Experimental studies on rewetting of hot vertical annular channel

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Abstract

Studies on the rewetting behaviour of hot vertical annular channels are of interest in the context of emergency core cooling in nuclear reactors following LOCA. Experimental studies were carried out to study the rewetting behaviour of a hot vertical annular channel, with hot inner tube, for bottom flooding and top flow rewetting conditions. The length of the inner tube of the test section was 3030 mm for bottom flooding rewetting experiments and 2630 mm for top flow rewetting experiments. The tube was made of stainless steel. Experiments were conducted for water flow rates in the annulus upto 7 lpm ($11.7 \times 10^{-5} \text{ m}^3 \text{ s}^{-1}$). The initial surface temperature of the inner tube was varied from 200 to 500°C. The experimental studies show that for a given initial surface temperature of the tube, the rewetting velocity increases with an increase in flow rate of water and it decreases with an increase in the initial surface temperature for a given water flow rate. For a given water flow rate and initial surface temperature, the rewetting velocity is 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. Using the experimental data of the present work, correlations for bottom flooding and top flow rewetting velocities are developed.

1. Introduction

Nuclear reactors generally use rod clusters housed in a channel as fuel. The coolant flows in between the fuel rods. They are designed for safety not only during normal operation, but also during abnormal and accident conditions. Following a loss of coolant accident (LOCA), which is the consequence of a rupture in the pressure boundary of the primary coolant system (PCS), the coolant which is at high pressure and high enthalpy escapes from the system in a very short time. Thus, the reactor core is voided rapidly and heat removal from the fuel is drastically reduced. Even after the reactor is shutdown, the decay heat and the stored energy in the fuel need to be removed. Further, if the fuel clad heats up sufficiently, energy may be liberated due to the exothermic metal–water reaction. The emergency core cooling system (ECCS) is provided to remove
the heat and mitigate the consequences following a LOCA.

The thermal hydraulic behaviour of hot vertical channels during emergency core cooling conditions and the heat transfer mechanisms encountered could be flow direction-dependent, i.e. whether the flow of coolant is from bottom to top or from top to bottom. Following the blow-down phase of LOCA, the clad temperature may rise quickly to a high value, so that the injected emergency coolant may not wet the clad immediately on coming into contact. Rewetting of the clad is essential for effective heat removal by the emergency coolant. The phenomenon of rewetting of hot surfaces is of great interest not only in the context of cooling of nuclear reactor fuel following a LOCA, but also in many other industrial processes involving quenching of hot solids.

Extensive studies on the rewetting of hot surfaces have been carried out earlier. Details of some of the published experimental work on bottom flooding and top flow rewetting are summarised in Tables 1 and 2, respectively. Apart from these, there have been studies with multiple injections. An example is the study by Duffey and Ackerman (1978) who conducted experimental studies on combined injection with steam/air flow from the bottom and water flow from the middle of the test section. The test section consisted of a heated rod of 14.2 mm diameter and length 450 mm, located centrally within a smooth transparent silica tube of 19.5 mm bore. Climbing quench fronts were observed which some times coexisted with the falling quench front.

From Tables 1 and 2, it is seen that most of the rewetting data on annular geometry are with test sections of length less than about 1.5 m. However, fuel rods used in nuclear reactors are generally of length 3 m or more. Earlier studies have brought out the influence of precursory cooling downstream of the wet front. As a consequence of this, the downstream tube regions away from the inlet can cool down considerably before the wet front reaches there. Consequently, for a given initial temperature along tube length, the rewetting velocity may be more in the downstream regions. Thus, tube length becomes one of the parameters to be considered, particularly if one is interested in the average rewetting velocity for a given set of initial conditions. Further, a majority of the earlier studies on both bottom flooding and top flow rewetting covered a narrow range of coolant flow rates and initial surface temperatures. Therefore, there is a need to study the rewetting behaviour in longer hot vertical annular channels over a wider range of coolant flow rates and initial surface temperatures and the present work is aimed in this direction. While experiments have been carried out earlier with rod bundles of length more than 3 m, because of the complex geometry involved, the data generated may not be of much help for the development of analytical models. The data obtained using a simple geometry such as annular test section will be more helpful in understanding the mechanism and developing a theoretical model. In the present study, both bottom flooding and top flow rewetting experiments were carried out on annular test sections over the range of parameters relevant to the emergency core cooling of nuclear reactor fuel. This would help in comparing the effect of the two modes of operation on rewetting behaviour for a given test section geometry.

