SIMULATION OF GEYSERING AT START-UP IN A NATURAL CIRCULATION LOOP

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Abstract: Geysering phenomenon is a type of unstable and periodic boiling occurring during start-up. Such phenomenon can induce instability in natural circulation system. It causes flow oscillations which can change the void fraction and reactivity. This makes the nuclear reactor difficult to control. Hence bench marking of the geysering is required. The present project involves development of a transient computer code based on second order finite difference technique considering a four equation drift flux model with appropriate model for subcooled boiling and condensation. The above phenomenon is considered in a two phase natural circulation boiling system and validated with the McMaster experimental data on axial void distribution.

Keywords: geysering, drift flux, subcooled boiling, condensation, natural circulation, bench marking, void distribution

1. INTRODUCTION

The current Light Water Reactors (LWR) achieves shut down through active safety systems. Passive safety systems have been proposed for advanced designs to enhance the reliability of safety functions. The advanced LWR would incorporate a number of passive safety features in its design. One of them is to adopt natural circulation core cooling during start-up, power raising, rated power conditions and accidental conditions. This concept is to eliminate the recirculation pumps which are normally present in conventional forced circulations BWRs. This is due to the reason that the forced circulation loop has the disadvantage of using a pump, which is costly. Again if by any reason the pump breaks down then the dissipation of fission heat is hampered. This results in tremendous accumulation of heat and may cause core melting in the reactor. Thereby it demands backup safety measures which will add to the cost of reactor.

However natural circulation systems require power to initiate the circulation through void generation. This mean the natural circulation reactor would be heated by fission energy from the startup under low temperature and low pressure condition. Thermal-hydraulic instabilities have been reported under low pressure conditions (Chiang *et al.*, 1994). If thermal hydraulic instabilities were to occur at startup then the reactor would not potentially continue operation during power up because the void fraction fluctuation in the reactor core would oscillate the reactivity. Therefore it is necessary to investigate and understand properly the thermal hydraulic instabilities during start up.

Aritomi *et al*. (1992, 1993) and Chiang *et al*. (1992, 1994) have conducted extensive research in the area of geysering under natural circulation. Masuhara *et al*. (1993) have also performed small scale experiment to demonstrate this phenomenon. These experiments illustrated that the geysering mode oscillation would occur at low pressures and low flow conditions. Aritomi *et al.*, (1992) had explained the driving mechanism of geysering as follows: When voids are generated in a heated channel, a large slug of bubbles forms, which grows due to decrease in hydrostatic pressure head as it moves towards the exit. The vapor then mixes with the liquid is the subcooled riser or upper Plenum and is condensed there. Due to bubble collapse and subsequent decrease in pressure, the subcooled liquid

re-enters the channels and restores the non-boiling conditions. This process repeats periodically causing flow oscillations. Hence it is evident that the bubble formations, growth and collapse phenomenon are of importance to geysering instability.

Earlier attempts to model startup instabilities (Aritomi *et al.*, 1992)and (Paniagua *et al*., 1996) indicate that, to predict the possible startup instabilities correctly, it is important to accurately predicts the vapor generation rate. In the present code the effect of the bubble formation as well as the condensation rate has been considered. Moreover, most of the models are envisaged for system with high pressures (greater than 20 bars) and thus are unsuitable for the simulation of geysering owing to the great influence of pressure on the void content in the subcooled boiling regime. Finally in the existing models there is no conclusive and physically well-defined description of the mass transfer rate between the vapor and liquid phase, an aspect which is of great significance for the understanding of phenomena in the subcooled boiling regime. In the present code a four equation drift flux model has been used which is numerically more stable than the five equation and six equation model.

2. FORMULATION AND SIMULATION SCHEME

The following code is based on the following thermal hydraulic modeling features:

- Four fundamental balance equations – one liquid mass balance, one vapor mass balance equation, one mixture momentum equation and one mixture energy balance equation.
- Second order finite difference formulation.
- Drift flux model for phasic velocities
- Appropriate vapor generation and vapor condensation model.

