AN APPROACH TO MODELLING THE EFFECTS OF A SMALL LOCA WITH A LOSS OF ECI UNDER NATURAL CIRCULATION CONDITIONS IN A CANDU REACTOR

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ABSTRACT

This paper presents a critical review of information pertaining to the degradation of fuel cooling during a small loss of coolant accident (SLOCA) in conjunction with a loss of emergency cooling injection (LOECI) and a loss of forced circulation in a CANDU reactor. This review provides the background information necessary to facilitate the creation of a computer program that models the thermalhydraulic behaviour during the postulated severe accident. The model will represent the thermalhydraulic variables and event timing associated with flow and heat transfer degradation in multiple-parallel fuel channels connected between the inlet and outlet reactor headers.

NOMENCLATURE

Symbol	Description	Subscript	Description
C_P	Specific heat capacity	cal	Calandria and moderator
D_e	Hydraulic diameter	ch	Channel
F	Friction factor	Fuel	Fuel
G	Acceleration due to gravity	i	Inflow
h	Enthalpy	IEF	Inlet end-fitting
H	Elevation difference	IF	Inlet feeder
HL	Heat loss	HH	Header-to-header
K	Equivalent resistance	j	Pipe section j
L	Pipe length	l	Liquid
M	Mass	o	Outflow
P	Pressure	OEF	Outlet end-fitting
Q	Heat	OF	Outlet feeder
ρ	Density	PT	Pressure tube
t	Time	REV	Flow reversal
T	Temperature	RIH	Reactor inlet header
u	Velocity	ROH	Reactor inlet header
W	Mass flow rate	s	Steam

1. INTRODUCTION

1.1 Objective

See ABSTRACT.

1.2 Motivation

Severe accidents are high-consequence, low-frequency events that are beyond the design basis of nuclear facilities. The modelling of such events is an increasingly important part of reactor safety analysis that conforms to modern international standards. The infrequent nature of some severe accident sequences has led the nuclear industry to use overly conservative guidelines in some scenarios. Nevertheless, in the recent past the Canadian nuclear industry has moved towards risk-informed decision making and towards best estimate code development.[1] Hence, revisiting some of the traditional accident scenarios provides an independent check of the state-of-the-art models as well as provides the opportunity to extend those models mechanistically in order to support a best estimate approach to safety analysis code development for design base accidents (DBA) as well as beyond design base accidents (BDBA). The SLOCA-LOCEI event falls at the boundary between the DBA and BDBA categories.[2] Therefore, having the ability to perform best estimate parametric analysis of these event sequences also aids the level 2 probability safety assessment (PSA) activities for CANDU nuclear power plants (NPP).[3]

1.3 Modelling a SLOCA-LOECI Event

In order to model the effects of a SLOCA-LOECI event under transient natural circulation conditions a best estimate methodology is desirable. A best estimate methodology, as employed by Ontario Hydro, includes using a mechanistic model that is based both on the most relevant and most accurate experimental findings.[1] The objective of the mechanistic model in the nuclear industry should be to provide physically reasonable and representative results without excessive conservatism being applied. Such a model for a SLOCA-LOECI event already exists for a single fuel channel in the SLLOH (Small LOCA-LOECI Heat Up) code. SLLOH was developed by Ontario Hydro[4], which in turn is based on the work of Luxat and Rance.[5] The work described in this paper will enhance the SLLOH (Small LOCA-LOECI Heat Up) methodology as well as other current mechanistic models by extending this previous work to a multiple-parallel fuel channels in a figure-of-eight loop (i.e. an entire reactor core).

