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Effect of heat transfer on the instabilities and transitions of supercritical CO_2 flow in a natural circulation loop

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ABSTRACT

System stabilities are of critical importance in natural circulation applications. Investigations show that for supercritical CO_2 flow new behaviors can be seen in natural convection systems considering its temperature-sensitive physical properties. In the present study, numerical simulations on a supercritical CO_2 natural circulation loop have been carried out to investigate the flow transitions and instabilities of such systems. In the present model heat sink temperature is kept at 298 K while heat source temperature varies in the range of 310–1023 K as a controlling parameter. It is found for the first time that for the present supercritical CO_2 model there exists a transition heat source temperature at which the system changes from unstable repetitive-reversal flow into stable one-direction flow with the increase of temperature, which is fundamentally different from previous studies for normal fluid. In particular, the critical transition fluid temperature is found to be near the second "pseudo-critical temperature" at around 375 K where the fluid properties experience major transitions with the increase of temperature. In addition, characteristics of flow stability behaviors are also analyzed in detail.

1. Introduction

Flow dynamics of supercritical CO_2 is of critical importance in both practical supercritical devices design and fluid flow sciences. As a natural working fluid, CO_2 is a nonflammable, nontoxic alternative that could be safely used in place of traditional CFCs, HCFCs and also hydrocarbons, ammonia in a lot of fields. CO_2 is also proved to be environmentally benign due to the fact that its ODP (Ozone Depletion Potential) = 0 and GWP (Global Warming Potential) = 1. In addition, using CO_2 as a working fluid provides another approach of CO_2 capturing and storage, which could also contribute to reaching the Kyoto Protocol's CO_2 emission-target. Now both in the laboratory and industrial fields, supercritical CO_2 is widely employed as in materials preparation [1,2], chemical extraction [3], new generation nuclear reactors [4], cryogenic refrigeration [5], and heat pump systems [6,7], etc.

The basic flow and thermal–physical behaviors of supercritical CO_2 have been discussed by Hall [8], Protopopov [9], and later by Jiang et al. [10], Jackson [11], recently by He [12]. Zappoli [13] and Duffey and Pioro [14] have made a comprehensive review. System behavior and optimal design of supercritical CO_2 flow have also been widely investigated [14,15]. Among these literatures natural circulation attracts a lot of attention. In the absence of pumps and their associated mechanical devices, a natural circulation system can work well and thus it has advantage over a forced circulation system in terms of cost, system reliability and maintenance. Natural circulation systems using supercritical CO_2 as working fluid give good performances [16,17]. However, for near critical CO_2 fluid the physical properties and transport coefficients would experience dramatic changes, leading to chaotic behaviors and instabilities. And the mechanisms of these behaviors, especially system instabilities are still not clearly learned and explained due to the complexities of both system geometries and various boundary conditions. In order to illustrate this, some studies have been conducted and published recently [18–20]. In these publications, a rectangular natural circulation loop (NCL) with a heat sink placed on one side and a heat source on the opposite side is used to analyze the basic features. The factors that might affect system stability are also identified. Table 1 shows the major conclusion of some investigations on supercritical flow instabilities in rectangular natural circulation loops (NCL) with a focus on the effect of heat input on system instabilities. Although stability maps are given in these works, their application is still limited considering various geometry design and flow conditions.

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Nomenclature

A	area (m^2)
c_p	specific heat capacity (J/kg K)
D	diameter of pipe (m)
E	energy (J)
g	gravitational acceleration (m/s^2)
H	length of vertical pipes (m)
L	heating (cooling) length of a pipe (m)
L_0	total length of a horizontal pipe (m)
L_1	adiabatic pipe length on horizontal pipe (m)
$\dot{m}$	mass flux (kg/m^2 s)
P	pressure force (Pa)
p	pressure of the fluid (Pa)
Re	Reynolds number
t	time (s)
T	temperature of fluid (K)
u	velocity (m/s)
$\overline{V}$	dimensional velocity (m/s)
x	x coordinate location (m)
y	y coordinate location (m)

Greek letters

λ	thermal conductivity (W/m K)
μ	dynamic viscosity (kg/m s)
Φ	dissipation function, ($\equiv (\bar{\tau} \cdot \nabla) \cdot \overline{V}$) ($J/m^3$ s)
$\bar{\tau}$	shear tensor, $\left(\equiv \begin{pmatrix} \tau_{xx} & \tau_{xy} \\ \tau_{yx} & \tau_{yy} \end{pmatrix}\right)$ (Pa)
ν	kinetic viscosity (m^2/s)
ρ	density of fluid (kg/m^3)