Each component has a one-dimensional representation with a variable cross-sectional area. The equations are solved by a partially implicit method that can use different time steps in different components. The components are discretized using staggered mess arrangements. The momentum equation is advanced explicitly that is, explicit updating of velocity has been done. The pressure has been updated implicitly. When the transients are initiated, the system pressure changes are assumed to be instantaneous and uniform throughout the individual computational cells. This leads to a quasi-steady pressure distribution throughout the system. The objective of our code is to determine the void fraction in the subcooled regime with proper consideration of bubble formation rate and bubble condensation rate.

3. GOVERNING EQUATIONS

The basic one-dimensional, four equation drift flux model for two phase flows consists of the following conservation equations

Liquid mass balance:

$$\frac{\partial}{\partial t}\left((1-a)r_l\right)+\frac{\partial}{\partial y}\left((1-a)r_l V_l\right)=\Gamma_c-\frac{U_{he}}{A}\Gamma_g \tag{1}$$

Vapor mass balance:

$$\frac{\partial}{\partial t}\left(ar_g\right)+\frac{\partial}{\partial y}\left(ar_g V_g\right)=-\Gamma_c+\frac{U_{he}}{A}\Gamma_g \tag{2}$$

Mixture momentum balance:

$$\frac{\partial}{\partial t}\left(r_m V_m\right)+\frac{\partial}{\partial y}\left(ar_g V_g^{\,2}+(1-a)r_l V_l^{\,2}\right)=-\frac{\partial P}{\partial y}+rg_y+f_{vis} \tag{3}$$

Mixture energy balance:

$$\frac{\partial}{\partial t}\left(r_m I_m\right)+\frac{\partial}{\partial y}\left(ar_g h_g V_g+(1-a)r_l h_l V_l\right)=KV_r^{\,2}+W_{vis}+Q \tag{4}$$

Here f_{vis} is the distributed losses (pipe wall friction and local losses due to sudden change in area), U_{he} is the heated perimeter, I_m is the mixture specific internal energy:
$r_m I_m = a r_g I_g + (1-a) r_l I_l$; W_{vis} is the energy dissipation term, V_r is the relative velocity between phases: $V_r = V_g - V_l$ and Q is the heat source term in kW.

4. MODELLING OF VOID FORMATION IN THE SUBCOOLED BOILING REGIME

In the subcooled boiling regime, boiling occurs at the liquid cooled heating surfaces due to high heat flow densities, although the fluid has on average not yet reached the saturation temperature associated with the system pressure. In accordance with a suggestion by Griffith (Griffith *et al*., 1958) four zones of heat transport and flow activity can be differentiated along a channel axis until saturation boiling has been reached. Zone I is referred to as single phase heat transfer zone, Zone II is onset of nucleate boiling (ONB) zone, Zone III is onset of significant Void (OSV) and Zone IV is the saturated core flow region. The equation of the following effect must be formulated in order to determine the void content in the subcooled boiling regime: (1) on set of nucleate boiling (ONB). (2) bubble formation and bubble growth (bubble generation rate) at the heating surface (3)onset of significant void (OSV) and bubble departure diameter (4)bubble condensation in the subcooled core flow.

4.1 *Onset of Nucleate boiling (ONB)*

It describes the point at which first boiling nuclei are activated at the boiling surface. A correlation by Bergels and Rohsenow (Bergels *et al*., 1981) has been used to determine the wall superheating at which ONB will be activated.

$$\Delta T_{sat} = \frac{5}{9}\left(\frac{q''}{1100}P^{-1.156}\right)^{0.463P^{0.0234}} \quad (5a)$$

$$T_w = T_{sat} + \frac{5}{9}\left(\frac{q''}{1100}P^{-1.156}\right)^{0.463P^{0.0234}} \quad (5b)$$

The range of validity of the correlation is: channel diameter 2.4 and 4.6mm; flow velocity: 3-7ms^{-1}.Pressure: 1-36 bar.