2. PROGRESSION OF FUEL COOLING DEGRADATION

2.1 Severe Accidents under Natural Circulation

A severe accident can be defined as an accident that leads to extensive damage of the fuel and structures within the core of a reactor due to an extended period of inadequate heat removal. The severity of these accidents is a function of the nature and extent of the damage occurring during its progression.[3] Moreover, these accidents can cause material deformation, high temperature failure and material phase transformations.[3]

During the normal operation and shutdown of a CANDU reactor, as well as in many accident events, the coolant is circulated by the primary heat transport system (PHTS) pumps, which keeps the reactor fuel cool via forced convection. However, certain events could occur where the pumps rundown, such as in the loss of class IV power. Under this scenario the pump speed decreases over a period of approximately 120 seconds leading the cooling conditions to deteriorate. In this case thermosyphoning, which is induced by a density gradient between hot and cold coolant, continues to cool the fuel.[4] However, thermosyphoning will break down as coolant inventory is depleted during a SLOCA. Therefore, at some point in time, stratification of the coolant in the fuel channels will occur. It is at this point that the coolant void increases towards the outlet of the fuel channel. The density gradient which drives the flow from reactor inlet header (RIH) to the reactor outlet header (ROH) becomes comparable to the pressure difference between the ROH and the RIH and flow stagnation and/or reversal could occur.[4] Once flow stagnation occurs, heat transfer can degrade quite rapidly.

2.2 SLOCA, LOECI and Extent of Accident Severity

During a SLOCA the PHTS slowly depressurizes and there is a gradual loss of coolant. Usually, once the PHTS pressure of the CANDU reactor decreases below 6 MPa there is an ECI in the header to maintain the coolant inventory and consequently the heat transfer in the core. However, if ECI system fails to operate, the amount of coolant void in the channels will continually increase. If these conditions are prolonged the coolant will eventually stratify and the coolant void will increase in the fuel channels leading to significant fuel heat-up.[3]

The onset of coolant stratification and disruption of liquid coolant supply to the fuel channels is a significant condition for severe core damage accident progression in a CANDU reactor, because it affects the overall timing of subsequent events such as fuel heat-up and potential fuel channel failure.

3. MECHANISTIC MODELLING OF A SLOCA-LOECI EVENT

As stated above, during natural circulation conditions in a CANDU reactor steam generation would first occur in the outlet feeder given that the coolant is closer to saturation than the inlet feeder. However, the inlet feeder would remain completely filled with liquid. Moreover, if the net force driving the coolant through the core became small enough stratification within the channel would occur. Initially, two phase intermittent venting of steam and water will occur from the fuel channel, which is referred to as intermittent buoyancy induced flow (IBIF). Eventually, after prolonged coolant depletion, this would lead to steady steaming, feeder draining, and channel boil-off.[4] In order to evaluate these three different phases in the progression of the SLOCA-LOECI event, a control volume will be taken between the reactor inlet header (RIH) and the reactor outlet header (ROH), as seen in Figure 1 below.

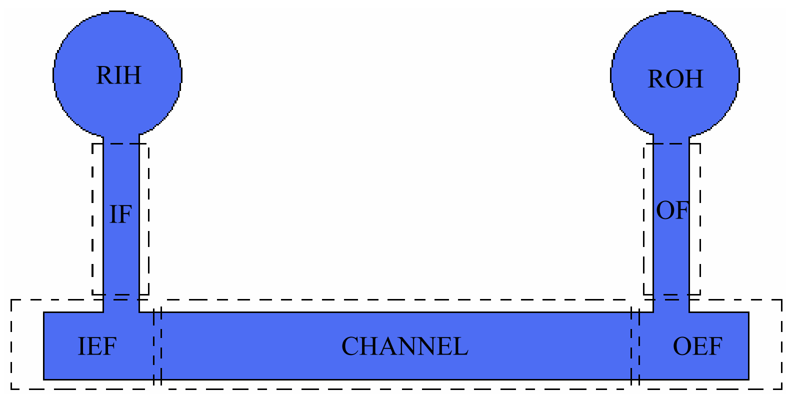

Figure 1: Model control volume

The basic thermalhydraulic equations that can be used to derive the equations for steady steaming, feeder draining and channel boil-off are listed below.[4]

