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SVECHA candling model for melt relocation process

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ABSTRACT: The candling model is a part of the code package SVECHA which is described in the report "Code Package SVECHA for Core Degradation" presented at this Conference (Division C). The candling model deals with the process of flowing down the fuel rod of molten materials during severe accident at Nuclear Power Plant. The influence of this process upon the global core behavior during the accident is conditioned by the fact that it results in a change of flow cross sections or a blockage of the cooling channels, further fuel rod heatup and extended core degradation. SVECHA candling model is based on the system of differential equations obtained by the integration of the hydrodynamical equations over the volume of the moving liquid element. The model allows to take into account: capillary effects and introduce capillary scale; viscous effects (viscous drag force, laminar/turbulent regimes); heat exchange influence. SVECHA candling model allows to describe: various types of flowing down (drops and rivulets), flowing down inside a gap formed by cladding and fuel pellet (gap candling).

1 INTRODUCTION

The process of molten materials flowing down the fuel rod during severe accident at Nuclear Power Plant is called a candling process. This process is very essential in the development of the accident because it may cause a change of the flow cross section or a blockade of the coolant channel and it may lead to decrease of the fuel rod coolability and futher heatup of the fuel rod at this elevation. So, dynamics and distribution of relocated masses along the fuel rod is of great interest.

In exsisting codes (for example, SCDAP/RELAP5) the candling process is modelled as an axisimmetrical motion of a film. However, drop and rivulet, rather than film, flow has been established experimentally in CORA experiments (Hering and Meyder 1988) as the dominant relocation process (SCDAP/RELAP5 Independent Peer Review 1994). The other important case is flowing down inside the gaps between clading and fuel pellets (gap candling), especially in a ballooned geometry. The present report briefly describes the main assumptions of SVECHA candling model.

2 DROPS AND RIVULETS

Consider a liquid element on a vertical wall. If its volume is sufficiently small, the liquid will rest on the wall: gravity force is balanced by the capillary drag force. The presence of this force is connected with the resistance of the contact line (which is formed at the intersection of liquid, solid and gas) to a displacement (Dussan V 1979), (Finn 1986).

Now let the volume of the liquid element V be gradually increasing. The liquid element will begin to move down as a single drop when V exceeds some critical value V_{c1} (first critical volume). As the volume of a drop is increased the linear dimensions a_d (width, thickness) are also increased. The nonlinearity of the capillary equation (Finn 1986) leads to complex dependence of these quantities on the value of drop volume V_d. But in some interval of values $V_{c1} < V < V_{c2}$ it may be assumed that

(1) $$a_d \propto V_d^{1/3}$$

So, a drop is determined as liquid formation with volume V_d within the interval $[V_{c1}, V_{c2}]$ and linear dimensions proportional to $V^{1/3}$.

The characteristic velocity of flowing down of the drop increases with the volume increase. When the volume of the drop reaches the value of V_{c2} (the second critical volume) the drop becomes unstable because the kinetic energy of liquid exceeds the surface energy and the capillary forces are not able to hold liquid in the shape of a drop any more. That is why a free flowing down liquid element with volume $V > V_{c2}$ after short transient process transforms into rivulet.

A rivulet has drop-like front part (due to the presence of the front contact line) and the main part, which is characterised by the length L_r, the width w_r and the average thickness h_r. The volume V_r of the rivulet is given by

(2) $$V_r = L_r w_r h_r.$$

Thus a rivulet is defined as a liquid element with volume $V > V_{c2}$ and the length proportional to V_r. The width w_r and the average thickness h_r have some fixed values, determined by the condition of the stability of the rivulet's shape.

3 EQUATIONS OF MOTION

The motion of drops and rivulets is governed by the system of balance equations: momentum equation for average (over the volume) velocity (i.e. the velocity of the center of masses); mass balance equation and energy equation for average (over the surface) rate of heat exchange. These balance equations were obtained by the integration of correspondent Navier-Stokes hydrodynamical equations over the volume of a drop (rivulet) with taking into account boundary conditions on the liquid-solid and liquid-gas interfaces.

