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Experimental research and theoretical analysis of flow instability in supercritical carbon dioxide natural circulation loop

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HIGHLIGHTS

- A new mechanism of flow instability of supercritical CO_2 was presented.
- Experiments on flow instability of supercritical CO_2 were carried out.
- Effects of typical thermal parameters on flow instability were detailed studied.
- The new mechanism agreed well with experimental results.

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ABSTRACT

In the last decade, supercritical carbon dioxide power cycle has attracted worldwide attention. The characteristics of flow instability are critical for the design and safe operation of supercritical carbon dioxide power cycle. In the present paper, theoretical and experimental study was carried out to investigate the characteristics of flow instabilities in supercritical carbon dioxide natural circulation loop. A new explanation of the mechanism of flow oscillation in supercritical carbon dioxide natural circulation has been put forward. It found that the pressure fluctuation, which resulted from the variation of heat transfer mode, might be amplified under the condition of appropriate non-dimensional pressure drop in supercritical fluids natural circulation loop. Effects of typical thermal parameters on flow instabilities of supercritical carbon dioxide natural circulation were discussed in detail. Results showed that, for supercritical fluids natural circulation system, an increase in the system pressure and the local resistance coefficient in the cold section, and a decrease in the local resistance coefficient in the hot section could enhance the system stability.

1. Introduction

Along with the problem of energy crisis and environmental pollution becoming increasingly outstanding, research on the advanced power cycle is highly concerned. In the last decade, supercritical carbon dioxide power cycle has attracted worldwide attention. One of the prominent features of supercritical carbon dioxide power cycle is its ability to achieve considerable efficiency in a variety of applications operating with intermediate temperature [1]. It has been suggested as the power cycle for solar-thermal system [2,3], the next generation of nuclear reactor [4,5], as well as waste heat recovery system [6]. One of the key issues is to assure safety of the systems mentioned above. Because of the simpler system structure and better reliability, natural circulation has been used to improve the passive safety of system. Some of the above systems are even designed as natural circulation systems [7]. The characteristics of flow instability in natural circulation is critically important for the design and safe operation of the system.

Density-wave oscillation is by far the most studied kind of two-phase flow instability. In two-phase natural circulation system, any disturbance could result in a significant change in density and void fraction. For natural circulation system, the hydrostatic head is sensitive to the variation of density(void fraction). The feedback between mass flow rate, density(void fraction) and hydrostatic head could lead to flow oscillation [8]. For supercritical fluids natural circulation, even though there is no phase change, the density is dynamically changed because the fluid density is strongly relied on the temperature (Fig. 1). The significant and dynamical variation of density near the pseudo-critical region would result in obvious feedback between flow, density and head, which could lead to flow oscillation in supercritical fluids natural circulation system.

There has been very few experimental investigations on the flow instabilities of supercritical fluids natural circulation. Harden and

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Nomenclature

Bu	buoyancy parameter
c_p	specific heat capacity, kJ/kg/K
D	diameter, m
f	friction coefficient
g	gravitational acceleration; m^2/s
G	mass flux; kg/m^2/s
$\overline{Gr_b}$	Grashof number based on density;
p	pressure, MPa
p^*	non-dimensional pressure
Pr	Prandtl number
$\overline{Pr}$	average Prandtl number
Re	Reynolds number
T	temperature, °C
v	velocity, m/s
x	axial distance, m

Greek symbols

β	volume expansion coefficient, 1/K
ρ	density of fluid, kg/m^3
$\bar{\rho}$	average density of fluid, kg/m^3
μ	dynamic viscosity, Pa·s
τ	shear stress, N/m^2
δ	thickness of buoyant layer, m
δ^+	non-dimensional thickness
Δ	difference value

