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ANALYSIS OF THE ONSET OF FLOW INSTABILITY IN RECTANGULAR HEATED CHANNEL USING DRIFT FLUX MODEL

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ABSTRACT

Two-phase flow excursion (Ledinegg) instability in boiling channels is of great concern in the design and operation of numerous practical systems especially in Research Reactors. Such instability can lead to significant reduction in channel flow, thereby causing premature burnout of the heated channel before the CHF point.

The present work focuses on a simulation of pressure drop in forced convection boiling in vertical narrow and parallel uniformly heated channels. The objective is to determine the point of Onset of Flow Instability (OFI) by varying input flow rate. The axial void distribution is also provided. The numerical model is based on the finite difference method which transforms the partial differential conservation equation of mass, momentum and energy, in algebraic equations. Closure relationships based upon the drift flux model and other constitutive equations are considered to determine the channel pressure drop under steady state boiling conditions. The model validation is performed by confronting the calculations with the Oak Ridge National Laboratory thermal Hydraulic Test Loop (THTL) experimental data set. Further verification of this model is performed by code- to code verification using the results of RELAP5/Mod 3.2 code.

1 INTRODUCTION

Recently, considerable interest has been expressed concerning the phenomena of the flow instability in two-phase systems, which has been observed to occur in design and operation of many industrial systems and equipment, like turbo-machinery, boiling water reactors, two-phase flow heat exchangers, microelectronics, steam generators, refrigeration systems and thermosiphon, etc.

The most common flow instabilities encountered in heated channels with forced convection are the flow excursion and density wave oscillations types [1].

The flow excursion or Ledinegg instability which belongs to the static instability is an undesirable phenomenon for several thermal-hydraulic (T/H) systems; it is a direct result of the interaction between the hydraulic characteristics of the boiling channel and the head-flow characteristics of the pump [2]. The OFI is defined as the occurrence of a minimum in the pressure drop versus flow rate curve (demand curve) for a uniformly heated channel with fixed inlet subcooling and exit pressure [1].

In the following, a steady state model is proposed for flow boiling in vertical uniformly channel at low pressure subcooled boiling conditions; the objective is to determine the point of Onset of Flow Instability (OFI).

The model is based on the drift flux model and is validated by comparison to the Best Estimate RELAP5/mod 3.2 code system [3] and to the Oak Ridge Thermal hydraulic Test Loop experimental data [4].

2 PHYSICAL MODEL

2.1 Conservation equations

a. Single phase region

The liquid is compressible and one dimensional with the variable thermodynamics and transport proprieties; the steady state conservation laws in one dimension along the flow direction are:

Continuity :

$$\frac{d(\rho_f V_f)}{dz} = 0 \Rightarrow \rho_f V_f = G = \text{Cst} \tag{1}$$

Momentum :

$$\frac{dP}{dz} = -\frac{f_f G^2}{2D_h \rho_f} - G^2 \frac{d}{dz}\left(\frac{1}{\rho_f}\right) - \rho_f g \tag{2}$$

Energy :

$$\frac{di_f}{dz} = \frac{q'' p_h}{A_c G} \tag{3}$$

In Eq 3, the kinetic energy and the potential energy terms are neglected.

b. Two-phase mixture region

In the present investigation, the drift flux model is used to solve the problem; in this model, the conservation laws are written separately for each phase and then combined for the mixture. The time-smoothed, one- dimensional conservation equations as derived by Ishii and Zuber (1970) [5] are:

Conservation of mass of the mixture

$$\frac{d(\rho_m V_m)}{dz} = 0 \quad \Rightarrow \rho_m V_m = G = Cst \tag{4}$$

Conservation of momentum of the mixture (neglecting the effect of surface tension)

$$\frac{dP_m}{dz} = -\frac{\rho_m f_m V_m^2}{2D} - \frac{d}{dz}\left[\alpha \rho_g V_g^2 + (1-\alpha)\rho_f V_f^2\right] - \rho_m g \tag{5}$$

