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Numerical investigation of flow instability in parallel channels with supercritical water

Edward Shitsi *, Seth Kofi Debrah, Vincent Yao Agbodemegbe, Emmanuel Ampomah-Amoako

University of Ghana, School of Nuclear and Allied Sciences, Department of Nuclear Engineering, P.O. Box AE 1, Atomic Energy, Kwabenya, Accra, Ghana

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ABSTRACT

SCWR is one of the selected Gen IV reactors purposely for electricity generation in the near future. It is a promising technology with higher efficiency compared to current LWRs but without the challenges of heat transfer and its associated flow instability. Supercritical flow instability is mainly caused by sharp change in the coolant properties around the pseudo-critical point of the working fluid and research into this phenomenon is needed to address concerns of flow instability at supercritical pressures.

Flow instability in parallel channels at supercritical pressures is investigated in this paper using a three dimensional (3D) numerical tool (STAR-CCM+). The dynamics characteristics such as amplitude and period of out-of-phase inlet mass flow oscillation at the heated channel inlet, and heat transfer characteristic such as maximum outlet temperature of the heated channel outlet temperature oscillation are discussed. Influences of system parameters such as axial power shape, pressure, mass flow rate, and gravity are discussed based on the obtained mass flow and temperature oscillations. The results show that the system parameters have significant effect on the amplitude of the mass flow oscillation and maximum temperature of the heated outlet temperature oscillation but have little effect on the period of the mass flow oscillation. The amplitude of mass flow oscillation and maximum temperature of the heated channel outlet temperature oscillation increase with heating power. The numerical results when compared to experiment data show that the 3D numerical tool (STAR-CCM+) could capture dynamics and heat transfer characteristics of the flow quite well and also predict flow instability in the parallel channels.

1. Introduction

Flow instability may occur in the operation of many industrial systems and equipment including nuclear reactors, thermosiphons, refrigeration plants, steam generators, heat exchangers and boilers. Hence, instability needs to be addressed during the design and operation of these systems and equipment.

Supercritical Water Cooled Reactor (SCWR) is one of the Six Generation IV nuclear reactors recommended by Generation IV International Forum (GIF) to be built in a near future. Generally, water enters the core of SCWR at temperatures between 250 °C and 300 °C, and leaves the core at temperatures between 500 °C and 600 °C respectively. Physical properties of water such as density, specific heat, viscosity and thermal conductivity experience drastic changes at and near the critical and pseudo-critical temperatures as shown in Figs. 1–4 respectively. An out of phase flow instability is likely to occur in SCWR during its operation as a result of the drastic change in the coolant properties (Xiong et al., 2012; Xi et al., 2014a,b). Abnormal operation conditions such as power excursion and sudden loss of coolant could lead to mass flow and temperature oscillations in SCWR during its operation. Severe flow rate and temperature oscillations can change a steady heat transfer process to go beyond the designed safety regime of heat transfer equipment such as SCWR (Yu et al., 2015). Studies are being carried out to address flow instability at supercritical pressures ahead of the development, design and operation of SCWR.

Studies have shown that flow instability at supercritical pressure conditions could have significant and detrimental effects on heat transfer and could therefore affect the safety of operation of SCWR (Gómez, 2009; Bae et al., 2007 and Bae et al., 2009). Researchers, therefore, have started working to address the challenges that flow instability would have on heat transfer at

Abbreviations: CFD, Computational Fluid Dynamics; LWRs, light water reactors; NPIC, Nuclear Power Institute of China; SCWR, supercritical water-cooled reactor.

* Corresponding author.
E-mail addresses: edwardshitsi@yahoo.com (E. Shitsi), s.debrah@gaecgh.org (S.K. Debrah), vincevalt@gmail.com (V.Y. Agbodemegbe), emmagaec@gmail.com (E. Ampomah-Amoako).

