AN APPROACH TO MODELLING OF INTERMITTENT BUOYANCY INDUCED FLOW

Justin Spencer
M.Sc. Candidate, McMaster University
Department of Engineering Physics
1280 Main Street West, Hamilton, Ontario, L8S 4L7
spencejh@mcmaster.ca

Abstract

In the event of a loss of forced circulation while at low power, heat sinks may be maintained by natural circulation phenomena including Intermittent Buoyancy Induced Flow (IBIF). The sensitivity of IBIF to a variety of parameters is an important consideration in determining its effectiveness as a cooling mechanism and in planning heat sinks. Although there has been some work done on IBIF in industry, there are no publicly available models of IBIF and very limited material available in open literature. This paper presents an outline of a proposed best-estimate IBIF model, to be used for uncertainty analysis.

1. Introduction

In scenarios where forced circulation is lost, heat sinks must be maintained to prevent fuel damage. Planning for loss of forced circulation scenarios must be carried out in advance, as even at decay heat levels melting can occur in several minutes if cooling is lost. Core Cooling in the Absence of Forced Flow (CCAFF) can follow several modes including: single-phase thermosyphoning, two-phase thermosyphoning, IBIF, and continuous steam venting.

If – subsequent to loss of forced circulation – flow through a fuel channel stagnates, the channel may reach saturation and begin voiding. Under these conditions, vapour and liquid are stratified, and due to the axial flux profile across the core, void is produced first in the centre of the channel. As the vapour bubble grows outward, it eventually comes into contact with the relatively cold end fittings, where condensation stops its outward expansion. Condensation heat transfer heats the end fitting until it approaches saturation temperature. When condensation is reduced sufficiently by the increasing end fitting temperature, the bubble will create a flow path to the feeder tube at one end of the channel and venting will occur, with cold liquid rushing in from the feeder at the opposite end of the channel to take its place. The IBIF cycle may then be repeated, with different values for parameters such as initial fuel, end fitting, and coolant temperatures, affecting venting time.

The length of the period from initial void generation to venting is of great interest, as the vapour bubble will uncover fuel pins and drastically reduce cooling. Consecutive IBIF cycles are also of interest, as although increasing end fitting temperatures lead to shorter venting times and lower maximum fuel temperatures, the cumulative effects of IBIF cycles on fuel and fuel channel behaviour must also be considered [1].

2. Proposed Modelling Approach

A one-dimensional, two phase model with unequal phase temperatures and velocities is outlined. For the sake of simplicity, modelling of some present heat transfer paths will be omitted. In particular, radiative heat transfer, heat transfer between liquid and vapour, and heat transfer to the pressure tube are likely to have little impact in comparison with convection and conduction between the following:

- Fuel pins and liquid
- Fuel pins and vapour
- Liquid and end fitting
- Vapour and end fitting

