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Stability analysis of parallel-channel systems under supercritical pressure with heat exchanging

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ABSTRACT

The flow in the core of supercritical water reactors (SCWRs) experiences drastic change in its thermodynamic properties and transport properties near the pseudo-critical temperature, thus the core flow may be susceptible to density wave oscillation instability, which is a challenge to the system safety and must be studied carefully. This work studies the stability characteristics of parallel-channel systems with heat exchanging, the prototype of which is originated from the thermal-spectrum zone assemblies of a newly designed mixed-spectrum SCWR (SCWR-M). A frequency-domain model has been developed for linear stability analysis, and marginal stability boundaries under several conditions are generated, which indicate that the system normal operational condition is in an absolute stable region. Decreasing the wall thermal conductivity can improve system stability while increasing mass flow is beneficial for the system stability. The system is not very sensitive to the axial power distributions. A one-dimensional time-domain model has also been developed for nonlinear analysis, and several transients with mass flow perturbations are calculated. The system marginal stability boundaries calculated by using frequency-domain and time-domain methods are in good agreement with each other. The existence of transitional stable region has been observed. A special case of parallel-channel systems with heat exchanging has been studied and achieved the conclusion that the second eigenvalue should be considered when studying the stability characteristics of complicated systems by using frequency-domain methods.

1. Introduction

Supercritical water reactor (SCWR) is one of the six recommended types of generation IV reactors. The use of water at supercritical pressure conditions allows achieving higher reactor outlet temperatures (about 800 K), raising the useful power fraction from classical figures of 33%, as in conventional light water reactors, up to about 44% (Squarer et al., 2003). SCWRs are also more compact than water reactors of generation II or III, thus fewer components are needed and, in turn, the costs are lowered. SCWR is also considered as a logical extension of the existing water-cooled reactors.

Though there are many advantages of using supercritical water as coolant and moderator for reactors, there are also many safety challenges of SCWR that need to be well studied. Strong variation of fluid properties in the vicinity of the pseudo-critical temperature, which can lead to oscillations and have adverse effects on both the thermal–hydraulic operation conditions and reactor materials, is one of major concerns in the SCWR R&D work. For most current SCWR designs, the fluid undergoes a great density variation with a density of about 780 kg/m^3 at the core inlet and about 90 kg/m^3 at outlet. Under such conditions density wave oscillation instabilities are very likely to happen according to the experiences of boiling water reactor operation, and these instabilities are highly undesirable since they might be detrimental to system safety (Jain and Rizwan-uddin, 2008).

Many investigations have been made to dynamical behaviors of systems operating under supercritical pressure in the last few years. These studies can be classified into four categories according to the structure of the studied objects: single-channel stabilities, parallel-channel stabilities, reactor core flow instabilities and natural circulation or closed-loop system stabilities. Flow stabilities of single-channel system have been sufficiently studied. Ambrosini et al. (2007, 2009), for example, studied frequency-domain stabilities of a single uniformly heated pipe with fixed inlet and outlet pressures, and discussed the stability of heated channels with different fluids at supercritical pressures. Sharabi et al. (2008) and Emmanuel Ampomah-Amoako (2013) used CFD software in supercritical stability studies of a sub-channel in fuel assemblies for more detail. There are also many efforts made to study parallel-channel system stabilities both numerically and by experiments. Xiong et al. (2012, 2013) studied on flow instability in a

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Nomenclature

List of abbreviations

A	flow area, m^2; coefficient matrix of the perturbation equation-system
B	coefficient matrix of the perturbation equation-system
D	hydraulic diameter, m
f	friction coefficient
G	mass flow flux, kg/m^{2}s
g	gravitational acceleration constant, m/s^2
h	fluid specific enthalpy, kJ/kg
J	junction connecting control volumes
L	pipe length, m
P	fluid pressure, Pa
t	time, s
V	control volume
x	system state variable vector
z	spatial coordinate, m

