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Analysis of flow stability in nuclear reactor subchannels with water at supercritical pressures

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ABSTRACT

The paper presents the results of the analysis by CFD models of flow stability in fuel bundle slices with upward, horizontal and downward flow orientations. Square and triangular lattice slices are both studied, basing on previous work that demonstrated the feasibility of such analyses. A uniform heat flux is applied to the slice walls in the current study, without addressing the internal structure of the rod. The STAR-CCM+ code is adopted, comparing the results obtained by a 3D model with those that were obtained by the 1D RELAP5 code; the steady-state characteristics of the two models are considered and the thresholds of instability identified by transient calculations are compared with maps set up by an in-house 1D code using a dimensionless formalism developed in previous work. Both static and dynamic instabilities are observed, in similarity with previous analyses performed for circular channels. The work represents a further step in a research aimed to establish a methodology for the analysis of flow stability in nuclear reactor cores by CFD codes.

1. Introduction

General Design Criterion 12 of United States 10 CFR 50 recommends that any oscillatory behaviour in nuclear reactor cores be ruled out by design or promptly detected and suppressed. This or similar recommendations hold, with different emphasis, for any kind of nuclear reactor and Generation IV proposed designs are "a fortiori" no exception. The development of methodologies for analysing stability of nuclear reactors is therefore a relevant step in support to reactor design, in addition to the good testing practices which must be applied to assess the level of stability of a reactor once it is built.

Supercritical Water Reactors (SCWRs) (see Pioro and Duffey, 2007; Oka et al., 2010; Schulenberg and Starflinger, 2012) are believed to be possibly prone to thermal–hydraulic unstable behaviour in similarity with boiling water reactors (see e.g., Bourè et al., 1973; March-Leuba and Rey, 1993; D'Auria et al., 1997; Kakaç and Bon, 2008). In fact, the known instability mechanisms occurring when a light fluid enters a heated channel expanding because of heating are presumably active even in the case of supercritical fluids.

As a matter of fact, models do predict limited degrees of stability for heated channels with supercritical fluids (see e.g., Zuber, 1966; Zhao et al., 2005; Ortega Gómez et al., 2008; Ambrosini, 2007; Ambrosini and Sharabi, 2008) and, given the similarity of the dynamics of boiling and supercritical fluids close to the pseudo-critical threshold, there is little doubt that similar phenomena can really be observed. Recently, experimental evidence of unstable behaviour in experimental apparatuses reinforced this conviction, providing further material and motivation for model development (Xiong et al., 2012; Lomperski et al., 2004; T'Joen and Rohde, 2012).

Models based on one-dimensional cross section averaged balance equations are a straightforward choice for predicting unstable behaviour by numerical or analytical means. In fact, they have been at the basis of many time-domain or frequency domain models and codes developed in the past mainly for boiling water reactor stability (see, e.g., the reviews by March-Leuba and Rey, 1993 and D'Auria et al., 1997). More sophisticated techniques, like CFD, seem difficult to be applied to two-phase flows in transient conditions as those addressed for stability issues; on the contrary, it was shown by previous work (Sharabi et al., 2008, 2009; Ambrosini et al., 2012; Ampomah-Amoako and Ambrosini, 2013) that this is not the case for supercritical fluids that, being single-phase fluids, though with very peculiar features, are in principle amenable to be treated by the mature CFD techniques developed for single-phase flow.

The present paper is focused on the prediction of flow stability by CFD models of subchannel slices cooled by supercritical fluids. In particular, the paper reports the results obtained in the second

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Nomenclature

Roman letters

C_{max}	maximum value of the Courant number
C_p	specific heat at constant pressure (J/(kg K))
D_h	hydraulic diameter (m)
f	friction factor
Fr	Froude number
g	gravity (m/s^2)
h	fluid specific enthalpy (J/kg)
K_{in}, K_{out}	Inlet and outlet singular pressure drop coefficient
L	channel length (m)
N_{SPC}	sub-pseudocritical number
N_{TPC}	apparent and true trans-pseudocritical numbers
$\dot{Q}$	power (W)
T	temperature (K) or period (s)
t	time (s)
v	specific volume (m^3/kg)
w	velocity (m/s)

Greek letters

β	isobaric thermal expansion coefficient (K^{-1})
Λ	friction dimensionless group (Euler number)
ρ	density (kg/m^3) or spectral radius

Subscripts

in	inlet
p	constant pressure
pc	pseudocritical

Superscripts

*	starred variables indicate dimensionless values

AbbreviationsBWR

	boiling water reactor
CFD	Computational Fluid Dynamics
SCWR	Supercritical Water Reactor

phase of a research going on at the University of Pisa on this subject, in cooperation with the University of Ghana. The general aim of the research is to further explore the problems and the capabilities of the application of CFD in stability analyses of heated channels with supercritical fluids, after the above mentioned works by Sharabi et al. (2008, 2009) who first demonstrated the feasibility of this methodology. While the first works on this matter were performed by the FLUENT code (2005), the research is now making use of the latest versions of STAR-CCM+(Cd-Adapco, 2012).

A paper was recently published (Ampomah-Amoako and Ambrosini, 2013) accounting for the first part of the research, addressing circular pipes represented by 2D axi-symmetric spatial discretisations. That work considered vertical upward, horizontal and downward flow, pointing out a reasonable degree of agreement of the stability thresholds obtained by the CFD code in transient analyses with stability maps obtained by a one-dimensional code based on balance equations cast in dimensionless form. Different fluids were also considered in order to assess similarity principles whose validity was already confirmed in previous analyses by one-dimensional models (Ambrosini, 2011).

The further step reported herein is devoted to the analysis of fuel channel slices having both square and triangular lattices. The analysis is limited to consider water at a supercritical pressure, relevant for nuclear reactor applications. The comparison of the results of the CFD code with stability maps obtained by the mentioned in-house code as a function of dimensionless coordinates is used to highlight the level of agreement between 1D models and 3D CFD representations. In this purpose, the RELAP5/MOD3.3 code (SCIENTECH, 1999) is also used for comparison, providing further data to discuss the relevant physical and numerical aspects involved in the prediction of the phenomena.

2. Addressed geometry and adopted model characteristics

A preview of the results to be presented in this paper was provided at the end of a previous paper (Ampomah-Amoako and Ambrosini, 2013), also introducing the main characteristics of the addressed systems. The geometry of the two rod bundle slices is the same considered by Sharabi et al. (2009) in their first calculations. Fig. 1 shows views of the two addressed computational domains.

The square lattice subchannel has a rod diameter of 10.2 mm, with a pitch of 11.2 mm and an active length of 14 ft (4.2672 m). The triangular lattice one has instead a rod diameter of 7.6 mm, with a pitch of 8.664 mm and an active length of 3 m. Both geometries are coherent with proposals of thermal and fast reactor configurations (Yamaji et al., 2001; Yoo et al., 2006). No throttling at the inlet and at the outlet of the subchannel was considered and the wall surface was assumed to be smooth.

Among the various possibilities offered by STAR-CCM+, a “trimmed” mesh made of regular hexahedral nodes was adopted to discretise the two configurations, making use of a mesh base size of 0.1 mm. The node close to the wall was chosen to be larger, making use of a “prism layer” with a single radial node, in order to adopt a “high y+” approach (i.e., allowing for the use of wall functions); the selected depth of the node at the wall was 0.19 mm. As in the case of the circular pipes considered in the previous work

(a) 1/8 square pitch assembly slice (b) 1/6 triangular pitch assembly slice

Fig. 1. Fuel bundle slices considered in the present work with their radial discretisation (from Ampomah-Amoako and Ambrosini, 2013).