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Numerical study on the effect of pipe wall heat storage on density wave instability of supercritical water

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ABSTRACT

A time-domain model is developed to study density wave oscillation (DWO) of supercritical flow. The model takes the wall heat storage process into account by introducing a wall metal heat storage equation and a convective heat transfer equation. The present model is compared with the similar studies from the previous literature. After that, the model is employed to study the effect of structural parameters (pipe length, wall thickness, etc.) on DWO of supercritical flow in a heated pipe. The results show that the wall heat storage significantly changes the influence rules of pipe structural parameters on flow instability. Under the situation without the wall heat storage (the wall thickness is zero), system stability first decreases with the pipe length and then tends to be unchanged. While for the case of the wall thickness beyond zero and the wall heat storage should be considered, the variation of the system stability with pipe length is different, and there exists a critical value about pipe length ('L_{cr}') where the variation of system stability with pipe length is reversed. When pipe length is less than L_{cr}, the system stability decreases with the pipe length. When pipe length is greater than L_{cr}, the system stability increases with the pipe length. Moreover, L_{cr} decreases with the wall thickness.

1. Introduction

With the development of the technology that using supercritical pressure water as the working medium, the operation parameters of the power unit have been raised by a wide margin, and the total thermal efficiency of the power station has been significantly improved. The useful power fraction can be raised from 33% as in conventional light water reactors (LWRs) to up to 44% as in supercritical water-cooled reactor (Squarer et al., 2003), and the net efficiency of (ultra) supercritical pressure coal-fired power plant can be raised to up to 40–45%, compared with the net efficiency (37%–38%) of subcritical pressure coal-fired power plant (Chen, 2005). With these advantages, supercritical water-cooled reactor and (ultra) supercritical coal-fired power plant have exhibited a wide application prospect. In the operation of supercritical water-cooled reactor and super (super) critical coal-fired power plant, supercritical pressure water in the cooling loop always experiences a large and continuous density variation in the large specific heat region, as seen in Fig. 1, although supercritical pressure water has no phase change. Considering this point, it can be expected that the density wave oscillation (DWO) phenomenon may also occur in the supercritical flow (Gómez et al., 2008). As we all known, DWO is characterized by a continuous oscillation of such parameters as mass flow rate, fluid temperature, tube wall temperature, etc., and may further induce mechanical vibrations, thermal fatigue of the pipe structure, and also result in problems in system controlling (Kakaç and Cao, 2009). Therefore, it is necessary to study and prevent DWO instability in supercritical water-cooled reactor and super (super) critical coal-fired power plant.

The factors that affect DWO instability can be generally grouped into two categories: the first category is the operating parameters such as mass flow rate, fluid pressure, inlet fluid temperature, heat flux, etc. The second category is the structural parameters, including pipe length, wall thickness, pipe diameter, etc.

Most of the past study focused on the first category of the factors, such as: Jing et al. (1996), Chen (2002), Li et al. (2005), Gao et al. (2005a,b), Huang et al. (2009, 2010) conducted a series of experimental studies based on the High Temperature and High Pressure two phase flow and heat transfer test loop (Hi-TaP-XJTU), and they further discussed about the effect of system pressure, mass velocity, inlet subcooling, total number of pipes, heat load, and other parameters on DWO instability of subcritical two-phase water in parallel pipes. Su (1998) and Su et al. (2002) conducted a large number of experiments on the two-phase DWO instability in a natural circulation system, and then discussed the variation of instability boundary with the system pressure, inlet mass flow velocity, and inlet fluid temperature. Zhang et al. (2014) proposed a frequency-domain model suitable for two-phase

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Nomenclature

A	cross-sectional area, m^2
C_p	specific heat at constant pressure, kJ/(kg·K)
C_M	metal specific heat capacity, kJ/(kg·K)
Cf	resistance coefficient
D	pipe inner diameter, m
F	inner surface area of the pipe wall per pipe length, m
f	frictional resistance coefficient
G	mass flow velocity, kg/(m^2·s)
g	gravitational acceleration, m/s^2
h	fluid enthalpy, kJ/kg
j	sequence number of calculated sections
K	local resistance coefficient
k	time layer
L	pipe length, m
M	mass flow, kg/s
Nu	Nussult number
P	pressure, MPa
Pr	Prandtl number
Q	heat flux per length transferred to the fluid, kW/m
Q_{ex}	heat flux per length on the outside pipe wall, kW/m
Q_{hsm}	heat flux per length stored in the pipe metal, kW/m
q	heat power, kW
Re	Reynolds number
T	temperature, °C
t	time, s
z	the axial distance from the pipe inlet, m
ΔP	pressure drop, MPa

