Nuclear Engineering and Design 241 (2011) 3879–3889

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Sensitivity analysis of numerically determined linear stability boundaries of a supercritical heated channel

C. T'Joen[a,b,*], L. Gilli[a], M. Rohde[a]

[a] Delft University of Technology, Department Radiation, Radionuclides & Reactors, Mekelweg 15, 2629 JB Delft, The Netherlands
[b] Ghent University, Department of Flow, Heat and Combustion Mechanics, Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium

ARTICLE INFO

Article history:
Received 11 April 2011
Received in revised form 29 June 2011
Accepted 1 July 2011

ABSTRACT

The large change in density which occurs when supercritical water is heated above or near to the pseudocritical temperature in a vertical channel can result in the onset of flow instabilities (density wave oscillations). Near to the critical point, substance properties such as enthalpy, density, viscosity, etc. all have larger relative uncertainties compared to subcritical conditions. The goal of this study is to quantify the effect of these property uncertainties and system uncertainties on numerically determined stability boundaries. These boundaries were determined through an eigenvalue analysis of the linearised set of equations. The sensitivity analysis is performed in a forward way. The results show that the impact of the density and viscosity tolerance individually as well as that of the uncertainty of the imposed pressure drop are negligible. The tolerance on the derivative of the density with regard to the enthalpy propagates only noticeably at low N_{SUB} numbers ($T_{in} > 370\,^{\circ}$C). The friction factor and the heat flux distribution uncertainties have a comparable effect, being more pronounced near the bend in the stability curve. The most significant uncertainty was found to be that of the geometry, even a $\pm 25\,\mu$m uncertainty on length scales results in a large uncertainty. The results also showed that the stability boundary is linked to the friction distribution rather than its average value, and that different correlations result in strong changes of the predicted boundary. This emphasizes the need for an accurate friction correlation for supercritical fluids. These findings are important to assess the design of experimental facilities which use scaling fluids.

1. Introduction

Despite the harsh requirements a supercritical fluid imposes on applications (due to the high pressure and temperature and possible strong corrosion), a strong drive exists to use supercritical fluids in a range of different applications. One of the prime movers is the power cycle for electricity generation (e.g. the Rankine cycle with a turbine). By raising the working pressure and temperature of the fluid, the cycle efficiency can be increased (Carnot law). This has lead to the development of (ultra-) supercritical coal fired electricity plants with a steam pressure as high as 33 MPa which are currently in operation worldwide (e.g. in Japan, Denmark or the United States; Susta, 2004). Using supercritical water has also been proposed for the power cycle of the Generation IV advanced nuclear reactor designs (the Supercritical Water Reactor-SCWR; U.S. DOE, 2002), as this not only results in increased thermal efficiency but also results in a reduced complexity of the auxiliary systems and components, cutting investment costs, as highlighted by Buongiorno and MacDonald (2003). On a smaller power scale there has been a lot of interest to use supercritical CO_2 as a natural refrigerant instead of Freon based hydrocarbons in compression cooling cycles as part of the ongoing struggle to reduce greenhouse gas emissions (see, e.g. Kim et al., 2003). Supercritical organic fluids are also considered for ORC cycles aimed at low temperature energy recovery (Schuster et al., 2010).

As such, supercritical fluids have attracted and continue to attract a lot of research interest. This has resulted in a very large number of papers published in technical literature dealing with different aspects of these fluids or the technical systems in which they are used. This paper focuses on the aspect of the *stability of the flow in a vertical heated channel*. It is well known from earlier research in boiling channels that the flow can become unstable. Bouré et al. (1973) presented a classification of the different types of instabilities. A static instability (flow excursion, the so called Ledinegg instability) can be described using only the steady state equations. In this case, a small change in the flow conditions will result in a new steady state not equal to the original one. For dynamic instabilities, such as density wave oscillations or DWO, the steady equations are not sufficient to predict the system behavior, or the threshold of instability. March-Leuba and Rey (1993) presented a detailed

* Corresponding author at: Delft University of Technology, Department Radiation, Radionuclides & Reactors, Mekelweg 15, 2629 JB Delft, The Netherlands.
Tel.: +31 15 278 3811; fax: +31 15 278 6422.
E-mail address: c.g.a.tjoen@tudelft.nl (C. T'Joen).

