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Natural convective flow and heat transfer of supercritical CO_2 in a rectangular circulation loop

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ABSTRACT

Fluid dynamics and heat transfer of supercritical CO_2 natural convection are important for nuclear engineering and new energy system design etc. In this paper, in order to study the flow and heat transfer behavior of supercritical CO_2 natural circulation system, a computational simulation on a closed natural circulation loop (NCL) model has been carried out. The fluid temperature in the loop varies between 298.15 K and 323.15 K, which is across the CO_2 critical temperature, and the density is found to be in the range of 250–800 kg/m^3. The results show a small temperature difference of 25 °C between heating and cooling sources can induce a mass flow with the Reynolds number up to 6×10^4 using supercritical CO_2 fluid. A periodic reversal flow pattern is found and presented in this paper. Enhanced heat transfer phenomenon is also found for the supercritical CO_2 natural convective flow. The mechanisms to this enhancement and the heating effect on the flow are also discussed in detail in the present study.

1. Introduction

Application system utilizing supercritical CO_2 as working fluid is one of the most popular research issues in recent years. The key problem is how to get higher efficiency based on better understanding about the mechanisms and the design of new systems and/or new processes. Now both in the laboratory and industrial stage, supercritical CO_2 offers a promising choice, it can be employed in the process of deposition and preparation of materials [1,2], nuclear reactor applications [3,4], chemical extraction [5,6], cryogenic refrigeration [7], and for the heat pump systems [8–10]. The main reason that supercritical CO_2 is chosen in these applications is that CO_2 is non-flammable, environmental benign, and generally displays high efficiency. However, there still exist difficulties in understanding the behavior of supercritical CO_2 system, due to the temperature-sensitive thermal properties and the geometric complexities of devices, which have been discussed in various previous studies [4,5,8].

The thermal physical properties of CO_2 under supercritical conditions vary greatly even when there is only a quite small change in temperature. Its critical temperature is 304.13 K, with the critical pressure is 7.38 MPa. Fig. 1 shows the thermal physical properties of CO_2 at 9.0 MPa. This pressure of 9.0 MPa represents a typical operation pressure in some energy systems, such as heat pump and solar thermal collector. It is seen that the density, thermal conductivity and viscosity drop dramatically when the temperature increases across the critical temperature. The specific heat curve forms a high peak near the critical temperature.

These thermal physical properties help to explain the flow and heat transfer behaviors exhibited in relevant studies using supercritical CO_2 as working fluids. The basic performance and flow property of supercritical CO_2 have been discussed originally by Hall [11], Protopopov [12], and later by Jiang et al. [13], Jackson [14], recently by He et al. [15,16]. Besides, a lot of studies on the thermal and hydraulic performances of supercritical fluids have also been carried out by other researchers. Bernard Zappoli has made a comprehensive review on these methods and results [17].

Utilizing CO_2 as working fluid in closed systems can also be seen as a way of CO_2 storage which is also very helpful to solve the environmental problems such as global warming and ozone layer depletion. Previous researches focus on basic flow properties and heat transfer behaviors of supercritical CO_2 [18–20]. Now the emphasis has partly shifted toward its application in engineering systems where the more complicated factor of geometric design is involved. For example, Zhang et al. [21,22] systematically studied the performance of a solar energy powered supercritical CO_2 cycle through both experiments and numerical simulations. Nikitin et al. [23] experimentally studied the thermal hydraulic performance of a CO_2 circulation loop.

Most of the systems using supercritical CO_2 as working fluid have shown advantages in both heat transfer behaviors and the

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Nomenclature

A	area
c_p	specific heat capacity
D	diameter of pipe
E	energy
g	gravitational acceleration
Gr	Grasholf number
h	heat transfer coefficient
H	length of vertical pipes
L	heating (cooling) length of a pipe
L_0	total length of a horizontal pipe
L_1	adiabatic pipe length on horizontal pipe
$\dot{m}$	mass flow rate
Nu	Nusselt number
P	external surface force
p	pressure of the fluid
Pr	Prandlt number
q	heat flux
Q_W	boundary heat input
Ra	Rayleigh number
Re	Reynolds number
t	time
T	temperature of fluid
u	velocity
$\overline{V}$	dimensional velocity
x	x coordinate location
X	dimensionless axial coordinate ($X = x/L_0$)
y	y coordinate location