2. Experimental set-up

A schematic of the experimental set up employed in the present work for bottom flooding and top flow rewetting experiments is shown in Fig. 1. The set-up consisted mainly of a source of power supply (1), a source of demineralised water supply (2), a test section and a data acquisition system (DAS) (3). The test section (Fig. 2) comprised of inner stainless steel (S.S.316) tube (4), outer stainless steel tube (5) and copper tubes (6). The copper tubes were brazed to the ends of the inner stainless steel tube. The Upper copper tube was clamped between two copper plates (7), each with a semicircular groove, with a nut and bolt arrangement. Similarly, the lower copper tube was also clamped between two copper plates (7). Electrical cables from power supply unit were connected to the copper plates. Electrical resistance heating was employed for heating the inner tube to the desired initial temperature using a low
<table>
<thead>
<tr>
<th>Serial no.</th>
<th>Author(s)</th>
<th>Test section geometry</th>
<th>Length of the heated tube (m)</th>
<th>Water flow rate range (lpm)</th>
<th>Initial surface temperature (°C)</th>
<th>Range of rewetting velocities (mm s$^{-1}$)</th>
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<tbody>
<tr>
<td>1</td>
<td>Duffey and Porthouse (1973)</td>
<td>Annulus</td>
<td>–</td>
<td>0.006–1.2</td>
<td>300–800</td>
<td>1–50</td>
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<td>Piggott and Duffey (1975)</td>
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<td>1.5–6.0</td>
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<tr>
<td>3</td>
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<td>1–33</td>
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<td>25–170</td>
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<td>Neti and Chen (1981)</td>
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<td>28–100</td>
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<tr>
<td>7</td>
<td>Lee and Shen (1985)</td>
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<td>–</td>
<td>350–550</td>
<td>40–220</td>
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<tr>
<td>8</td>
<td>Yonomoto et al. (1987)</td>
<td>Rod bundle</td>
<td>1.8</td>
<td>34</td>
<td>630</td>
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<tr>
<td>9</td>
<td>Muto et al. (1990)</td>
<td>Rod bundle</td>
<td>3.708</td>
<td>1.0–5.0 × 10$^6$ kg m$^{-2}$ h$^{-1}$</td>
<td>Transient tests with power varied</td>
<td>Rewetting correlation developed</td>
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<td>Tuzla et al. (1991)</td>
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<td>–</td>
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<td>160–380</td>
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<td>12</td>
<td>Huang et al. (1994)</td>
<td>Tube</td>
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<td>0.12–2.4</td>
<td>Test section heated upto stable film boiling regime</td>
<td>Minimum film boiling temperature and CHF obtained</td>
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Table 2  
Details of some experimental studies on top flow rewetting

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<th>Water flow rate range (lpm)</th>
<th>Initial surface temperature (°C)</th>
<th>Range of rewetting velocities (mm s⁻¹)</th>
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<td>Shires et al. (1964)</td>
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<td>Upto 45</td>
<td>Up to 500</td>
<td>7–290</td>
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<tr>
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<td>300–600</td>
<td>3.5–28</td>
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<td>Annulus</td>
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<td>Up to 500</td>
<td>7–290</td>
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<tr>
<td>5</td>
<td>Duffey and Porthouse (1972)</td>
<td>Filled rod</td>
<td>0.1 and 0.18</td>
<td>Up to 2.22</td>
<td>850</td>
<td>1.5–100</td>
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<tr>
<td>6</td>
<td>Piggott and Duffey (1975)</td>
<td>Tube</td>
<td>0.2 and 0.25</td>
<td></td>
<td>600, 650</td>
<td>1–100</td>
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<tr>
<td>6</td>
<td>Piggott and Duffey (1975)</td>
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<td>0.1–0.55</td>
<td>700</td>
<td>1.5–6</td>
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<tr>
<td>7</td>
<td>Cumo et al. (1980)</td>
<td>Flat plate</td>
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<td>0.06–1.8</td>
<td>350</td>
<td>6.2–24.8</td>
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<tr>
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<td>Tube</td>
<td>3.5</td>
<td>0.5–3.6</td>
<td>550</td>
<td>28–100</td>
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</table>
voltage high current power supply. Chromel–Alumel thermocouples (8) soldered to the inner tube were used to measure the temperatures. The size of the naked chromel–alumel wires is 0.3 mm. They are insulated individually and both together with fibreglass insulation resulting in overall diameter of 1.2 mm. The thermocouples used in the present study have a response time of about 0.01 s. The thermocouple wires were brought out from the inside of the inner tube and connected to a junction box (9). The lead wires (10) from the junction box were connected to the DAS. The test section was insulated by asbestos rope wound around the outer tube for minimizing the heat loss to the surrounding.