4.2 *Onset of Significant Void (OSV)*

Assuming that the subcooled boiling occurs, the total heat Q supplied to the fluid from the heating surface per unit area can be arbitrarily partitioned into the following fractions:

$$Q = Q_{1\Phi} + Q_{GV}$$

Heat required to generate void is given by:

$$Q_{GV} = Q_{evap} + Q_{condensation}$$

$$q'' = q''_{1\Phi} + q''_{evap} + q''_{condensation} \quad (6)$$

The heat flux associated with the single phase convection from the heating surface is given as:

$$q''_{1\Phi} = B_{1\Phi} h_{1\Phi}\left(T_w - T_l\right) \quad (7)$$

Where T_w and T_l are the wall and liquid temperature respectively and $h_{1\Phi}$ is the heat transfer coefficient of the single phase liquid flow, which can be determined from the Dittus-Bolter correlation as:

$$h_{1\Phi} = 0.023\frac{k_l}{d_h}\mathrm{Re}^{0.8}\mathrm{Pr}^{0.4} \quad (8)$$

The factor $B_{1\Phi}$ is dependent on the void and is intended to take into consideration the fact that with increasing with the wall superheating, the number of bubbles formed will increase. $B_{1\Phi}$ describes the heating surface fraction in direct contact with the subcooled liquid.

$$B_{1\Phi} = \frac{A_{eff}}{A_{he}} = \frac{A_{he} - A_b}{A_{he}} = 1 - p\sum_{i=1}^{n} R^2_{i,B}$$

$$= 1 - np\,\overline{R}^2_B \quad (9)$$

Where A_b is the surface covered by bubbles, A_{he} is the heated surface n is the number of bubbles per unit area and $p\,\overline{R}_B^{\,2}$ is the projection area of a bubble on the heated surface, Although the bubbles have statistically different radii, the calculation has been carried out with average radius $\overline{R_B}$ for the sake of simplicity .

Hainoun(1994) has proposed $B_{1\Phi}$ as:

$$B_{1\Phi} \approx 1 - \frac{p}{16}\frac{a}{a_{osv}} \quad for\ a \le \frac{16a_{osv}}{p} \quad (10)$$

$$B_{1\Phi} \approx 0 \quad for\ a \ge \frac{16a_{osv}}{p} \quad (11)$$

where a_{osv} is the void fraction at the point when the bubbles become detached from the heating surface(OSV).Experimental data shows that a_{osv} may be about 5%-10%(Rogers *et al*.,1987)

Subcooling at OSV: The bubble will be detached from the wall only when the drag and buoyancy forces are greater than the holding force. The point at which the bubbles are first detached from the wall (this is OSV: Onset of Significant Void) is determined by the subcooling of the liquid at this location. The subcooling has been calculated using Saha and Zuber's model (Saha and Zuber, 1974) as follows:

$$\Delta T_{sub} = 0.0022 q'' \frac{d_h}{k_l} \qquad Pe \le 70000 \quad (12)$$

$$\Delta T_{sub} = 153.8 \frac{q''}{V_l r_l C_{p,l}} \qquad Pe \ge 70000 \quad (13)$$

where Peclet number can be found by the correlation $Pe=Re*Pr$.
Validity of the correlation:
P=0.1-13.8 MPa, m=95-2760 kg.m^{-2}s^{-1},
q'' =0.28-1.9MWm^{-2}

Bubble Departure Radius: The radius at which the bubbles are detached from the wall after reaching their critical size and required subcooling is called the bubble departure radius. Bubble departure radius has been calculated using Unal's semi empirical model(Unal,1976)

$$R_{bd} = 1.21\times10^{-5} \frac{p^{0.709} S}{\sqrt{b\Phi}} \quad (14)$$

where

$$b = \frac{T_{sat} - T_l}{2}\left(1 - \frac{r_g}{r_l}\right)$$

$$\Phi = \left(\frac{V_l}{0.61}\right)^{0.47} \qquad for \quad V_l > 0.61 ms^{-1}$$

$$= 1 \qquad for \quad V_l < 0.61 ms^{-1}$$

$$S = \frac{T_w - T_{sat}}{2 r_g h_{evap}}\left(\frac{k_w r_w C_{p,w}}{p}\right)^2$$

The range of validity of the correlation:
Pressure: 0.1-17.7 MPa
Heat flux: 0.47-10.64 MWm^{-2}
Velocity: 0.08-9.15 ms^{-1} and
Liquid sub-cooling: ΔT_{sub} =3-86 K