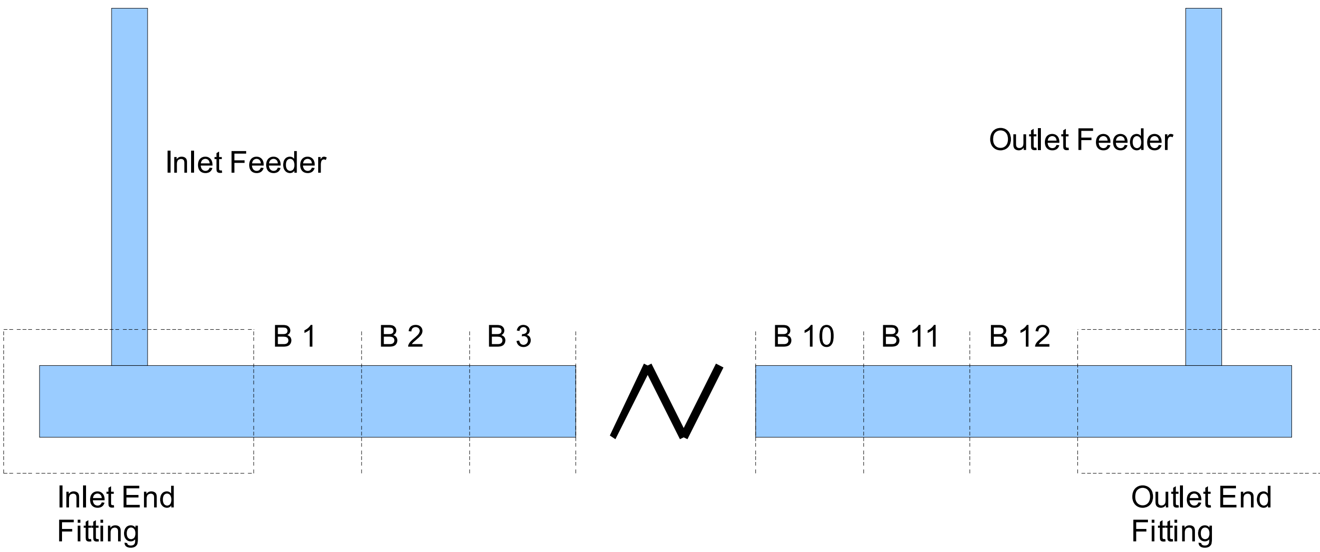

Figure 1: Schematic of Fluid Nodes

As shown in Figure 1, the system will be divided into 14 nodes, 2 representing the end fittings and 12 representing the parts of the channel coinciding with each fuel bundle. Each node communicates with neighbouring nodes to the left and right, with the end fitting nodes being adjacent to the feeders – which are taken to have constant properties prior to venting. With the system modelled this way, the mass transfer pathways are:

- Vapour flux to left and right
- Liquid flux to left and right
- Condensation of vapour
- Boiling of liquid

2.1 Energy Conservation Equations

With the heat and mass transfer paths established, the energy conservation equation for any node can be expressed:

$$\sum_{pins}\int_0^t q_d(t)dt = \sum_{pins}\int_{T_{pin}(0)}^{T_{pin}(t)} m_{pin}Cp_{pin}dT_{pin} + \int_{T_{e.f.}(0)}^{T_{e.f.}(t)} m_{e.f.}Cp_{e.f.}dT_{e.f.} +$$
$$\int_o^t \left[\dot{m}_{L,vap.\,flux}(t)h_{L,vap.}(t) + \dot{m}_{R,vap.\,flux}(t)h_{R,vap.}(t) + \dot{m}_{L,liq.\,flux}(t)h_{L,liq.}(t) + \dot{m}_{R,liq.\,flux}(t)h_{R,liq.}(t) \right] dt \tag{1}$$
$$+ \sum_{pins}\int_0^t \left[h_{fuel,liq}(T_{pin} - T_{liq}) - h_{e.f.,liq}(T_{liq} - T_{e.f.}) + h_{fuel,vap}(T_{pin} - T_{vap}) - h_{e.f.,vap}(T_{vap} - T_{e.f.}) \right] dt$$

With the terms from left to right representing:

a) decay heat added to the fuel
b) heat energy stored in fuel pins
c) heat energy stored in end fitting
d) H removed from vapour by mass transfer to node on left
e) H removed from vapour by mass transfer to node on right
f) H removed from liquid by mass transfer to node on left
g) H removed from liquid by mass transfer to node on right
h) H added to liquid by heat transfer from fuel pins
i) H removed from liquid by heat transfer to end fitting
j) H added to vapour by heat transfer from fuel pins
k) H removed from vapour by heat transfer to end fitting

It is also worth noting that the form of the heat transfer terms is not necessarily an accurate reflection of the terms that may be used in the model – which are potentially more complex heat transfer correlations. The enthalpy transferred between liquid and vapour via boiling and condensation mass transfer cancels in the overall conservation equation, but of course must not be overlooked when expressing the liquid and vapour equations:

$$\Delta H_{liq} = \int_o^t \left[\dot{m}_{L,liq.\,flux}(t)h_{L,liq}(t) + \dot{m}_{R,liq.\,flux}(t)h_{R,liq}(t) \right] dt$$
$$+ \int_0^t \left[h_{fuel,liq}(T_{fuel} - T_{liq}) - h_{e.f.,liq}(T_{liq} - T_{e.f.}) \right] dt - h_{vap.,sat}\,\dot{m}_{boiled} + h_{liq.,sat}\,\dot{m}_{condensed} \tag{2}$$