Subscripts

b	bulk
r	radial direction (m)
ref	reference value, bulk value
x	local, value of specific axial location

The system stability of rectangular natural circulation loop is also a science problem that involves fluid dynamics. Table 2 is a summary of investigations on symmetric rectangular NCLs, in which water is generally used as working fluid. In these literatures system instabilities can be divided into two groups: chaotic fluctuating flow and flow reversal. Those two kinds of flow instabilities have already been found both in numerical simulations and real experiments as shown in summary Table 2. Tables 1 and 2 show the major concerns of this research subject. Generally five factors are found responsible for rectangular NCL systems instabilities: heat transfer condition, loop diameter, aspect ratio, loop inclination angle and gravity intensity. In Table 2, various system stability maps are found for water cases. It can be seen that the system instability is very often associated with large heat input rate, large loop diameter, very high or very low aspect ratio and unit aspect ratio; and for loop inclination and gravity intensity there exist critical bifurcating values.

A simple assumption is often made that the supercritical system should be similar to that of a water-based system shown in Table 2. However, due to the unique thermal and transport properties of supercritical CO_2 this simple assumption is not always true. For example, the supercritical fluid viscosity is quite low and thus the flow can be affected a lot by even a slight change of forces acting on it, and the change of temperature can also affect that a lot. So it is of importance to obtain in-depth knowledge of supercritical flow stabilities and it is also reasonable to give those five factors mentioned above a second consideration here. And for most previous studies (see Tables 1 and 2), one-dimensional model is assumed. This one-dimensional model neglects the fluid–wall interaction and prescribes a uniform distribution of parameters along the radial direction of loops and that may be too simplified to unveil the true flow and field behavior of NCL. Thus some publications recommend trying two- or three-dimensional models for the information that a one-dimensional model is not able to capture [32].

The present study focuses on a two-dimensional model for a rectangular natural circulation loop utilizing supercritical CO_2 as working fluid. The purposes of this paper are: (1) to investigate effect of heat transfer conditions on the stability of such a natural convection system; (2) to study the supercritical CO_2 flow behavior at different heat transfer levels and discuss the mechanisms; and (3) to give a brief stability map and transition features involving the effect of heat transfer condition.

2. Physical model and approaches

2.1. Physical model

In the present study, a rectangular circulation loop as shown in Fig. 1 is used to investigate the influence of heat input on the flow instabilities and transitions of a supercritical CO_2 natural convective system. The circulation loop is two-dimensional with constant diameter of D. The height and length of the loop is H and L_0, respectively. The heating wall and cooling wall are two sections of horizontal pipes with length L, whose walls are kept with constant temperatures T_H and T_L, respectively. Other walls are assumed to be adiabatic. The present model is simplified from a solar collecting system using supercritical CO_2 as working fluid [15]. The wall thickness is assumed to be zero. The acceleration due to gravity g is 9.8 m/s^2 as shown in Fig. 1.

For convenience, the upper cooling wall of the upper pipe is named as Wall 1, the lower cooling wall of the upper pipe is named as Wall 2, the upper heating wall of the lower pipe named as Wall 3 and the lower heating wall of the lower pipe named as Wall 4. It is also shown in Fig. 1 that some cross-sections and planes are assigned with numbers near the corners and at the inlet and the outlet to monitor the important variables before/after the main heat transfer wall areas.

2.2. Governing equations and defined parameters

In this numerical analysis the set of equations including the continuity equation, the modified Navier–Stokes equation and the energy equation are solved. Since flow-velocity (0–7 m/s) in the loop is relatively low compared with the acoustic speed (>2 × 10^2 m/s) of CO_2 fluid under current model conditions, the incompressibility is assumed. Then the governing equations can be written as following:

Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \quad (1)$$

Navier–Stokes equation for incompressible flow

$$\frac{\partial (\rho \vec{V})}{\partial t} + \nabla \cdot (\rho \vec{V}\,\vec{V}) = -\nabla P + \nabla \left[\mu(\nabla \cdot \vec{V})\right] + \rho \vec{g} \quad (2)$$