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Assessment of criteria for Onset of Flow Instability in vertical narrow rectangular channels with downward flow

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ABSTRACT

This paper presents an assessment study of criteria for the prediction of the Onset of Flow Instability (OFI) in heated vertical narrow rectangular channels with downward flow. The onset of flow instability is a limiting safety issue in nuclear research reactors, since it may lead to flow starvation and eventually boiling crisis in some of the core channels.

The experimental database consists of OFI tests at low pressure, with gap sizes between 1.37 and 3.23 mm, and with uniform and non-uniform heat flux profiles.

Two typologies of criteria were tested, following a global and local strategy, respectively.

According to the global approach, the Whittle-Forgan and Stelling criteria only use global system parameters to predict OFI. Relatively good results can be obtained over the whole database.

The local approach is based on the prediction of the Net Vapor Generation (NVG) along the channel. The standard Saha-Zuber correlation fails to capture OFI for Peclet numbers lower than 70000. On the other hand, the Saha-Zuber KIT correlation identifies OFI in all the experiments with uniform heat flux. In the case of a non-uniform heat flux along the width of the rectangular channel, the use of thermal-hydraulic parameters averaged over the cross section is not sufficient to predict the local onset of NVG. Nevertheless, this issue can be solved if a local estimate of the flow conditions is employed, so that the effect of the non-uniform heat flux can be accounted for. These results are consistent with the ones found for upward flow in previous studies. No significant effect of the flow direction is therefore observed.

KEYWORDS

NARROW RECTANGULAR CHANNEL, ONSET OF FLOW INSTABILITY, DOWNWARD FLOW, NUCLEAR RESEARCH REACTOR

1. INTRODUCTION

Nuclear research reactors are very important to support the existing fleet of commercial nuclear power plants, develop new technologies for future reactors, and produce radioisotopes for medical and research applications. These reactors operate at relatively low pressures (< 1 MPa) and, in some cases (e.g. the Orphée reactor at CEA-Saclay), with downward flow. Narrow rectangular channels are usually employed for the core cooling due to their high-performance heat removal capabilities within compact volumes, and they are arranged in a parallel configuration. Such an arrangement may be subject to the so-called flow excursion instability (or Ledinegg instability [1, 2]), that can lead to flow starvation and eventually boiling crisis in some of the core channels. This type of instability is therefore a primary concern for the safe operation of research reactors.

The objective of this paper is to assess the predictive capabilities of selected criteria for the Onset of

Flow Instability (OFI) in heated vertical narrow rectangular channels with downward flow. Experimental data from several sources were therefore gathered together and analyzed in a coherent manner. The data cover a wide range of conditions, with uniform and non-uniform heat flux profiles. Additionally, the current investigation aims to contribute to a better understanding of the influence of several parameters on the prediction of the onset of flow instability, in particular the flow direction and the presence of non-uniform heat fluxes.

The paper is organized as follows: in the next section the flow excursion instability is briefly introduced together with some of the most used criteria; in Section 3 the experimental database is described; in Section 4 the results are presented and discussed; in Section 5 conclusions are drawn.

2. FLOW EXCURSION INSTABILITY IN PARALLEL CHANNELS

The instabilities in two-phase flow can be static or dynamic [2]. A static instability occurs when the system, due to a small change/disturbance in operating conditions, reaches a steady state far from the original one, or a periodic behavior. Such instability can be studied using steady-state laws. On the contrary, a dynamic instability is strongly influenced by the flow inertia and other feedbacks, so its analysis needs the modeling of the dynamic behavior of the system.

2.1. Phenomenology

The flow excursion [1] is a static instability that can cause a rapid decrease of the mass flow-rate in a heated channel. The condition for its occurrence arises when the slope of the curve pressure drop – mass flux for the external supply system (e.g., imposed by a pump characteristic) becomes larger than the one for the internal channel demand:

$$\left. \frac{\partial \Delta p}{\partial G} \right|_{Supply} \geq \left. \frac{\partial \Delta p}{\partial G} \right|_{Demand} \quad (1)$$

The OFI mechanism is schematized in Fig. 1. The typical demand curve of a heated channel (also called S- or flow redistribution curve) is represented with the blue line. For the case of parallel channels, the slope of the supply curve is zero (red lines) because the total pressure drop is approximately constant. The operating conditions corresponds to the intersection between the two curves.

