Nuclear Engineering and Design 325 (2017) 1–11

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Numerical study of the heat transfer and flow stability of water at supercritical pressures in a vertical tube

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ARTICLE INFO

Keywords:
Heat transfer
Flow instability
Supercritical water

ABSTRACT

The subcritical steam generators in the current High-Temperature-Reactor Pebble-Bed Module, HTR-PM, in China can be replaced by supercritical steam generators to better coordinate the reactors and the supercritical steam turbines to improve thermal efficiencies with no phase change at supercritical pressures. This study numerically analyzed the heat transfer and the flow instabilities of supercritical pressure water. Five turbulence models were evaluated to model the heat transfer with a constant wall heat flux for steady-state calculations with the results showing that the RNG k-ε model with the enhanced wall treatment gave the best results. This model was then used in transient calculations with the wall heat flux increasing linearly with time. The flow and heat transfer characteristics and the velocity and turbulence fields at various times were used to analyze the influences of flow rate variations, thermophysical property variations, buoyancy and flow acceleration. The effects of the fluid inlet enthalpy and pressure drop along the tube on the flow instabilities were also studied.

1. Introduction

The High Temperature Gas-Cooled Pebble-Bed Reactor, HTR-PM, designed by the Institute of Nuclear and New Energy Technology of Tsinghua University, is a typical Generation IV nuclear reactor that is inherently safe and very efficient with many applications as a high-temperature heat source (Zhang et al., 2009). The current thermal efficiency of HTR-PM power plants is 42% with two subcritical steam generators and one steam turbine. However, a large fraction of current thermal power plants are supercritical systems and China has much experience in designing and fabricating supercritical turbines. The higher thermal efficiency of supercritical units is a significant advantage with estimated efficiencies of up to 45% with supercritical steam generators, in which the supercritical pressure fluid flows in the secondary loop, and a supercritical steam turbine. At a subcritical pressure, as the coolant temperature exceeds the boiling point, the occurrence of a boiling crisis causes an abrupt decrease of the heat transfer rate and an increase of the tube temperature beyond its limit. This is one of the major concerns for a nuclear system design (Bae and Kim, 2009). The supercritical pressure fluid density changes substantially but there is no phase change, so the heat transfer deterioration is relatively moderate compared with subcritical pressure fluids, which is also good for the steam generator. The third technical program for HTR-PM power plant development in China is to combine current high-temperature gas-cooled reactors with supercritical steam generators and supercritical steam turbine units (Zhang et al., 2009). Thus, the fluid flow, heat transfer and the flow instabilities of water at supercritical pressure are of great importance.

When the fluids are at supercritical pressures in the steam generator, small fluid temperature and pressure variations can result in drastic changes in the thermophysical properties as shown in Fig. 1. The specific heat, c_p, has a sharp peak at a specific temperature (383.07 °C at a pressure of 24.5 MPa) defined as the pseudo critical temperature, T_{pc}. Other properties including the density, thermal conductivity and viscosity vary also significantly within a small range of temperatures in the vicinity of T_{pc}. These thermophysical property variations such as the viscosity and the density can strongly influence the flow resistance and the heat transfer of the supercritical pressure water. During the flow and the heat transfer process, the fluid thermophysical properties change significantly near the pseudo-critical temperature. The density difference between the fluid near the wall and the fluid in the core is large due to the sharp thermophysical property variations caused by the temperature. The buoyancy force near the wall could accelerate the flow near the wall more/less than in the core according to the fluid flow direction, and the average velocity difference between these two regions would be reduced/increased, and the shear stresses between the

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http://dx.doi.org/10.1016/j.nucengdes.2017.09.013
Received 11 May 2017; Received in revised form 1 September 2017; Accepted 18 September 2017
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Nomenclature

c_p	specific heat ($\mathrm{kJ \cdot kg^{-1} \cdot K^{-1}}$)
ρ	fluid density ($\mathrm{kg \cdot m^{-3}}$)
λ	thermal conductivity ($\mathrm{W \cdot m^{-1} \cdot K^{-1}}$)
μ	molecular viscosity (Pa·s)
v	kinematic viscosity ($\mathrm{m^2/s}$)
Pr	Prandtl number
μ_T	turbulent viscosity (Pa·s)
σ_T	turbulent Prandtl number
r	radial coordinate (m)
x	axial coordinate (m)
d	tube diameter (m)
R	tube radius (m)
L	tube length (m)
u	axial velocity ($\mathrm{m \cdot s^{-1}}$)
v	radial velocity ($\mathrm{m \cdot s^{-1}}$)
y^+	non-dimensional length
g	gravitational acceleration ($g = 9.81\ \mathrm{m \cdot s^{-2}}$)
α_p	isobaric thermal expansion coefficient ($\mathrm{K^{-1}}$)
β	isothermal compression coefficient ($\mathrm{M\,Pa^{-1}}$)
G	mass flow rate ($\mathrm{kg \cdot m^{-2} \cdot s^{-1}}$)
Q	heating power (W)
q	heat flux ($\mathrm{W \cdot m^{-2}}$)
h	heat transfer coefficient ($\mathrm{W \cdot m^{-2} \cdot K^{-1}}$)
p	pressure (Pa)
ΔP	inlet to outlet pressure drop (kPa)
T	temperature (°C)
T_b	bulk temperature (°C)
T_{pc}	pseudo critical temperature (°C)
h_b	bulk enthalpy ($\mathrm{kJ \cdot kg^{-1}}$)
h_{in}	inlet enthalpy ($\mathrm{kJ \cdot kg^{-1}}$)
h_{pc}	pseudo critical enthalpy ($\mathrm{kJ \cdot kg^{-1}}$)
k	turbulence kinetic energy ($\mathrm{m^2 \cdot s^{-2}}$)
ε	turbulence dissipation rate ($\mathrm{m^2 \cdot s^{-3}}$)
t	time (s)
Bo^*	non-dimensional buoyancy parameter
Gr^*	Grashof number
$\mathrm{K_{VT}}$	non-dimensional thermal expansion acceleration parameter
Re	Reynolds number
$\mathrm{N_{SPC}}$	sub-pseudocritical number
$\mathrm{N_{TPC}}$	trans-pseudocritical number

