PREDICTION OF FLOW INSTABILITY DURING NATURAL CONVECTION

Kazem Farhadi
Head of Tehran Research Reactor Research Group
Nuclear Research Center
Atomic Energh Organization of Iran (AEOI)
Tehran-Iran
kfarhadi@aeoi.org.ir

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ABSTRACT

The occurrence of flow excursion instability during passive heat removal for Tehran Research Reactor (TRR) has been analyzed at low-pressure and low-mass rate of flow conditions without boiling taking place. Pressure drop-flow rate characteristics in the general case are determined upon a developed code for this purpose. The code takes into account variations of different pressure drop components caused by different powers as well as different core inlet temperatures. The analysis revealed the fact that the instability can actually occur in the natural convection mode for a range of powers per fuel plates at a predetermined inlet temperature with fixed geometry of the core. Low mass rate of flow and high sub-cooling are the two important conditions for the occurrence of static instability in the TRR. The calculated results are compared with the existing data in the literature.

1. Introduction

A flow may be subjected to a static instability should the flow conditions change by a small step from the original steady state, another steady state is not possible in the neighboring of the original state [1]. The outcome state could be in either steady or periodic situation. The occurrence of the phenomenon is governed by the steady state laws. Consequently, the threshold of the phenomenon can be predicted merely by applying steady-state laws [1]. Ledinegg [2] fruitfully attempted to analyze excursive instabilities. The Ledinegg instability, flow excursion, involves a sudden change in the flow rate to a lower value [1]. Under certain conditions the curve of steady-state system pressure drop versus flow (internal characteristic of the heated channel) has not a single-value function of pressure drop and as a consequence a flow excursion may take place [2].
Several studies have been carried out to investigate the phenomenon with particular attention to its application in the nuclear industry. The most recent work attributed to Ishii [3], Lahey and Yadigaroglu [4], and Yadigaroglu [5], respectively.

2. Theory of instability

The steady-state operating condition for a flow in a given heated channel is defined by:

$$\Delta P_{\text{int}} = \Delta P_{ext.} \qquad (1)$$

Upon certain physical conditions, the slope of the internal pressure drop curve, plotted versus inlet mass flux, becomes algebrically smaller than that of the external pressure drop curve. The external pressure drop is provided either by a hydrostatic head in natural circulation or by

a pump in forced flow. It is adequate, however, to analyze the internal pressure drop (demand) curve for its minimum point in the process of predicting flow excursion. The physical situation leading to the minimum point will be given by:

$$\frac{\partial \Delta P_{\text{int.}}}{\partial G_{in}} = 0 \qquad (2)$$

The internal pressure drop equation is in fact axial momentum equation along any given vertical channel. The usual form of this equation is obtained after averaging over the pipe cross-sectional area and then integrating over the pipe length. Should the slope of the external pressure drop-versus-flow curve (pump characteristic) be greater than the slope of the internal pressure drop-versus-flow curve (system characteristic), the system undergoes a static flow transition, namely, flow excursion takes place. The condition under which this phenomenon happens is expressed as follows:

$$\frac{\partial \Delta P_{ext.}}{\partial G} < \frac{\partial \Delta P_{\text{int.}}}{\partial G} \qquad (3)$$

The meeting point of the external (pump characteristic) pressure drop curve and the internal (system characteristic) pressure drop curve determine the operating conditions of the system as shown in Fig. 1.

The curve relating pressure drop to mass flow rate for a given heated channel cooled by flowing water consists of three distinct regions. Of the three, two of which have a positive slope and the third one a negative slope. The regions of positive slope correspond approximately to single-phase flow. Either all liquid or all steam as the case may be. However, in the region of negative slope, three different physical conditions are highly expected to exists. These are low quality, boiling, and high quality, respectively.

The phenomenon of excursive-flow instability is a consequence of the change in slope from positive to negative as the liquid mass flow rate is diminished and boiling happens in the coolant channel.