Subscripts

a	accelerated
b	bulk
c	cold
d	local
f	frictional
h	heated
in	inlet
w	wall

Buggs [9], Cornelius [10] investigated the characteristics of flow instability in natural circulation using Freon as working fluid. Flow instabilities were observed when the bulk fluid temperature in the loop got close to the pseudo-critical temperature. The authors suggested that the oscillation might be caused by the interaction between the heat transfer and variation of the thickness of thermal boundary. However, no further discussion was carried out. Chen et al. [11] experimentally found that flow oscillation occurred when the outlet temperature of the heating section got close to the pseudo-critical temperature in the supercritical water natural circulation loop. The authors speculated that the temperature-sensitive thermal properties near the pseudo-critical region would result in perturbation in the boundary layer, which would lead to the occurrence of flow oscillation. However, no detailed theoretical analysis was performed. Sharma et al. [12,13] performed experiments on the characteristics of flow instability of supercritical water and carbon dioxide natural circulation. Flow instability was only observed in a narrow window of power, which might be attributed to the authors' experimental method. In the experiments of Sharma et al., the inlet temperature of heating section was increased with power. When the inlet temperature got close to the pseudo-critical temperature, the threshold power for flow instability would increase obviously. The authors speculated that the flow instabilities in the supercritical fluids natural circulation can be attributed to high volumetric thermal expansion coefficient for supercritical fluids and the high specific heat capacity near the pseudo-critical temperature. Merlin [14] and Lv et al. [15] observed flow oscillations of high frequence (35–60 Hz) as well as low frequency (~0.02 Hz) when the bulk fluid temperature was close to the pseudo-critical temperature in supercritical water natural circulation loop. Yu et al. [16] carried out investigation on the steady-state and instability of supercritical water natural circulation, and no instability was found. It is worthwhile to note that the system pressure was higher than the critical pressure, while the fluid temperature in the apparatus was much lower than the critical temperature in the experiments of Yu. Chen et al. [17] carried out experiments on transcritical and supercritical carbon dioxide natural circulation flow in a rectangular loop, and no flow instability was found. The test loop was operated without a pressurizer. Hence, the system pressure would increase with power, which would increase the threshold power of flow instability.

Various researchers have performed numerical studies on the flow instability of supercritical fluids natural circulation. Chatoorgoon [18,19], Jain [20], Jain and Rizwan-uddin [21] and Sharma et al. [22,23] studied the characteristics of flow instability in supercritical water and carbon dioxide natural circulation with one-dimensional

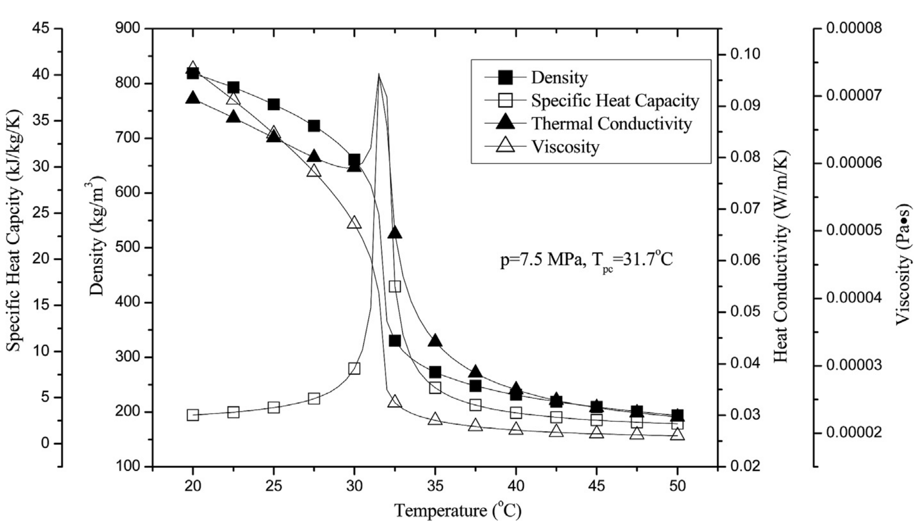

Fig. 1. Variations of thermal properties with temperature near the pseudo-critical temperature.