range between the values is measured up to 63.73°C, whereas the Pearson's coefficient is estimated to be approximately 0.7726. However, for the experiments at 33.34 $g{\cdot}s^{-1}$ mass flow-rate and the same coolant inlet temperature the standard deviation of the quench temperature is 9.43°C, the range between the values is measured up to 33.31°C and the Pearson's coefficient is 0.6005. The reason for this differentiation can be attributed to the stronger precursory cooling effect upon the preceding solid surface in high mass flow-rate experiments. A strong precursory cooling effect corresponds to a faster drop in the wall temperature thus signifying lower quenching temperatures even at high initial surface temperatures.

Furthermore a parallel investigation has been conducted on the quench temperature applied in previous top rewetting experiments [10]. These experiments have been performed at the same experimental facility at atmospheric saturated conditions for coolant mass flow-rate within the range of 8.33 to 16.67 g s^{-1}. Figure 11 presents the data of the top rewetting experiments. It is clearly observed that the quench temperature is barely influenced by mass flow-rate whereas it is strongly affected by initial wall temperature. In addition, the observed trend seems to be the same as the one noticed at low mass flow-rate bottom rewetting experiments. The similarity may lie in the fact that top rewetting mechanisms and low mass flow-rate bottom rewetting mechanisms are almost identical as described in detail by Carbajo [4].

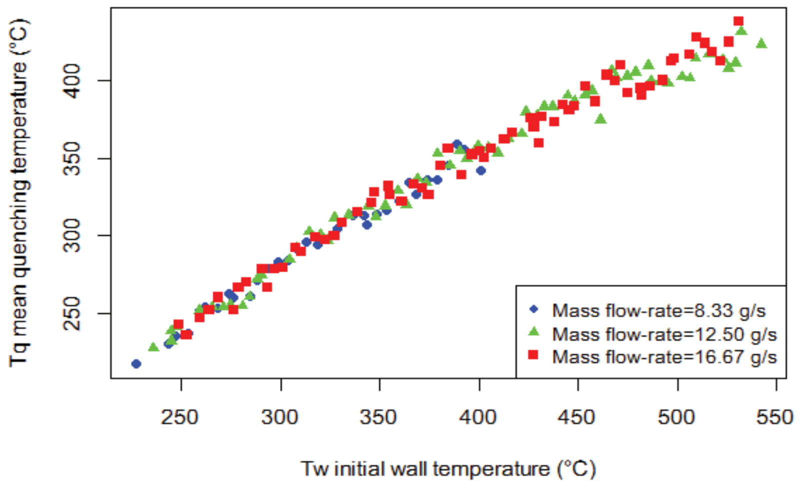

Figure 11. Effect of mass flow-rate on quench temperature at top rewetting experiments.

The observations that derive from Figures 10 and 11 are of great importance in the study of the theory of rewetting and can be valuable to a future prediction of an empirical correlation of the quench temperature in relation to the initial experimental conditions for both top and bottom rewetting experiments.

Finally, a statistical dimensional analysis of 393 bottom rewetting experimental data points is performed in order to deduce the final empirical correlation that predicts the quench temperature. To this purpose, it is required to select the proper variables that affect the rewetting process and thus the quench temperature. It is postulated [16,18,20,23] that the evaluation of the quench temperature is affected by the physical properties of the heated surface in combination with the experimental conditions as shown in Eq. 3.

$$T_q=f\left(\rho, k, c, P_{rod}, \varepsilon, R, T_s, T_w, T_c, G\right) \quad (3)$$

Based on our analysis and on the information provided by previous researchers [9,16,22] the following dimensionless parameters are obtained. The constant values of Eq. 3 are portrayed in Table III.

$$p_1=\frac{T_q-T_s}{T_w-T_s} \qquad p_2=\frac{T_c-T_s}{T_w-T_c} \qquad p_3=\frac{cG\varepsilon}{k} \qquad p_4=\frac{P_{rod}}{k(T_w-T_s)\varepsilon}$$

Table III. Constant values

Variables	Values
ρ (kg/m³)	8238
k (W/(m K))	17
c (J/(kg K))	468
$\mathbf{P_{rod}}$ (W)	2500
ε (m)	0.00372
R (m)	0.015875
$\mathbf{T_s}$ (°C)	100

In order to determine the individual influence of each dimensionless term on p_1, a single linear regression analysis has been performed and the linear correlation coefficient has been calculated. The results of the analysis are summarized in Table IV in which the significance of each parameter is defined by the p-value of the linear correlation coefficient. It should be noted that since there has been shown no significant effect of the variables ρ and R on the quench temperature, these two variables are not included in the present analysis.