In order to close the problem, the total momentum equation must then be supplemented with constitutive relationships giving the so-called drift velocity as proposed by Zuber and Findlay, 1965 [5]

$$V_{gj} = 1.41\left[\frac{\sigma g(\rho_l - \rho_g)}{\rho_l^{\,2}}\right]^{1/4} \quad (6)$$

$$V_g = \frac{G}{\rho_m} - \frac{\rho_l}{\rho_m}\left[V_{gj} + (C_0 - 1)j\right] \quad (8)$$

$$C_0 = 1.18 \quad (9)$$

With: $V'_{gj} = V_{gj} + (C_0 - 1)j$

The momentum equation becomes:

$$\frac{dP_m}{dz} = -G^2 \frac{d}{dz}\left(\frac{1}{\rho_m}\right) - \frac{d}{dz}\left[V'^2_{gj}\left(\frac{\rho_f \rho_g}{\rho_m}\frac{\rho_f - \rho_m}{\rho_m - \rho_g}\right)\right] - \frac{f_m G^2}{2D_h \rho_m} - \rho_m g \quad (10)$$

The Conservation of energy of the mixture (neglecting the effect of the kinetic and potential energy):

$$\frac{di_m}{dz} = \frac{q'' p_h}{A_c G} - \frac{1}{G}\frac{d}{dz}\left[V'_{gj}\left(\frac{\rho_f \rho_g}{\rho_m}\right)\frac{\rho_f - \rho_m}{\rho_f - \rho_g} i_{gf}\right] \quad (11)$$

The mixture density ρ_m, the mixture pressure P_m, the mixture velocity V_m and the mixture enthalpy i_m are defined as:

$$\rho_m = \alpha\rho_g + (1-\alpha)\rho_f$$

$$P_m = \alpha P_g + (1-\alpha)P_f$$

$$V_m = \frac{\alpha\rho_g V_g}{\rho_m} + \frac{(1-\alpha)\rho_f V_f}{\rho_m}$$

$$i_m = \frac{\alpha\rho_g i_g}{\rho_m} + \frac{(1-\alpha)\rho_f i_f}{\rho_m}$$

The following simplification assumptions are introduced:

- There is no pressure difference between the phases: $P_m = P_g = P_f = P$
- The enthalpy of the vapor phase is constant and is equal to the corresponding saturation value.

2.2 Heat transfer and constitutive correlations

To understand the phenomenon of heat removal during up-flow in a heated channel, the different regimes that could appear in the channel should be identified and considered separately with adequate transition from one to another [5]. However, in the present, only flow patterns before CHF will be investigated. For illustration, idealized flow patterns encountered in a vertical upward flow in a heated channel are schematically shown in figure1.

The first step is to identify the different heat transfer mechanism involved. This consist in the identification of the location where onset of nucleate boiling (ONB) is initiated; up to this position, single phase heat transfer prevails and the related position is noted Z_{onb}. Upstream Z_{onb}, some bubbles are formed but they remain attached to the wall or condense when they detach until a certain position where the bubbles that detach do not condense and mix with the subcooled liquid; this position is noted Z_d. Upstream Z_d, the two-phase flow regime prevails until the liquid reaches the saturation. Constitutive correlations are used to define the T/H conditions relevant to these two positions.