Deminerilised water from a pressurised storage tank was fed to the test section using isolating valves (11) and control valves (12). The direction of flow of water for bottom flooding rewetting is indicated by solid lines and for top flow rewetting is indicated by dotted lines in Fig. 1. Water distributor (13) was used to distribute the water in the case of top flow rewetting, whereas no distributor was used for bottom flooding rewetting. Various components of the test section were assembled using stainless steel flanges (14).

![Fig. 1. Schematic of the experimental set-up.](image-url)
2.1. Test section details

The details of the vertical test section are shown in Fig. 2. The lengths of the inner tube are 3030 and 2630 mm for bottom flooding and top flow rewetting experiments, respectively. The overall length of the test section is 3675 mm including the copper tubes attached to either end of the inner
The outer and inner diameters of the inner tube for both types of rewetting experiments are 15 and 12 mm, respectively. The wall thickness of the inner tube was measured at various locations and the maximum variation was found to be within ±10% of the average value. The inner diameter of the outer tube is 21 mm, thus forming a vertical annulus of 3 mm width. For top flow rewetting, water enters into the annulus through a water distributor (13) to avoid channeling of water. The copper tubes, brazed to either end of the inner tube, act as current conductors. The copper tubes were connected to a 10 V, 800 A A.C. power supply using appropriate connectors. The rest of the test section was electrically insulated from the current carrying inner tube including copper tubes by using fibreglass (16) and asbestos gasket (17). At the lower end of the inner tube, a flange with 'O' ring seal (18) was slipped on the copper tube, as shown in Fig. 2 to allow for thermal expansion/contraction of the inner tube when it is heated/cooled. The 'O' ring also serves as electrical insulation. The outer tube of the test section was made up from three sections, which were joined with the help of stainless steel flanges for easy installation and dismantling of the test sections.

2.2. Instrumentation

The instrumentation consisted mainly of provision for measuring temperatures. For bottom flooding rewetting experiments, thermocouples were fixed at eight axial locations along the inner tube from the bottom with equal axial spacing of 400 mm between two adjacent locations as shown in Fig. 3. The thermocouples at these locations are designated as t1 to t8. The thermocouples t3a, t3b, t3c, t3d and t6a, t6b, t6c, t6d were fixed around the circumference, spaced at 90 degrees, on the inner tube. The distance between the first (t1) and the last (t8) thermocouples is 2800 mm. For top flow rewetting experiments, thermocouples were fixed at seven different axial locations along the inner tube with equal spacing of 400 mm between two adjacent axial locations. These are designated as t1 to t7. The thermocouples t2a, t2b, t2c, t2d and t5a, t5b, t5c, t5d were fixed around the circumference, spaced at 90 degrees, on the inner tube. The distance between the first (t1) and the last (t7) thermocouples is 2400 mm.

Adequate care was taken to ensure that the mounting of the thermocouple does not affect the rewetting process. For this purpose, a suitable thermocouple installation technique, developed earlier (Venkat Raj, 1985) was used. When the technique was developed, separate tests were carried out to ensure that the installation of thermocouples does not have any affect on the rewetting process. The thermocouples were installed from the inside of the inner tube in such a way that the hot junction remains flush with the outer surface of the inner tube. Thermocouple installation details are shown in Fig. 4. The installed thermocouples were also checked to ensure that they measure the temperature of the outer surface of the inner tube and not the temperature at the inside of the tube surface (Saxena, 1998).

![Fig. 3. Thermocouple locations in bottom flooding rewetting.](image_url)
3. Experimental procedure and range of parameters

After installing the test section, a check was made to ensure that it was vertical using a spirit level. Fig. 1 shows the cooling water flow directions and the locations of control valve and isolating valves. The solid lines represent the flow direction for bottom flooding rewetting and the dotted lines represent the flow direction for top flow rewetting. The inner tube was heated gradually to the required temperature by increasing the power in steps. The power supply to the inner tube was then switched off. Then, the DAS was started and cooling water was allowed to flow at the desired flow rate. The temperature transients generated at various thermocouple locations during the experiments were measured and stored in the DAS. The water flow rate was measured again at the end of the experiment to check the constancy of the flow rate during the experiment. The same procedure was adopted for different initial surface temperatures and flow rates. For initial surface temperature of 400°C and above, bowing of the inner tube was observed. Whenever this was observed, the test section was dismantled and inner tube was either straightened for reuse or a new tube was used. Experiments were conducted for water flow rates in the range of 1–7 lpm and initial surface temperatures in the range of 200–500°C, considering the conditions expected during ECCS injection in nuclear reactors.