$$\Delta H_{vap} = \int_{o}^{t} \left[\dot{m}_{L,vap.\,flux}(t) h_{L,vap.}(t) + \dot{m}_{R,vap.\,flux}(t) h_{R,vap.}(t) \right] dt$$

$$+ \int_{0}^{t} \left[h_{fuel,vap} (T_{fuel} - T_{vap}) - h_{e.f.,vap} (T_{vap} - T_{e.f.}) \right] dt - h_{liq.sat} \dot{m}_{condensed} + h_{vap.sat} \dot{m}_{boiled} \tag{3}$$

2.2 Mass Conservation Equations

The overall mass conservation equation for a given node can be expressed:

$$\Delta M = -\int_{0}^{t} (\dot{m}_{R,liq.\,flux} + \dot{m}_{L,liq.\,flux} + \dot{m}_{R,vap.\,flux} + \dot{m}_{L,vap.\,flux}) dt \tag{4}$$

With the terms from left to right representing:

a) change in total mass
b) mass flux of liquid to node on right
c) mass flux of liquid to node on left
d) mass flux of vapour to node on right
e) mass flux of vapour to node on left

Considering liquid and vapour separately, the condensation and boiling terms appear:

$$\Delta M_{liq} = \int_{0}^{t} (\dot{m}_{condensed} - \dot{m}_{boiled} + \dot{m}_{R,liq.\,flux} + \dot{m}_{L,liq.\,flux}) dt \tag{5}$$

$$\Delta M_{vap} = \int_{0}^{t} (\dot{m}_{boiled} - \dot{m}_{condensed} + \dot{m}_{R,vap.\,flux} + \dot{m}_{L,vap.\,flux}) dt \tag{4}$$

2.3 Liquid and Vapour Migration

Due to the stagnated nature of flow conditions in the IBIF scenario, liquid and vapour phases are stratified when both are present. With this in mind, a CFD approach to modelling fluid flow in the channel is not necessary. Though net flow across the channel is stagnated, some localised flow must take place as vapour migrates to the end fittings, condenses, and flows back toward the centre of the channel as liquid. In the place of a detailed model, a predefined bubble shape based on total vapour volume will be applied, with the difference between vapour production and allocation in each node determining vapour flows. Similarly, change in vapour bubble size (and opposing change in the remaining volume occupied by liquid), and the rate of liquid loss through boiling in each node can be used to model the flow rate of liquid between nodes. Bubble growth early in the cycle will tend to force liquid away from the centre of the channel and into the end fitting and feeders, while a nearly constant bubble size will result in a slow liquid flow toward the centre of the channel, balancing the higher velocity vapour flow in the opposite direction.

There is evidence that some turbulent mixing between vapour and liquid phases may occur in the end fittings [2], however the use of CFD will again be foregone due to the associated difficulties and lack of empirical data. The effects of the mixing may be roughly approximated using spatially varied heat transfer boundary conditions between the end fitting wall and the vapour and liquid phases, namely, by applying appropriate boundary conditions in two-phase regions.

2.4 Key Parameters

A variety of parameters must be judiciously selected for the code to accurately reflect reality. Some of these parameters are excellent candidates for sensitivity studies. These include: Heat Transfer Coefficients and Correlations, bubble shape factor, pressure, pin powers (including spatial variation and evolution with decay), and initial temperatures of coolant, fuel, and end fittings.

2.4.1 Heat Transfer Coefficients and Correlations

Heat transfer terms h) through k) of equation (1) – though not necessarily shown in the form that will be used in the model – play a central role in determining the progression of the IBIF cycle. As such, use of reasonable heat transfer coefficients and correlations is crucial in arriving at accurate results. While some correlations may provide reasonable approximations of the situation (for example the Rohsenow pool boiling heat transfer correlation for fuel pin – liquid heat transfer at saturation), it is important to determine the sensitivity of the model to variation of these parameters.