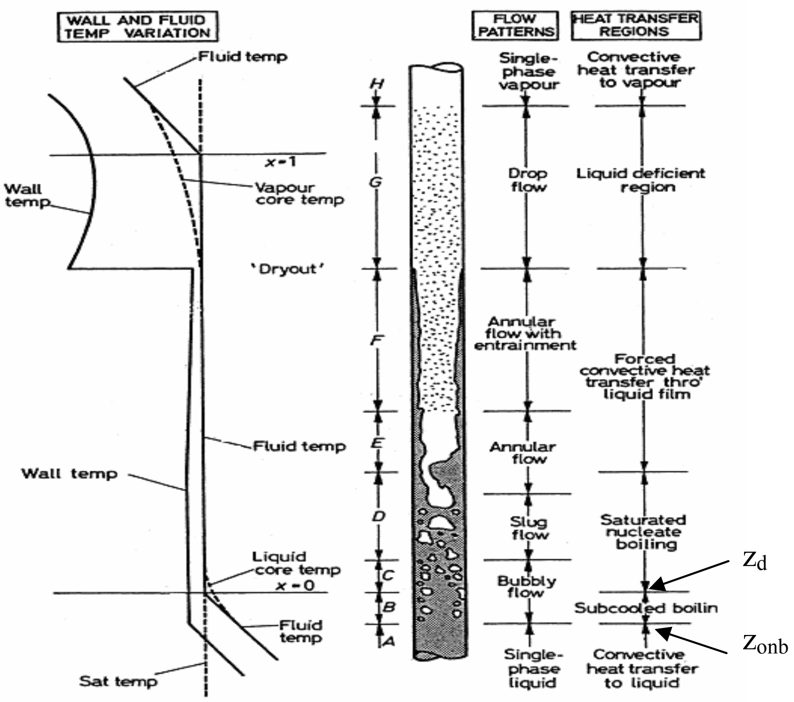

Figure 1: Patterns encountered in a vertical upward flow in a heated channel [5]

2.2.1 Single phase region

The heat transfer coefficient h_{sp} is calculated for turbulent forced flow by Dittus-Boelter correlation [5]

$$Nu = \frac{h_{sp} D_h}{K_L} = 0.023 \left(\mathrm{Re}_l\right)^{0.8} \left(\mathrm{Pr}_l\right)^{0.4} \tag{12}$$

2.2.2 The Onset of Nucleate Boiling

Subcooled nucleate boiling (corresponding to Z_{onb}) is initiated when wall temperature exceeds local coolant saturation temperature by ΔT_{onb} given by Bergles-Rohsenow correlation [5]

$$\Delta T_{onb} = \left(\frac{5}{9}\right) \left[\frac{q''}{1082 p^{1.158}}\right]^{\frac{p^{0.0234}}{2.16}} \tag{13}$$

2.2.3 Partial Subcooled nucleate boiling region: $T_l(z) \le T_l(z_d)$

In this region, which is upstream of OSV and downstream of ONB, the heat transfers are done at the same time by nucleate boiling (h_{NCB}) and by forced convection in liquid phase (h_{CF}). The surface heat flow exchanged is given by the modified Chen correlation [5]

$$q'' = h_{NCB}(T_w - T_{sat}) + h_{CF}(T_w - T_f) \tag{14}$$

- The wall surface temperature is given by the modified Chen correlation [5]

$$T_w(z) = \frac{q'' + h_{NB}T_{sat}(z) + h_{CF}T_l(z)}{h_{NCB} + h_{CF}} \tag{15}$$

$$h_{CF} = 0.023\left[\frac{G(1-X)D_h}{\mu_l}\right]^{0.8}\left[\frac{\mu_l Cp_l}{k_l}\right]^{0.4}\left(\frac{k_l}{D_h}\right)F \qquad \text{and} \qquad F = 1 \tag{16}$$

For h_{NCB}, Chen used the equation of Zuber and Forster correlation:

$$h_{NCB} = 0.00122\left[\frac{k_l^{0.79}Cp_l^{0.45}\rho_l^{0.49}}{\sigma^{0.5}\mu_l^{0.29}H_{gl}^{0.24}\rho_v^{0.24}}\right]\Delta T_{sat}^{0.24}\Delta P_{sat}^{0.75}S \tag{17}$$

2.2.4 The Onset of Significant Vapor (OSV)

The detachment temperature corresponding to axial position z_d is identified when:

$$T_{sat} - T_l(z) \le \Delta T_d \tag{18}$$

Where, according to Saha and Zuber criteria:

$$\Delta T_d = 0.0022\left[\frac{q'' D_h}{k_f}\right] \quad \text{if} \quad P_e < 70000 \tag{19}$$

$$\Delta T_d = 153.8\left[\frac{q D_h}{G C_P}\right] \quad \text{if} \quad P_e \ge 70000 \tag{20}$$

2.2.5 Partial Subcooled nucleate boiling region: $T_l(z) \le T_{sat}(z\ \ )$

- Evolution of the temperature of the wall

The wall surface temperature is given by the modified Chen correlation

$$T_w(z) = \frac{q'' + h_{NB}T_{sat}(z) + h_{CF}T_l(z)}{h_{NCB} + h_{CF}} \tag{21}$$