4. Method of determination of rewetting velocity

The main aim of the present study is to understand the rewetting behaviour of hot surfaces and determine the rewetting velocity. Hence, it is necessary to define a proper criterion for determining the occurrence of rewetting, from the experimental temperature transients. Typical temperature transients obtained at an initial surface temperature of 290°C and a water flow rate of 5.9 lpm are shown in Fig. 5 for bottom flooding rewetting. At various locations along the inner tube, each temperature transient exhibits three distinct phases. Initially, the temperature decrease is gradual and

2.3. Experimental errors

The important parameters measured during the rewetting experiments are
1. Inner tube surface temperatures
2. Water flow rate

The errors/uncertainties in the outer surface temperature of the inner tube are basically due to measurement error and variation in tube outer surface temperatures at different axial locations as compared to the nominal value. The error in the measurement of the outer surface temperature of the inner tube is due to (i) Thermocouples and (ii) DAS. Error due to thermocouple is \( \pm 2.5^\circ C \) for temperatures below 333°C and \( \pm 0.75\% \) for temperatures over 333°C. Error due to DAS is \( \pm 0.01\% \). The maximum variation in the tube outer surface temperatures at different axial locations as compared to the nominal value was found to be within \( \pm 12\% \). The error in volumetric flow rate measurements is \( \pm 0.5\% \). Considering all these factors, the maximum uncertainty in the experimental rewetting velocity is assessed to be \( \pm 20\% \).
then there is a large sudden decrease in temperature followed by more or less constant temperature. The large sudden decrease in temperature is attributed to the rewetting of the surface. The rewetting time successively increases from the bottom to the top thermocouple location. Rewetting is considered to occur at the time when the maximum rate of change of temperature takes place. Fig. 3 shows the heights from the bottom of the stainless steel portion of the inner tube at which the thermocouples are fixed for the rewetting experiments under bottom flooding conditions. The symbol ‘x’ in Fig. 5 represents the distance of the thermocouple location from the bottom of the stainless steel portion of the inner tube and is same as depicted in Fig. 3. The time at which rewetting occurs for different experimental runs for bottom flooding rewetting and top flow rewetting was determined by obtaining the transients on the monitor of the personal computer connected to the DAS and the cursor was put at the location of maximum change in slope as observed visually on the transient curve. The time corresponding to this location of the cursor was noted as the time of occurrence of rewetting at that location. As an alternative, a computer program was also developed and used to locate the time at which the maximum gradient occurs. The times obtained by both these methods agree closely.

![Fig. 5. Experimental rewetting transients in bottom flooding rewetting ($T_i = 290^\circ C$, $Q = 5.9$ lpm).](image-url)
The rewetting velocity is a measure of the speed with which surface rewetting occurs. It gives an indication of how quickly the injected emergency coolant contributes to effective heat removal from the fuel. Following the above-mentioned criterion of rewetting, the rewetting times at various thermocouple locations were obtained from the corresponding transients. In principle, the rewetting velocity between successive locations can be calculated from the values of rewetting times and the distance between the locations. However, an average rewetting velocity over the entire length of the inner tube is desirable. To estimate the average rewetting velocity, the time of progress of the wet front versus the distance covered by the wet front is plotted. Fig. 6 illustrates such a plot for the transients shown in Fig. 5 for $T_i = 290^\circ C$ and $Q = 5.9$ lpm. The experimental points tend to fall on a straight line. A straight line is fitted by linear regression analysis using the method of least squares. The average rewetting velocity is obtained as inverse of the slope of this line. Similarly, rewetting velocities for other experimental runs were obtained.

5. Results and discussion

Cold flooding velocity (also called refilling velocity) corresponding to given flow rates is the velocity of water in the annulus if the inner tube were not hot. It is calculated by dividing the volumetric flow rate with the cross-section area of annulus. The operating conditions, the rewetting and cold flooding velocities for bottom flooding and top flow rewetting are given in Tables 3 and 4, respectively.