Greek letters

α	thermal diffusivity
β	volumetric expansion coefficient
λ	thermal conductivity
μ	dynamic viscosity
Φ	dissipation function, $(\equiv (\overline{\tau} \cdot \nabla) \cdot \overline{V})$
$\overline{\tau}$	shear tensor, $\left(\equiv \begin{pmatrix} \tau_{xx} & \tau_{xy} \\ \tau_{yx} & \tau_{yy} \end{pmatrix}\right)$
v	kinetic viscosity
ρ	density of fluid

Subscripts

b	bulk
r	radial direction
ref	reference value, bulk value
$wall$	wall value
x	local, value of specific axial location

compactness of system design. But the mechanisms of the behaviors, especially their instabilities are still not clearly known because of the complexities in both geometry and boundary conditions. For CO_2 systems, Yoshikawa et al. [24] numerically and experimentally studied a CO_2 circulation system and found unstable behavior of velocity field, and recommended two or three dimensional model for more detailed knowledge. Chatoorgoon et al. [25] conducted numerical experiments and developed a non-dimension parameter to describe the flow stabilities of supercritical CO_2 in a natural convection loop. Jain and Rizwan-uddin [26] numerically studied the stability threshold in power-curve of two-phase supercritical CO_2 flow in a natural circulation loop. Those works got some useful results, which fit quite well with respective experiments. However, their systems are mostly rectangular loops where an inlet and outlet boundary condition is assumed and the results can be used only through case-by-case analysis, and the general flow behaviors and stabilities for supercritical CO_2 flow are yet to be learned in further studies. Most recently, Kumar and Gopal [27] simulated a closed sub-critical CO_2 based natural circulation loop, and reported that optimal designs for particular system do exist. However, Kumar and Gopal's study used a one-dimensional steady state model and many strict assumptions were made, thus the detailed behavior and inferences are to some extent limited.

In the present system, a closed rectangular circulation loop utilizing supercritical CO_2 is set. The system works under simple heating–cooling condition and no pumping devices are used. Such a simplified model can be considered as a fundamental study and the purpose is threefold: (1) to investigate the flow behavior and stability of such a "without-valve" natural convection system; (2) to study the heat transfer performance of such a supercritical CO_2 based system; and (3) to discuss the mechanisms and inferences of the system. With these aims set, this study can improve our understanding about natural convection energy conversion and other supercritical CO_2 based implicational systems.

2. Physical model and approaches

2.1. Physical model

In the present study, a rectangular circulation loop is set up and shown in Fig. 2 to investigate the flow behaviors and stabilities of

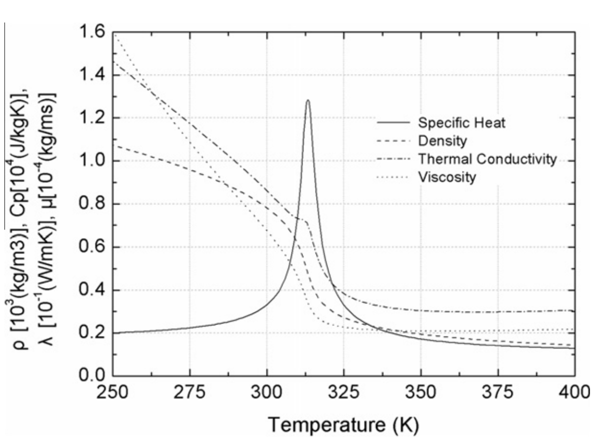

Fig. 1. Thermal physical properties of CO_2 around critical temperature (9.0 MPa).

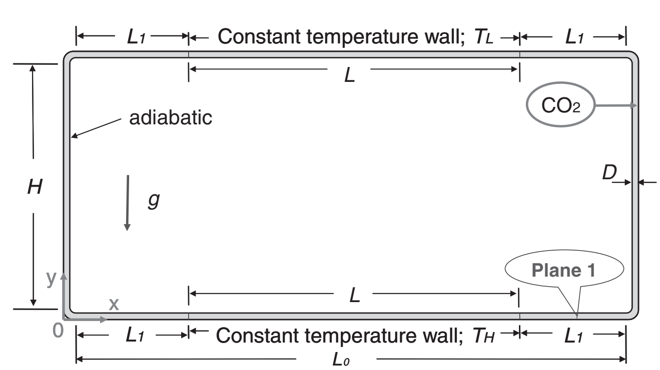

Fig. 2. Schematic of the problem (NCL) studied.