Table IV. Results of Single Linear Regression Analyses

	Single Linear Regression Analysis	
Parameters	**Linear correlation coefficient**	**p-value**
$\mathbf{p_2}$	0.454	$<2.2\cdot10^{-16}$
$\mathbf{P_3}$	0.696	$<2.2\cdot10^{-16}$
$\mathbf{p_4}$	0.616	$<2.2\cdot10^{-16}$

From the above analysis it can be concluded that all the aforementioned dimensionless parameters affect the final result in a statistically significant way and they should be included in the proposed empirical correlation to which experimental data will be fitted. Finally, a multiple linear regression analysis is conducted and the final correlation for Eq. 3 is given below:

$$p_1=0.278 - 0.757p_2 - 36.542p_3+ 0.004p_4 \tag{4}$$

The adjusted R^2 of Eq. 4 is calculated to equal 0.804 which shows that there is a good fit among the four dimensionless parameters. As a result, the final functional relationship is provided by Eq. 5:

$$T_q=T_s+ (T_w-T_s)(0.278 - 0.757\frac{T_c - T_s}{T_w - T_c} -36.542\frac{cG\varepsilon}{k}+0.004\log\left(\frac{P_{rod}}{k(T_w-T_s)\varepsilon}\right)) \tag{5}$$

The estimated linear correlation coefficient for the measured values of mean quench temperature and the predicted values of quench temperature by Eq. 5 is equal to 0.826.

4. CONCLUSIONS

The current study presents experimental work upon the quenching mechanisms of bottom flooding of a vertical annular channel enclosing a heated rod concentrically. Experimental results have been obtained to study the effect of various initial experimental conditions on the quench velocity and temperature. The observed trends for quench velocity are in agreement with experimental results of the international literature. However, in order to reach a final conclusion concerning the effects of the experimental conditions on the quench velocity, a more detailed investigation on the influence of coolant inlet temperature on the rewetting rate should be carried out.

In addition, the effect of the annular geometry on the bottom rewetting mechanisms by comparing the present data with the data obtained from other experimental investigations is examined. It is concluded that the geometry of the annulus that contains the heated rod does not appear to affect the mechanisms that occur in the rewetting of an overheated surface.

Moreover, the effect of the experimental conditions on the quench temperature is thoroughly examined as regards previous top rewetting experiments along with the current bottom flooding experiments. Furthermore, an empirical correlation for the prediction of the quench temperature regarding the initial experimental conditions for the current bottom flooding experiments, which were conducted at a stainless steel heated rod, is introduced. To study and confirm the application of the correlation with other test section geometries as well as with other rod materials, much more data is necessary. An extension of the proposed correlation with both top and bottom rewetting experiments is also suggested, in order to acquire a more thorough image of the variables that affect the quench temperature.

Finally the current work may be expanded to examine the effect on the rewetting mechanisms of other parameters such as pressure and rod oxidization in order to improve the recommended correlations.

Nomenclature

Bi_{mod}	Modified Biot number, $(s^2 \cdot K)/m$
c	Specific heat of stainless steel, $J/(kg \cdot K)$
D_h	Hydraulic diameter (mm)
G	Mass flow-rate, $g \cdot s^{-1}$
k	Thermal conductivity of stainless steel, $W/(m \cdot K)$
P_{rod}	Power of rod, W
Pe	Dimensionless quench velocity
R	Diameter of the rod, m
T_c	Coolant temperature, °C
T_q	Quench temperature, °C
T_s	Saturation temperature, °C
T_w	Wall temperature, °C
u	Quench velocity, m/s
ε	Thickness of the rod, m
ρ	Density of stainless steel cladding, kg/m^3

REFERENCES

[1] J. Duncan and J. Leonard, "Heat Transfer in a Simulated BWR Fuel Bundle cooled by Spray under Loss-Of-Coolant Conditions," GEAP 13086, San Jose, California (1970).

[2] L. Tong, "Heat-transfer Mechanisms in Nucleate and Film Boiling," *Nuclear Engineering and Design,*Vol. 21, pp. 1-25 (1972).

[3] T. Thompson, "Simulated Bottom-Flooding Emergency Cooling of a Close-Spaced Rod Bundle," *Proceedings of European Two-Phase Flow Group Meeting*, Rome, Italy (1972).

