International Journal of Heat and Mass Transfer 90 (2015) 922–930

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Experimental investigation of natural convection in a supercritical binary fluid

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ARTICLE INFO

Article history:
Received 18 August 2014
Received in revised form 20 June 2015
Accepted 6 July 2015

Keywords:
Supercritical binary fluid
Natural convection
Piston effect
Soret effect
Dufour effect

ABSTRACT

We experimentally investigate natural convection of a supercritical nitrogen/argon (0.9/0.1 in molar fraction) binary fluid in a bottom-heated cavity with an aspect ratio of 2.5 in the present study. We obtain the development process of natural convection by the holographic interferometry technique, which is divided into three phases: Stable thermal boundary layer (TBL) phase, Developing phase, and Stable flow phase. After thermal perturbation applied at the bottom, the TBL is thickened and then loses stability and thermal plumes are generated, which signifies the onset of natural convection. Thereafter, natural convection gradually develops to a stable state. As the heat input increases, the experimental results show that the convection grows more intense and spreads deeper into the bulk of the fluid. The TBL in supercritical binary fluid is hydrodynamically more unstable and the natural convection develops faster than the case of a pseudo-pure fluid due to the existence of the Soret effect (SE) and the Dufour effect (DE). The SE and DE are analyzed by comparing the temperature variation in the bulk of a supercritical nitrogen/argon binary fluid with the case of its pseudo-pure fluid counterpart, showing that they enhance the heat transfer in the fluid and further accelerate the development of natural convection.

1. Introduction

Frequently appearing in many occasions, Rayleigh–Bénard (RB) convection attracts much attention in the fields of hydrodynamics in past decades. It is the kind of natural convection in a closed cavity with heating at the bottom and cooling on the top (usually kept at constant temperature) under the gravity. The fluid close to the bottom is heated up and then expands to be lighter than the fluid bulk. When the buoyance driven by the density difference is strong enough to break through the stability of the thermal boundary layer (TBL), thermal plumes are generated and the hot fluid flows upward, which is replaced by the cold fluid in turn near the bottom. The development of RB convection is dominated by the evolution of the TBL, and the flow pattern and the corresponding scaling law highly depend on its stability [1].

RB convection is widely studied in conventional fluids [2–4]. The onset of natural convection only occurs on the heated bottom, i.e., the appearance of thermal plumes, which then gradually develop to the entire fluid domain. However, this process is much different in the case of supercritical fluids because of the diverging variation trends of the thermo-physical properties when approaching the critical point. Some typical characteristics during the development of RB convection in supercritical fluids have been depicted clearly by the numerical and experimental results, which showed that a very thin hot TBL is formed at the bottom, then a homogeneously heated bulk settles in the core at a lower temperature, and a cooler TBL also formed at the top with the colder temperature of the upper wall [5–7]. Amiroudine and Zappoli [8] found an interpretation of the observed unexpected temperature oscillations at the onset of convection under the effect of the piston effect. Furukawa et al. [9] obtained the results for natural convection about supercritical ^{3}He numerically and experimentally, which were compared over a temperature range corresponding to a variation of compressibility by a factor of 40. Shen and Zhang [10] investigated RB convection in supercritical nitrogen confined in a shallow cavity with a slight bottom heating of $q_b = 1\ \mathrm{W\,m^{-2}}$, and the aspect ratio (defined as the ratio of height to width for a rectangular cavity) was 0.25. They found that the temperature rise in the fluid bulk was dominated by the piston effect (PE) and the thermal plumes appeared near both the bottom and top walls, merging later with each other to form the natural convection. Besides, the very onset of RB convection in supercritical ^{3}He close to its critical temperature was discussed by Kogan et al. [11]. Assenheimer and

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.07.019
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Nomenclature

c	molar fraction, –
C	constant, $m^3\ kg^{-1}$
c_P	specific heat at constant pressure, $J\ kg^{-1}\ K^{-1}$
c_v	specific heat at constant volume, $J\ kg^{-1}\ K^{-1}$
k	thermal conductivity, $W\ m^{-1}\ K^{-1}$
N	number of fringe
n	refractive index, –
δn	variation of refractive index
P	pressure, Pa
δP	variation of pressure, Pa
q_b	bottom heat flux, $W\ m^{-2}$
T	temperature, K
δT	variation of temperature, K
t	time, s
u_s	sonic velocity, $m\ s^{-1}$
v_i	molar volume, $m^3\ mol^{-1}$
δt	time interval, s

Greek symbols

α_T	isothermal compressibility, Pa^{-1}
β	thermal expansivity, K^{-1}
ε	dimensionless reduced temperature, –
γ	ratio of specific heats, –
η	dynamic viscosity Pa s
κ	thermal diffusivity, $m^2\ s^{-1}$
ρ	density, $kg\ m^{-3}$
$\delta\rho$	variation of density, $kg\ m^{-3}$
λ	wave length of laser, nm

Steinberg [12] measured the critical temperature difference for the onset of RB convection in supercritical SF_6, which was found to depend largely on the thermo-physical properties according to the further analysis.

