STUDIES ON REWETTING OF NPP THORIA FUELS

Anil Kumar Saxena\textsuperscript{a*}, Limaye Sanjay Prabhakar\textsuperscript{b}, Subrata Bera\textsuperscript{c}, Anuj Kumar Deo\textsuperscript{c}

\textsuperscript{a}Ex. Research Reactor Services Division, \textsuperscript{b}Reactor Engineering Division
BARC, Mumbai, 400085
\textsuperscript{c}Nuclear Safety Analysis Division, AERB, 400094
*saxenaanil3@gmail.com

ABSTRACT
There should never be second opinion to the fact that in-depth knowledge of rewetting and its successful verification for NPPs (Nuclear Power Plants) is foremost requirement as far as their safety is concerned. In the absence of correlation for heat transfer coefficient(s) applicable in the region of rewetting front, its critical assessment is the need of hour. Computer programs: CCRA (Conduction Controlled Rewetting Analysis) and RAMM (Rewetting Analysis using Moving Mesh) are developed for prediction of the heat transfer coefficient and rewetting velocity respectively. Main outcome of CCRA and RAMM is availability of handy and trustworthy method for prediction of heat transfer coefficient and rewetting velocity. Dependency of heat transfer coefficient on PuO\textsubscript{2} percentage is presented in the paper.

Keywords
Rewetting, Rewetting Front, Heat Transfer Coefficient, LOCA

INTRODUCTION
Literature review reveals that significant R & D contribution by various researchers has been made on the study of rewetting phenomenon. Some selected contributions are as follows:

Juan J. Carbajo [1] did parametric study on rewetting velocities obtained with a two-dimensional heat conduction code. McAdams [2] provided correlation which provides heat flux as function of wall temperature and saturation temperature. Duffey and Porthouse [3] conducted experiments on the cooling of high temperature surfaces by water jets and drops. They selected heated lengths 0.18, 0.10, 0.20 and 0.25 m of different materials. It is mentioned that based on work by Richards (1972) at low pressures the average value of heat transfer coefficient was 100 W/m\textsuperscript{2}K. Hsu-Chieh [4] presented an analytical solution to fuel and cladding model of the rewetting of a nuclear fuel rod. Fuel and cladding were considered as single region instead two separate regions. Sibamoto Yasuteru, et al. [5] performed experiments to clarify boundary conditions necessary for post boiling transition analysis. The model calculates temperature distribution in the fuel and in the clad as well as rewetting velocities. Yadigaroglu G. et al. [6] reviewed state of art in modeling reflooding situations, mainly with the two-fluid system analysis codes. Sahu S. K. et al. [7] analysed two different cases comprising a two dimensional slab and a rod. They concluded that an accurate value must be used for boiling heat transfer coefficient while an approximate value for convective heat transfer coefficient will not significantly affect the rewetting analysis.

It is evident from above mentioned and some other references that areas on heat transfer correlations and method for prediction of heat transfer coefficient in the region of wet front are needed to be addressed. Present work is aimed in that direction.

Program Description

Main Program
Two dimensional heat conduction equation in cylindrical coordinates in dimensionless form is as follows:
Eq. (1) is applicable for fuel, gap and clad of a nuclear reactor fuel assembly. For the analysis in the present paper, fuel is considered in the form of a vertical solid rod, clad is in the form of solid cylindrical tube concentric to fuel, gap is provided in between fuel and clad. A vertical tube is also considered concentrically with fuel, gap and clad such that the annulus formed between clad and tube is used for the flow from ECCS.

Where:

\[ R = \frac{r}{\varepsilon}; \quad \theta = \frac{T - T_{w}}{T_{o} - T_{s}}; \quad Z = \frac{z}{\varepsilon} \]  

(2)

For \( z = 0, Z=0; \quad z = l_{w}, Z = L_{w}; \quad z = l, Z=L \)

Peclet No., \( Pe \) is defined as,

\[ Pe = \frac{\rho C_{u}}{k} \]  

(4)

Stanton No., \( St \) is defined as,

\[ St = \frac{Q \varepsilon}{\rho C_{u}(T_{o} - T_{s})} \]  

(5)

CCRA and RAMM are briefly described below:

(a) **CCRA**

**Assumptions:**

(i) Two regions exist on outer surface of clad: First, rewetted region at upstream to rewetting front second, unrewetted region at downstream to rewetting front.