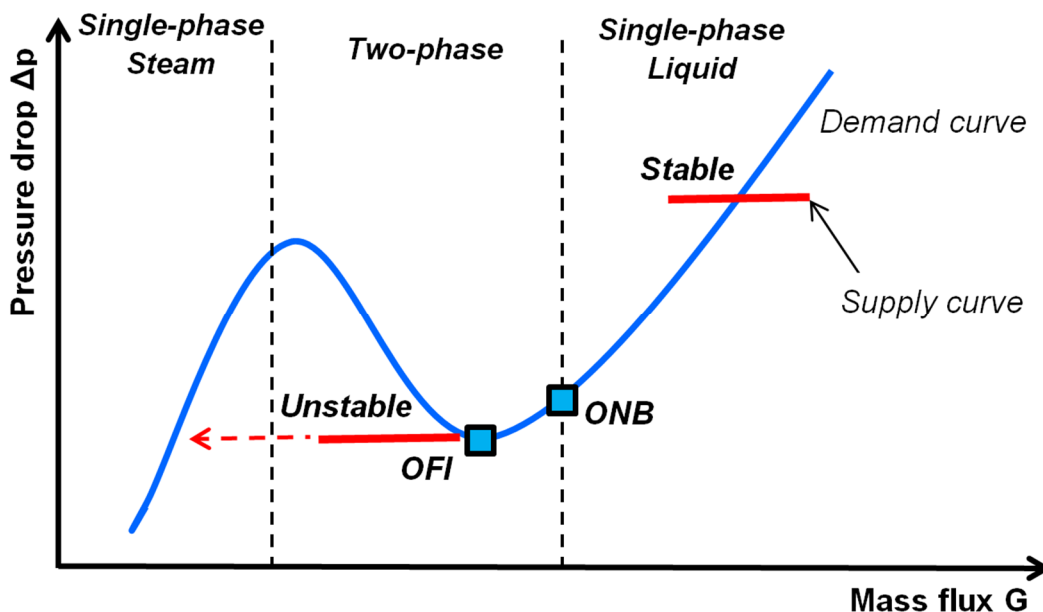


Fig. 1 Onset of Flow Instability for heated parallel channels.

In the single-phase liquid region, the system is stable since the slope of the supply curve is smaller than the one of the S-curve. At a lower mass flux, the Onset of Nucleate Boiling (ONB) can occur. Small bubbles are generated at the heated walls, but the slope of the demand curve remains positive since the void fraction is negligible. Again, the operating point is stable.

Reducing further the mass flux, the bubbles grow bigger and they eventually detach from the walls, so that the void fraction starts to increase significantly. The detachment of the bubbles is usually indicated as the Onset of Significant Void (OSV) or the Net Vapor Generation (NVG). During this phase, the slope of the S-curve decreases due to the impact of the void fraction on the pressure drop, until the minimum of the demand curve is reached (corresponding to a zero slope). Since the slope of the supply curve is also zero, then the onset of flow instability can be identified by determining such a minimum. Thus, the NVG is expected to slightly precede the OFI [3, 4], so that it is often referred as a 'conservative' indicator of the flow redistribution. In fact, although a rapid growth of void fraction begins from the NVG point, a large part of the channel is still in single-phase condition. In addition, the NVG is a local phenomenon determined by the local flow conditions (e.g., pressure and local heat flux); on the other hand, the OFI is a global phenomenon that depends also on the geometry configuration of the channel (e.g., the length to diameter ratio L/D) and the type of supply curve.

For mass fluxes smaller than the one at OFI, the only possible stable operating point is on the pure single-phase steam curve, where the slope of the S-curve is positive. During the flow excursion transient, the growth of the void fraction determines an increase of the channel resistance. The latter causes a further reduction of the mass flow-rate and therefore an enhancement of the void fraction production (positive feedback), until the stable operating point on the pure steam curve is reached. The flow redistribution instability can thus trigger the occurrence of the critical heat flux.

2.2. OFI criteria

The need for an accurate prediction of the flow excursion instability led to the development of several OFI criteria. In this paper, two typologies of criteria were tested, following a global and local strategy, respectively.

2.2.1. Criteria based on a global approach (FIR)

The criteria based on a global approach only require the knowledge of global system parameters to predict OFI. The Whittle-Forgan [3] and Stelling [5] criteria fall into this category.

The Whittle-Forgan relationship is one of the most commonly used OFI predictor. It is based on experiments with sub-cooled water flow and uniform heat flux, at low pressure, in four narrow rectangular channels (gap between 1.4 and 3.23 mm) and in one circular tube (diameter of 6.4 mm). The experimental minima of the flow redistribution curves were correlated using the ratio:

$$R = \frac{T_{L,out} - T_{L,in}}{T_{sat,out} - T_{L,in}} \quad (2)$$

where the increase of liquid temperature between the inlet and outlet of the channel is divided by the temperature rise needed to reach saturation at the exit. Based on the hypothesis that the bubble detachment takes place at OFI and that the specific heat capacity is constant, Eqn. (2) was expressed as a function of the heated-length-to-heated-diameter ratio:

$$R_{WF} = \frac{1}{1 + \eta \frac{D_{heat}}{L_{heat}}} \quad (3)$$

The value of the parameter η was experimentally determined by Whittle-Forgan and set equal to 25. Nevertheless, in the literature, the value of 32.5 is usually suggested and it is claimed to be conservative [6, 7]. The latter value was used as reference in this study. A Flow Instability Ratio (FIR) can then be

defined as [7]:

$$FIR = \frac{R_{WF}}{R} \quad (4)$$

where R is computed by using the actual temperature rise in the channel. If the ratio is smaller than or equal to 1, the OFI conditions are reached.

Stelling et al. [5] developed a similar criterion using experimental data for downward water flow in vertical uniformly heated tubes with diameters between 9.1 and 28 mm. Based on their experimental data, the parameter η in Eqn. (3) was replaced with the quantity $(0.25/St_{SZ} = 38.46)$, where the Stanton number calculated with the Saha-Zuber correlation (see Eqn. (5)) was introduced. This criterion was validated against experiments with $Pe > Pe_0 (= 70000)$.