<u>Mass Conservation Equation</u>

$$M(t) = M(0) - \int_0^t W_0(t)dt + \int_0^t W_i(t)dt \Lambda \quad (1)$$

Where the terms from left to right represent,

1. The mass of water in the feeders, end-fittings and channel at time t,
2. The mass of water in the feeders, end-fittings and channel at time 0,
3. The integrated channel exit flow to the reactor outlet header from t(0) to t(t)
4. The integrated channel inflow from the reactor inlet header from t(0) to t(t)

Momentum Conservation Equation

$$\left(P_{RIH} - P_{ROH}\right) = \left(\frac{fL}{D_e}\right)_i \frac{\rho_l u_l^2}{2g} + \sum_{\inf low} K_j \frac{\rho_l u_{jl}^2}{2g} + \rho_l g H_i + \left(\frac{fL}{D_e}\right)_{ch} \frac{\rho_{ch} u_{ch}^2}{2g}$$
$$+ \sum_{ch} K_{ch} \frac{\rho_{ch} u_{jch}^2}{2g} + \left(\frac{fL}{D_e}\right)_o \frac{\rho_s u_s^2}{2g} + \sum_{outflow} K_j \frac{\rho_s u_{js}^2}{2g} + \rho_s g H_o \Lambda \quad (2)$$

Where the terms from left to right represent,

1. The pressure difference between the inlet and outlet headers
2. The friction losses in the inlet feeder
3. The flow resistance terms for the inflowing coolant
4. The hydrostatic head gain due to inflow from the header to the channel
5. The friction losses in the channel
6. The flow resistance terms for the fluid moving through the channel
7. The friction losses for the out flowing coolant
8. The flow resistance terms for the out flowing coolant
9. The hydrostatic head loss due to outflow from channel to header

Energy Conservation Equation

$$\int_0^t Q(t)dt = \int_0^t \left(W_i(t)h_i(t) - W_o(t)h_o(t)\right)dt' + \int_{T_{IF}(0)}^{T_{IF}(t)} \left(MC_P\right)_{IF} dT_{IF} + \int_{T_{IEF}(0)}^{T_{IEF}(t)} \left(MC_P\right)_{IEF} dT_{IEF}$$
$$+ \int_{T_{Fuel}(0)}^{T_{Fuel}(t)} \left(MC_P\right)_{Fuel} dT_{Fuel} + \int_{T_{PT}(0)}^{T_{PT}(t)} \left(MC_P\right)_{PT} dT_{PT} + \int_{T_{OEF}(0)}^{T_{OEF}(t)} \left(MC_P\right)_{OEF} dT_{OEF} + \int_{T_{OF}(0)}^{T_{OF}(t)} \left(MC_P\right)_{OF} dT_{OF}$$
$$+ HL_{IF} + HL_{IEF} + HL_{cal} + HL_{OEF} + HL_{OF} \Lambda \quad (3)$$

Where the terms from left to right represent,

1. The net heat energy stored in the system
2. The thermal power of the fuel
3. The heat energy stored in the inlet feeder
4. The heat energy stored in the inlet end-fitting
5. The heat energy stored in the fuel
6. The heat energy stored in the pressure tube
7. The heat energy stored in the outlet end-fitting
8. The heat energy stored in the outlet feeder
9. The heat energy loss of the inlet feeder
10. The heat energy loss from inlet end-fitting
11. The heat energy loss from the core to the moderator
12. The heat energy loss from outlet end-fitting
13. The heat energy loss of the outlet feeder

3.1 Phase 1: Steady Steaming

As mentioned above, the first phase of degraded flow that occurs during a SLOCA-LOECI event is called steady steaming. Steady steaming is the state at which the inlet feeder is completely filled with liquid while the outlet feeder contains voided coolant. During steady steaming the steam mass flow rate out of the channel is equal to the liquid flowing into the channel from the inlet feeder.[4] This phase is depicted below in Figure 2.