2.3 Friction factors

The Fanning friction factor f, is given under the following conditions:

$$f = 24\,\text{Re}_f^{-1} \qquad \text{for } \text{Re}_f < 2300 \tag{22}$$

$$f = 5.4E-3 + 2.3E-8(\text{Re}_f)^{3/4} \qquad \text{for } 2300 \le \text{Re}_f < 4000 \tag{23}$$

$$f = 1.2810^{-3} + 0.1143\,\text{Re}_f^{-0.3} \qquad \text{for } 4000 \le \text{Re}_f \tag{24}$$

The friction factor is equal to: $f_f = 4 * f$

In the region, which is upstream of OSV and downstream of ONB, f_f is corrected by the two phase multiplier factor given by the Owens and Schrock formula [5] as :

$$f_f = 4f\left[0.97 + 0.28\exp(6.13\psi)\right] \qquad (25)$$

$$\psi = 1 - \frac{\left(T_{sat} - T_f(z)\right)}{\left(T_{sat} - T_f(z_{onb})\right)} \qquad (26)$$

Upstream Zd, the friction factor is given by Blasius correlations [5]:

$$f_m = 0.316(\mathrm{Re}_{tp})^{-0.25} \quad \text{for} \quad \mathrm{Re}_{tp} < 10^5 \qquad (27)$$

$$f_m = 0.079(\mathrm{Re}_{tp})^{-0.25} \quad \text{for} \quad \mathrm{Re}_{tp} \geq 10^5 \qquad (28)$$

2.4 Numerical resolution

The conservations equations together with the equation of state and the constitutive relations are solved under the following conditions:

- Constant inlet temperature $T_{f,inlet}$.
- Constant and uniform heat flux q''.
- Constant exit pressure $P_{\exp}$.
- No pressure difference between the phases.

The enthalpy of the vapor phase is a constant and is equal to the corresponding saturation value. The governing equations are discretized in the flow direction using the finite difference method and are solved iteratively for a given inlet mass flow G and arbitrary inlet Pressure P_{in}. The outlet pressure is then calculated and compared to the tabulated (or known and fixed) value $P_{\exp}$. The results are accepted when the difference is lower than a specified acceptable error. The physical properties of the liquid are calculated at each node depending on the local conditions (P, T) by using NBS/NRC Steam Tables [6].

3 VALIDATION

3.1 Experimental apparatus

The Oak-Ridge National Laboratory (ORNL) –Thermal Hydraulic Test Loop (THTL) [4] is an experimental facility aimed to support the development of the ORNL Advanced Neutron Source Reactor (ANSR). The primary objective of this facility was to investigate thermal limits of the ANSR nominal conditions for normal operations and safety margins analysis. The THTL was built and designed to provide a simulated full-length coolant subchannel of the ANSR, allowing experimental determination of the thermal limits (FE and CHF) under anticipated ANSR T/H conditions. A schematic diagram of the cross section of the test section is given in Figure 2.

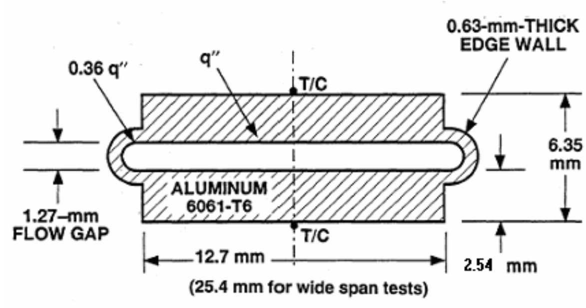

Figure 2: cross section of the test section and the cooling channel [4]

The experiments were conducted under these T/H conditions:
- Coolant is light water in upward flow.
- Inlet coolant temperature: 45°C.
- Exit coolant pressure: 1.7 MPa.
- Local (exit) heat flux range: 0.7 -18 MW/m2.
- Corresponding exit velocity range: 2.8 – 28.4 m/s.
- Channel configuration: rectangular 1.27 x 12.7 x 507mm.