2.2.2. Criteria based on a local approach (NVGR)

The criteria based on a local approach rely on the prediction of the net vapor generation along the channel, since the NVG is often regarded as a ‘conservative’ OFI indicator (see Section 2.1).

One of the most commonly used NVG correlation is the Saha-Zuber one [8]. It was built on thermal and hydrodynamic theoretical considerations, which led to the choice of the Nusselt and Stanton numbers as representative scaling groups. From experimental data with several geometries (annular, circular and rectangular) and coolants (water and Freon), in the range of pressure between 0.1 and 13.8 MPa, the following relationship was obtained:

$$\begin{cases} \text{if } Pe > Pe_0 & \rightarrow St_{SZ} = \frac{\phi}{G \Delta i_{sub,SZ}} = 65 \cdot 10^{-4} \\ \text{if } Pe < Pe_0 & \rightarrow Nu_{SZ} = \frac{\phi Pe}{G c_{p,l} \Delta T_{sub}} = \frac{\phi c_{p,l} D_{hydr}}{\Delta i_{sub,SZ} k_l} = 455 \end{cases} \quad (5)$$

Such expressions can be re-written in terms of liquid enthalpy, as:

$$\begin{cases} \text{if } Pe > Pe_0 & \rightarrow \Delta i_{sub,SZ} = \frac{\phi}{65 \cdot 10^{-4} G} \\ \text{if } Pe < Pe_0 & \rightarrow \Delta i_{sub,SZ} = \frac{\phi c_{p,l} D_{hydr}}{Nu_{SZ} k_l} = \frac{\phi c_{p,l} D_{hydr}}{455 k_l} \end{cases} \quad (6)$$

Modifications of the Saha-Zuber correlation can be found in the literature. An example is the Saha-Zuber KIT relationship. It was developed and validated at CEA [9] using KIT experiments [10], which were performed in a vertical pipe with a diameter of 11.7 mm, pressures between 4.4 and 11 MPa, heat fluxes between 0.43 and 1.72 MW/m², and mass fluxes between 340 and 2100 kg/m²s. It reads:

$$\begin{cases} \text{if } Pe > 0.52 \cdot Pe_0 & \rightarrow \Delta i_{sub,SZ-KIT} = 2 \frac{\phi c_{p,l} D_{hydr}}{65 \cdot 10^{-4} k_l Pe_0 (Pe/Pe_0)^{1.4}} \\ \text{if } Pe < 0.52 \cdot Pe_0 & \rightarrow \Delta i_{sub,SZ-KIT} = 5 \frac{\phi c_{p,l} D_{hydr}}{455 k_l} \end{cases} \quad (7)$$

A possible OFI criterion can be derived as a ratio between the local liquid sub-cooling and the one necessary to attain NVG conditions:

$$NVGR = \frac{i_{l,sat} - i_l}{\Delta i_{sub,NVG}} \quad (8)$$

The Net Vapor Generation Ratio (NVGR) is computed along the heated test section and the minimum value is retained. A value smaller or equal to 1 indicates that the NVG (and therefore OFI) occurred.

3. EXPERIMENTAL DATABASE

An experimental database of 143 OFI points in vertical narrow rectangular channels with downward flow was collected from the literature. It includes tests with uniform and non-uniform heat flux profiles.

3.1. Test section

The experiments were carried out in electrically heated narrow rectangular channels with gap sizes between 1.37 and 3.23 mm. The geometric features are reported in Table 1, and schematized in Fig. 2.

Table 1. Geometry of the test sections.

	<i>N. tests</i>	<i>Gap [mm]</i>	<i>l_{heat} [mm]</i>	<i>L_{heat} [mm]</i>	<i>D_{hydr} [mm]</i>	<i>L_{heat}/D_{heat}</i>
<i>Experiments with uniform heat flux</i>						
Whittle-Forgan [3]	7	3.23	25.4	609.6	5.72	94.5
Lafay SE1 [11]	30	1.94	37.0	600	3.69	150.5
Lafay SE2 [11]	24	2.49	37.2	600	4.67	117.8
Lafay SE3 [11]	26	2.78	37.3	600	5.18	105.8
Lafay SE4 [11]	27	3.20	37.4	600	5.90	92.3
<i>Experiments with non-uniform heat flux</i>						
Croft SE1 [12]	8	1.37	25.4	1219.2	2.65	369.5
Croft SE2 [12]	12	1.83	25.4	1219.2	3.50	274.0
Croft SE3 [12]	9	2.39	25.4	1219.2	4.51	206.9

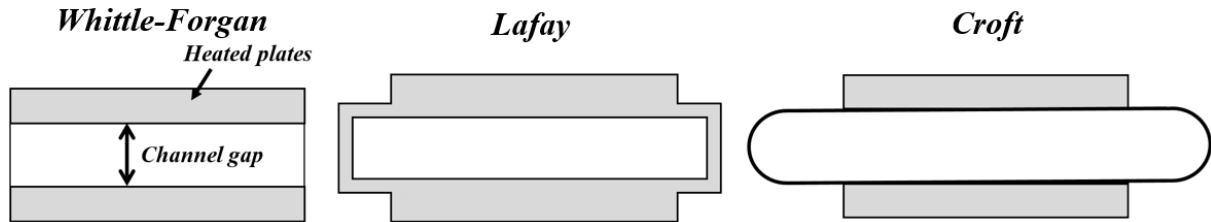


Fig. 2 Schematic representations of the test sections (top view, not in scale).