(ii) Water/steam are at saturation temperature at atmospheric pressure throughout the annulus.

(iii) One value of heat transfer coefficient is taken in rewetted region.

(iv) No heat is transferred through ends of fuel, gap and clad.

(v) No heat is transferred through outer surface of outer tube.

Gauss Seidel elimination method is employed for solving Eq. 1.

**Initial Condition**

\( t = 0 \)

\( Z \gg 0 \)

Fuel: \( \theta = \theta_{f} \); Gap: \( \theta = \theta_{g} \); Clad: \( \theta = \theta_{c} \); Coolant: \( \theta = 0 \)

\( Z=0, 0 \leq R \leq R_{3}, \quad \theta = 1; \quad R > R_{3}, \quad \theta = 0 \)

**Boundary Conditions:**

\( t > 0 \)

\( Z=0, 0 \leq R \leq R_{3}, \quad \theta = 1 \)

\[ 0 \leq Z \leq L_{w}, \quad R = R_{3}, \quad \frac{\partial \theta}{\partial R} = -Bi \theta \]  

(9)

\[ Z \gg L_{w}, \quad R = R_{3}, \quad \frac{\partial \theta}{\partial R} = 0 \]  

(10)
Subroutine HEATB is included in the program. Eq. (11) is obtained by equating the heat transferred from wetted region to coolant to the heat transferred from dry region of fuel, gap and clad to wetted region of the same.

\[
R_i Bi \int_0^{L_f} \theta_R \, dZ = P_{ef} \int_0^{R_e} R(\theta_L - \theta_0) \, dR + P_{ec} \int_{R_o}^{R_e} R(\theta_L - \theta_0) \, dR + \frac{St_f P_{ef} R_i^2 L}{2} + \frac{St_s P_{es} (R_i^2 - R_o^2) L}{2} + \frac{St_r P_{er} (R_i^2 - R_o^2) L}{2}
\]

Since heat generation in gap and clad is zero. Eq. (11) reduces to:

\[
R_i Bi \int_0^{L_f} \theta_R \, dZ = P_{ef} \int_0^{R_e} R(\theta_L - \theta_0) \, dR + P_{ec} \int_{R_o}^{R_e} R(\theta_L - \theta_0) \, dR + \frac{St_f P_{ef} R_i^2 L}{2}
\]

Eq. (1) is solved with an initial value of heat transfer coefficient. Output temperatures are scrutinized. A node, namely M is identified as the last node in the rewetted nodes. Difference of LHS and RHS of Eq. (11) is calculated for M. If the difference is more than a specified limit, Eq. (1) is again solved with higher heat transfer coefficient which is obtained by previous heat transfer coefficient multiplied by temperature at node (M+1). The process is repeated and is stopped when difference of LHS and RHS of Eq. (12) converges to specified value.

\[(b) \ \text{RAMM}\]

RAMM is developed for calculation of rewetting velocity. The program is validated using experimental data [8, 9]. Eq. (1) is solved by Marching method to calculate rewetting velocity [8]. Initial temperature distribution (higher than rewetting temperature) is provided to all nodes. Fine mesh size is selected from entrance node to a specific axial node N1 covered in a given rewetting front region. From N1 to last node N3 a coarse mesh size is selected. Appropriate heat transfer coefficients are provided to nodes from 1 to N1 through subroutine COFFI. No heat transfer coefficient is provided to nodes from N1 + 1 to N3. When nodes from 1 to N1 are rewetted the rewetting front region is advanced to nodes from N1 + 1 to N2. Mesh sizes are: coarse mesh from 1 to N1, fine mesh from N1 + 1 to N2 and coarse mesh from N2 + 1 to N3. Nodes updating and temperature updating are achieved through subroutines NODEUP and TEMPUP. As last node of fine mesh is rewetted the fine mesh region is further advanced. This is done up to the stage when last node of clad outer surface is rewetted. Rewetting transients corresponding at specific nodes are analysed and rewetting velocity is calculated. The rewetting velocity appearing in Eq. 3 is obtained using RAMM.

