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On the analogies in the dynamic behaviour of heated channels with boiling and supercritical fluids

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Abstract

In this paper, the origin and the consequences of a new dimensionless formalism recently introduced for analysing the dynamic behaviour of heated channels with fluids at supercritical pressures are discussed. A unified view of boiling and supercritical fluid instabilities is proposed, basing on the argument that, despite the strong differences in their operating conditions, in both cases the relevant dynamics results from the changes in density that the fluid undergoes along the channel.

The discussion is presently supported only by modelling, performed both by a simplified program and a system code; however, considering the complete independence of these modelling tools, the close agreement observed between their results provides a reasonable level of confidence in the proposed conclusions.

Interesting thermodynamic relationships, devised as a by-product of the introduction of the new dimensionless parameters, are also presented, in the aim to stimulate further studies capable to provide greater insight into the fascinating aspects raised by recognising the intimate similarity of these two classes of phenomena, which have such a remarkable relevance for present and future nuclear reactor technology.

1. Introduction

The dynamic behaviour of heated channels in which a fluid undergoes liquid-to-vapour phase change (in short, “boiling channels”) has been for decades the subject of a long sequence of studies aimed at the investigation of basic phenomena and modelling techniques (see, e.g., Wallis and Heasley, 1961; Ishii and Zuber, 1970; Bourè et al., 1973; Yadigaroglu and Chan, 1979; Lahey and Moody, 1993). Overviews of up-to-date plant observations, models and code applications have been also presented at different stages in this research line (see, e.g., Bourè et al., 1973; March-Leuba and Rey, 1993; D’Auria et al., 1997).

Owing to these relevant studies and to the multitude of other works devoted to related specific physical and numerical aspects, which would be out of scope to refer here in a complete account (see D’Auria et al., 1997 for an extensive and relatively recent review on this subject), boiling channel dynamics can be considered a rather clearly understood matter. In fact, the amount of material produced in this field allows at present time to give for granted the description of most of the fundamental phenomena; thus, the attention can be focused on complex plant applications requiring detailed reactor plant representations, including 3D neutronics and modelling of out-of-core components responsible for constraining the core behaviour with relevant external boundary conditions. In summary, though there is still motivation for increasing the understanding of the behaviour of systems, as represented by basic models or large thermal-hydraulic system codes (see, e.g., Ambrosini and Ferreri, 2006; Podowski, 2006), a great effort in this field is presently devoted to the assessment of the capabilities of codes in predicting the complex behaviour observed in large reactor plants (see, e.g., Lombardi Costa et al., 2006; Hsieh et al., 2006), in order to establish reliable estimates of stability margins (e.g., the evaluation of decay ratios in the proximity of the operating area excluded from normal reactor manoeuvres). This objective is nevertheless a rather challenging one, at least for two reasons:

- the large amount and the detail of the information on plant configurations necessary to set-up reliable models for simulating the overall behaviour with reasonable accuracy;

Abbreviations: CFD, computational fluid dynamics; EVET, equal velocities equal temperatures; HEM, homogenous equilibrium model; UVUT, unequal velocities unequal temperatures

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Nomenclature

A	cross section area (m^2)
C_p	specific heat at constant pressure (J/(kg K))
D_h	hydraulic diameter (m)
f	friction factor
$f_q(z)$	normalized distribution of heat flux
Fr	Froude number
g	gravity (m/s^2)
G	junction mass flux (kg/(m^2 s))
h	fluid specific enthalpy (J/kg)
j	volumetric flux (m/s)
K_{in}	localized pressure drop coefficient at the channel inlet
K_{out}	localized pressure drop coefficient at the channel outlet
L	channel length (m)
N_{pch}	phase change number
N_{sub}	subcooling number
N_{SUBPC}	sub-pseudo-critical number
N'_{TPC}, N_{TPC}	apparent and true trans-pseudo-critical numbers
p	pressure (Pa)
q''	heat flux (W/m^2)
t	time (s)
v	specific volume (m^3/kg)
w	velocity (m/s)
z	axial coordinate along the channel (m)
z_R	real part of a complex exponent
z_I	imaginary part of a complex exponent

Greek letters

β	isobaric thermal expansion coefficient (K^{-1})
δ_d	dimensional Dirac delta function (m^{-1})
δ^*	dimensionless Dirac delta function
Λ	friction dimensionless group (Euler number)
Π_h	heated perimeter (m)
ρ	density (kg/m^3)

Subscripts

f	saturated liquid
g	saturated vapour (steam)
fg	difference between saturated vapour and saturated liquid
in	inlet
out	outlet
p	constant pressure
pc	pseudo-critical
0	reference value

Superscripts

*	starred variables indicate dimensionless values

- the need to compare simulation results with reference figures of merit of plant stability margins obtained by different mathematical models based on the analysis of time series of relevant variables recorded during plant tests; this step, due to the differences in adopted approaches, often introduces uncertainties about the actual meaning of the variables to be compared.

On the other hand, heated channels containing fluids at supercritical pressure crossing the threshold of pseudo-critical temperature offer an additional example of systems in which heating causes the fluid density to undergo remarkable changes along the channel axis. As well known, the renewed interest for these systems in nuclear technology is motivated by the proposal of supercritical water reactors as suitable innovative concepts aimed at increasing the performance and energy conversion efficiency of LWRs (see, e.g., Dobashi et al., 1998; Heusener et al., 2000; Squarer et al., 2003). Despite the striking similarity between boiling channels and heated channels with supercritical fluids, relevant differences exist between the two systems; the fact that in the former case interfaces are formed, with the appearance of an additional phase owing to boiling, while in the latter the rather sudden change in fluid density occurs in a single-phase fluid, raises reasonable doubts about the similarity of the mechanisms driving the dynamic behaviour of the two systems.

Recent papers proposed discussions of these aspects in addressing heated channels containing fluids at supercritical pressures; relevant analogies and possible differences of the unstable behaviour of these systems with respect to boiling channels were pointed out, with main regard to the occurrence of density-wave oscillations and Ledinegg excursions (Zhao et al., 2005; Ortega Gómez et al., 2006; Ambrosini and Sharabi, 2006; Chatorgoon, 2006a). In particular, dimensionless parameters were introduced in the case of heated channels with fluids at supercritical pressures, in similarity with classical definitions for two-phase systems, allowing extending most of the concepts applied in treating boiling channels to the case of supercritical fluids.

The papers by Ambrosini and Ferreri (2006) and Ambrosini and Sharabi (2006) recently published at the ICONE14 Conference, of which this paper is intended to be a follow-up, represented companion works addressing boiling channels and heated channels with supercritical fluids respectively, making use of very similar techniques, based on the use of a simplified model and a system code, namely RELAP5/MOD3.3 (SCIENTECH Inc., 1999). In both cases, linear stability maps obtained by the simplified model, capable of both linear and nonlinear stability analysis in dimensionless form, were compared with the stability boundaries predicted by the system code through transient calculations for uniformly heated channels closely representing real life equipment. The degree of matching or discrepancy observed between the predictions obtained by the two codes provided interesting information for discussing the effect of flow models and spatial discretisation on stability predictions. Some of the conclusions from these two papers, providing the background for the present discussion, are summarized as follows:

- In the case of boiling channels, the differences in the predictions obtained by the equal velocity equal temperature (EVET) model and the unequal velocity unequal temperature