3.1 *Momentum equation*

The momentum equation has the form

(3) $$\rho V \frac{dU}{dt} = -F_c - F_v + \rho g V.$$

Here ρ is the density, U is the velocity of the center of masses, g is gravity acceleration. The value of capillary drag force is given by (Dussan V and Tao-Ping Chow 1983)

(4) $$F_c = C_c \sigma w,$$

where σ is surface tension coefficient, w is the width of the liquid element ($w \propto V^{1/3}$) and C_c is some constant which is determined from the condition of equality of F_c and gravity force when $V = V_{c1}$

(5) $$C_c = \frac{V_{c1}}{w_{c1}} \frac{\rho g}{\sigma} = \frac{V_{c1}}{a_c^2 w_{c1}}$$

Here w_{c1} is the width of the drop with the volume V_{c1} and

(6) $$a_{c1} = \left(\frac{\sigma}{\rho g}\right)^{1/2}$$

is well-known capillary length (Landau and Lifshitz 1959).

The presence of the viscous drag force F_v is connected with energy dissipation inside the drop (rivulet) due to viscosity. In present model it is assumed that the value of F_v depends only on velocity of center of masses U but not on its time derivative dU/dt (quazi-stationary approximation). Then, according to similarity law the velocity distribution inside the drop (and hence, viscous drag force F_v) may depend only on Reynolds number $\mathrm{Re} = \rho Uw/\eta$:

(7) $$F_v = C_v \frac{\eta^2}{\rho} \mathrm{Re}^\gamma .$$

Here η is the viscosity of liquid; constant C_v is determined by the geometrical shape of drop (rivulet) and does not depend on velocity. The exponent γ is equal to 1 in the limit of small Re and satisfy the unequality $3/2 < \gamma < 2$ at $\mathrm{Re} >> 1$.

In the case of a rivulet the rate of energy dissipation due to viscosity (and, consequently, viscous drag force) is assumed to be proportional to the length L_r because of the identical nature of the motion of the liquid inside the different parts of the main part of the rivulet:

(8) $$F_v \propto \frac{\eta^2}{\rho} \mathrm{Re}^\gamma \frac{L_r}{w_r} .$$

In the limit of rivulets with big length L ($L \to \infty$) the relative influence of the capillary force F_c goes to zero and a balance of viscous and gravity forces determines the value of steady state rivulet velocity

(9) $$U_r \propto \frac{\eta}{\rho w} \left(\frac{w}{\delta_{gv}}\right)^{3/\gamma} .$$

Here

(10) $$\delta_{gv} = \left(\frac{\eta^2}{\rho^2 g}\right)^{1/3}$$

is well-known characteristic length of gravitational-viscous interaction. The value of rivulet steady-state velocity U_r (9) is expressed in terms of the width of a rivulet, characteristic length of gravitational-viscous interaction, viscosity, etc. At the same time it can be measured directly. In the present model the value of U_r is considered as empirical quantity along with critical volumes V_{c1} and V_{c2}.

3.2 *Mass balance equation*

As experiments show when moving liquid mixture wets the clad surface and leaves a track. The mass balance equation has the form

(11) $$\frac{dV}{dt} = -hwU$$

where h is a thickness of a track. The estimations based on the available experimental data show that the value of h is much less than the characteristic size of the drop:

(12) $$h << w \propto a_c$$

This fact makes it possible to reduce the problem of a drop's track to the problem of a plane which is taken out from the liquid perpendicular to its surface. The last problem was considered by Landau and Levich (Levich 1962). Their expression for the thickness of a track, remaining on a plane has the following form:

(13) $$h = B\frac{(\eta U)^{2/3}}{\sigma^{1/6}(\rho g)^{1/2}}$$

Here B is some constant of order of unity.

The difference between three-dimensional situation of a drop and two-dimensional situation of a plane may lead to some deviations from the expression (13). However, one may believe that the dependence of the track thickness h on the velocity of a drop U will be just the same. Really, the expression (13) can be rewritten in terms of characteristic lengths and dimensionless Reynolds number:

(14) $$h = B\,\frac{\delta_{gv}^2}{a_c}\,\mathrm{Re}^{2/3}$$

Since the difference beween a drop and a plane cases (different shape of the liquid surface) is due to capillary effects, one may expect that it will manifest itself in the dependence of h on capillary characteristic size a_c, but not in the dependence on Re. Together with unequality (13) this consideration represents sufficient basis for the relation (14) to be used in the present model.