3.2 Simulation procedure

The Flow excursion tests (without burnout) are initiated by controlling the test section flow to level where no boiling exists at the target heat flux level before the power is applied to the test section. Exit pressure is controlled and set to 1.7MPa whereas the inlet temperature was fixed through a heat exchanger to 45°C and the system is let to stabilize. After a while, the inlet velocity is reduced to a lower level and the system is allowed to stabilize at the new fixed velocity and the corresponding channel pressure drop and other important parameters were recorded. The same process is followed until the upturn of the pressure drop curve is observed. Following this process, pressure drop curves have been reported for different heat fluxes.

In order to reflect this experimental procedure by the model, the flow rate is decreased gradually step by step beginning from higher flow rate until the minimum of pressure drop is obtained allowing the system to stabilize between two successive steps.

3.3 RELAP5/Mod 3.2 Nodalization

RELAP5/Mod 3.2 has been used to recalculate four experimental operating conditions in the THTL [3]. The objective was to determine the T/H conditions that induce an Onset of Flow Instability (OFI). This is done by representing the curve Pressure Drop (ΔP) vs. Mass flux (G) and to identify the minimum of this curve. This point is identified as the OFI point.

4 RESULTS AND DISCUSSION

In a first step, the cold case with no power applied to the test section is reproduced by the model as shown on figure 3. The pressure drop obtained by our model shows good agreement with experimental data. The mean deviation is about 7%. The good agreement obtained for cold case allows us to consider that the correlation used as suitable for the test section configuration.

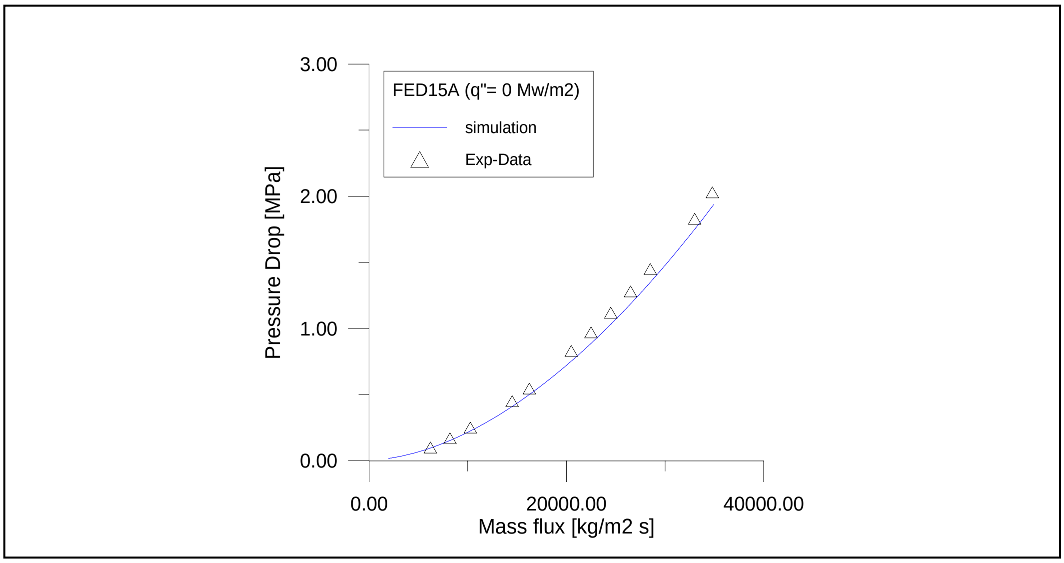

Figure 3 : Reproduction of the cold case

In a second step, four hot cases are reproduced with this model and the pressure drop curves obtained are shown on figures 4 through 7. On this figures, one can notice a good representation of the pressure drop of the considered test cases and the deviations observed are quite acceptable regardless the simplicity of the model. The summary of the main parameters obtained are compared to experimental data on table 1. Also a comparison with RELAP5/mod 3.2 [3, 7] is provided.

The comparison with RELAP5 results has shown that the discrepancies are growing from higher heat flux to lower heat fluxes whereas the inverse is valuable for the developed model.

