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Numerical study of oscillatory flow instability in upward flow of supercritical water in two heated parallel channels

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ABSTRACT

A 3-D numerical study of turbulent flow of supercritical water flowing upward in two heated parallel channels with constant applied wall heat flux was developed using a RANS model in the Computational Fluid Dynamics (CFD) code ANSYS CFX. Oscillatory flow instabilities were investigated using the standard k-ε turbulence model with scalable wall functions. The effects of changes to the grid sizes and the time step size on flow instabilities were studied first. Then the instability thresholds of experimental cases were obtained with the CFX code. For comparison purposes, Chatoorgoon's 1-D non-linear SPORTS code was also used to determine the instability boundary. These two new numerical results were compared with the experimental data and previous numerical results by other investigators. Additionally, the effects on the instability thresholds of changing the outlet plenum volume, the turbulent Prandtl number, the turbulence inlet conditions, the channel outlet K factor, the maximum iterations per time step in the transient analysis, and the order of the transient scheme were examined.

1. Introduction

In order to satisfy the growing demand for electrical energy as well as reduce greenhouse gas emissions caused by the continued large-scale combustion of fossil fuels for electricity generation, constructing additional nuclear power plants for electricity supply is deemed a most viable, effective and logical solution. Furthermore, providing electrical power this way is economic, safe, reliable, and sustainable [1]. Nuclear power reactors have improved with each generation. Currently, advanced and innovative Generation IV nuclear reactors are proposed and, thus, are being studied.

The Supercritical Water cooled Reactor (SCWR) is considered one of the six most promising concepts of the new Generation IV nuclear reactors. It has a high potential for electrical power generation at lower costs because of its improved overall thermal efficiency (44% or more versus 34–36% for current reactors) and considerable plant layout simplification [2]. However, there are many technological issues for the SCWR, one of which is thermal hydraulic instabilities. Flow instability is an operating limit of a nuclear reactor; hence, it must be avoided at all costs. Boure et al. [3] identified two types of flow instabilities: static (also called 'excursive') instabilities and dynamic (also called 'oscillatory' and 'density-wave oscillation') instabilities. The present study deals with the latter one. For oscillatory instabilities in SCWRs, three typical categories have been reported by Zhao et al. [4]. The first case is a single channel or parallel-channel oscillation which can be modelled by a single channel with constant pressure drop. The second case is out of phase or region-wide instability, which can be modelled by a two-parallel-channel system with constant total mass flow rate. The third case is the core-wide in-phase instability which can be modelled as circulation loop instability. Most supercritical flow instability investigations are based on these three cases, and can be divided into three configurations: single channel, parallel-channel systems, and circulation loop.

For supercritical flow instability study in single channel, Zuber [5] pioneered the initial theoretical study. He presented three mechanisms that may give rise to instabilities at supercritical pressures and suggested some improvements that could eliminate the onset of flow oscillations. Zhao et al. [4] constructed stability maps whereby the effects of the inlet orifice, inlet flow, system pressure, and inlet temperature on the single channel instability were examined. New non-dimensional parameters for water were proposed by Ortega Gómez et al. [6] to generate the stability map for a uniformly heated channel. Their results showed that no Ledinegg or pressure drop instabilities occurred with the test cases. Ambrosini et al. [7] also derived universal non-dimensional parameters for supercritical fluids in heated channels and these non-dimensional parameters are the ones most commonly used today. These new dimensionless parameters use the pseudo-critical state as the only reference state and Ambrosini [8,9] proved them to be a success for a number of fluids. Using a single channel model, the

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Nomenclature

A	cross-sectional area (m^2)
C_P	specific heat at constant pressure (J/(kg K))
D	hydraulic diameter of section (m)
f_r	friction factor
g	gravity (m/s^2)
G	mass flux (kg/(m^2 s))
h	enthalpy (J/kg)
h_{tot}	total enthalpy (J/kg)
I	turbulence intensity
k	turbulence kinetic energy (m^2/s^2)
K	local pressure drop coefficient
$\dot{m}$	mass flow rate (kg/s)
$\dot{m}^*$	normalized mass flow rate
N_{TPC}	trans-pseudo-critical number
P	static pressure (Pa)
P'	modified pressure (Pa)
P_r	Prandtl number
Pr_t	turbulent Prandtl number
q''	heat flux (W/m^2)
Q	heating power (kW)
Re	Reynolds number
$S_{M,buoy}$	momentum source term due to buoyancy (kg/(m^2 s^2))
$S_{M,frict}$	momentum source to model local pressure drop (kg/(m^2 s^2))
T	temperature (K)
t	time (s)
U	mean velocity in the x direction (m/s)
V	mean velocity in the y direction (m/s)