RESULT and DISCUSSIONS

(a) 1 m high fuel assembly

The temperature profile, given in Fig. 1 for fuel assembly of 1 m height is obtained using CCRA. The temperature at node 1 corresponds to inlet boundary condition and temperature at last node is obtained using CCRA. The polynomial representing Fig. 1 is given by Eq.13. Mox fuel comprising ThO$_2$ and PuO$_2$ is taken up for the analysis. Fig. 2 shows data points in a plot of heat transfer coefficient versus PuO$_2$ percentage in Mox fuel. The curve shows 2$^{nd}$ order polynomial fit which is represented by Eq.14.
The polynomial representing Fig. 1 is as follows:

\[ \theta = d + eN - fN^2 + gN^3 - hN^4 \]  

(13)

\[ \begin{align*} 
  d &= 0.09 \\
  e &= 0.02 \\
  f &= 2.83 \times 10^{-5} \\
  g &= 1.15 \times 10^{-8} \\
  h &= 9.16 \times 10^{-12} 
\end{align*} \]

Where \( \theta \) (dimensionless temperature) and \( N \) (Axial nodes) are as shown on Y and X axes respectively in Fig. 1.

2\(^{nd}\) order polynomial representing Fig. 2 is as follows:

\[ h = a + bPuO_2 + cPuO_2^2 \]  

(14)

\[ \begin{align*} 
  a &= 806.2 \\
  b &= -137.37 \\
  c &= 125.71 
\end{align*} \]

Where \( h \) and \( PuO_2 \) are heat transfer coefficient and \( PuO_2 \) percentage respectively as shown in Fig. 2.

(b) **1.5 m high fuel assembly**

Data for fuel assembly of 1.5m height are also obtained using CCRA. Heat transfer coefficient for 2.0 percentage \( PuO_2 \) is 1234 W/m\(^2\)K. Heat transfer coefficient for fuel assembly of 1m height for same \( PuO_2 \) percentage is 1037 W/m\(^2\)K. This is expected because heat to be dissipated will be higher for fuel assembly of greater height as compared to fuel assembly of lesser height. Thus required heat transfer coefficient for 1.5 is higher than that for 1m high fuel assembly.
CONCLUSIONS and SCOPE of work

Profile given in Fig. 1 is as expected under the conditions mentioned in the paper. Handy and trustworthy method is made available for the calculation of heat transfer coefficient. There are limitations in deriving suitable correlation for prediction of heat transfer coefficient due to varying nature of flow pattern in the vicinity of rewetting front. Nevertheless scope of work is wide open as difficult task is to ascertain the wet front region heat transfer coefficient with acceptable accuracy. Importance of rewetting and therefore availability of appropriate heat transfer coefficient for mitigation of consequences due to loss of coolant accident (LOCA) needs to be emphasised. The polynomial can be used to predict the heat transfer coefficient for a given PuO$_2$ percentage selected in the provided range.

ACKNOWLEDGMENT

Hearty thanks due to staff of Hall 7 and Reactor Group of BARC, staff of Chemical Engineering department of IIT Mumbai for providing unreluctant support and deep sense of gratitude and indebtedness to Shri Avinash J. Gaikwad, Director NSAD, AERB for whole hearted cooperation during course of work.

NOMENCLATURES

- $Bi$: Biot number = $h \theta / k_c$
- $C$: Specific heat, J/kgK
- $H$: Heat transfer coefficient, W/m$^2$K
- $Pe$: Peclet number
- $Q$: Heat generation, W/m$^3$
- $L$: Height of fuel assembly, m
- $L$: Dimensionless height of fuel assembly
- $R$: Dimension less distance
- $S_t$: Stanton number
- $t$: Time, s
- $T$: temperature, K
- $U$: Rewetting velocity, m/s
- $Z$: Distance, m
- $Z$: Dimensionless distance

Greek Symbol

- $\theta$: Dimensioless temperature
- $\rho$: Density, kg/m$^3$
- $\epsilon$: Thickness of clad, m

Subscripts

1: Surface of fuel
2: Inner surface of clad
3: Outer surface of clad
F: Fuel
G: Gap between fuel and clad
o: Rewetting temperature
s: Saturation
w: Location of rewetting
REFERENCES


