

## Application of Subcooled Boiling Model to Thermal-hydraulic Analysis inside a CANDU-6 Fuel Channel

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### 1. Introduction

Forced convection nucleate boiling is encountered in heat exchangers during normal and non-nominal modes of operation in pressurized water or boiling water reactors (PWRs or BWRs). If the wall temperature of the piping is higher than the saturation temperature of the nearby liquid, nucleate boiling occurs. In this regime, bubbles are formed at the wall. Their growth is promoted by the wall superheat (the difference between the wall and saturation temperatures), and they depart from the wall as a result of gravitational and liquid inertia forces. If the bulk liquid is subcooled, condensation at the bubble-liquid interface takes place and the bubble may collapse. This convection nucleate boiling is called as a subcooled nucleate boiling.

As for the fuel channel of a CANDU 6 reactor, forced convection nucleate boiling models for flows along fuel elements enclosed inside typical CANDU-6 fuel channel has encountered difficulties due to the modeling of local effects along the horizontal channel. Therefore, the subcooled nucleate boiling has been modeled through temperature driven boiling heat and mass transfer, using a model developed at Rensselaer Polytechnic Institute [1]. Therefore, the objectives of this study are: (i) to investigate a proposed sub-cooled boiling model developed at Rensselaer Polytechnic Institute and (ii) to apply against a experiment and (iii) to predict local distributions of flow fields for the actual fuel channel geometries of CANDU-6 reactors. The numerical implementation is conducted using by the FLUENT 6.2 CFD computer code. The RPI model has been implemented in FLUENT 6.2 via user-defined functions (UDFs) in conjunction with the Eulerian multiphase model.

### 2. Subcooled Boiling Model Description

Convective subcooled boiling occurs when heated walls are superheated while bulk liquid is subcooled under given operating pressure. The bubble interface mass transfer depends on several system variables, such as the liquid and saturation temperatures, interfacial heat transfer coefficient, bubble diameter, and vapor void fraction. Boiling at the wall depends on the evaporation heat flux and the wall heat transfer coefficient, which combines single phase heat transfer with the quenching effect of

liquid filling the void near the wall after the bubble departs. Mechanistic prediction of this phenomenon is developed at Rensselaer Polytechnic Institute (Podowski, 1997) [2]. According to RPI model, the total heat flux from wall to liquid is partitioned into three components:

$$q_w'' = q_l'' + q_Q'' + q_E''$$

which are liquid convective heat flux, quenching heat flux and evaporative heat flux. Under subcooled boiling conditions, the wall surface is subdivided into portion  $\Omega$  ( $0 \leq \Omega \leq 1$ ) covered by nucleating bubbles and portion  $1 - \Omega$  covered by fluid. Therefore, convective heat flux is expressed as

$$q_l'' = h_{lw} \cdot (T_w - T_l^{cell}) \cdot (1 - \Omega)$$

where  $h_{lw}$  single phase heat transfer coefficient is derived from either log law if flow is logarithmic or Fourier law if flow is laminar. Liquid phase properties must be used while calculating  $h_{lw}$  for either turbulent or laminar flow.

Quenching heat flux  $q_Q''$  models additional energy transfer related to liquid filling the wall vicinity after the bubble detachment:

$$q_Q'' = 2\pi^{-0.5} \Omega (f \kappa_l \rho_l C_{pl})^{0.5} (T_w - T_l^{cell})$$

Evaporative heat flux is given by

$$q_E'' = \frac{\pi}{6} d_{vw}^3 f n \rho_v L$$

Here, correct prediction of bubble departure diameter  $d_{vw}$  is very important because evaporation heat rate depends strongly on this parameter. It can be calculated from the following relation (Unal, 1976, Wei and Morel, 2002):

$$d_{vw} = 2.42 \cdot 10^{-5} \cdot p^{0.709} \cdot a \cdot (b\theta)^{-0.5}$$

where all variables are in SI units.

### 2. An Evaluation of a Frigg Assembly

Experiments for upflow of liquid Refrigerant-113 (R-113) through a vertical concentric annular channel were conducted at Arizona State University (1999). The test

section consists of 15.8 mm ID, 38.1 mm OD, 3.66 m long, pressurized (269 kPa) annulus, oriented vertically and inner wall was heated. To model the experiment, a two dimensional axisymmetric computational domain was used, consisting of 3,900 quadrilateral cells with 15 cells in the radial. The experimental condition is shown in Table 1.