[4] S. Sahu, P. Das and S. Bhattacharyya, "An Experimental Investigation on the Quenching of a Hot

Vertical Heater," *Nuclear Engineering and Design,* Vol. 240, pp. 1558-1568 (2010).

[5] A. Yamanouchi, "Effect of Core Spray Cooling in Transient State after Loss of Coolant Accident," *Nuclear Science and Technology* , Vol. 11, pp. 547-557 (1968).

[6] M. Sawan, G. Zaki and H. Temraz, "A Three-Regions Rewetting Model with Heat Generation and Subcooling," *Atomkernenergie-Kerntechnik Bd,* Vol. 34, pp. 199-204 (1979).

[7] C. Tien and L. Yao, "Analysis of Conduction Controlled Rewetting of a Vertical Surface," *Journal of Heat Transfer, ASME,* Vol. 97, pp. 161-165 (1975).

[8] R. Duffey and D. Porthouse, "The Physics of Rewetting in Water Reactor Emergency Core Cooling," *Nuclear Engineering and Design,* Vol. 25, pp. 379-394 (1973).

[9] A. Saxena, V. Venkat Raj and V. Govardhana Rao, "Experimental Studies on Rewetting of Hot Vertical Annular Channel," *Nuclear Engineering and Design,* Vol. 208, pp. 283-303 (2001).

[10] P. Kastanidis, A. Nikoglou, E. Hinis and S. Simopoulos, "An Experimental Study of the Rewetting of a Hot Surface at Atmospheric Conditions Using Subcooled Liquid at Various Flowrates," *Proceedings of 15th International Topical Meeting on Nuclear Reactor Thermalhydraulics, NURETH-15*, Pisa, Italy (2013).

[11] S. Chatzidakis, A. Nikoglou, E. Hinis and S. Simopoulos, "A Study on the Rewetting of a Hot Surface Using Low Pressure, Subcooled Liquid," *Proceedings of 15th International Topical Meeting on Nuclear Reactor Thermalhydraulics, NURETH 15*, Pisa, Italy (2013).

[12] J. Carbajo, "A Study on the Rewetting Temperature," *Nuclear Engineering and Design,* Vol. 84, pp. 21-52 (1985).

[13] Y. Murao and T. Dudoh, "A Study on Quench Phenomena during Reflood Phase," *JAERI-M 6984* (1977).

[14] F. Cadek, D. Dominicis and R. Leyse, "PWR FLECHT final report," WCAP-7665, 1971.

[15] J. Cermak, A. Kitzes, F. Cadek, R. Leyse and D. Dominicis, "PWR Full Length Emergency Cooling Heat Transfer," WCAP-7435 (1970).

[16] A. Kim and Y. Lee, "A Correlation of Rewetting Temperature," *Letters in Heat and Mass Transfer,* Vol. 6, pp. 117-123 (1979).

[17] D. Andreoni and M. Courtaud, "Study of Heat Transfer during the Reflooding of a Single Rod Test Section," *Proceedings of CREST Specialist Meeting on Emergency Core Cooling for Light Water Reactors*, Munich, Germany (1972).

[18] V. Dhir, R. Duffey and I. Catton, "Quenching Studies on a Zircalloy Rod Bundle," *Journal of Heat Transfer,* Vol. 103, pp. 293-299 (1981).

[19] K. Tuzla, C. Unal and J. Chen, "An Experimental Study of Bottom Rewetting in a Rod Bundle Geometry," *Nuclear Engineering and Design,* Vol. 125, pp. 189-200 (1991).

[20] M. Naitoh, K. Chino and H. Osagawara, "Cooling Mechanism during Transient Reflooding of a Reactor Fuel Bundle after Loss Of Coolant," *Nuclear Engineering and Design,* Vol. 125, pp. 193-200 (1977).

[21] H. Kim, B. Truong, J. Buongiorno and L. Hu, "Effects of Micro/Nano-scale Surface Characteristics on the Leidenfrost Point Temperature of Water," *Journal of Thermal Science and Technology,* Vol. 7, pp. 453-462 (2012).

[22] R. Duffey and D. Porthouse, "Experiments on the Cooling of High Temperature Surfaces by Water Jets and Drops," *Proceedings of CREST Specialist Meeting on Emergency Core Cooling for Light Water Reactors*, Munich, Germany (1972).

[23] M. De Salve and B. Panella, "Validation of a Bottom Flooding Model," *Nuclear Engineering and Design,* Vol. 199, pp. 213-222 (1987).