The process may be well understood by referring to Fig. 1. As it is clear from the figure, curves S_1, S_2, S_c, S_4 represent the system characteristic (internal pressure drop) curves for different channel powers, respectively. The curve AA represents pump characteristic (external pressure drop) curve for forced convection. The equilibrium mass flow rate is determined by the intersection of the pump characteristic curve and the system curve. For a given channel power less than that corresponding to S_c, the operating point is at L, giving mass flow rate M. Upon increasing the power from zero to a value corresponding to S_c has little effect on the channel mass flow rate. The curve S_c is tangent to the pump characteristic curve AA. Any increase in power input above S_c results in a situation in which the only intersection of the S-curve with AA will be at F. The “operating point” of the channel therefore moves along AA from L to F as the power is increased slightly from its critical value. And the mass flow rate drops abruptly from M to M_c. This large change in the mass flow rate leads to a situation in which burn-out can occur with consequent overheating and possibly melting of fuel plates unless the power is reduced (Whittle and Forgan [6]). The onset of flow instability may be caused due to either increased channel power or decreased channel mass flow rate.

3. Derivation of the model

3.1. Physical model

For a conceptual model of a natural circulation loop (system), the pressure losses around the loop(system), including the acceleration and friction losses, are equal to the driving force arising from the buoyancy of the bubbles. Under natural circulation conditions, a loop (system) operates without a pump, and the flow is driven entirely by the buoyancy-generated pressure head. Nuclear reactors are generally benefit from the natural circulation potential in obtaining a decay power removal capability. However, the exact power that may be removed from the core varies according to the concerned plant design.

The steady state internal pressure drop (system characteristic) of any closed system may be obtained by integrating momentum equation that rules the system. For a vertical channel where the coolant is forced to flow in upward direction, the momentum equation is given by:

$$P_{in} - P_{out} = \Delta P_{inertia} + \Delta P_{acceleration} + \Delta P_{gravity} + \Delta P_{friction} + \Delta P_{form} \qquad (4)$$

Should the system operates in forced convection mode, then the sum of the pressure drop components in Eq. (4) must be equal to the balancing external pump head. In other words:

$$P_{in} - P_{out} = \Delta P_{pump} \qquad (5)$$

However, in natural circulation mode the balancing head resulting from buoyancy equals the total pressure drop components given by Eq. (4). As a consequence, for natural circulation mode in the steady-state operation, the pressure drop equation takes the form:

$$\Delta P_{buoyancy} = \Delta P_{inertia} + \Delta P_{acceleration} + \Delta P_{gravity} + \Delta P_{friction} + \Delta P_{form} \qquad (6)$$

Eq. (6) is convenient to use for the decay heat removal in the nuclear reactors. Due to time variations of density as a function of temperature, it is more practical to use the average value of density in the vertical channel as well as in the chimney placed obove the core. One should bear in mind that for upward flow, fluid thermal expansion assists the mass flow rate in upward flow direction and the convection pressure drop component must appear in the total pressure drop of the system. In contrast to upward flow direction, thermal expansion resists the mass flow rate of the liquid. Also, notice that gravity actually aids the flow of liquid in downward flow direction, whereas it is a pressure drop component in the upward flow direction.

3.2. Basic assumptions

The path where the pressure drop components are taken into account includes entry to the fuel element, active length of the fuel plates, chimeny, and exit of the fuel element.

The basic assumptions used in the derivation of the model are as follows:

(1) uniform heat flux distributions along the active length of the fuel plates.
(2) velocity variations of the coolant outside the fuel elements are ignored.
(3) density variations are considered to be varied linerly with temperature.

(4) sub-cooled flow at the inlet to the coolant channel and subject to a constant, paralell channel type pressure drop boundary conditions.
(5) all physical properties of the coolant along the fuel plates are ignored, but the density variations.
(6) the pressure drop along the chimney is ignored.