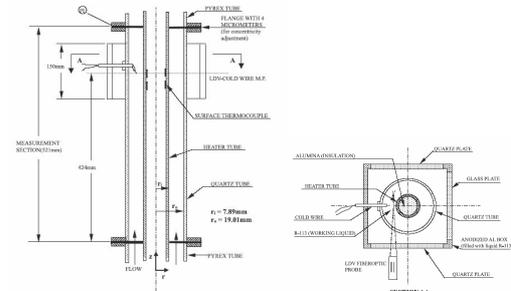


Fig. 1. Subcooled refrigerant annular flow experiment

Table 1 Parameters of experiments used in validation.

| Parameter  | EXP 1  | EXP 2  | EXP 3   |
|--|--------|--------|---------|
| Inner wall heat flux, W/m <sup>2</sup>           | 80,000 | 95,000 | 116,000 |
| Fluid mass velocity, kg/m <sup>2</sup> /sec      | 565    | 785    | 785     |
| Mean liquid subcooling at test section inlet, °C | 37.8   | 30.3   | 30.3    |

Measurements from these experiments were compared to FLUENT 6.2 predictions based on the same operating conditions.

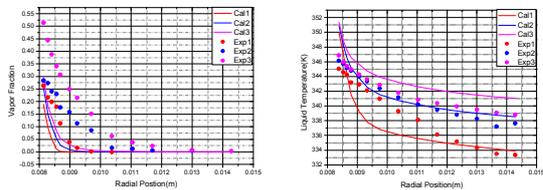


Fig. 3 outlet vapor fraction Fig. 4 outlet liquid temperature

### 3. An Evaluation of Fuel Channel of CANDU-6

To investigate the convective sub-cooled boiling occurs inside the fuel channel under operating pressure, local distributions of flow fields and concentrations for both phases can be predicted for the actual fuel channel geometries of CANDU-6 reactors. The operating conditions are shown in Table 2.

Table 2 Operating parameters in validation.

|                                   |                    |
|-----------------------------------|--------------------|
| Channel length                    | 5.94 m             |
| Diameter                          | 0.10312 m          |
| Diameter of rod                   | 0.0131 m           |
| Mass flowrate                     | 28.281 kg/sec      |
| Inlet temperature                 | 541.163 K          |
| Saturation temperature            | 586 K              |
| Heat generation from fuel surface | function of region |

The comparison between RELAP/CANDU, 1-D thermal-hydraulic code and Fluent CFD predictions at the center and outer fuel elements are as follows:

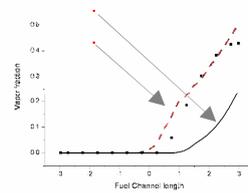


Fig. 5 Void fraction

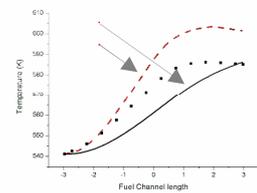


Fig. 6 Temperature distribution

As to the transient case of LBLOCA+LOECC, the comparison of void fraction and temperature distribution at the center and outer fuel elements are as follows:

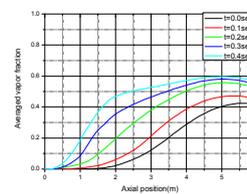


Fig. 7 Void fraction

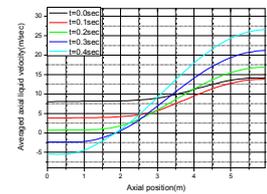


Fig. 8 Velocity distribution

### 4. Conclusion

To investigate the convective sub-cooled boiling occurs inside the fuel channel of the CANDU-6 reactor, the RPI subcooled boiling model has been implemented in FLUENT 6.2 using the Eulerian multiphase framework. The model was able to adequately predict the behavior of subcooled convective boiling in a vertical annulus. The results are encouraging for CANDU-6 fuel channels that involve the complex physics of phase change in a multi-fluid environment.

### REFERENCES

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