Greek letters

α	heat transfer coefficient, kW/(m^2·K)
β	isobaric thermal expansion coefficient, 1/K
ρ	density, kg/m^3
θ	inclination angle with respect to horizontal direction
λ	thermal conductivity, W/(m·K)
μ	dynamic viscosity, kg/(m·s)

Subscripts

b	bulk
in	inlet
M	pipe metal
out	outlet
pc	pseudo-critical point
w	pipe wall

instability in the internally-ribbed tubes, and used this model to analyze the effect of inlet fluid subcooling, and inlet mass flux on the system stability. Chatoorgoon et al. (2001, 2005) analyzed the instability phenomenon of supercritical fluid in a single-channel natural circulation system using the non-linear stability SPORTS code, and then obtained the threshold heat load under different inlet fluid temperature, different mass flow, and different system pressures. Xiong et al. (2013) developed a time-domain model suitable for the DWO instability of supercritical flow in parallel two pipes, and used the model to investigate the effect of inlet temperature and total flow rate on the system stability. In general, a large number of these experimental and numerical studies had formed a mature and unified understanding for the effect of the first category of factors on DWO, such as: increasing system pressure and inlet mass flux, or decreasing heat load of the pipe can prevent DWO phenomenon and enhance system stability, and so on. However, the experimental study on DWO of supercritical fluid was still scarce, due to the danger and difficulties brought by relatively higher pressure.

The second category of factors (such as the pipe length, wall thickness, etc.) also imposes a great impact on DWO, but was rarely discussed by past studies. Colombo et al. (2012) studied DWO under subcritical two-phase conditions by using RELAP5/MOD3.3 code, and they found that a parallel pipe system exhibited a marked stabilization with the increase in pipe length, but the stability of a single pipe system had a slight change with the increase in pipe length. Zhang (2015) used a frequency domain method to study the effect of pipe length on DWO at subcritical two-phase conditions and found that a single pipe system always tended to generate DWO instability in a longer pipe. Crowley et al. (1967) conducted an experiment in which Freon was used as the working medium, and they measured DWO process in one heated pipe with different lengths under the condition of fixed inlet total mass flux and fixed total heat power. They found that a forced flow was more stable in a shorter pipe. Jin and Pan (2005) developed a nonlinear numerical model to research two-phase instability phenomenon in a natural circulation system affected by the nuclear reaction coupling, and their results showed that lengthening the riser length had an unstable effect on system stability due to enlarging the pressure drop of the system. In all of the above studies, there existed two problems. One is that some differences existed in the conclusions among different literature. The other one is that, the heat storage process of the pipe wall was always ignored in most of these existing numerical models. These models considered that changing pipe length may affect DWO through bringing some impacts to the pressure drop variation along the system. However, the wall heat storage objectively exists, and also greatly affects DWO instability. It is not difficult to understand that the total heat power on the external surface of the pipe wall is not directly, instantly, and completely transferred to the working medium in the pipe, but is first transferred to the wall metal. Then wall metal absorbs and stores a part of the total heat power, and transfers the remaining heat power to the working medium. Moreover, the heat load stored in the wall metal varies with pipe length. As a result, the heat load absorbed by the working medium also changes, and this finally affects the property variation of the working medium, as well as DWO instability of the flow in the pipe. Because most of the industrial pipelines systems were composed of thin-wall pipes in early time, so the effect of wall heat storage was not obvious (Zhang et al., 2014). In recent years, the operation parameters of the power unit have been significantly raised in supercritical water-cooled reactor and supercritical boiler, and the

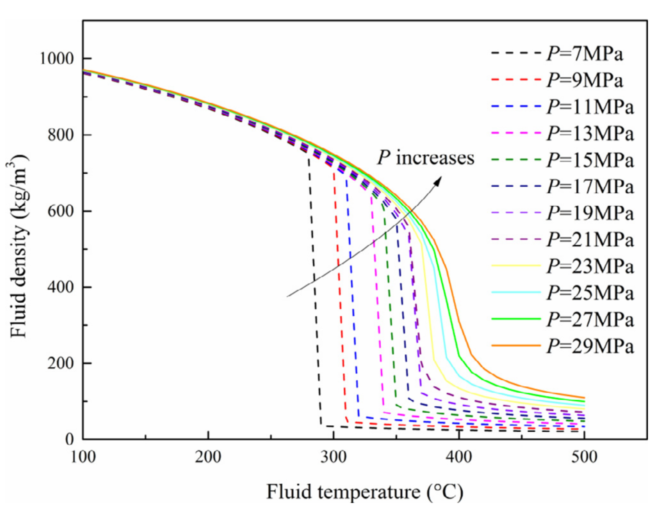

Fig. 1. Variation of water density with fluid temperature at different pressures.