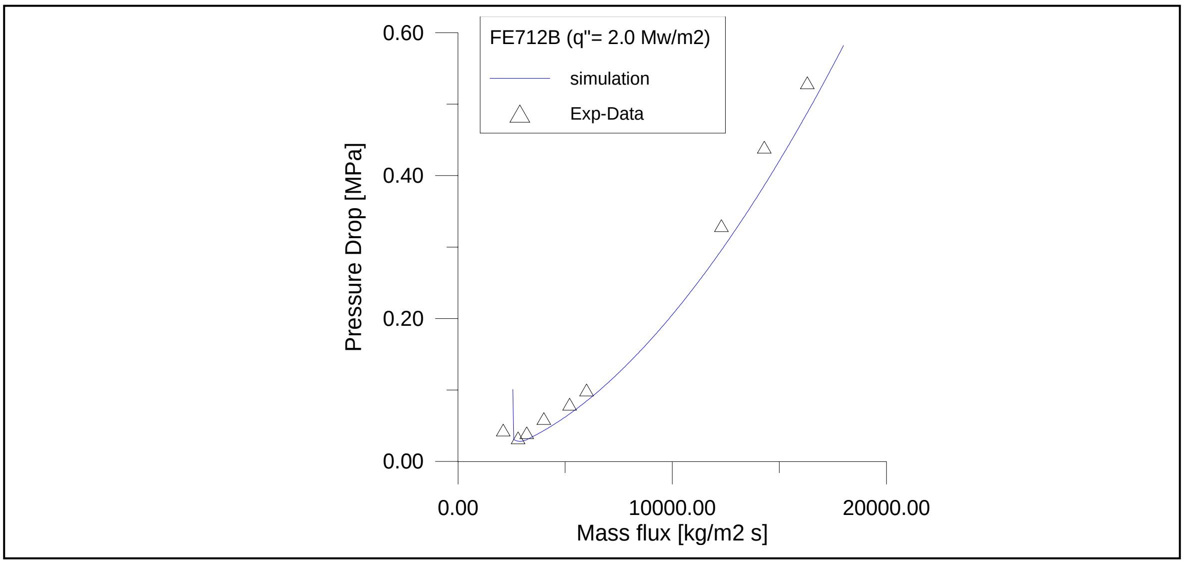

Figure 4: Pressure drop for heat flux of 2.0 MW/m2

Furthermore, the critical flow which may induce flow instability is obtained by the model with an acceptable error (between 2 and 11%). The code RELAP5 estimates this critical mass flow with an error ranging between 9.4 to 18.6% [7].

Considering the low fraction of void obtained by our model, one can assume that the OFI could appear in the highly subcooled region, far from OSV point whereas, in case of the code RELAP5/Mod 3.2, calculated void fractions are almost greater indicating that the OFI could arise after OSV. However, as indicated by the authors [3, 7], the void is overestimated due to some lacks of the RELAP5/mod 3.2 subcooled model at low pressure; this fact also confirmed by several other authors.