6. Bottom flooding rewetting velocity

The variation of rewetting velocity with cooling water flow rate for a given initial surface temperature is plotted in Fig. 7. Fig. 7 includes the data...
on cold flooding velocities also. As can be seen from the Table 3 and the data presented in Fig. 7, the cold flooding velocities are much higher than the rewetting velocities for initial surface temperature of 290°C and more. However, as expected the rewetting velocities are close to cold flooding velocities at initial surface temperature of 200°C. The experimental rewetting velocities for all given initial surface temperatures increase approximately linearly with water flow rate. The straight lines are obtained by linear regression analysis using the method of least squares.

At initial surface temperature of 200°C, the effect of flow rate is more predominant. The rate of increase of rewetting velocity with respect to flow rate is large at initial surface temperature of 200°C, whereas it is much less at higher initial surface temperatures. At a given flow rate of water, the rewetting velocity decreases with an increase in initial surface temperature.

7. Top flow rewetting velocity

The rewetting velocities are plotted against the flow rate for different values of initial surface temperature in Fig. 8. The trend of the experimental rewetting velocity data for a given initial surface temperature indicates that its variation with water flow rate is approximately linear. The straight lines shown in Fig. 8 are obtained by linear regression analysis using the method of least squares. For all temperatures, the rewetting velocity increases with the flow rate of water. The slopes of the lines for different temperatures do not show significant variation. The rewetting velocity at a given water flow rate decreases with an increase in initial surface temperature. Fig. 9 shows the variation of both cold flooding velocity and rewetting velocity with flow rates for $T_i = 200°C$ under top flow rewetting conditions. The cold flooding velocity is much higher than the rewetting velocity at 200°C, thus indicating that in the case of top flow rewetting even at temperatures as low as 200°C the rewetting velocity deviates significantly from the cold flooding velocity. Also, the slopes of the two lines are quite different in contrast to the observed behaviour for bottom flooding rewetting (Fig. 7) wherein the line which represents the variation of rewetting velocity with flow rate for $T_i = 200°C$ is quite close to the line which represents the variation of cold flooding velocity. However, as in the case of bottom flooding rewetting, the difference between cold flooding velocity and rewetting velocity increases as $T_i$ is increased for a given water flow rate.

### Table 3
Cold flooding and rewetting velocities (bottom flooding rewetting)

<table>
<thead>
<tr>
<th>Serial no.</th>
<th>$T_i$ (°C)</th>
<th>$Q$ (lpm)</th>
<th>$u$ (mm s$^{-1}$)</th>
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<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>1.0</td>
<td>98.3</td>
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<td>2</td>
<td>200</td>
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<td>226.1</td>
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<tr>
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<td>200</td>
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<td>295.0</td>
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<td>200</td>
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### Table 4
Cold flooding and rewetting velocities (top flow rewetting)

<table>
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<th>$Q$ (lpm)</th>
<th>$u$ (mm s$^{-1}$)</th>
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<td>0.9</td>
<td>88.5</td>
</tr>
<tr>
<td>13</td>
<td>500</td>
<td>2.7</td>
<td>265.4</td>
</tr>
<tr>
<td>14</td>
<td>500</td>
<td>6.5</td>
<td>638.9</td>
</tr>
</tbody>
</table>

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8. Correlations for rewetting velocities

Several analytical solutions for rewetting velocity involving the use of an appropriate heat transfer coefficient have been reported in the literature. But no generally accepted correlation for heat transfer coefficients is available yet and the applicability of these analytical solutions is limited. While they predict the general trends reasonably well, the predicted values for rewetting velocity deviate significantly from the experimental values. The disagreement between the predictions of the correlations themselves is also not insignificant. Based on theoretical analysis, Duffey and Porthouse (1973) derived analytical expressions for the rewetting velocity. These are based on the approximate quasi-static solution of the one-dimensional as well as the two-dimensional heat conduction
equations with heat flux boundary conditions. They considered two regions, viz. wet region and dry region, along the surface undergoing rewetting. The common boundary between the two regions is kept moving as rewetting progresses. Using their experimental data in combination with the analytical expression, they developed a semi-empirical correlation for the rewetting velocity as given by Eq. (1), which is stated to be applicable for both top flow and bottom flooding rewetting. The experimental data used in the development of the correlation covers the following range: (i) water flow rate up to 2 lpm, (ii) surface temperature range of 300 to 800°C and (iii) length of the test section 20 cm.

Piggott and Porthouse (1975) also derived analytical expressions for the rewetting velocity. Their derivation is also based on the approximate quasi-static solution of the one-dimensional as well as the two-dimensional heat conduction equations.

