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Numerical stability analyses of upward flow of supercritical water in a vertical pipe

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ABSTRACT

A numerical study is performed for 2-D axisymmetric turbulent flow of supercritical water flowing upward in a vertical pipe with constant applied wall heat flux. This study uses Computational Fluid Dynamics (CFD) to analyze supercritical flow instability in a vertical heated channel. The governing equations are solved using two RANS models in the CFD code ANSYS CFX v14.5. Analyses of static and oscillatory flow instabilities are performed using the standard k–ε model with a scalable wall-function and the k–ω-based SST model. The instability threshold results of the CFD code are compared with 1-D non-linear code predictions. Also, criteria for approximating the thresholds of static and oscillatory instabilities based on steady-state results are assessed and discussed. The effect of changing the turbulent Prandtl number (Pr_t) on the instability threshold is also examined. It was observed that the instability threshold results obtained using the k–ε and the SST models are similar. Also, the results of the CFD and 1-D codes are different due mainly to the different pressure drop predictions between the two methodologies. Comparisons of instability threshold predictions between CFD and 1-D codes showed smaller differences for static instabilities and greater differences for oscillatory instabilities. In addition, approximating the flow instability threshold by the criteria proposed generally holds true for a CFD solution. Results also indicate that the value of Pr_t does not have a noticeable effect on the instability threshold for the cases examined in the present study.

1. Introduction

The Supercritical Water Reactor (SCWR) has been proposed by the U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum [1] as one of the six concepts for new Generation IV reactors. Using supercritical water in reactors as a primary coolant should provide an improvement in overall plant efficiency compared to other types of Light Water Reactors (LWRs) (approximately 45% versus 33% for LWRs). Considerable design simplification is another feature of an SCWR, which distinguishes it from other LWRs. However, despite the benefits of using supercritical water in terms of overall efficiency, thermal hydraulic instabilities are likely to arise in Supercritical Water Reactors due to the sharp variations of some physical properties (mainly the density) along a heated pipe. A flow is stable if, when disturbed, its new operating conditions tend asymptotically towards the original initial condition; otherwise, the flow is said to be unstable. Two different kinds of instabilities have been reported: static (also called 'excursive'), and dynamic (also called 'oscillatory' and 'density-wave oscillation'). Both types of instabilities are undesirable and flow conditions should be designed with a sufficient margin against them to ensure safe operation of the respective design.

There have been very few properly documented experimental studies on supercritical water flow stability in heated channels. A noteworthy one was recently reported by Xiong et al. [2], who performed an experimental study on the stability of supercritical water in two parallel channels connected by a plenum at both the inlet and outlet. In their experiments, the heat flux was increased gradually while keeping other parameters constant until the instability boundary was found. Daney et al. [3] performed experiments to obtain the flow instability boundaries in supercritical helium. In their experiment, supercritical helium was flowing in a long, heated channel. They observed density-wave oscillations, during which the outlet temperature and the inlet mass flow rate of the channel oscillated in phase. Fukuda et al. [4] conducted an experimental study on the instability of supercritical helium flowing in a spiral tube. The pressure and the mass flux were kept constant, while the heat flux was changed. They observed three types of flow oscillations: (1) type A was accompanied by the oscillations of inlet and outlet pressure and not the temperature; (2) type B

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Nomenclature

D	diameter
g	acceleration due to gravity
G	mass flux
h	enthalpy
h_{tot}	total enthalpy ($h_{tot} = h + \frac{1}{2}U_iU_i + k$)
k	turbulence kinetic energy per unit mass ($k = \frac{1}{2}\overline{u_iu_i}$)
K_{loss}	loss coefficient
L	length
$\dot{m}$	mass flow rate
p	static pressure
P'	modified pressure ($P' = p + \frac{2}{3}\rho k$)
Pr	Prandtl number
Pr_t	turbulent Prandtl number
q''	wall heat flux
R	tube radius
S_M	momentum source term
T	temperature
t	time
U	velocity magnitude
u	fluctuating velocity component in turbulent flow
u_τ	friction velocity
y	distance of the first node from the wall
y^+	dimensionless distance of the first node from the wall ($y^+ = \rho u_\tau y/\mu$)

Greek symbols

ε	turbulence dissipation rate
$\epsilon_{ins,CFD}$	relative difference of $\dot{m}_{ins}$ between turbulence models
ρ	density
λ	thermal conductivity
μ	dynamic viscosity
μ_t	eddy viscosity
ω	turbulence frequency

Subscripts

C	Chatoorgoon criterion
ins	instability threshold
L	Ledinegg criterion
O	oscillatory instability
S	static instability

was accompanied by both temperature and pressure oscillations; and (3) type C was accompanied by both temperature and pressure oscillations, but with lower periods than type B. They concluded that type A is a Helmholtz instability caused by the compressibility in the tubing, while types B and C are density-wave oscillations caused by large changes in physical properties.