The arrangement of the lateral corners of the walls varies from test to test. The short sides of the lateral corners are mostly un-heated in the Whittle-Forgan experiments. In the Lafay case, the lateral corners are heated, but thinner to avoid heat concentration effects that may cause early thermal crisis [13]. Their thickness is 1/3 of the one of the central plates and provides a small contribution in terms of power to the liquid, i.e. about 5.6 % to 6.8 % of the power from the central region depending on the test section. For the purpose of modeling, the additional heating from the corners is taken into account by calculating an equivalent heated plate length l_{heat} , which preserves the total power transferred to the liquid and the heat flux in the central part of the plates. The equivalent heated width is estimated as:

$$l_{heat} = l_{plate} \left(1 + \frac{A_{corner}}{A_{plate}} \right) \quad (9)$$

where l_{plate} is the plate width, A_{corner} is the cross-sectional wall area of the corners and A_{plate} is the cross-sectional wall area of the main plates. In the Croft test section, the lateral corners are circular and a large part of them is unheated (the ratio P_{hydr}/P_{heat} varies between 1.25 and 1.31). The impact of the unheated corners on the liquid temperature was experimentally evaluated. The bulk liquid temperature measured at the exit of the channel in the central part of the cross section was found significantly higher than the one averaged over the whole cross section. The discrepancies for all the tests Croft were equal to 12.9 °C on average with a standard deviation of 4.6 °C (they vary between 2.8 and 23.9 °C). These measurements showed that a little lateral mixing exists in the channels.

3.2. Experimental conditions and test procedure

The experiments cover the following range of conditions (Table 2): average heat flux between 0.4 and 8.7 MW/m²; outlet pressure between 0.06 and 1.74 MPa; mass flux between 822 and 17076 kg/m²s; and outlet sub-cooling between 5.3 and 28.8 °C (i.e. sub-cooled flow conditions). The Whittle-Forgan and Lafay tests are characterized by an axially uniform heat flux profile. On the contrary, an axially chopped cosine with a peak to average heat flux equal to 1.4 is applied to Croft experiments.

Table 2. Experimental database: range of system conditions.

	ϕ [MW/m ²]	p_{out} [MPa]	$T_{l,in}$ [°C]	G [kg/m ² s]	$DT_{sub,out}$ [°C]	Pe_{out}
<i>Experiments with uniform heat flux</i>						
Whittle	0.4 – 1.5	0.12	45 – 55	822 – 3350	9.9 – 13.1	29145 – 118580
Laf SE1	0.9 – 4.4	0.28 – 0.39	20 – 70	2151 – 7070	10.2 – 21.7	48953 – 160630
Laf SE2	0.9 – 3.6	0.06 – 0.17	20 – 70	2290 – 7636	6.7 – 24.3	66291 – 223830
Laf SE3	0.8 – 3.9	0.09 – 0.17	20 – 70	2122 – 6837	5.4 – 20.1	67666 – 220740
Laf SE4	0.9 – 4.5	0.08 – 0.17	20 – 70	2200 – 7646	7.7 – 24.8	79981 – 283400
<i>Experiments with non-uniform heat flux</i>						
Cro SE1	2.1 – 6.3	0.59 – 1.61	52.2 – 115	7441–16808	7.9 – 16.8	129030–288540
Cro SE2	4.1 – 8.2	0.58 – 1.74	38.3 – 110	9141–17076	9.3 – 21.0	205880–383500
Cro SE3	6.2 – 8.7	0.57 – 1.59	50.6 – 58.3	9336–13806	5.3 – 28.8	271020–398420

In order to determine the OFI conditions, Whittle and Forgan reproduced the flow redistribution curve in a single channel configuration. Therefore, the outlet pressure, inlet temperature and power were fixed, while the mass flux was decreased in steps until the minimum of the S-curve could be identified. On the other hand, both Lafay and Croft used an experimental loop with a large bypass ($A_{bypass} > 10 \cdot A_{channel}$) in parallel to the test section. The bypass was used to impose a constant pressure drop over the channel. In this configuration, the real flow excursion phenomenon could be observed. For all tests Lafay and some tests Croft, the experimental procedure consisted in increasing the heat flux, while maintaining all the other parameters constant. In the other cases, the total mass flowrate or the system pressure was decreased. When a sudden increase in wall temperature was detected, the OFI conditions were registered.

Several experimental uncertainties may affect the results. These uncertainties are related to the geometry of the test section, the measurements of the system parameters (e.g. pressure, mass flowrate), and the exact identification of the OFI conditions. Unfortunately, these information are not available, thus no uncertainty quantification could be performed.