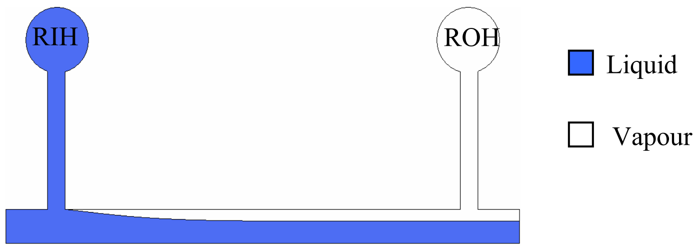

Figure 2: Steady steaming [4]

3.2 Phase 2: Feeder Draining

The second phase is feeder draining and end-fitting draining. Feeder draining is where there is increased voiding in the inlet header due to a continuous loss of coolant through the break, which eventually leads no further inflow of liquid into the inlet feeder.[4] As a result, the remaining liquid in the inlet feeder drains into the channel, which can be seen in Figure 3 below.

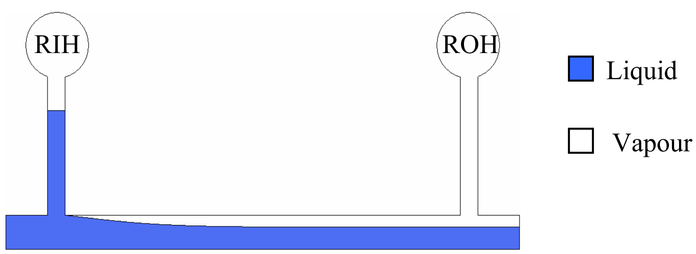

Figure 3: Feeder draining [4]

As inlet feeder is draining the height of the liquid column in the feeder decreases at a rate controlled by the liquid inlet into the fuel channel.[4] As the liquid height falls in the feeder, the driving force due to the difference in density and the exit steam flow rate decreases. In turn, given that there is less steam flowing from the channel, the average void fraction in the channel increases.

Once the feeder has completely drained, the void propagates into the inlet end-fitting.[4] In the SLLOH model it is assumed that the channel average void fraction remains constant until the end-fitting has drained to the level of the channel.

3.3 Phase 3: Channel Boil-Off

The third and final phase is the channel boil-off. This occurs when the inlet feeder no longer contains any liquid coolant, and the inlet end-fitting has the same void fraction as the channel.[4] Any remaining liquid in the channel and end-fitting then boils as seen in Figure 3 below.

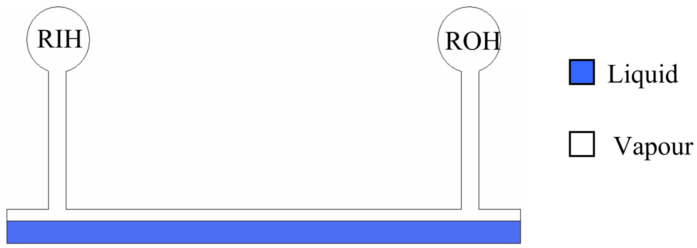

Figure 4: Channel boil-off [4]

4. FUTURE WORK

4.1 Development of Base Model

The first step in developing a computer code to accurately depict a SLOCA-LOECI event under natural circulation conditions is to establish a base model. This base model will enhance the SLLOH methodology. Some of the background theory for this base model has been detailed in section 3 above.

Once the base model has been created using the simplifying assumptions of the SLLOH methodology it will be tested to determine the sensitivity of the program with respect these assumptions. In addition, a parametric analysis will be done on the system variables in order to verify the performance of the model.

4.2 Extension of Base Model to Multiple-Parallel Fuel Channels

The second step of the computer code development will be to extend the single fuel channel model to a multiple-parallel fuel channel arrangement (i.e. an entire CANDU core). This will be done in order to determine where stratification and flow stagnation/reversal will occur. As mentioned above, the flow through the fuel channel is governed by the pressure difference between the headers as well as the density head difference between the inlet and outlet feeders. Assuming that the pressure difference between the inlet and outlet header is the same for every channel, flow stagnation could first occur in the upper most channels where the hydraulic head driving force is the smallest. This is caused by the different heights of the fuel channels which illustrated in Figure 5 below.