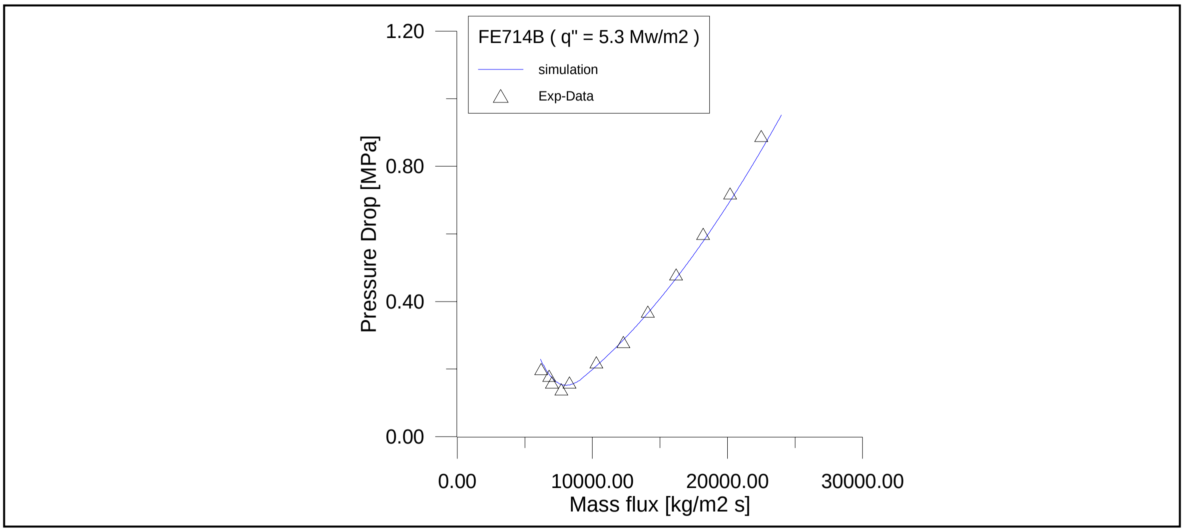

Figure 5: Pressure drop for heat flux of 5.3 MW/m^2

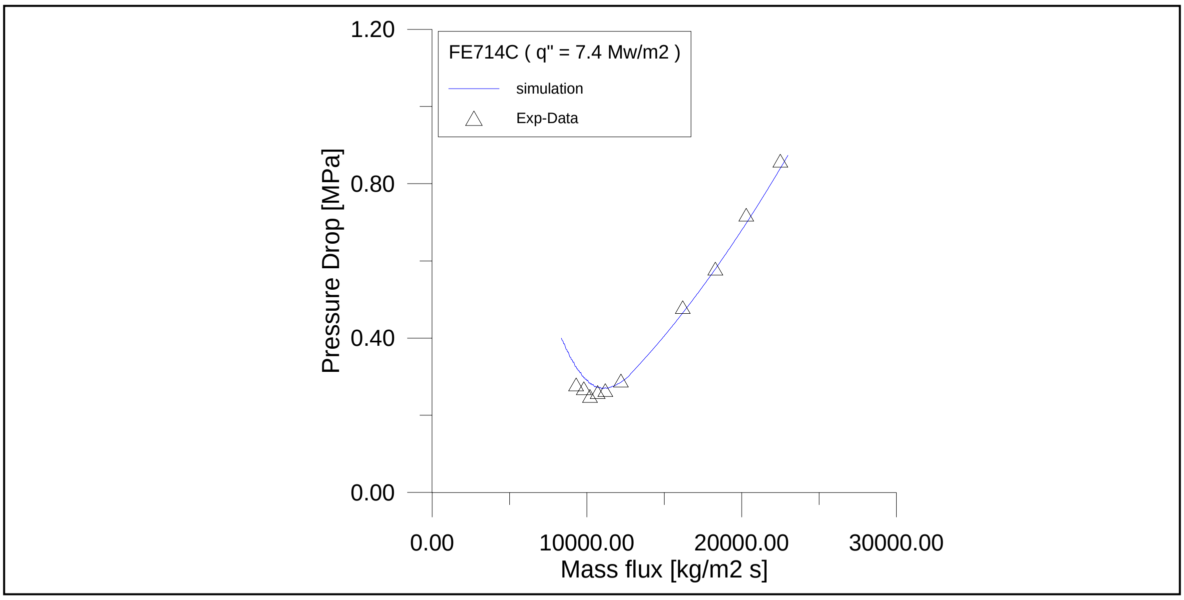

Figure 6: Pressure drop for heat flux of 7.4 MW/m^2

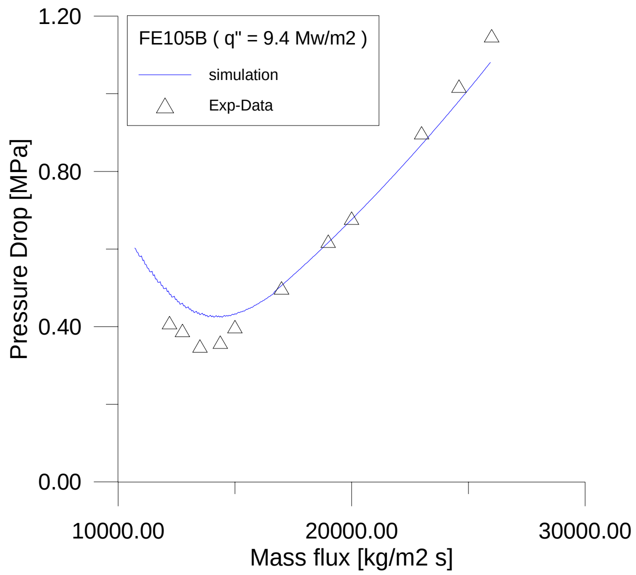

Figure 7: Pressure drop for heat flux of 9.4 MW/m^2

Table 1: Summary of main parameters

Experiment N°	FE712B				FE714B			
Parameter	Model	Relap5	Exp	Err	Model	Relap5	Exp	Err
q" [Mw/m^2]	2.00				5.3			
DP at OFI [MPa]	0.030	0.023	0.033	9.10	0.151	0.105	0.142	6. 33
G at OFI [kg/m^{2}s]	2850	2360	2900	1.72	8100	6180	7500	8.00
$T_{f,exit}$ [^{o}C]	169.77	197.6	183.1	7.28	162.61	197.1	174.32	6. 32
$T_{w,exit}$ [^{o}C]	213.66	226.5	214.39	0. 34	218.6	243.4	225.59	3.09
Void %	4.18	32	-	-	1.88	49.76	-	-

Experiment N°	FE714C				FE715C			
Parameter	Model	Relap5	Exp	Err	Model	Relap5	Exp	Err
q" [Mw/m^2]	7.4				9.4			
DP at OFI [MPa]	0.268	0.187	0.248	8.06	0.432	0.312	0.359	20.33
G at OFI [kg/m^{2}s]	10950	8680	10000	9.50	14900	12230	13500	10.37
$T_{f,exit}$ [^{o}C]	162.78	196.7	182.3	10.70	157.75	187.5	173.6	9.13
$T_{w,exit}$ [^{o}C]	223.57	251.5	228.37	2.10	219.86	251.7	250.0	12.05
Void %	1.60	49.85	-	-	1.18	16.16	-	-

Note:

q" : applied heat flux
G: inlet mass flux
DP: pressure drop
$T_{f,exit}$: Bulk liquid exit temperature
$T_{w,exit}$: wall temperature
Exp : Experimental data
Err: standard deviation of our model data to experimental data

5 CONCLUSION

