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Effect of axial power distribution on flow instability in parallel channels with water at supercritical pressures

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A B S T R A C T

Stability of the operation of SCWR at the supercritical conditions has become a major concern to the nuclear engineers worldwide, especially around the pseudo-critical point where dramatic changes of the fluid properties are experienced. This concern of addressing supercritical flow instability is due to various studies showing that the efficiency of light water reactors can be improved considerably from 33% at subcritical pressures to 45% at supercritical pressures.

This work investigates effect of axial power distribution on flow instability in parallel channels with water at supercritical pressures. The axial power distributions considered include axially decreased and homogeneous axial power shapes. The study also seeks to examine the performance of the 3D numerical tool STAR-CCM+ in predicting flow instability at supercritical pressures. The effects of parameters such as mass flow rate, pressure and gravity on flow instability were also discussed. Sensitivity analysis of some selected turbulence models and time steps were initially carried out with the aim of selecting suitable turbulence model and time step for the numerical simulations. For a system operated exclusively at two different pressures 23 MPa and 25 MPa with 125 kg/h mass flow rate, inlet temperatures from 180 °C to 360 °C and with gravity influence, stability of the system with axially decreased or homogeneous power shape decreases and increases respectively below and above a particular threshold power with inlet temperature. The system was found more stable with homogeneous Axial Power Shape (HAPS) than that of axially decreased power shape (ADPS). Similar observation was made for a system operated at mass flow rate of 125 kg/h, system pressure of 23 MPa, and with or without gravity influence. When the system is operated at 23 MPa pressure, 145 kg/h mass flow rate and with gravity influence, there is a threshold power below which stability decreases and above which stability increases with inlet temperature for HAPS. In this case, there is no inflection point for ADPS and the stability deceases with inlet temperature. At low inlet temperatures, the system is more stable with ADPS but at high inlet temperatures the system is more stable with HAPS for the system operated at 23 MPa pressure and 145 kg/h mass flow rate. The system with ADPS or HAPS becomes more stable with the change of the system operated with gravity influence to the system operated without gravity influence, and also with the change of system pressure from 23 MPa to 25 MPa. With the change of the system mass flow rate from 125 kg/h to 145vkg/h, the system with ADPS becomes more stable at low inlet temperatures and less stable at high inlet temperatures, whereas the system with HAPS becomes less stable for the various inlet temperatures. For a system operated under experimental conditions of 125 kg/h mass flow rate, 23 MPa pressure, inlet temperatures from 180 °C to 260 °C and with gravity influence, the trends of the numerical instability boundary results agree quite well with the trends of the experimental instability boundary results for most of the inlet temperatures, but there is no inflection point for experimental HAPS as it is the case for numerical HAPS. The system with HAPS is more stable than that with ADPS, a finding also obtained for the experimental results. The dynamics characteristics such as amplitude and period were also compared with experimental results for ADPS at mass flow rate of 125 kg/h, 23 MPa, and with gravity influence. The experimental amplitude was largely under-predicted and the experimental period was quite well predicted by the numerical tool adopted. The results of this study show that the type of axial power shape

Abbreviations: ADPS, axially decreased power shape/distribution; BWR, boiling water reactor; DWOs, density wave oscillations; HAPS, homogeneous axial power shape/distribution; LWRs, light water reactors; MSBs, marginal stability boundaries; NPIC, Nuclear Power Institute of China; PWR, pressurized water reactor; SCWR, supercritical water-cooled reactor; THRUST, thermal-hydraulic solver undertaking supercritical water.

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adopted in supplying heat to the fluid flowing through heat transfer system has significant effect on the stability of the system. From the comparison of the numerical and experimental results, the 3D numerical tool, STAR-CCM+ code could predict flow instability in the parallel channels irrespective of the type of axial power shape adopted. However, there is an evidence that the presence of heating structures in the geometrical model adopted may change the predicted behavior, as shown in previous works. More relevant experiments at supercritical pressures should be carried out for validation of numerical tools adopted for similar studies.