4.3 Bubble formation rate

The heat flux required for evaporation which is transferred from superheated boundary layer into the bubble can be calculated by:

$$q'' = nf V_{bd} r_g h_{evap} \quad (15)$$

f is the detachment frequency of the nucleation center at which bubbles are formed. n is the number of bubble nucleation center per unit area of heating surface. The heat flux required to reconstruct the superheated thermal boundary layer is given by:

$$q''_{GV} = nf Q_{recons} \quad (16)$$

Q_{recons} is the quantity of heat per nucleation centre withdrawn from the superheated wall to reconstruct the thermal boundary layer. To eliminate the unknown product *nf, a* parameter E is being defined as:

$$E = \frac{q''_{GV}}{q''_{evap}} = \frac{Q_{recons}}{V_{bd} r_g h_{evap}}$$

$$= \frac{q'' - q''_{1f}}{q''_{evap}} \quad \Rightarrow \quad q''_{evap} = \frac{q'' - q''_{1f}}{E} \quad (17)$$

Also from Meister consideration for thermal boundary layer (Meister, 1979), the parameter E can be calculated as:

$$\frac{1}{E} = 2C_{evap}\left(\frac{T_w - T_{sat}}{T_w - T_l}\right)^2 \quad (18)$$

C_{evap} = evaporation parameter
≈ 0.5

Finally, evaporation heat flux is given by:

$$q''_{evap} = 2(q'' - q''_{1\Phi})C_{evap}\left(\frac{T_w - T_{sat}}{T_w - T_l}\right)^2 \quad (19)$$

Bubble formation rate:

$$\Gamma_g = \frac{q''_{evap}}{h_{evap}} \quad (20)$$

4.4 Bubble condensation rate

The condensation of bubble in a subcooled liquid is governed by two effects: (1) heat transfer at the phase interface; (2) inertia of the surrounding liquid. In the case of a large bubble formed with low subcooling and low flow rate, condensation proceeds very slowly. Hence the inertia of liquid surrounding the bubble can be neglected. In this case condensation is mainly governed by heat transfer at the phase interface. On the other hand, small bubbles, resulting in the case of considerable sub-cooling and high flow rate, condense very rapidly. Owing to the inertia of condensation, the surrounding fluid cannot flow fast enough to fill the space vacated by the condensed bubble. Hence it cannot compensate for the resulting underpressure. So, a large local pressure fluctuation may arise; this is termed as cavitation effect (Hamit, 1980). Mayinger and Nordman (1976) have showed that the pressure fluctuations in the vicinity of condensed bubbles increases greatly above Jacob number 100. This is an indication that condensation is predominantly controlled by inertia above Jacob number 100. Chen (1986) has demonstrated by measurements on bubble condensation with the aid of holographic interferometry that a thermal boundary layer exists in the vicinity of condensed bubble up to Jacob number of 60-80. Up to this boundary the pressure fluctuations at the end of condensation are slight which is an indication of heat transfer controlled condensation. Thus Jacob number can be used to differentiate different condensation regions. The Jacob number indicates the ratio between the energy that the liquid requires to reach the saturation state and the heat stored in the steam at the same volume.

$$Ja = \frac{r_l C_{p,l}\left(T_{sat} - T_l\right)}{r_g h_{evap}} \tag{21}$$

(1) $Ja \le 80$: condensation is largely determined by heat transfer at the phase boundary.
(2) $80 < Ja < 100$: transition region. Both the heat transfer and inertia effects are significant.
(3) $Ja \ge 100$: inertia effect is dominant.

Heat transfer controlled condensation
Heat transfer controlled condensation rate has been calculated using Hainoun *et al's* model (1996) as:

$$\Gamma_c = C_c 3.6 \frac{a}{d_{bd}^2} r_g u_l Nu_1 Ja \quad for \ \mathrm{Re}_k < 10^4 \tag{22}$$

$$\Gamma_c = C_c 3.6 \frac{a}{d_{bd} d_h} r_g u_l Nu_2 Ja \quad for \ \mathrm{Re}_k > 3\times 10^4 \tag{23}$$