The model presented in this present study enabled us to predict the Ledinegg onset of flow instability (OFI), with a good agreement with the measurement. It shows that the instability appears before the OSV (Onset of Significant Vapor) since the number of Stanton obtained by simulation in all the experiments, remains lower than 0.0065.

Furthermore, this study confirms once more that the drift flux model is a reasonable and useful model to obtain acceptable results in relatively short time compared to more sophisticated models such as RELAP5 code.

NOMENCLATURE

Pr	Prandtl number, $c_p \mu / K_f$	**Re**	Reynolds number, $G.D_h/\mu$
q"	Heat flux density, [W/m^2]	**T**	Temperature, [°C]
V	fluid velocity, [m/s]	**X**	Thermodynamic quality
α	Void fraction	Γ_g	Mass rate of vapor generation per unit volume,[kg/m^{3}s]
ρ	Density,[kg/ m^3]	σ	Surface tension, [N/m]
μ	Dynamic viscosity of the fluid, [Pa.s]	A_c	Cross-section area, [m]
C_p	Specific heat, [J/kg k]	D_h	hydraulic diameter, [m]
f	Fanning friction factor	f_f	Single phase liquid friction factor
f_m	Two-phase mixture friction factor	**g**	Acceleration due to gravity, [m/s^2]
G	Mass velocity, [kg/m^{2}s]	**h**	Local heat transfer coefficient, [W/m^{2}K]
i_{gf}	Latent heat of evaporation, [J/kg]	i	Enthalpy, [J/kg]
j	Volumetric flux, [m/s]	k_f	Liquid thermal coefficient
P	Pressure, [MPa]	P_h	Heated perimeter, [m]
P_e	Peclet number, $G D_h C_p/ K_f$		

Subscripts

g	Vapour phase	**f**	Liquid phase	**onb**	onset of nucleate boiling
sp	Single phase	**m**	mixture	**osv**	onset of significant void
tp	Two-phase	**w**	wall	**DNB**	departure of nucleate boiling

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