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Criteria for Onset of Flow Instability in heated vertical narrow rectangular channels at low pressure: An assessment study

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ABSTRACT

In this paper, an assessment of the criteria for the prediction of the flow excursion instabilities in vertical narrow rectangular channels is presented. The experimental database consists of 166 flow excursion points at low pressure with upward flow, and with uniform or non-uniform heat flux profiles. The test sections have gap sizes between 1.27 and 3.6 mm, hydraulic diameters between 2.37 and 6.58 mm, and length to heated diameter ratio between 70.9 and 196.8. A wide range of parameters is covered: the mass flux is between 740 and 20,325 kg/m^2 s; the outlet pressure is between 0.12 and 1.73 MPa; the heat flux is between 0.4 and 14.9 MW/m^2; the Peclet number is between 15,889 and 358,460; the outlet sub-cooling is between 4.8 and 35.1 °C. None of the tests reaches saturation at the exit of the test section.

Several criteria for identifying the Onset of Flow Instability (OFI), were tested. Such criteria can rely on correlations for the Onset of Nucleate Boiling (ONB), the Net Vapor Generation (NVG), the onset of Fully Developed Boiling (FDB), or can relate global parameters of the system. All these models have good performances on average, with both uniform and non-uniform axial heat fluxes.

The ONB-based relationships are largely conservative as expected since the ONB always precedes the OFI. The NVG criteria can provide relatively good results, but a crucial issue is related to the value of Peclet number at which the transition between the thermally and the hydro-dynamically driven bubble detachment takes place in narrow rectangular channels. In view of this, the standard Saha–Zuber correlation cannot predict OFI for Peclet numbers lower than 70,000; while the Saha–Zuber KIT correlation, whose transition Peclet number is smaller, identifies the OFI for all the experiments. The approach that makes use of a FDB correlation can capture the OFI in most of the cases, although its performance also depends on the type of correlation that is applied for the single-phase heat transfer. The Flow Instability Ratios (FIRs) like the ones developed by Whittle–Forgan or Stelling et al., are of particular interest because they only require global system parameters, and because they are shown to be a valid option for determining the flow excursion in the experiments included in this study. For instance, the Stelling FIR with the Saha–Zuber KIT correlation estimates OFI in all the tests. Finally, best-fitting procedures of the available data were also introduced in order to optimize such FIRs.

1. Introduction

When considering heated channels with sub-cooled liquid flow, one limiting issue for reliable and safe operations is related to the possible generation of vapor with the consequent onset of the Ledinegg instability [1,2]. Such a phenomenon is undesirable because it may generate mechanical vibrations and trigger the occurrence of the boiling crisis. The analysis of the flow stability is particularly important for cooling systems that are arranged in parallel channels. In fact, un-even flow and heat flux distributions may determine unstable conditions that eventually lead to flow starvation in some of the channels.

The paper is focused on the evaluation of correlations for the Onset of Flow Instability (OFI) in heated vertical narrow rectangular channels, at low pressure. These types of channels have flow area with gaps of few millimeters and relatively large width-to-gap ratios, and they are of interest in those engineering systems that require high performance cooling capabilities, within compact volumes [3]. Examples of such applications can be found

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Nomenclature

A	flow area, m^2
c_p	specific heat capacity, J/kg/K
D_{heat}	heated diameter $D_{heat} = \frac{4A}{P_{heat}}$, m
D_{hydr}	hydraulic diameter $D_{hydr} = \frac{4A}{P_{wet}}$, m
G	mass flux $G = \frac{\dot{m}}{A}$, $kg/m^2/s$
h	heat transfer coefficient, $W/m^2/K$
i	specific enthalpy, J/kg
Δi_{sub}	liquid sub-cooling $\Delta i_{sub} = i_{l,sat} - i_l$, J/kg
k	thermal conductivity, W/m/K
l_{heat}	equivalent heated width, m
L_{heat}	heated channel length, m
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number $Nu = \frac{hD_{hydr}}{k}$, –
p	pressure, Pa
Δp	pressure drop, Pa
Pe	Peclet number $Pe = Re\,Pr = \frac{Gc_{p,l}D_{hydr}}{k_l}$, –
Pr	Prandtl number $Pr = \frac{\mu c_p}{k}$, –
P_{heat}	heated perimeter, m
P_{wet}	wetted perimeter, m
Re	Reynolds number $Re = \frac{GD_{hydr}}{\mu}$, –
St	Stanton number $St = \frac{Nu}{RePr} = \frac{\phi}{Gc_{p,l}\Delta T_{sub}}$, –