Greek symbols

β	isobaric thermal expansion coefficient (K^{-1})
δ	surface roughness (m)
ε	turbulence dissipation rate (m^2/s^3)
λ	thermal conductivity (W/(m K))
μ	dynamic viscosity (Pa s)
μ_t	eddy viscosity (Pa s)
ρ	density (kg/m^3)
ρ_{ref}	reference density (kg/m^3)
$\rho\overline{u_i u_j}$	Reynolds stress (N/m^2)
τ_{ij}	shear stress (N/m^2)

Subscripts

1	channel 1
2	channel 2
g	gravity
in	inlet
out	outlet
o	channel outlet
pc	pseudo-critical
thold	threshold
tot	total

Acronyms

CANDU	Canada Deuterium Uranium
CFD	Computational Fluid Dynamics
DWO	Density Wave Oscillation
NPIC	Nuclear Power Institute of China
RANS	Reynolds Averaged Navier-Stokes
SCWR	Supercritical Water Cooled Reactor
THRUST	Thermal-Hydraulic Solver Undertaking Supercritical Water

Abbreviation

exp	experiment

in-phase mode of Density Wave Oscillations (DWOs) in the CANDU SWCR was studied by Dutta et al. [10] with the 1-D THRUST code. The effects of various parameters on the stability boundaries of the reactor were examined, including the effect of axial heat flux profile. Besides these analytical and numerical methods, computational fluid dynamics (CFD) has been a useful tool in supercritical flow instability analyses. Sharabi et al. [11] performed an instability study of supercritical water inside a single heated channel using Fluent. Results revealed that the standard k-ε turbulence model with wall functions could capture the onset of unstable behaviour. A series of investigations was conducted by Ampomah-Amoako et al. [12–14] with the STAR-CCM + CFD code, the 1-D RELAP5/MOD3.3 code, and an in-house linear code. The agreements of different codes in predicting the flow instabilities in single heated channel gave confidence in using the CFD code for future stability analyses. Ebrahimnia et al. [15] studied the supercritical water flow instabilities in a single heated vertical channel using the ANSYS CFX code. Negligible effects of turbulent Prandtl number variation on instability thresholds were observed and the k-ε turbulence model was recommended for stability prediction.

For instability study in parallel channels, Chatoorgoon [16] did an early investigation in two horizontal parallel channels with supercritical water. Non-dimensional parameters defining instability boundaries were analytically derived and were numerically verified with the 1-D SPORTS code. The importance of an accurate state equation for predicting supercritical flow instabilities in parallel channels was pointed out. Hou et al. [17] used linear and non-linear methods to investigate the stability performance in parallel channels of a newly designed mixed-spectrum SCWR (SCWR-M). Results showed that stability in parallel channels was mostly determined by the hottest channel. The existence of a transitional stability region was also identified. Liu et al. [18] examined the effects of energy transfer on flow instability in parallel channels of the SCWR-M and reported that decreasing the wall thermal conductivity could stabilize the system and that the system was not very sensitive to the distributions of axial power. Xiong et al. [19] experimentally analyzed the stability in two vertical parallel channels with supercritical water. Nine points of oscillatory instability thresholds were obtained at different flow conditions. Over the range of conditions tested, increasing the system pressure and decreasing the inlet temperature stabilized the flow. These experiments were subsequently simulated with a 1-D nonlinear in-house code [20] and 3-D CFX code [21]. Both 1-D and 3-D codes were proved able to predict the onset of oscillatory instability in parallel channels. Because the CFX code predictions agreed better with the experiments than the 1-D code predictions, Xi et al. [21] stated that the CFX code yielded better predictions of the onset of flow instability than the 1-D code. Xi et al. [22] also carried out another similar experiment of supercritical water flowing upward in vertical parallel channels. Their experimental loop was the same as that of Xiong et al., but the channel heated sections used a larger wall thickness. The influence of axial power shape on the flow instability prediction was studied; results indicated that the system would be more stable with a uniform axial power