![Graph](image)

Fig. 8. Rewetting velocity versus flow rate under top flow rewetting conditions.
with heat flux boundary conditions. They also reported a semi-empirical correlation as given by Eq. (2), based essentially on their own experimental data and the data of Duffey and Porthouse (1973). Eq. (2) is obtained with minor modification in Eq. (1) by including the water subcooling effect. This correlation is also stated to be applicable for both top flow and bottom flooding rewetting. The data of Piggott and Porthouse (1975) covers the following range: (i) water flow rate upto 2 lpm, (ii) surface temperature range of 300–700°C and (iii) length of the test section 20 cm.

\[
\begin{align*}
   u &= \frac{5140}{\rho C \phi} \left( \frac{Q}{2 \pi r_2} \right)^{0.86} \\
   u &= \frac{15200}{\rho C} \left( \frac{T_S - T_i}{T_i - T_{SP}} \right) \frac{Q}{2\pi r_2}
\end{align*}
\]

The above two correlations are chosen for comparison of the present experimental data because they are developed
1. Based on theoretical considerations and the experimental data generated by the authors themselves.

2. They found that the theoretical expressions developed by them predict the general trend of experimental data reported over a wide range of experimental conditions, given in Table 5, even though differences in predicted values are sometimes considerable.

The values of rewetting velocities were calculated from Eqs. (1) and (2) for the test conditions employed in the present work. The value for sputtering temperature, \( T_{SP} \), was taken as 200°C (Venkat Raj, 1985) and the value of \( T_i \) for our data was taken as 30°C. Piggott and Porthouse (1975) have also used a value of 100°C for \( (T_{SP} - T_S) \), i.e. \( T_{SP} = 200°C \) for atmospheric pressure. Selection of \( T_{SP} \) as 200°C is also in line with the suggestion by Duffey and Porthouse (1973). They deduced a value of \( T_{SP} \) between \( (T_S + 100) \) and \( (T_S + 150)^\circ C \) for low pressure, high sub-cooling data. The lowest value of \( T_{SP} \) in this range is 200°C at atmospheric pressure. Farmer and Coney (1974) also suggested the value of \( T_{SP} \) as \( (T_S + 75)^\circ C \), i.e. \( 175°C \) at atmospheric pressure. This value of \( T_{SP} \) is also not far from 200°C, the value taken in the present work. For bottom flooding rewetting, Eq. (1) underpredicts (range of percentage deviations being 28.8–60.4) the rewetting velocity, whereas Eq. (2) overpredicts (range of percentage deviations being from −131.0 to −4.6) the rewetting velocity in comparison with the values obtained in the present work; thus, it may be noted that the agreement is poor. For top flow rewetting, the agreement between the values calculated from Eq. (1) and the experimental rewetting velocities is satisfactory for \( T_i \geq 300 \) C and \( Q \geq 1 \) lpm, whereas the agreement for \( T_i = 200°C \) is poor. The present top flow experimental data did not agree well with the predictions of the correlation given by Eq. (2) and the range of percentage deviations is from 40.8 to −211.4.

The poor agreement of the present experimental data for bottom flooding rewetting with Eqs. (1)

<table>
<thead>
<tr>
<th>Equation no.</th>
<th>Flow direction</th>
<th>Water flow rate range (gm s(^{-1}))</th>
<th>Surface temperature range (°C)</th>
<th>Test sections used</th>
</tr>
</thead>
</table>
| Eq. (1)      | Bottom flooding conditions | 0.91–102 | 400–1000 | (i) S. S. rod in tube  
(ii) S. S. rod cluster  
(iii) Cluster of rods (S. S. clad filled with copper)  
(iv) Cluster of rods (S. S. clad filled with boron nitride)  
(v) S. S. tube clusters  
(vi) Inconel clusters |
|              | Top flow conditions | 0.24–65 | 400–600 | (i) Rod (S. S. clad filled with magnesia)  
(ii) Copper tube  
(iii) S. S. tube |
| Eq. (2)      | Bottom flooding conditions | 0.8–40 | 390–720 | (i) Cluster of rods (S. S. clad)  
(ii) Cluster of rods (Inconel clad)  
(iii) Rod (Inconel clad filled with magnesium oxide) |
|              | Top flow conditions | 7.5–30 | 350–750 | (i) Inconel tube  
(ii) S. S. tube  
(iii) Zircaloy tube  
(iv) Cluster of rods (S. S. clad) |
and (2) may be due to the following reasons: The correlations given by Eqs. (1) and (2) are stated to be applicable for both top flow rewetting and bottom flooding rewetting. The semi-empirical correlations were developed based on the experimental data covering limited range. The water flow rates covered are approximately not more than 2 lpm, whereas those covered in present experiment are 1 to 7 lpm; the test section employed in present work is of length around 3 m. The rewetting velocities in bottom flooding and top flow rewetting may not differ significantly for smaller test section length, whereas for longer test sections they may differ due to the retardation of the wet front by the generated steam in top flow rewetting. The steam generated rises up and counters the down coming water flow. In fact our data show that the rewetting velocities for bottom flooding rewetting are as much as 70% higher when compared with top flow rewetting, for the same conditions of initial surface temperature and water flow rate. It is interesting to note that our experimental rewetting velocities for bottom flooding rewetting are also as much as 60% higher when compared with the values calculated from Eq. (1). Duffey and Porthouse (1973) also noted that data of some of the earlier investigators (Yoshioka and Hasegawa, 1970; Martini and Premoli, 1972; Campanile and Pozzi, 1972) were outside the general trend predicted by their correlation. They further noted that though their theory predicts the general trends of a large pool of experimental data over a wide range of operating conditions, test section material and geometry, their theory could correlate the data within a factor of two only.