A significant number of analytical and numerical analyses on the stability of supercritical flows have been reported. The first comprehensive analytical study of various supercritical flow instability modes was reported by Zuber et al. [5]. They discussed the mechanisms that could induce thermo-hydraulic oscillations at supercritical pressures and suggested improvements to eliminate the onset of oscillations. Bouré et al. [6] presented a classification of different types of two-phase flow instabilities. They suggested that a static instability (also called a Ledinegg instability) can be determined using only the steady-state equations. In this case, a small change in the flow conditions results in either a new steady-state dissimilar to the original one or an unreturnable excursion away from the initial steady-state condition. In addition, they also stated that, for dynamic instabilities such as density-wave oscillations, the steady-state equations are insufficient to predict the threshold of instability. More recently, Chatoorgoon et al. [7] and Chatoorgoon [8] proposed a hypothesis for predicting the oscillatory instability threshold in heated channels that relies solely on the system steady-state solution. The hypothesis, applied to heated channels with inlet and outlet plena, states that the oscillatory instability threshold lies very close to the flow rate corresponding to $\partial^2\Delta(p+\rho u^2)/\partial\dot{m}^2 = 0$. In addition, Chatoorgoon [8] performed a study to develop non-dimensional parameters for predicting the static instability boundary using an in-house linear instability code. He concluded that static instability is most likely to happen in vertical down-flow and least likely to occur in vertical up-flow, while oscillatory instability is most likely to happen in up-flow and least likely to happen in down-flow.

Xiong et al. [9] developed an in-house 1-D code by applying a time-domain approach and modeled the experimental study of Xiong et al. [2]. They compared numerical and experimental results and concluded there was good agreement on predicting the stability boundaries. They also showed that the inlet temperature has a non-monotonic effect on the power threshold.

In recent years, there has been an increase in use of CFD simulations in stability analysis of supercritical flow. Sharabi et al. [10] used FLUENT and applied the k–ε turbulence model with standard wall functions and with a low-Reynolds number model on a circular pipe. They compared CFD instability results with linear and non-linear 1-D model results and concluded that, for supercritical pressure conditions, CFD solutions confirm the occurrence of density wave oscillations at relatively large power-to-flow ratios. The results obtained using both turbulence models were in agreement with 1-D code results of Ambrosini et al. [11] and Idaho National Laboratory (INL) [12]. In another study, Sharabi et al. [13] studied density-wave oscillations in triangular and square pitch rod bundles using FLUENT. They compared the results of instability thresholds and found good agreement between CFD and the 1-D codes of Ambrosini et al. [11] and INL [12]. They also concluded that density-wave oscillations in triangular and square pitch rod bundles have similar characteristics to density-wave oscillations in circular channels.

In another study, Ampomah-Amoako and Ambrosini [14] studied the performance of CFD in analyzing supercritical flow stability. They used STAR-CCM+ and compared the CFD instability threshold results with the results of their in-house 1-D code [11] for a circular pipe, as well as triangular and square pitch rod bundle channels. Their work confirmed the occurrence of both static and dynamic instabilities depending on the inlet fluid sub-cooling. To find the instability boundary, they first chose an inlet mass flow boundary condition and obtained the corresponding steady-state condition. Then the boundary condition was changed to a stagnation inlet with an assigned value of pressure upstream of the inlet section, while preserving the flow rate value obtained from the steady-state solution. The power was then increased in steps in search of the instability boundary. The problem with this method is that the same constant pressure drop is imposed across the channel for the different powers, without considering the fact that changing the power changes the channel pressure drop as well.

In a recent and important study, Xi et al. [15] carried out a 3-D numerical simulation of two heated parallel channels with supercritical water using CFX4 to find the instability boundaries. They studied the water experiments of Xiong et al. [2] and compared their results of instability thresholds with the experimental results