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Parametric effects on coupled neutronic-thermohydraulic stability characteristics of supercritical water cooled reactor

Daya Shankar, Manmohan Pandey *, Dipankar N. Basu

Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, India

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ABSTRACT

Supercritical Water-Cooled Reactor (SCWR) is one of the advanced reactor types under Generation IV program. Similar to BWR, there are large changes in thermodynamic properties of the coolant in SCWR, but its dynamic characteristics are different from existing reactors due to the supercritical conditions of the coolant. This necessitates study of the stability behaviour of SCWR, which requires a dynamic model of the reactor. A simple unsteady lumped parameter model (LPM) for coupled neutronic-thermohydraulic transients in SCWR has been developed in this paper. The LPM includes point reactor kinetics for neutron balance and a two region model for fuel and coolant thermal hydraulics. The two regions considered in the model are separated from each other by a boundary that depends on the pseudocritical temperature of the coolant. The results of dynamic simulation and linear stability analysis are shown by plotting stability maps. These results show good agreement with each other. Furthermore, to study the effect of parameters on the stability of the system, variations of some geometric, control and neutronics parameters are studied. The stability maps predicted by the LPM are also compared with those obtained with RELAP5 code, and are found to show similar trends.

1. Introduction

Supercritical water exhibits excellent heat transfer characteristics and large volumetric expansion near the pseudocritical point, which identifies it as a potential coolant for advanced nuclear reactors. It also promises enhanced thermal efficiency, compact design and economically competitive structure owing to the elimination of several bulky components such as the steam separator, dryer and recirculation channels. Absence of distinct phase change eliminates the constraint associated with the critical heat flux (CHF) as well, however, at the expense of complicated stability behaviour. Operation in the unstable regime is undesirable, as that can lead to diverging thermohydraulic and power oscillations, particularly in natural circulation based systems. Induced mechanical vibration in structure, fatigue damage of reactor components and failure of control systems are also possible, often leading to catastrophic consequences. That makes it essential to gain a comprehensive insight about the probable operating regime of such systems under both natural and forced flow situations, with primary focus on maximizing the flow rate and heat transfer coefficient.

A supercritical fluid experiences drastic changes in thermodynamic and transport properties around the pseudocritical point. Accordingly the SCWR can exhibit large variation in density across the core, making it susceptible to density wave instability, quite similar to BWRs (Blázquez et al., 2013; Gajev et al., 2013; Peng and Zhao, 2009), necessitating emphasis on passive safety design. Consequently number of researchers have studied the stability response of supercritical flow systems in the recent past following diverse approaches, with more inclination towards the natural circulation loops. Yi et al. (2004) studied the stability characteristics of a SCWR core based on the once-through light water cooled reactor concept proposed by Oka and Koshizuka (2001), by calculating the decay ratio of the system under a pulse perturbation. Zhao et al. (2005) used a three-region model for approximating the variation in density with enthalpy. They defined a few dimensionless scaling groups for analysing thermal hydraulic stability for US reference design of SCWR. A multi-channel stability code in frequency domain (SCWRSA) was developed by Yang (2005), employing an iterative solution scheme, to calculate the steady state flow distribution among parallel channels under a fixed total flow rate and equal pressure drop boundary condition. Stability of single uniformly heated channel with fixed inlet and outlet pressures was studied by Ambrosini (2009) and Ambrosini and Sharabi (2008), as they discussed the stability behaviour at different pressures by

* Corresponding author.
E-mail addresses: manmohan@iitg.ernet.in, mpandeyiit@gmail.com (M. Pandey).

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Nomenclature

A	area (m^2)
C	precursor density (cm^{-3})
C_f	heat capacity of fuel rod ($kJ\,K^{-1}$)
C_p	isobaric specific heat ($kJ\,kg^{-1}\,K^{-1}$)
D_h	hydraulic diameter (m)
f	friction factor (–)
g	gravitational acceleration ($m\,s^{-2}$)
G	mass flux ($kg\,m^{-2}\,s^{-1}$)
h	enthalpy ($kJ\,kg^{-1}$)
k	feedback reactivity (–)
K	restriction coefficient (m^{-1})
L	core length (m)
n_f	number of fuel rods (–)
N_{Eu}	Euler number (–)
N_{Fr}	Froude number (–)
N_{SPC}	Sub-Pseudo critical number (–)
N_{TPC}	Trans-Pseudo critical number (–)
p	pressure ($N\,m^{-2}$)
P	power (kW)
q''_o	heat flux ($kW\,m^{-2}$)
t	time (s)
T	absolute temperature (K)
z	space coordinate (m)