The OFI criteria presented in Section 2.2, are evaluated against the experimental data. Parameters, such as the saturation temperature, fluid temperature, enthalpy and pressure along the channel, are not directly available from the experiments. Nevertheless, the missing data were calculated from the measured system conditions, using the thermal-hydraulic code CATHARE [14]. The comparison with the experimental outlet flow temperature and total pressure drop showed that the global heat balance was correctly estimated and that the pressure profiles along the channel were calculated in a reliable way.

4. RESULTS AND DISCUSSION

The selected OFI criteria are assessed against the experimental data in vertical narrow rectangular channels with downward flow. Considering one OFI estimator, a value is calculated for each of the tests; then the mean over all the experiments is computed, together with the standard deviation. The mean is a measure of how close to the optimal value (equal to unity), on average, the criterion is. The standard deviation provides the variability of the OFI predictor.

4.1. Criteria based on global parameters

The performance of the Whittle-Forgan criterion ($\eta = 32.5$) is shown in Fig. 3. Relatively good results (i.e. FIR around the ideal value of 1) can be obtained for all the tests.

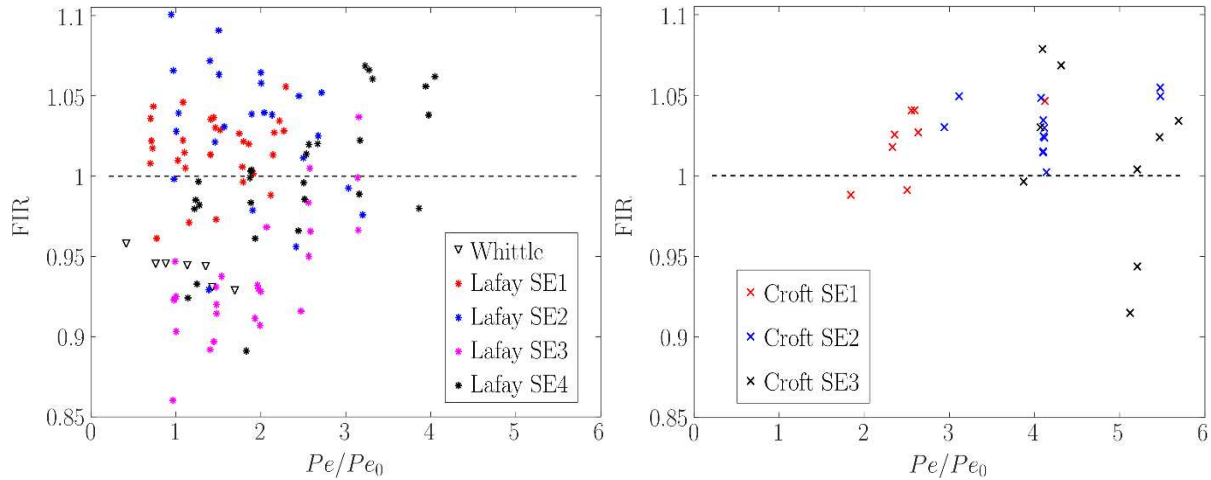


Fig. 3 Results with the FIR Whittle-Forgan ($\eta = 32.5$).

In Table 3, the analysis of the Whittle-Forgan FIR is summarized. In addition, the values of η computed from the ideal FIR equal to one, are reported. The table shows that the average performance of the Whittle-Forgan criterion over the whole database is very good (average FIR = 0.999), so that the reference η value of 32.5 can be considered as optimal. Since a significant number of points is above one, the maximum FIR value (= 1.1) can be taken as a limiting and conservative threshold for application purposes.

Table 3. FIR Whittle-Forgan and ideal η .

	FIR Whittle-Forgan ($\eta = 32.5$)				η			
	<i>mean</i>	<i>std</i>	<i>min</i>	<i>max</i>	<i>mean</i>	<i>std</i>	<i>min</i>	<i>max</i>
Whittle-Forgan	0.942	0.010	0.929	0.958	25.2	1.3	23.4	27.2
Lafay	0.996	0.051	0.860	1.101	32.2	7.3	13.2	47.6
Croft	1.022	0.034	0.915	1.079	39.7	9.3	12.1	51.3
All tests	0.999	0.049	0.860	1.101	32.4	8.3	12.1	51.3

These results are consistent with a previous work [15] that assessed the Whittle-Forgan criterion over an experimental database of vertical narrow rectangular channels with similar geometries (gap between 1.27 and 3.6 mm) and flow conditions, but upward flow. In [15], an ideal η value of 28.3 was found. This small discrepancy may be explained by the different experimental setups, conditions and by the experimental uncertainties. Nevertheless, it may also indicate that the OFI occurs at slightly higher mass fluxes (keeping constant all the other parameters) in the case of downward flow. Unfortunately, no sufficient data are available to confirm this hypothesis.

In contrast with [15-17], no clear influence of the channel geometry (i.e. gap size, L_{heat}/D_{heat} ratio) could be identified.

In the case of the FIR Stelling, similar results are obtained: an average value of 0.960, a standard deviation of 0.048, a minimum of 0.832, and a maximum of 1.055. The estimated values are smaller and therefore more conservative than the ones from the Whittle-Forgan FIR. The larger conservatism is due to the higher parameter η in Stelling case, which is set equal to 38.46.