For $10^4 < \mathrm{Re}_k < 3\times 10^4$, Γ_c is interpolated between the two regions.
where C_c is the condensation parameter and equal to 0.16. Nu_1 has been given by Hewitt *et al* (1990) as :

$$Nu_1 = 0.185\,\mathrm{Re}_B^{0.7}\,\mathrm{Pr}^{0.5} \tag{24}$$

Re_B is the Bubble Reynold's number given by:

$$\mathrm{Re}_B = \frac{V_r d_{bd}}{u_l} \tag{25}$$

$$Nu_2 = 0.228\,\mathrm{Re}_c^{0.7}\,\mathrm{Pr}^{0.5}\,Av^{0.25} \tag{26}$$

Here Re_c is the channel Reynold's number. Av has been introduced by Avdeev (1986) which can be found from the correlation:

$$Av = 1 \quad \text{for } a \le 5\%$$
$$Av = (1-a)^{-2.53} \quad \text{for } a > 5\% \tag{27}$$

Inertia controlled condensation
Inertia controlled condensation has been estimated by Hamit's correlation (1980) as follows:

$$\Gamma_c = C_c r_g \frac{a}{t_c} \tag{28}$$

t_c is the condensation time (Hamit, 1980) which is given by:

$$t_c = 0.458 d_{bd}\left(\frac{r_l}{P_l}\right)^{\frac{1}{2}} \tag{29}$$

Now the expressions for the evaporation rate Γ_g in $kgm^{-2}s^{-1}$ [equation (20)] and condensation rates Γ_c in $kgm^{-3}s^{-1}$ [equations (22), (23) and (28)] have been calculated. Finally Γ_g and Γ_c are put in the vapor mass balance equation [equation (2)] to find out the void fraction. The simulation has been

then verified by comparing it with the McMaster experimental data on axial void distribution.

5. RESULTS

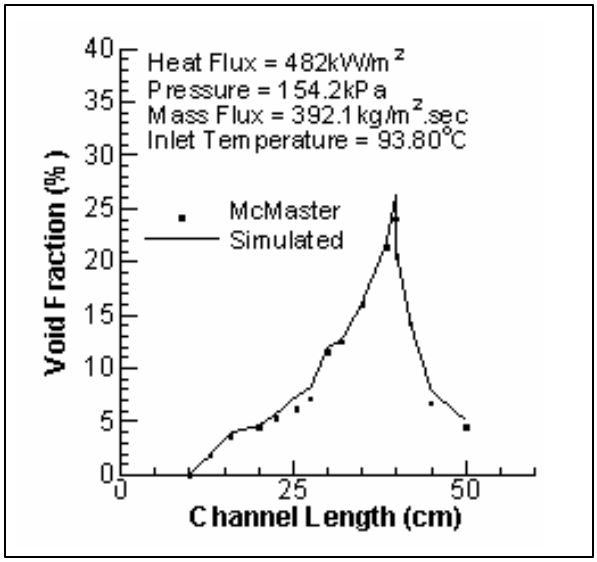

Fig.1 Comparison of simulated results with McMaster test data for axial void distribution in sub-cooled boiling regime

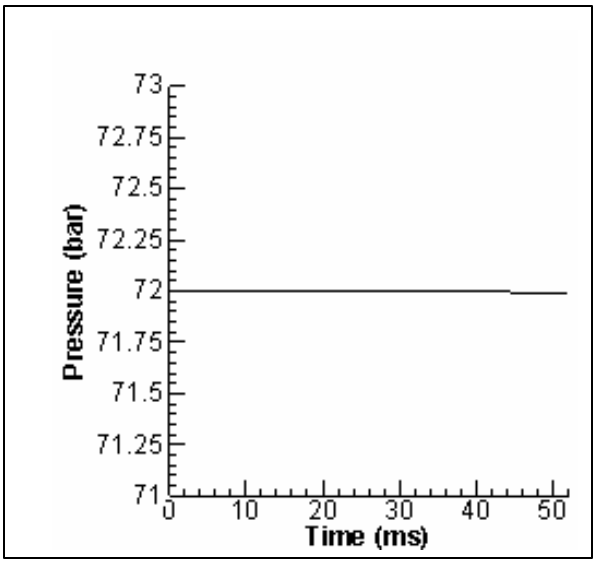

Fig. 3 Channel Pressure Variation with respect to time with initial pressure of 72 bar