Nomenclature

$C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$	turbulence model coefficients
G	acceleration due gravity (m/s^2)
G	mass flux (kg/m^2 s)
G_b	generation of turbulence kinetic energy due to buoyancy (kg J/m^3 s)
G_k	generation of turbulence kinetic energy due to mean velocity gradient (kg J/m^3 s)
G_ω	generation of ω (kg/m s^4)
K	hydraulic loss coefficient
K_{in}	localized pressure drop coefficient at the channel inlet
K_{out}	localized pressure drop coefficient at the channel outlet
L	length of the pipe (m)
L_H	heated length (m)
M_t	total mass flow rate (kg/s)
M_{in1}	total mass flow rate at channel 1 inlet
M_{in2}	total mass flow rate at channel 2 inlet
S_k	source term in k equation (kg J/m^3 s)
S_T	source term in energy equation (kg K/m^3 s)
S_u	source term in x momentum equation (kg/m^2 s^2)
S_v	source term in y momentum equation (kg/m^2 s^2)
S_w	source term in z momentum equation (kg/m^2 s^2)
S_ε	source term in ε equation (kg/m s^4)
S_ω	source term in ω equation (kg/m s^4)
T	emperature (K)
u	velocity (m/s)

Greek letters

ε	turbulent dissipation rate (m^2/s^3)
ω	specific turbulent dissipation rate (1/s)
λ	thermal conductivity (W/m K)
k	turbulent kinetic energy, m^2/s^2
μ	viscosity (Pas)
μ_t	turbulent viscosity (Pas)
ρ	density of the fluid (kg/m^3)
σ_k	Prandtl number correspond to k
σ_ε	Prandtl number correspond to ε
σ_ω	Prandtl number correspond to ω
τ_k	effective diffusivity of k (kg/m s)
τ_ω	effective diffusivity of ω (kg/m s)

Subscripts

b	bulk
g	gravity
In	inlet
out	outlet
p	constant pressure
pc	pseudo-critical

1. Introduction

Stability of the operation of SCWR at supercritical conditions has become a major concern to the nuclear engineers worldwide, especially around the pseudo-critical point where dramatic change of the fluid properties is experienced as shown in Figs. 1–4 (Xi et al., 2014a). This is due to various studies showing that the utilization of supercritical fluids can considerably increase efficiency of light water reactors from 33% at subcritical pressures to 45%. Instability is undesirable as high amplitude sustained flow oscillations beyond uncontrollable limits may cause forced mechanical vibration of components; and also disturb control systems and cause operational problems in nuclear reactors (Ampomah-Amoako, 2013; Nayak and Vijayan, 2008).

There are three kinds of approaches for flow instability investigation including theoretical analysis with frequency domain method (FDM); time domain method (TDM) with one dimensional (1D) and three dimensional (3D) codes; and by experiment. Due to the limitation of high temperature and pressure, there are just few experiments of interest relating to flow instability at supercritical pressures. Most of the investigations are based on FDM and TDM (Xi et al., 2014a). Frequency-domain analysis is based on the linearization of nonlinear equations by perturbing the governing equations around a steady-state point. Once the linear model has been converted from time domain to a frequency domain, exact analytical solutions can be obtained. As a result, marginal stability boundaries (MSBs) in a parameter space can be determined and the space is divided into stable and unstable regions. In order to obtain stability boundaries in Time-domain analysis, the nonlinear time domain approach relies on a digital numerical simulation of

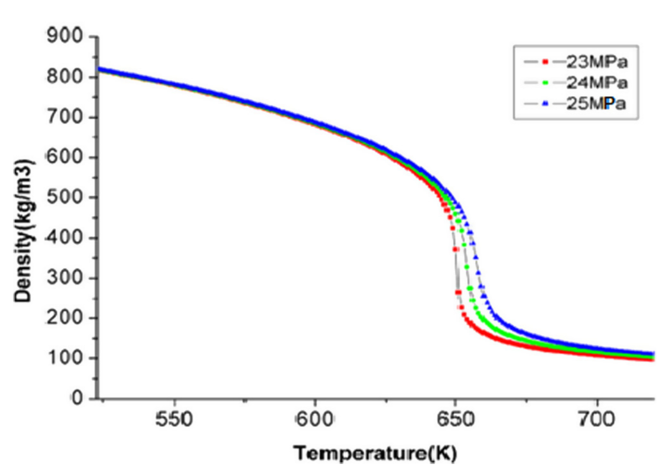

Fig. 1. Density change of water with the increase of temperature.