4.2. Criteria based on NVG correlations

The analysis of the local criteria based on the NVG correlations is divided between the tests of Whittle-Forgan and Lafay with uniform heat flux and the tests of Croft with non-uniform heat flux.

4.2.1. Experiments with uniform heat flux

In this subsection, the assessment of the NVGR criteria for the 114 OFI points with uniform heat flux is presented. Since the axial heat flux profile is uniform, the minimum of the NVGR occur at the end of the heated channels. The results are summarized in Fig. 4.

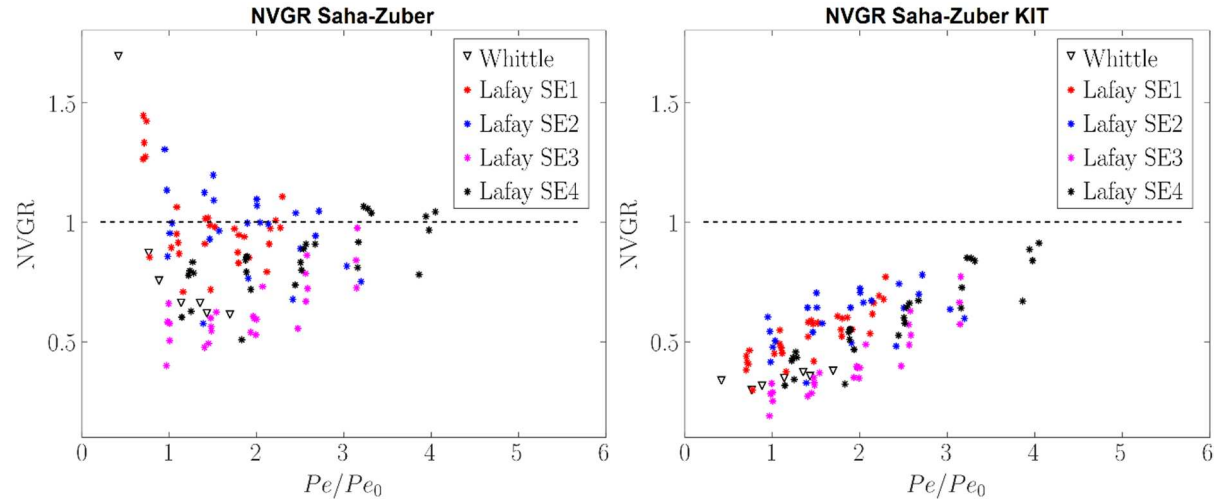


Fig. 4 Tests with uniform heat flux: NVGR criteria.

The standard Saha-Zuber correlation (see Eqn. (6)) fails to predict the OFI in many tests, especially for Peclet numbers lower than Pe_0 (i.e. 70000). These results suggest that the transition between the thermally and hydro-dynamically driven bubble detachment may occur at lower Peclet numbers in narrow rectangular channels. Such a behavior has been already observed in previous studies in narrow rectangular channels with upward [15] and downward [16] flow. In particular, [16] found a transition value of 14000 for Pe_0 .

The Saha-Zuber KIT formula, given in Eqn. (7), predicts the NVG occurrence in all the cases, as shown in Fig. 4 and Table 4. Thus, it can be regarded as a conservative OFI estimator. This result is coherent with the fact that the NVG should precede the OFI. Furthermore, the NVGR approaches one for increasing Peclet numbers. This suggests that the OFI and the NVG points tend to be closer at high Peclet. Contrary to the standard Saha-Zuber correlation, the predictor is significantly conservative at low values of Pe , thanks also to the smaller transition value equal to $0.52*Pe_0$.

Table 4. NVGR Saha-Zuber KIT for the tests with uniform heat flux.

	<i>mean</i>	<i>std</i>	<i>min</i>	<i>max</i>
Whittle-Forgan	0.344	0.029	0.298	0.379
Lafay	0.533	0.157	0.191	0.912
All tests	0.522	0.159	0.191	0.912

The results presented here, are consistent with the ones found in the case of upward flow [15]. No significant effect of the flow direction is therefore observed.

4.2.2. Experiments with non-uniform heat flux

The assessment of the NVGR criteria for the tests Croft is presented here. These experiments are characterized by a non-uniform heat flux profile both axially and along the width of the rectangular channel (Section 3).

In order to compute the OFI criteria, two different assumptions can be made. If a perfect lateral mixing is considered (as it was done for all the previous results), the thermal-hydraulic parameters are averaged over the cross section. Under this hypothesis, both the standard Saha-Zuber and the Saha-Zuber KIT relationships cannot predict the OFI, since the NVGRs are significantly larger than unity (see Fig. 5 and Table 5).