However, what unique characteristics will be on display once RB convection occurs in a binary fluid? As far as is presently known, the prerequisites for natural convection are thermal perturbation and gravity. Once a binary fluid is subjected to a thermal perturbation, two unique thermo-physical phenomena will occur, i.e., the Soret effect (SE) and the Dufour effect (DE). The SE is a mass diffusion process driven by the temperature gradient, which will lead to relative transportation between the two components of a binary fluid [13]. The DE is the reciprocal phenomenon to the SE referring to the energy transport carried by the moving molecules in the SE [14]. Coupled with thermal diffusion, the heat and mass transfer in a binary fluid is a double diffusive process, i.e., thermal diffusion and mass diffusion. Consequently, compared with the case of a pure fluid, RB convection will also be affected by mass diffusion in a binary fluid. Huppert and Turner [15] conducted a comprehensive analysis and discussion on convection under double diffusion in salty solutes (typical binary fluids), noticing that the mass diffusion would affect the generation of thermal plumes. Okong'o et al. [16] performed a numerical study about the SE and DE under supercritical conditions, and their results showed that the two effects did enlarge transport matrix. Zimmermann et al. [17] theoretically studied RB convection in an ethanol/water binary fluid using linear theory and the results of which showed satisfactory agreement with experiments. Béghein et al. [18] numerically investigated natural convection in a square cavity filled with air under the initial conditions of horizontal temperature and concentration gradients, obtaining the correlations for the heat and mass transfer rates under various conditions.

Many similar studies can be found in the literature [19–22], but almost all of them are about the binary or multicomponent fluids at conventional states (gaseous or liquid state). However, the double diffusion process in a supercritical binary fluid is much different because of the existence of the PE, SE, and DE, which can considerably affect the onset and the development of natural convection. Therefore, the thermal diffusion process in a supercritical binary fluid must include the thermal conduction and the DE, and the mass diffusion process is dominated by the SE, and the heat can be further transferred by the PE – an adiabatic process. So far, the double diffusion in supercritical binary fluid was only reported by Nakano [23] and Raspo et al. [24], but no further research has been conducted on the topic of RB convection under the effect of double diffusion in supercritical binary fluids.

In the present study, we focus on the natural convection (RB) in a rectangular cavity filled with a supercritical nitrogen/argon binary fluid. The experimental approach is applied to investigate the development of natural convection under the effect of double diffusion. The difference between the natural convections in a supercritical binary fluid and a supercritical pure fluid can be obtained through the experiments, and then we obtain the effect of the double diffusion from the experimental data. These results are quite new for the studies of both supercritical fluid and supercritical binary fluid, and can be helpful to understand the mechanism of heat and mass transfer in a supercritical binary fluid. In the following sections, we introduce the experimental method first, and then present the discussion on the experimental results.

2. Experimental setup and method

The laser holographic interferometry technique [25] is adopted to observe the development of natural convection. The density and temperature variations in the entire fluid domain can be obtained from the holographic interferograms. In the following text, the experimental setup, experimental scheme, and the data reduction will be introduced.

2.1. Experimental setup

The schematic illustration of the experimental cell, with 16 mm in length, 40 mm in height, and 66 mm in the *z*-direction (the direction of laser path), is shown in Fig. 1 a. Three RTDs (Resistance Temperature Detector) are located at the top, middle, and bottom of the cell to monitor the temperatures in the fluid. The experimental cell is placed in a cryostat to maintain the required cryogenic experimental conditions since the critical temperatures of nitrogen and argon are much lower than room-temperature fluids. In Fig. 1 b, we show the schematic illustration of the cryostat. The detailed information of the experimental cell and the cryostat has already been introduced by Nakano and Shiraishi [26]. As we charge a binary fluid with a specific composition into the experimental cell, we use a fluid charging system that was used in our previous study [27] to charge the required amount of each component.

The schematic illustration of the entire experimental setup is shown in Fig. 2. The experimental cryostat is placed at the right position in the objective beam path. As the laser beam passes through the fluid in the experimental cell, the density variations in the fluid change the spatial phase distribution of the laser beam,