9. Proposed correlations based on the present work

In view of the large deviation of the predictions of the earlier semi-empirical correlations from the present experimental data, new correlations are proposed for the rewetting velocity. Separate correlations are proposed for top flow and bottom flooding rewetting because of the large differences between the rewetting velocities for these two types of rewetting, as mentioned earlier.

10. Bottom flooding rewetting

Taking the effect of both temperature and flow rate, a correlation as given by Eq. (3) was developed based on the experimental data using least square regression analysis:

\[ u = \frac{17476}{\rho C \phi^{1.57}} \frac{Q}{2\pi r_2} \]  

(3)

The correlation has a standard deviation (S.D.) of 23.2% based on the data for all temperatures, whereas the standard deviations for each of the initial surface temperatures are: 9.6% for \( T_i = 200^\circ C \), 17.3% for \( T_i = 290^\circ C \), 10.7% for \( T_i = 400^\circ C \) and 45.5% for \( T_i = 500^\circ C \). From these standard deviation values, it is evident that this correlation is not very satisfactory for initial surface temperature of 500°C.

During LOCA, the temperature of the fuel cladding in a nuclear reactor is expected to reach values considerably higher than 200°C before the emergency coolant is injected. Therefore, rewetting velocity at initial surface temperature higher than 200°C is more important from the point of nuclear reactor safety. Also, as mentioned earlier \( T_{SP} = 200^\circ C \). Considering these, a correlation as given by Eq. (4) is proposed based on the data at initial surface temperatures of 290, 400 and 500°C, excluding the data at initial surface temperature of 200°C.

\[ u = \frac{7285}{\rho C \phi} \left( \frac{Q}{2\pi r_2} \right)^{0.84} \]  

(4)

The experimental rewetting velocities obtained in the present work and the rewetting velocities calculated from Eq. (4) are plotted in Fig. 10. All the data points except two lie within 12.2% and −8.6% error bounds. The S.D. for all the data points is 12.4%.
11. Top flow rewetting

The following correlating equation was developed based on our experimental data for top flow rewetting:

\[ u = \frac{1734}{\phi^{0.64}} \rho C \left( \frac{Q}{2 \pi r_2} \right)^{0.54} \tag{5} \]

The correlation has a S.D. of 30.8% based on the data for all temperatures, whereas the standard deviations for each of the initial surface temperatures are: 18.5% for \( T_i = 200^\circ C \), 29.8% for \( T_i = 300^\circ C \), 21.9% for \( T_i = 400^\circ C \) and 49.5% for \( T_i = 500^\circ C \).

For the same reasons mentioned earlier for bottom flooding rewetting, the following correlating equation was obtained based on experimental data points excluding those for initial surface temperature of 200\(^\circ\)C.

\[ u = \frac{5546}{\phi^{1.13}} \rho C \left( \frac{Q}{2 \pi r_2} \right)^{0.8} \tag{6} \]

The experimental rewetting velocities obtained in the present work and the rewetting velocities calculated from Eq. (6) are plotted in Fig. 11. All the data points except three are within 16.6% and \(-12.7\%\) error bounds. The S.D. for all the data points is 23.2%.
12. Comparison of rewetting behaviour under bottom flooding conditions and top flow conditions

The bottom flooding and top flow rewetting velocities obtained in the present experimental work are compared in Figs. 12 and 13. The rewetting velocity for a given initial surface temperature and water flow rate is higher in case of bottom flooding rewetting as compared to that in case of top flow rewetting. The slopes of the best-fit lines are always higher for bottom flooding rewetting, thus indicating the greater influence of flow rate in bottom flooding rewetting. The rewetting velocities for bottom flooding rewetting are about 1.3 to 1.7 times the values obtained for top flow rewetting over the range of water flow rate and initial surface temperature investigated. The reasons for this are as mentioned below:

1. In top flow rewetting, the generated steam in an attempt to move counter to the downward flowing water, provides additional resistance to the flow of water and hence the progress of the wet front is retarded. In addition, the steam also adversely affects the movement of the water droplets towards the hot surface.