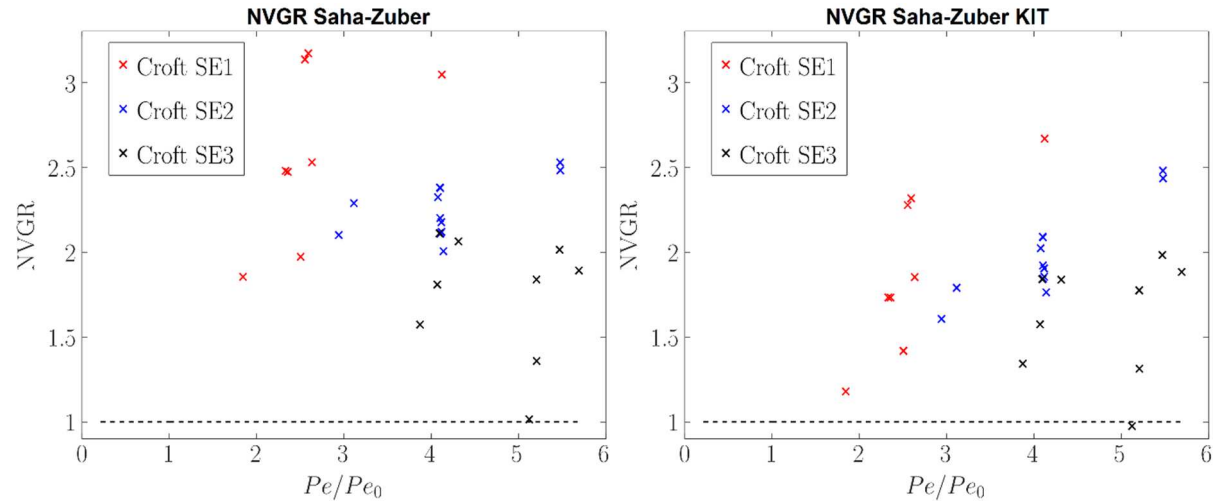


Fig. 5 Tests Croft: NVGR with the hypothesis of perfect lateral mixing.

Table 5. Tests Croft: NVGR criteria with different assumptions for the lateral mixing.

	<i>Perfect mixing</i>				<i>Experimental mixing</i>			
	<i>mean</i>	<i>std</i>	<i>min</i>	<i>max</i>	<i>mean</i>	<i>std</i>	<i>min</i>	<i>max</i>
NVGR Saha-Zuber	2.187	0.472	1.016	3.170	0.291	0.314	0	0.865
NVGR Saha-Zuber KIT	1.845	0.383	0.976	2.668	0.243	0.267	0	0.766

Experimentally, it was observed that a little lateral mixing exists in Croft channels, so that the local bulk temperatures in the central part of the channel cross section are significantly higher than the averaged ones (see discussion in Section 3.1). For a more realistic and local estimate of the NVGR criteria, the local bulk temperatures should be therefore employed. If the central liquid temperatures experimentally measured at exit of the channel are used, the NVG is correctly predicted by both the standard Saha-Zuber and the Saha-Zuber KIT correlations (Table 5). The NVGR equal to zero corresponds to local saturation conditions at the exit of the channel.

These results show that, for an accurate evaluation of the criteria based on the local conditions of the fluid (in this case, the NVGR), the non-uniform lateral heat flux profile has to be carefully taken into account.

5. CONCLUSIONS

Several criteria for the prediction of the flow excursion instability are assessed against experimental data in narrow rectangular channels at low pressures and with downward flow.

The database consists of 143 experimental points with uniform and non-uniform heat flux profiles. The test sections have gap sizes between 1.37 and 3.23 mm, hydraulic diameters between 2.65 and 5.9 mm,

and length to heated diameter ratio between 92.3 and 369.5. The thermal-hydraulic conditions ranged between 0.06 and 1.74 MPa for the outlet pressure, between 822 and 17076 kg/m²s for the mass flux, between 0.4 and 8.7 MW/m² for the heat flux and between 5.3 and 28.8 °C for the outlet sub-cooling.

The Whittle-Forgan and the Stelling criteria only uses global system parameters to predict the flow redistribution. The performances of these formulae are good over the whole database, and the average Flow Instability Ratios are very close to the ideal value of one.

The Saha-Zuber and Saha-Zuber KIT correlations estimate the onset of the Net Vapor Generation along the heated channels. These relationships are used to build OFI criteria (NVGR) based on the observation that the NVG precedes or coincides with the flow excursion instability. Nevertheless, the standard Saha-Zuber formula fails to capture OFI in many tests with uniform heat flux, especially when the Peclet number is smaller than 70000. This suggests that the transition between the thermally and the hydrodynamically driven bubble detachment in narrow rectangular channels occurs at Peclet lower than 70000. On the other hand, the Saha-Zuber KIT correlation identifies OFI in all the experiments with uniform heat flux. Thus, it can be regarded as a conservative criterion. These results are fully consistent with previous studies in narrow rectangular channels, but with upward flow. No significant effect of the flow direction is therefore observed.

In the case of a non-uniform heat flux along the width of the rectangular channel, the use of thermal-hydraulic parameters averaged over the cross section is not sufficient to predict the local onset of the NVG. In fact, it was experimentally observed that the bulk temperatures in the central part of the cross section are significantly higher than the averaged ones. If the central bulk temperatures are employed, a more realistic and local estimate of the NVGR can be obtained and the onset of the NVG is predicted for all tests, as expected. Thus, it can be concluded that the criteria based on the Net Vapor Generation require an accurate estimate of the local flow conditions, especially in the case of a non-uniform heat flux.