T	temperature, °C
ΔT	temperature difference, °C
ΔT_{sub}	liquid sub-cooling $\Delta T_{sub} = T_{sat} - T_l$, °C
z	axial distance, m

Greek symbols

μ	dynamic viscosity, kg/m/s
ρ	density, kg/m^3
σ	surface tension, kg/s^2
ϕ	heat flux, W/m^2

Subscripts

g	gas
$heat$	heated
in	channel inlet
l	liquid
out	channel outlet
sat	saturation
sub	sub-cooled
w	wall

in nuclear research reactors [4–8], fusion energy [9], and power systems in ships [10].

Several experimental studies on the topic were performed in the past (e.g., [11–20]). Flow instability experiments were also carried out in the Sultan-JHR facility [21,22], in support to the design of the Jules Horowitz Reactor [8]. The main goal is therefore to gather most of these experiments together and analyze them in a coherent manner to test a set of instability criteria available from the literature. The data cover a wide range of conditions for upward flows, with uniform and non-uniform axial heat flux profile. In view of this, the current investigation also aims to contribute to a better understanding of the influence of several parameters on the prediction of the Onset of Flow Instability.

The paper is organized as follows: in the next section the flow excursion instability is discussed along with some of the most used predictive criteria; in Section 3 the experimental database together with its validity range and the modeling of the experiments are explained; in Sections 4 and 5 the results for uniform and non-uniform heat flux profiles are commented; in Section 6 conclusions are drawn.

2. Flow excursion instability in parallel channels

Two-phase flows may be subject to various types of instabilities, which are usually classified in static or dynamic instability [1]. A static instability occurs when the system, because of a small change/disturbance in the flow conditions, cannot find a steady state close to the initial one; then a different steady state (far from the original one) or a periodic behavior is reached. Such instability can be predicted using steady-state laws. On the contrary, a dynamic instability is strongly influenced by the flow inertia and other feedbacks, so that its prediction requires the modeling of the dynamic behavior of the system.

2.1. Phenomenology

The flow excursion, also known as Ledinegg instability [2], is a static instability which causes a rapid decrease of the mass flowrate in a heated channel. This condition occurs when the slope of the curve pressure drop – mass flux for the external supply system (e.g., determined by a certain pump characteristic) becomes larger than the one for the internal channel demand:

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

In Fig. 1, the typical demand curve (also known as S- or flow redistribution curve) for a channel with a given power input, is shown (blue line). For the case of parallel channels, the total pressure drop along the channel is approximately constant and the slope of the supply curve is zero (red lines). The channel operative condition corresponds to the intersection between the demand and the supply curves.

In the single-phase liquid region, the mass flux is sufficiently high and the system is stable, since the slope of the supply curve is smaller than the one of the demand curve. At lower values of mass flux, the channel reaches the Onset of Nucleate Boiling (ONB) where bubbles start to be generated at the heated walls. The bubbles are small and still attached to the walls; the void

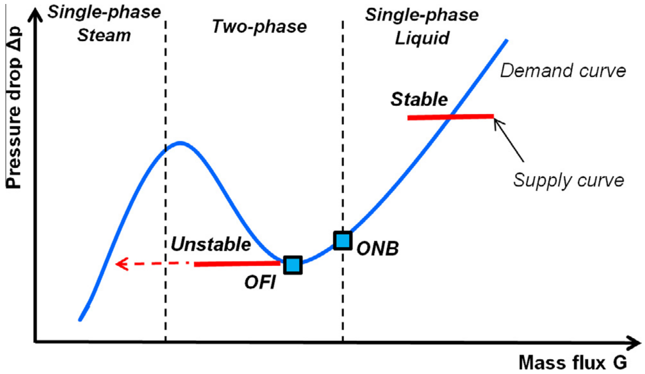

Fig. 1. Onset of Flow Instability for heated parallel channels. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)