In exploring sensitivity, it will be useful to explore the effects of heat transfer coefficients corresponding to minimum Nusselt numbers and infinite heat transfer coefficients – as employed between vapour and end fitting in the code THERMOSS-II [2]. With very low heat transfer coefficients between vapour and end fittings, it is possible that faster venting times could be achieved as the increasing volume of vapour in the end fittings is not withheld from venting by condensation. Though this scenario may constitute a dubious reflection of the physical IBIF process, it does raise the possibility of a non-extremum ‘worst case’ heat transfer coefficient between vapour and end fitting, where end fitting heating is slowed by a small heat transfer coefficient, but vapour condensation proceeds at a sufficient rate to avert venting prior to the end fitting achieving saturation temperatures.

2.4.2 Bubble Shape Factor

The factor defining bubble shape will have great impact on the simulation results. For example, a factor corresponding to a ‘deep bubble’, with a large vapour accumulation in the centre of the channel prior to outward migration, will slow venting times, as heat transfer to the end fittings is slowed through decreased vapour generation resulting from a reduction in wetted fuel pins. Bubble shape is likely to vary in a physical IBIF scenario in response to variables such as the degree of creep and sag.

In exploring bubble shape factor sensitivity, it will prove useful to consider extreme scenarios such as the aforementioned ‘deep bubble’ and a reversed bubble shape where all vapour generated flows immediately to the end fittings.

2.4.3 Pressure

The pressure in an IBIF scenario is likely to be much lower than in normal operation – on the order of 2 bar. At these pressures, the relative difference between the highest and lowest channels of the core is significant. Pressure will likely have some effect on the progression of the IBIF cycle, however, outside of the effect on time to initial vapour generation due to the increased saturation temperature, it is unclear what these effects will be.

2.4.3 Pin Powers

The rate of heat production in the fuel pins is of great concern in modelling IBIF. A wide variety of power levels are possible depending on variables such as the power level prior to shutdown and the length of time between shutdown and the IBIF cycle in question. The axial power distribution along the channel could also be affected by variables such as fuel burnup and would have some impact on the progression of the cycle.

2.4.4 Initial Temperatures – Coolant, End Fittings, Fuel Pins

The initial temperatures of the coolant, end fittings, and fuel pins could vary widely depending on the scenario preceding the cycle in question – for example, whether thermosyphoning has just broken down or if the simulation follows a series of other IBIF cycles. The progression of the simulation will be affected by all of these, and determining sensitivity of the results to each of them within the range of possible values will be valuable.

2.5 End Fitting Model

End fitting heating is a key factor in determining venting time, as a close approach to saturation temperature is necessary to allow venting. A bulk model of the end fitting can provide a rough indication of how the accident proceeds, but would tend to over-predict venting times as the entire end fitting must be heated rather than only the portions in contact with vapour as in the physical system. To deal with this issue, a 3-D heat transfer model of the end fitting body will be constructed and coupled with the model of liquid and vapour in the channel and end fitting. This will result in a more realistic temperature distribution throughout the end fitting body.

3. Conclusion

An approach to modelling IBIF is outlined, with parameters for sensitivity studies incorporated and discussed. A model will be developed following the outline provided in this paper and used to study the sensitivity of IBIF progression to various parameters. This will provide the first publicly available IBIF model, and contribute to the understanding of the function of IBIF as a cooling mechanism, thus potentially impacting heat sink planning.

4. References

[1] Lei Q.M. and Gulshani P., "Assessment of Fuel Fitness-for-Service After Standing-Start Process Under Gentilly 2 Shutdown Conditions", *CNS 19th Annual Conference*, 1998

[2] Gulshani P., "THERMOSS-II: A Model for Thermohydraulics of CANDU Fuel Channel with Subcooled Stagnant Initial Conditions", *CNS 9th Annual Conference*, 1988

[3] Gulshani P., "Prediction of Void Fraction in Steady Horizontal Stratified Flow", *CNS 7th Annual Conference*, 1986

[4] Gulshani P., "Assessment of Fuel Cooling Under Shutdown Conditions in Gentilly 2", *CNS 20th Annual Conference*, 1999

[5] Soedijono P., Osamusali S., Tahir A. and Wan P., "A Mechanistic Model to Predict ΔP_{HH} under Two-Phase Natural Circulation Flow and Comparison against Experimental Results in RD-14M", *CNS 22nd Annual Conference*, 2001