The error dut to uniform heat flux along the active length of the fuel plates is small compared to real heat flux and is less than 5% (Zvirin, [7]).
Due to time variations of density as a function of temperature, it is more practical to use the average value of density in the vertical channel as well as in the chimney. Therefore for average density of coolant along the chimney one may derive the following relation:

$$\bar{\rho}_c = \frac{\rho_L L_{eff} + \rho_{ch} L_{ch}}{L_{eff} + L_{ch}}$$

For ease of calculations, it is assumed that the generated heat is uniform along the fuel plates. Therefore, the temperatue rise of the coolant along the heated channel will be linear:

$$T_{f(z)} - T_{f(in)} = \left(\Delta T_f\right)_{rise}\left(\frac{z}{L_{eff}}\right)$$

It is also assumed that the density variations due to temperatue follows the Boussinesq approximation:

$$\rho = \rho_\infty\left[1 - \beta\left(\Delta T_f\right)_{rise}\left(\frac{z}{L_{eff}}\right)\right]$$

Therefore, for the coolant channel exit density (average density of the coolant in the chimney) one may obtain:

$$\rho_{out} = \rho_\infty\left(1 - \frac{\beta\dot{q}}{Wc_p}\left(\frac{L}{L_{eff}}\right)\right)$$

For the average density along the coolant channel and chimney the following relations may be obtain:

$$\bar{\rho}_L = \frac{1}{L_{eff}}\int_0^{Leff} \rho dz = \rho_\infty\left(1 - \frac{\beta\dot{q}}{2Wc_p}\left(\frac{L}{L_{eff}}\right)\right)$$

and

$$\bar{\rho}_c = \frac{\rho_\infty\left(1 - \left(\frac{\beta\dot{q}}{2Wc_p}\right)\times\left(\frac{L}{L_{eff}}\right)\times L\right)}{L + L_{ch}} + \frac{\rho_\infty\left(1 - \left(\frac{\beta\dot{q}}{Wc_p}\right)\times\left(\frac{L}{L_{eff}}\right)\times L_{ch}\right)}{L + L_{ch}}$$

3.3. Model derivation

Under steady state conditions all the time-dependent terms disappear from the momentum equation. Thus the momentum equation reduced to

$$\Delta P_f = \Delta P_b \qquad (7)$$

The buoyancy head is equal to the difference between the maximum coolant density and minimum coolant density along the loop (system) times the difference in elevation between the thermal center of heat extraction and thermal center of heat addition. The buoyancy head can be expressed as

$$\Delta P_b = (\rho_\infty - \overline{\rho}_c) g (L_{eff} + L_{ch}) \qquad (8)$$

Upon substitutions

$$\Delta P_b = \rho_\infty \left[1 - (L_{eff} + L_{ch}) \frac{\beta}{2} \times \frac{\dot{q}}{W c_p} \times \frac{L}{L_{eff}} \times (1 + 2L_{ch}) \right] \times g \times (L_{eff} + L_{ch}) \qquad (9)$$

One should bear in mind that the model derived so far would apply for single phase and in case of two-phase flow the necessary modification must be made to include the effect of vapor phase in the whole system (Farhadi, [8]).
The effect of inlet temperature on the external characteristic of the system for a given power can be analyzed as follows. For highly sub-cooled coolant, the component of pressure drop are mainly ΔP_f and ΔP_g, respectively. Therefore, the total pressure drop for highly sub-cooled region will be

$$\Delta P = \Delta P_g + \Delta P_f \qquad (10)$$

Upon substitutions

$$\Delta P = \rho g L + f \frac{L}{D_e} \left(\frac{W^2}{2 \rho A^2} \right) \qquad (11)$$

Finally

$$\Delta P = W^{0.8} \left[0.33 \left(\frac{D_e}{\mu A} \right)^{-0.2} \left(\frac{L}{2 D_e A^2} \right) \left(\frac{1}{\rho_\infty} \right) (L + L_{ch}) \right] - \left[\rho_\infty (L + L_{ch}) - \rho_\infty \frac{\beta}{2} \frac{\dot{q}}{W^2 c_p} L (L + 2L_{ch}) g \right]$$

Eq. 12 will be used for finding the minimum point on the system characteristic curve.