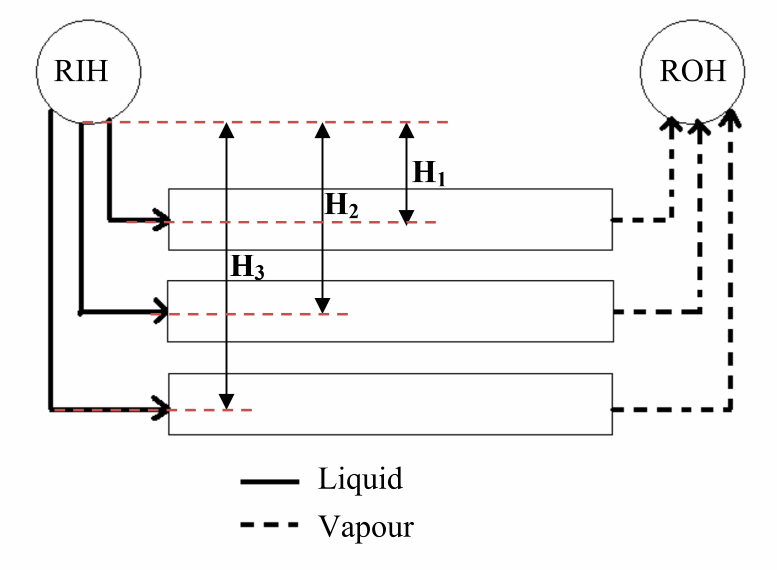

Figure 5: Multiple-parallel fuel channels model

4.4 Validation of Model

Two common ways to validate a computer code for pressurized heavy water reactors are to compare the results generated from the code to experimental results as well as to the results of other validated codes.[6]

4.4.1 Comparison with Experimental Data

Several tests have been performed at ACEL research facilities to provide insight into the progression of SLOCA-LOECI events. The RD-14M facility is a multiple channel figure-of-eight loop test facility. Several reports on the findings from the RD-14M two-phase thermosyphoning experiments have been published.[7, 8, 9] A simple onset of flow reversal criterion has been presented in these reports. Explicitly, flow reversal is said to occur when:

$$\Delta P_{HH} < \Delta P_{REV} \Lambda \ (4)$$

Where;

$$\Delta P_{REV} = -\int \left(\rho_{IF}(z,t) - \rho_{OF}(z,t)\right) g\, dz \Lambda \ (5)$$

The results from this flow reversal criterion are in good agreement between the experimental data.[7] However, it has been shown in the RD-14M tests that the header-to-header pressure differentials can become oscillatory and hence this quasi-steady flow reversal criterion becomes inadequate. A dynamic flow reversal criterion is required to capture the transient and feedback processes occurring inside the feeders and channels.[8] Moreover, Wan et al. have reported large heat losses occurred in the RD-14M thermosyphoning tests and thus any interpretation or extrapolation of the test results must account for these heat losses.[7] Hence, after accounting for the heat losses the results of these experiments can be compared with the results of the computer code in order to determine if the model is valid.

4.4.2 Comparison with Validated Computer Codes

Another type of validation would be to compare the results of the computer code with other already validated computer codes. In fact other codes, such as TUF and CATHENA, have already been used to model the thermosyphoning tests conducted at RD-14 and RD-14M respectively.[7, 10] Moreover, MAAP4-CANDU and CANTHENA have modeled a LOCA-LOECI event under thermosyphoning conditions for CANDU reactors.[1, 11] Thus, the trends and parameter magnitudes in the aforementioned codes can be used in-part to validate results of a new computer code.

5. CONCLUSION

In summation, it is the goal of this current body of work to provide the foundation for developing a computer program that can model the effect of a SLOCA-LOECI event under natural circulation conditions in CANDU reactor. Using the information in this report a base model will be established, extended and validated. This will provide an independent capability to analyze heat transfer degradation sequences in multiple parallel channels, as well as aid level 2 PSA analyses by establishing figures of merit and a time line for the severe accident progression.

6. REFERENCES

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