List of Greek symbols

δ	perturbation of system state variable
θ	system inclination angle
λ	system dominant eigenvalue
ρ	fluid density, kg/m^3

subscripts

Re	the real component of a complex variable
Im	the imaginary component of a complex variable
i	the index of control volumes and junctions

superscripts

0	the initial steady value
n	the old time value
n+1	the new time value

two-parallel-channel system with supercritical water by experiments first and then by numerical modeling and analysis. Su et al. (2013) studied theoretically on the flow instability of supercritical water in the parallel channels. The stabilities of many postulated SCWR reactor core were also studied. Yi et al. (2004) studied the stability characteristics of a SCWR core based on Oka's design by calculating the decay ratio of the system under a pulse perturbation. Zhao (2005) established a few new dimensionless scaling parameters concerning supercritical fluid-dynamic stabilities in a SCWR core based on the U.S. reference design (Buongiorno and Macdonald, 2003). Furthermore, Yang(2005) developed a multi-channel thermal–hydraulics stability analysis code SCWRSA in frequency domain, and the code is applied to calculate the decay ratio of the same SCWR core as Zhao (2005).Chatoorgoon (2001), Jainand Rizwan-uddin (2008), Sharma et al. (2010), etc. studied supercritical flow in natural circulation loops in which fluid is heated in a horizontal section at the bottom of loop, and cooled at the top. Cheng and Yang (2008a) conducted stability investigation using a simplified point-hydraulics model to study the SCWR system stabilities.

Based on thermal-spectrum or fast-spectrum SCWR designs, a mixed-spectrum SCWR (SCWR-M) core design with multi-layer fuel assemblies has been proposed by Cheng et al. (2008b). The core consists of two zones with different neutron spectrums, one with thermal spectrum and the other with fast one, which is shown in Fig. 1. The fluid flows downward into the thermal spectrum zone (the peripheral region) co-currently going through the coolant channels and the moderator channels, and then upward through the fast-spectrum zone (the central region).

The fuel assembly in thermal spectrum zone is much more complicated than those in pressurized water reactors of generation II or III (Fig. 2). Each assembly consists of a coolant channel and 9 moderator channels. The supercritical water flowing in the coolant channel is used to cool down fuel rods and transfer the heat generated by nuclear reactions out of the reactor core. The water flowing in the moderator channels is used to slow down fast neutrons to the thermal spectrum. Each assembly has an outer box to keep coolant within it and no mass interchange between assemblies. 9 square moderator channels are symmetrically distributed in the assembly, and each channel has a box to separate the coolant and moderator. Though many studies about parallel-channel system instability have been carried out, very few studies on systems with heat exchanging and relevant special system characteristics have been reported. This work mainly focuses on a detailed stability analysis of parallel-channel system originated from the thermal-spectrum zone assemblies of the SCWR-M core. The counterpart studies about the fast-spectrum zone of SCWR-M core were reported by Hou et al. (2011).

2. Stability analysis methods

The frequency-domain method is used for linear stability analysis, and the time-domain method is adopted for nonlinear analysis. Both of these two methods will be presented briefly in this section, and the detailed methodology was described by Hou et al. (2011).

2.1. Governing equations

For one-dimensional fluid flow, the time dependent conservation governing equations for mass, energy and momentum are as follows:

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

$$\frac{\partial \rho h}{\partial t}+\frac{\partial Gh}{\partial z}=\frac{q_l}{A} \tag{2}$$

$$\frac{\partial G}{\partial t}+\frac{\partial}{\partial z}\left(\frac{G^2}{\rho}\right)=-\frac{dP}{dz}-\rho\tilde{g} - \left(\frac{f}{2D}+K_{in}\delta(z,0)+K_{exit}\delta(z,L)\right)\frac{G^2}{\rho} \tag{3}$$

Eqs. (1)–(3) are discretized by the standard staggered-mesh method with upwind schemes (Patankar, 1980).Each channel is divided into several sub-volumes called control volumes with equal lengths of Δz from the inlet to the outlet as shown in Fig. 3 in which the ith volume is labeled as V_i. Every control volume connects to its adjacent volumes with junctions labeled as J_{i-1}, J_i and J_{i+1}, etc. The mass and energy equations are discretized by integrating the field variables over each control volume, and the resulting equations are:

$$\Delta z\frac{\partial \rho_i}{\partial t}=G_i-G_{i+1} \tag{4}$$

$$\Delta z\frac{\partial \rho_i h_i}{\partial t}=G_i h_{i-1}-G_{i+1}h_i+\frac{q_i}{A} \tag{5}$$