3.3 *Energy equation*

The energy equation has the form:

(15) $$V\frac{d\varepsilon}{dt} = -Q - R - W + H$$

Here ε is internal energy per unit volume, Q, is the heat flow into fuel rod, R and W, are heat flow due to radiation and heat flow to coolant, respectively; H is internal heat generation. The value of ε depends on the current temperature of the drop (above liquidus temperature, in two-phase region, below solidus temperature) and the chemical composition of mixture. The velocity of mixture flowing down is sufficiently high (dozens of cm per second), so the liquid inside a drop is mixing intensively and the temperature is practically uniform. As it was shown by Palagin (1993) high velocity of drop makes it possible to reduce three-dimensional drop - fuel rod heat exchange problem to one-dimensional and to derive approximating formula for heat conduction flow Q.

4 GAP CANDLING

When flowing down a liquid element may be in contact with several vertical surfaces. This may happen due to geometry changes during core degradation. For example, balooning leads to decreasing of the distance between adjacent fuel rods and to increasing of a gap thickness between the fuel pellets and cladding inside the rod; melting and relocation lead to the formation of cavities inside the rods and to a blockade of a coolant channel. In both cases long and narrow empty spaces are formed, and it is necessary to take into account the interaction between a liquid element and vertical walls. In the present model such type of flowing down is considered in terms of a narrow gap formed by two parallel walls and is reffered to as gap candling. The relation between the characteristic dimensions of the gap is assumed to be:

(16) $$L_g >> w_g >> d_g$$

where L_g is the vertical size (length), w_g is the width and d_g is the thickness of the gap.

The description of a liquid element motion inside a gap is given in terms of balance equations in exactly the same way as in the case of drops and rivulets. However, the influence of the second wall on the motion of the liquid element leads to some differences in the expressions for the momentum, mass and energy flows.

Liquid element inside the gap has planar shape. The capillary force determines the shape of the liquid element only at its upper and lower ends. Since the liquid is in contact with two walls there exist two contact lines, one line at each wall. The gap candling critical volume V_{cg} is determined in the ordinary way: liquid element inside the gap with $V < V_{cg}$ is held by capillary forces; if $V > V_{cg}$ liquid element can flow down. In the simplest case of constant gap thickness one has

(17) $$V_{cg} = 2V_{c1}\frac{w_g}{w_{c1}}$$

It should be noted that this formula for V_{cg} does not contain gap thickness d_g. More complex case of a gap with variable thickness is considered by Palagin and Veshchunov (1994). The capillary drag force is connected with the gap candling first critical volume V_{cg} by simple relation

(18) $$F_c = \rho g V_{cg}$$

Estimations (Palagin and Veshchunov 1994) show that the motion of liquid inside the gap is practically always laminar. In the context of quazi-stationary approximation used in the present model the value of gap candling viscous drag force F_{vg} is linear in U and is given by

(19) $$F_{vg} = 12\frac{\eta^2}{\rho}\mathrm{Re}_g\frac{w_g l_g}{d_g^2}$$

This relation was obtained using the solution of correspondent steady state solution.

Notice, that as in the case of rivulet the value of F_{vg} is proportional to the length l_g of the liquid element (due to the assumption of the uniform nature of the energy dissipation along the liquid element).

Due to the contact with two walls the mass and heat flows in correspondent equations should be doubled.

5. CONCLUSION

SVECHA candling mode is based on the system of differential equations obtained by the integration of the hydrodynamical equations over the volume of the moving liquid element with taking into account boundary conditions. The model allows to take into account: capillary effects and introduce capillary scale; viscous effects (viscous drag force, laminar/turbulent regimes); heat exchange influence. SVECHA candling model allows to describe: various types of flowing down drops and rivulets, flowing down inside a gap formed by cladding and fuel pellet (gap candling). A set of key values: critical volumes V_{c1} and V_{c2}, steady-state rivulet velocity U_r and some others are used in the candling model. All these values correspond to well-defined critical phenomena or steady-state processes and can be easily measured directly.

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