4. Results and discussion

Tehran Research Reactor is a pool-type research reactor, operating with Max. 5 MW thermal, water-cooled and moderated reactor. The reactor core is rectangular in geometry with vertical fuel elements parallel to the core axis. The coolant is gravity driven through

the coolant channels to an external heat exchanger and eventually returned to the bottom of the reactor pool.
Fig. 2 shows the calculated acceleration, friction, form, and gravity pressure drop components for the water-cooled and moderated Tehran Research Reactor. When the mass rate of flow to the heated coolant channel decreases, the internal pressure drop across the channel caused by pipe friction decreases. When the mass rate of flow to the heated channel increases, the internal pressure drop across the channel caused by coolant acceleration first increases and then decreases. This later effect, for a given power and constant cross-sectional area of the coolant channel, is mainly due to density variations as a result of coupled effect of mass rate of flow as well as temperature distributions at the exit and entry of the coolant channels. The internal pressure drop across the coolant channel due to form losses increases smoothly with increasing mass rate of flow and this is caused by density variations at the inlet to the heated coolant channel and at the exit of the heated coolant channel. All the terms on the right hand side of the frictional, accelerational, and form losses components of pressure drop are functions of mass rate of flow as well as proportional to the square of the mass rate of flow. Details of which is given in Farhadi, 2003. The gravitational pressure drop component is not a function of mass rate of flow. The internal pressure drop curve clearly shows a minimum which is a characteristic of excursive instability. The minimum pressure drop point occurs always at low mass rate of flow for this type of flow instabilities.
Eq. 12 is differentiated with respected to mass rate of flow and equated to zero. This is done so in order to find the positions of minimum on the pressure drop-mass rate of flow curve and the results is shown in Fig. 2. The figure shows that for a given pressure drop, the points of minimum (mass rate of flow) on the pressure drop-mass rate of flow curve move towards right as the power is increased.
Whittle and Forgan suggested the following correlation for predicting the onset of flow static instability

$$R = \frac{T_{out} - T_{in}}{T_{sat} - T_{in}} = \frac{1}{1 + \eta\left(\frac{D_h}{L_h}\right)}$$

where η is bubble detachment parameter is depends only on the system pressure. The correlation is valid for sub-cooled coolant (ordinary water) flowing (upward and downward) in narrow heated channels (width 2.54 cm, thickness 0.14 to 0.32 cm, and length 40 to 61 cm) under the following conditions:

$$1.2 \le P_{exit} \le 1.7 bar$$

$$83 \le \frac{L_h}{D_h} \le 190$$

where
L_h=heated length of channel.
D_h=heated equivalent diameter of the channel.

They could correlate many experimental data accordingly. Fig. 3 shows the calculated data band for Tehran Research Reactor. For a given fuel plate power as the inlet

temperature into the core begins to increase from a predetermined value, the value of *R* starts to increase. Due to this increase the whole system tends toward the unstable condition (see Fig. 3 for clarity). The probable range of flow static instability is given in Table 1.

5. Conclusions

A theoretical parametric study for flow static instabilities of coolant flow in the upward direction (natural convection) has been performed. A computer program has been developed which predicts the probable onset of the flow static instability within a range of inlet temperature into the core of Tehran Research Reactor.

1. Static instability can actually occur in a natural convection system (passive heat removal) depending on inlet temperature into the core for a given power and fixed geometry of the core. For Tehran Research Reactor and for inlet temperature into the core ranging 15-65 ºC and corresponding power per fuel plate ranging 200-300 W/plate, the static instability is expecting to take place and this is shown as data scatter band on Fig. 4.
2. The mechanism of static type flow instability can be interpreted by means of analyzing the characteristic curves of the driven head (pump in case of forced convection) and the loop (system) flow resistance, and the operation curve for natural convection.
3. The obtained results could be used in Tehran Research Reactor Safety Analysis Report in order to license it for futur safe operation.

Nomenclature

A cross-sectional area
D_e hydraulic diameter
c_p heat capacity at constant pressure
f friction factor
L coolant channel length
L_{ch} length of chimney
L_{eff} effective length of coolant channel
$\dot{q}$ heat flux
G_{in} inlet mass rate of flow
β thermal expansion coefficient
μ viscosity
ρ density
ΔP pressure drop
ΔT_f coolant temperature difference
W coolant mass rate of flow
z axial length along coolant channel

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