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Nomenclature

$C_{1\varepsilon}, C_{2\varepsilon}, C_{3\varepsilon}$	turbulence model coefficients
D_H	hydraulic diameter (m)
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)
M_t	total mass flow rate (kg/s)
p	system pressure (Pa)
p	system pressure drop (Pa)
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	temperature (K)
u	velocity (m/s)
y^+	wall y plus
Y_M	contribution of fluctuation dilatation in compressible turbulence (kg J/m^3 s)
Y_ω	dissipation of ω due to turbulence (kg/m s^4)

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)
ξ	frictional number

Subscripts

g	gravity
in	inlet
out	outlet
p	constant pressure
pc	pseudo-critical
1	channel 1
2	channel 2

supercritical pressure conditions (Jain and Rizwan-uddin, 2008; Zhao et al., 2005; Chatoorgoon, 2001, 2006; Gómez et al., 2006, 2008; Ambrosini and Sharabi, 2007, 2008). Ambrosini (2007) reported the findings that were given particular attention by some previous researchers on supercritical instabilities. These findings are

- static and dynamic nature of the instabilities predicted to be observed in systems with fluids at supercritical pressure;
- dimensionless parameters to be adopted in a dynamic similarity perspective to propose stability thresholds from calculations and future experiments in a compact and relatively universal way;
- effects related to single and multiple parallel channels as well as to systems in natural circulation.

Previously, other researchers have focused on using numerical tools namely one dimensional (1D) system codes and three dimensional Computational Fluid Dynamics (CFD) codes for stability analysis of heated channels with supercritical fluids. In STAR-CCM+, CFD approach adopts the fundamental governing conservation equations and are solved using Finite Volume method whilst system codes adopts the lump parameter approach. These researchers have called for further studies to explore more and improve upon the existing works done using these numerical tools in this area of supercritical instability (Ambrosini and Sharabi, 2007, 2008; Ambrosini, 2007, 2011; Sharabi et al., 2008; Sharabi, 2008; Gómez et al., 2008; Ampomah-Amoako and Ambrosini, 2013; Ampomah-Amoako, 2013; Debrah et al., 2013a,b; Xiong et al., 2013; Jingjing et al., 2015). Xi et al., 2014b compared 1D and 3D CFX code results for parallel channels. It was observed that 3D results were better than the 1D results and the 3D results were within the acceptable limit of 10% relative error when compared the two results with the experimental results. Thus more accurate results are obtained with the use of 3D or CFD code. Moreover 1D codes cannot address the three-dimensional effects of fluid flow (e.g., swirling flows, separated flows, flows in complex geometries, stratification, etc.), which add significant value to the safety analysis (Farah, 2012).

This following study, an experimental test performed in a parallel channels facility operated at Nuclear Power Institute of China with supercritical water, clearly showing unstable behavior, is taken as reference for discussing effects of some chosen parameters. The main effect of parallel channel on fluid flow and heat transfer with heating power beyond the threshold or critical power of flow instability is the occurrence of out of phase mass flow rate

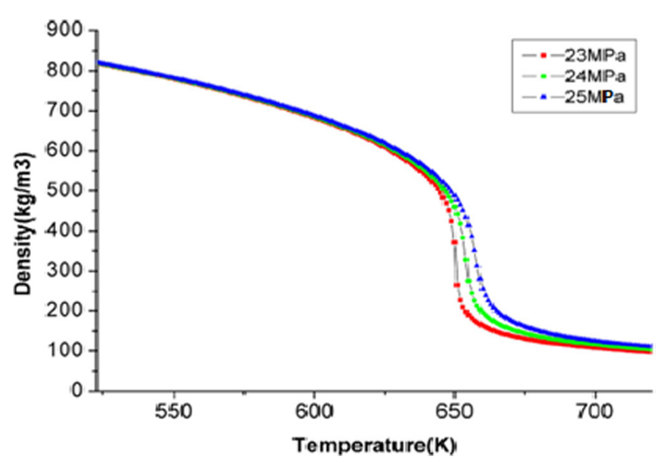

Fig. 1. Density change of water with the increase of temperature.