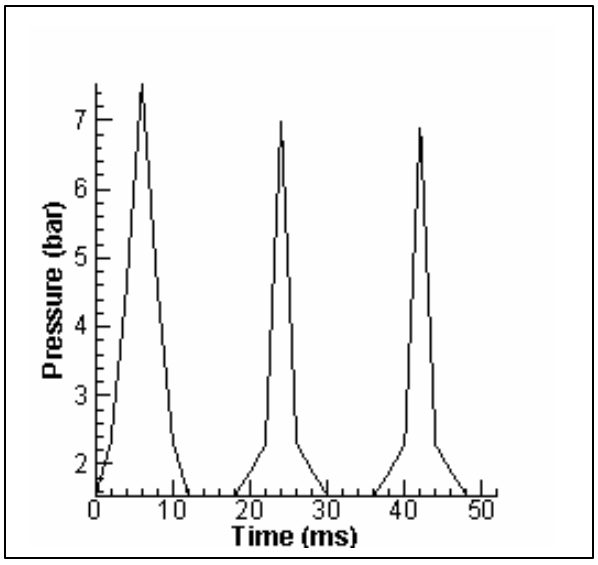

Fig. 2 Channel Pressure Variation with respect to time with initial pressure of 1.542 bar

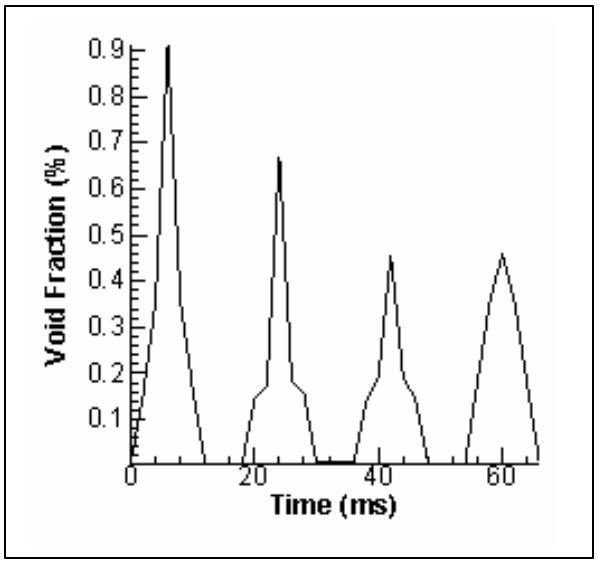

Fig. 4 Channel Average Void Distribution with respect to time with initial pressure of 1.542 bar

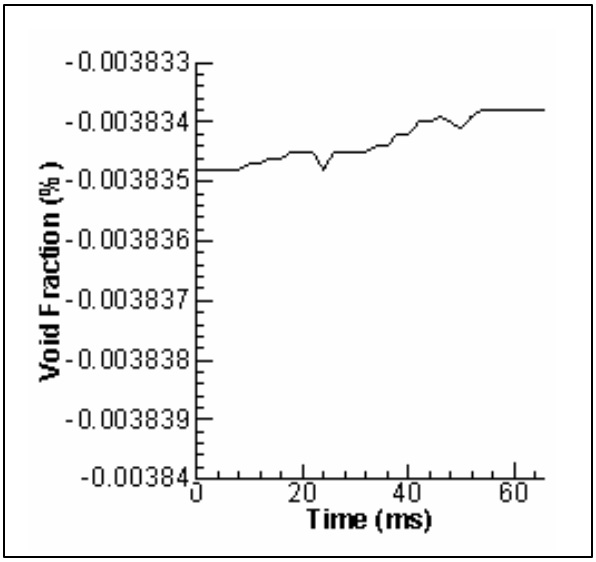

Fig. 5 Channel Average Void Distribution with respect to time with initial pressure of 72 bar

6. CONCLUSION

A computer code has been developed for the calculation of axial void fraction in the subcooled boiling regime using a four equation drift flux model with proper consideration of bubble formation and bubble condensation rates. The results obtained are in agreement with the McMaster experimental data on axial void distribution, as shown in figure 1. In figure 2, the variation of channel pressure with respect to time, with initial pressure 1.542 bar, is shown. The figure shows that at a low initial pressure during startup, boiling instabilities are prominent, which is a clear indication of geysering. The geysering period can also be determined from this figure, which is found to be about 20 ms for the case studied. Figure 3 shows that at a high initial pressure during startup, boiling instabilities are absent. The void fraction variation shown in figures 4 and 5 also confirm the above conclusion.

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