0029-5493/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.nucengdes.2011.07.005

Nomenclature

A	flow surface area (m^2)
C_k	local friction value (orifice)
C_p	specific heat capacity (J/kg K)
D_h	hydraulic diameter (m)
f	Darcy–Weisbach friction factor
g	gravimetric acceleration (m/s^2)
G	mass flux (kg/m^2 s)
h	enthalpy (J/kg)
L	length of the heater (m)
p	static pressure (Pa)
P	dynamic pressure (Pa)
P_h	heated perimeter (m)
Δp	pressure drop (Pa)
q'	linear power (W/m)
q''	heat flux (W/m^2)
q'''	volumetric heat input (W/m^3)
Re	Reynolds number, $\frac{GD_h}{\mu_b}$
t	time (s)
w	velocity (m/s)
z	coordinate (m)

Greek symbols

β	isobaric thermal expansion coefficient (1/K)
δ	Dirac delta function
ε	surface roughness (m)
θ	angle relative to the horizontal axis, 90° in this study
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
υ	specific volume (m^3/kg)

Subscripts

cp	evaluated using constant properties
in	inlet
out	outlet
pc	value at the pseudocritical point
ref	value at the reference point
wall	value at the wall temperature

Superscripts

+	upper bound
−	lower bound

explanation of the DWO and the feedback mechanisms, which is driven by the interaction of inertia and friction for the thermo-hydraulic modes. In a nuclear reactor another feedback mechanism is present: the neutronic feedback which couples the instant fluid density to the power production through the moderation and a fuel time constant. This results in a much more complex behavior, as shown by Van Bragt and van der Hagen (1998) for the ESBWR reactor and recently by Yi et al. (2004a) for the US design of a SCWR.

This study considers a heated channel with supercritical fluid flowing upwards. This case is identical to the one considered by Ambrosini and Sharabi (2008) and will be described in detail in the next section. Neutronic feedback is not considered. As is well known, the uncertainty on fluid properties near the critical point can be quite large. There is also no consensus with regards to the friction correlations which should be used for supercritical fluids. This study thus aims at quantifying the impact of the substance property and system uncertainties on the predicted linear stability boundaries. This study is also interesting from a scaling view point. In experimental facilities often other fluids are used to alleviate pressure and temperature constraints (e.g. supercritical R23 to mimic the behavior of supercritical water, Rohde et al., 2011) or boiling R134a to mimic water in Marcel et al. (2008). It would be interesting to know the significance of the uncertainties in this scenario, and see how this affects the idea of scaling.

2. Model description

The proposed system is a single heated vertical tube with a length of 4.2672 m (14 ft.) with upwards flow, shown in Fig. 1. It is identical to the one considered by Ambrosini and Sharabi (2008), but for clarity the geometric parameters will be repeated here. Ambrosini and Sharabi (2008) state that the geometric and operational properties were freely inspired by those proposed for a square lattice in a previous stability analysis (e.g. Yi et al., 2004b). In such a lattice the fuel rods are enclosed between two parallel plates due to the presence of a moderator box. This type of fuel assembly is typical for thermal reactors with supercritical water. The tube connects two reservoirs with a fixed pressure, so the pressure drop over the channel is a constant imposed value (0.14 MPa). The proposed system thus mimics a single fuel channel present in a reactor core, whereby the pressure drop is imposed by the remainder of the

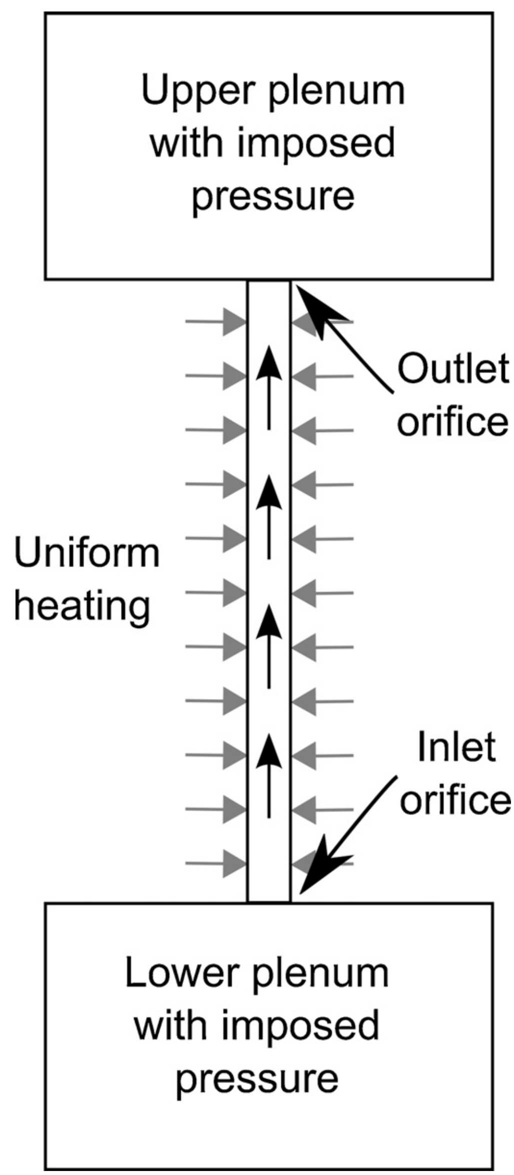

Fig. 1. Studied heated channel.