Greek symbols

α	heat transfer coefficient ($kW\,m^{-2}\,K^{-1}$)
$\bar{\beta}$	volumetric expansion coefficient (K^{-1})
β	delayed neutron fraction (–)
γ	nondimensionalized neutron generation time (–)
ρ	density ($kg\,m^{-3}$)
σ	$= \beta/\gamma$ (–)
π_h	heated perimeter (m)

Subscripts and superscripts

0	reference
a	acceleration
c	core
f	fuel rod/friction
g	gravitational
i	inlet
L	loss
o	outlet
pc	pseudocritical
$*$	dimensionless quantities

introducing new sets of non-dimensional numbers for the stability analysis. Sharabi and Ambrosini (2009) predicted the unstable behaviour of heated channels carrying supercritical fluid using a CFD package and analysed a sub-channel of fuel assembly. Subsequently Ampomah-Amoako and Ambrosini (2013) considered the standard $k-\varepsilon$ model, equipped with wall functions, for similar analysis. Dynamic stability characteristics of the fast-spectrum zone of a newly designed mixed-spectrum SCWR (SCWR-M) was studied by Hou et al. (2011) and that was characterized as a parallel-channel system. Quite a few studies to investigate the dynamical behaviour of supercritical natural circulation loops can also be found in the literature (Chatoorgoon, 2001; Jain and Rizwan-uddin, 2008; Sarkar et al., 2014; Sharma et al., 2010), most of which apply finite difference simulation of the governing equations. However, the predictions from such computations are strongly dependent on the choice of grid spacing and time steps, and can often lead to contrasting outcome due to the strong presence of artificial damping.

It is evident from a scrupulous survey of relevant literature that, while the natural circulation based systems have received reasonable attention, supercritical channels with forced flow generally experience a larger density variation across the core and hence are more susceptible towards thermohydraulic instabilities. Heat transport characteristics of such systems, demonstrating the possible appearance of heat transfer deterioration and exploring the effect of buoyancy and flow acceleration on the same, has been the subject of several research studies over last decade (Jäger et al., 2011; Ruspini et al., 2014). However, there are limited number of studies on stability response of supercritical flow channels, particularly with two-phase-like property variation over a short distance around the pseudocritical point (Marcel et al., 2009; Sharabi et al., 2008; Sharma et al., 2010). Adoption of both linear and nonlinear approaches can be identified within the limited database available, with each having its pros and cons. While the linear stability analysis is quick and easy to compute, it can also predict the location of marginal stability based on the eigenvalues, but fails to ascertain the nature of instability. The same can be obtained by transient simulation of conservation equations, but at the expense of substantial computational resource requirement. Both the methods can rather be viewed to complement each other for methodical stability appraisal. Present work, therefore, focuses on understanding the thermohydraulic and coupled neutronic-thermohydraulic stability behaviour of a forced flow heated channel carrying supercritical water and envisages the effect of associated system parameters on stability boundaries employing both linear stability analysis and dynamic simulation of the governing equations. While dealing with the complete set of conservation equations can be cumbersome, adoption of a reduced-order model by decoupling the momentum and energy equations can often provide a swift and reliable estimate. Such models are computationally less expensive compared to finite-difference-kind of approaches and hence are often preferred to obtain a first estimate. Accordingly, a lumped parameter based approach is followed, visualizing the channel to consist of two distinct zones, separated by the pseudocritical point. Integrating the conservation equations over each zone, a system of algebraic and ordinary differential equations (ODEs) is developed, which is subsequently employed for studying the parametric effects through both linear and transient analysis.

2. Mathematical modeling

2.1. Conservation equations

A circular forced flow channel of uniform diameter is simulated in the present study, under uniform heat flux boundary condition imposed on the wall. The channel is subjected to constant pressure drop boundary condition under both steady and transient conditions. Accordingly, the one-dimensional conservation equations for mass, momentum and energy can be summarized as follow.

$$\frac{\partial \rho}{\partial t} + \frac{\partial G}{\partial z} = 0 \tag{1}$$

$$\frac{\partial G}{\partial t} + \frac{\partial}{\partial z}\left(\frac{G^2}{\rho}\right) = -\frac{\partial p}{\partial z} - \rho g - \left[\frac{f}{D_h} + 2K_i\delta(z) + 2K_o\delta(z-L)\right]\frac{G^2}{2\rho} \tag{2}$$