2. Due to channeling of water in top flow rewetting, the cooling of the inner tube in the region preceding rewetting is lower than that in bottom flooding rewetting. Thus, the actual surface temperature occurring locally just before rewetting is lower in bottom flooding rewetting than that in top flow rewetting.

Fig. 11. Comparison of rewetting velocities under top flow experiments with those obtained by correlation (Eq. (6)).
The experimental rewetting velocity values obtained and plotted in the figures are the average rewetting velocities along the length of the inner tube, obtained as explained earlier in the section on ‘Method of determination of rewetting velocity’. These average rewetting velocity values have been used in the development of correlations (3) to (6) and are not directly related with the local rewetting velocity. Thus equations (3) to (6) give the average rewetting velocity and not the local rewetting velocity. The correlating equations (4) and (6) based on our experimental data are similar to the correlating equation (1) proposed by Duffey and Porthouse (1973) which has been derived based on certain theoretical considerations. The exponent for $\phi$ and $Q$ in Eqs. (4) and (6) also do not differ much from those in Eq. (1). Duffey and Porthouse noted that the exponent of $Q$ is in reasonable agreement with the value of 0.8 adopted in conventional forced convection heat transfer correlation. However, the magnitude of the constant in Eq. (4) for bottom flooding rewetting is much higher as compared to that in Eq. (6) since, as explained earlier, the rewetting velocity is higher in bottom flooding rewetting, as compared to that in top flow rewetting under identical $T_i$ and $Q$. For top flow rewetting, Eqs. (1) and (6) predict comparable rewetting velocities. The values of exponents for $\phi$ and $Q$ in Eqs. (4) and (6) do not differ significantly from unity and hence for all practical purposes it may be considered that the rewetting velocity is more or less linearly dependent on coolant water flow rate and inversely proportional to the initial surface temperature of the inner tube.

13. Conclusions

The present study leads to the following conclusions. For both bottom flooding and top flow rewetting conditions: (i) For a given cooling water flow rate, the rewetting velocity increases as the initial surface temperature is decreased. (ii) The
rewetting velocity increases with increase in the flow rate for a given initial surface temperature. These trends are in line with the observations of earlier investigators. For a given initial surface temperature and cooling water flow rate the rewetting velocity is higher for bottom flooding rewetting as compared to that for top flow rewetting. Two semi-empirical correlating equations are proposed to estimate the rewetting velocity for bottom flooding and top flow rewetting conditions. The functional dependence of rewetting velocity on flow rate and initial surface temperature agrees closely with that proposed by Duffey and Porthouse (1973). At temperatures reasonably higher than the sputtering temperature, for all practical purposes, it may be assumed that the rewetting velocity is more or less linearly dependent on the water flow rate and inversely proportional to the initial surface temperature.

**Appendix A. Nomenclature**

- $C$: specific heat of inner tube (kJ (kgC)$^{-1}$)
- $Q$: volumetric flow rate of water (lpm)
- $r_2$: outer radius of the inner tube (mm)
- $T$: temperature (C)
- $U$: rewetting velocity (mm s$^{-1}$)
- $V$: cold flooding velocity (mm s$^{-1}$)

**Greek symbols**

- $\rho$: density of inner tube (g cm$^{-3}$)
- $\phi$: dimensionless initial surface temperature, $\frac{T_i - T_S}{T_{SP} - T_S}$

**Subscripts**

- I: initial fuel pin surface
- L: liquid at inlet
- S: saturation
sputtering

Abbreviations
ECCS emergency core cooling system
S.D. standard deviation = \[
\frac{1}{100} \left[ \frac{1}{n-1} \sum \left( \frac{u_{\text{exp}} - u_{\text{cal}}}{u_{\text{exp}}} \right) \right]^{0.5}
\]
Lpm litres per minute
DAS data acquisition system
LOCA loss of coolant accident

References