NOMENCLATURE

A	m ²	Flow area	\dot{m}	kg/s	Mass flow rate
c_p	J/kg/K	Specific heat capacity	Nu	-	Nusselt $Nu = \frac{hD_{hydr}}{k}$
D_{heat}	m	Heated diameter $D_{heat} = \frac{4A}{P_{heat}}$	p	Pa	Pressure
D_{hydr}	m	Hydraulic diameter $D_{hydr} = \frac{4A}{P_{wet}}$	Pe	-	Peclet $Pe = RePr = \frac{Gc_{p,l}D_{hydr}}{k_l}$
G	kg/m ² /s	Mass flux $G = \frac{\dot{m}}{A}$	Pr	-	Prandtl $Pr = \frac{\mu c_p}{k}$
i	J/kg	Specific enthalpy	P_{wet}	m	Wetted perimeter
Δi_{sub}	J/kg	Liquid sub-cooling $\Delta i_{sub} = i_{,sat} - i_l$	P_{heat}	m	Heated perimeter
k	W/m/K	Thermal conductivity	Re	-	Reynolds $Re = \frac{GD_{hydr}}{\mu}$
l_{heat}	m	Heated width	St	-	Stanton $St = \frac{Nu}{Re Pr} = \frac{\phi}{G \Delta i_{sub}}$
L_{heat}	m	Heated channel length	T	°C	Temperature

Greek symbols

μ	kg/m/s	Dynamic viscosity	ρ	kg/m ³	Density
ϕ	W/m ²	Heat flux			

Subscripts

in	inlet	sat	saturation
l	liquid	sub	sub-cooled
out	end of heated channel		

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REFERENCES

1. M. Ledinegg, "Instability of flow during natural and forced circulation", *Die Wärme* **61**, pp. 891-898 (1938).
2. J. A. Boure, A. E. Bergles, L. S. Tong, "Review of two-phase flow instability", *Nuclear Engineering and Design* **25**, pp. 165-192 (1973).
3. R. H. Whittle, R. Forgan, "A correlation for the minima in the pressure drop versus flow-rate curves for sub-cooled water flowing in narrow heated channels", *Nuclear engineering and design* **6**, pp. 89-99 (1967).
4. I. Babelli, M. Ishii, "Flow excursion instability in downward flow systems. Part I. Single-phase instability", *Nuclear Engineering and Design* **206**, pp. 91-96 (2001).
5. R. Stelling, E. V. McAssey Jr., T. Dougherty, B. W. Yang, "The onset of flow instability for downward flow in vertical channels", *ASME Journal of Heat Transfer* **118**, pp. 709-714 (1996).
6. International Atomic Energy Agency, "Research reactor core conversion guidebook, vol. 2", *Technical report*, IAEA-TECDOC-643, Vienna, Austria (1992).
7. A. P. Olson, "Analysis of flow excursion experiments relevant to research reactors: revisited", *Proceedings of the international meeting on Reduced Enrichment for Research and Test Reactors (RERTR)*, Cape Town, South Africa (2006).
8. P. Saha, N. Zuber, "Point of Net Vapor Generation and vapor void fraction in subcooled boiling", *Proceedings of the 5th International Heat Transfer Conference*, Tokyo, Japan, vol. 4, pp. 175-179 (1974).
9. V. Kalitvianski, "Qualification of CATHARE 2 V1.5 Rev. 6 on subcooled boiling experiments (KIT tests)", *Technical report*, CEA, Grenoble, France (2000).
10. L. Sabotinov, "Experimental investigation of void fraction in subcooled boiling for different power distribution laws along the channel", *PhD thesis*, Moscow Power Engineering Institute, Moscow, Russia (1974).
11. J. Lafay, "Détermination expérimentale du flux de redistribution de débit à basse pressions et en régime permanent: influence du diamètre hydraulique", *Technical report*, CEA, Grenoble, France (1965).
12. M. W. Croft, "Advanced test reactor Burnout heat transfer tests", *Technical USAEC report: IDO-24465*, Babcock & Wilcox Company, Lynchburg, Virginia, USA (1964).
13. W. R. Gambill, R. D. Bundy, "Heat transfer studies of water flow in thin rectangular channels. Part I – Heat Transfer, Burnout and Friction for water in turbulent forced convection", *Nuclear Science and Engineering* **18**, pp. 69-79 (1964).
14. G. Geffraye, O. Antoni, M. Farvacque, D. Kadri, G. Lavialle, B. Rameau, A. Ruby, "CATHARE 2 V2.5_2: A single version for various applications", *Nuclear Engineering and Design* **241**, pp. 4456–4463 (2011).
15. A. Ghione, B. Noel, P. Vinai, C. Demazière, "Criteria for onset of flow instability in heated vertical narrow rectangular channels at low pressure: an assessment study", *International Journal of Heat and Mass Transfer* **105**, pp. 464-478 (2017).
16. J. Lee, H. Chae, S. H. Chang, "Flow instability during subcooled boiling for a downward flow at low pressure in a vertical narrow rectangular channel", *International Journal of Heat and Mass Transfer* **67**, pp. 1170-1180 (2013).
17. J. Bonjour, M. Lallemand, "Flow patterns during boiling in a narrow space between two vertical surfaces", *International Journal of Multiphase Flow* **24**, pp. 947-960 (1998).