wall and the core and the turbulence production would be reduced/increased, which affects the flow and heat transfer. Moreover, the fluid accelerates along the tube during heating so the axial pressure gradient increases. The shear stress in the vicinity of the wall will be reduced to balance the increased pressure gradient, so the turbulence near the wall is suppressed which impairs the heat transfer (Jackson and Hall, 1979).

Many studies of the in-tube flow and convection heat transfer of supercritical fluids have been conducted in recent years. Jiang et al. (2012, 2013) and Zhao and Jiang (2011) with many experiments and numerical studies of the flow and heat transfer of supercritical pressure fluids such as CO_2, R22, R134a and ethanol in normal and micro-size tubes to evaluate the effects of buoyancy, flow acceleration, and the significant variations in the thermophysical properties. He et al. (2008a) and Kim et al. (2008) used an ‘in-house’ CFD code named SWIRL to simulate the supercritical pressure fluid heat transfer by comparison with DNS results available in the literature to evaluate the performance of low-Reynolds number turbulence models, especially the features enabling them to respond to the changes with turbulence field due to the influences of flow acceleration and buoyancy. Their results showed that for strong buoyancy influenced cases, most models were able to reproduce the turbulence recovery reasonably well but not the heat transfer improvement, which was attributed to the inability of the turbulence models to reproduce the turbulent heat flux using a constant turbulent Prandtl number. Pan et al. (2011) conducted experiments with water flowing in smooth and rifled tubes at subcritical and supercritical pressures to explore the heat transfer characteristics of the rifled tube at low mass fluxes. Their results showed that the rifled tube significantly improved the heat transfer of supercritical water, especially near the pseudo-critical point. Recently, Yoo (2013) presented an overview of recent progress towards understanding the mechanisms of supercritical pressure flows in the pseudocritical temperature region.

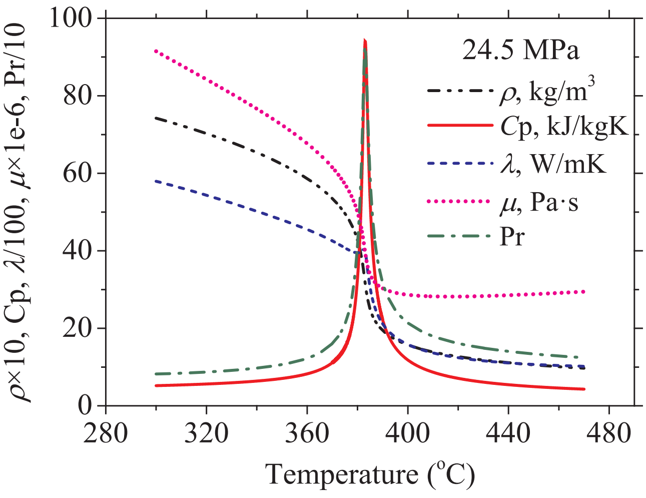

Fig. 1. Thermophysical property variations with temperature.

For the flow instabilities, Ruspini et al. (2014) reviewed the research on two-phase flow instabilities including experimental and analytical results regarding density-wave and pressure-drop oscillations, as well as Ledinegg excursions, introducing descriptions of the main mechanisms during these phenomena. Ambrosini and his group have done many numerical studies of fluid flow instabilities. They first analyzed the mechanism during density-wave oscillations in a boiling channel with a uniform, constant heat flux using linear and nonlinear analytical tools (2000) and proposed a unified view of the boiling and supercritical flow instabilities (2007) with dimensionless numbers to analyze the supercritical fluid stabilities in heated channels (2008). They used the standard k-ε turbulence model with the non-equilibrium wall functions and the low-Reynolds number, Yang and Shih model in Fluent to simulate the unstable supercritical pressure water flow in a heated channel, with the results compared with predictions of a one-dimensional model (Sharabi et al., 2008). Ambrosini (2011) assessed the flow stability boundaries in a heated channel with different supercritical pressure fluids and found that an appropriate dimensionless formalism gave nearly the same stability thresholds at a given heat flux for very different fluids.

Another non-dimensional groups for supercritical pressure fluid stability maps were proposed by Gomez et al. (2008) and the authors found that while density-wave oscillations occurred, Ledinegg excursive instabilities and pressure drop oscillations did not occur in supercritical water systems. Zhang et al. (2015) presented new partitions for supercritical water to better deal with the large physical property variations near the pseudo critical point and used this model to study the density wave instabilities for supercritical water flowing in tubes in the frequency domain with more accurate results than the previous models. Ebrahimnia et al. (2016) used ANSYS CFX with the standard k-ε model with the scalable wall-function and the k–ω-based SST model to

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