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Numerical simulations of the piston effect for near-critical fluids in spherical cells under small thermal disturbance

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ABSTRACT

Near the liquid–vapor critical point, strong anomalies in thermodynamic and transport properties induce the piston effect. In the present study, the piston effect is investigated in spherical cells filled with near-critical fluids under zero gravity and small thermal disturbance conditions by numerically solving the thermodynamic model. The results show typical fast-responding bulk temperature, together with high and stable temperature efficiency, which is determined by the particular nature of near-critical fluids. Particularly, a nondimensionalization method is developed to study the influences of the specific heat ratio on the piston effect by simulations for eight near-critical fluids. Results show the specific heat ratio is an efficient indicator, which is negatively correlated with the nondimensional bulk temperature change. The influences of the characteristic length and the boundary conditions on the piston effect are also studied for near-critical carbon dioxide. In addition, some rules concerning the boundary heat flux and the overall heat transfer are also discussed and concluded.

1. Introduction

The liquid–vapor critical point is the end point of the pressure-temperature curve under which a liquid and its vapor can coexist. At the liquid–vapor critical point, defined by a critical pressure P_c and a critical density ρ_c, phase boundaries vanish. A supercritical fluid is any substance at a temperature and pressure above its critical point. In this study, near-critical fluid refers to a supercritical fluid whose state slightly above critical state. Approaching the liquid–vapor critical point, strong anomalies can be found in thermal and transport coefficients. For example, both of the isothermal compressibility and thermal expansion grow dramatically while the thermal diffusivity tends to zero [1]. The peculiar thermophysical properties of fluids induce a new mode of heat transfer in fixed-volume cells filled with near-critical fluids, which is called the piston effect (PE) [2–4].

In microgravity environment, the thermal relaxation of a near-critical fluid was long thought to be infinitely slow without convection, which was termed as the critical slowing down. However, in 1985, Nitsche and Straub [5] carried out a space experiment and found the temperature at the center of the fluid following the rising wall temperature closely, which meant they actually observed a critical speeding up. Early theoretical studies mainly focused on the physical process of the PE. In 1990, three independent teams [2–4] put forward their explanations using different approaches. Afterwards, Zappoli and Carlès [6] applied matched asymptotic expansions and multiple-time-scale techniques to solve the one-dimensional compressible Navier–Stokes equations for a van der Waals gas and revealed the leading role of the acoustic waves in the PE. Then they [7] used matched asymptotic descriptions techniques and noted that ignoring the influence of bulk viscosity, energy should be transported by acoustic process very close to the critical point. And in this regime, the reflection rules of acoustic waves on thermostatted boundaries are inverted [8]. The amplitude of the reflected wave changes of sign, which is different from normal compressible gases. Moreover, Carlès [9] discovered the existence of viscous regime, during which going closer to the critical point, the heat transfer then slows down. As for density relaxation, Bailly and Zappoli [10] presented a complete hydrodynamic theory of density relaxation. They used matched asymptotic expansion technique to solve one-dimensional Navier Stokes equations and noted that the density relaxation is governed by the PE and heat diffusion. The whole process can be summarized as an expansion-compression zone traveling at the diffusion velocity and ultimately

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disappearing before reaching the other end of the sample cell. Early experimental studies [11–14] mainly focused on the verification of the PE.

In 2006, Miura et al. [15] made the first experimental observation of the thermally induced acoustic waves. Then part of their experimental data was verified analytically by Carlès [16] using asymptotic methods. Onuki [17] presented a general theory of thermoacoustic waves involving the heat conduction in the boundary walls and bulk viscosity. Afterwards, the nature of thermoacoustic waves attracted increasing attention. Shen and Zhang studied the thermoacoustic waves emission, propagation and reflection under different temperature boundary conditions by solving the governing hydrodynamic equations [18]. Besides, they studied the thermoacoustic waves emission under internal and boundary thermal disturbance [19]. Hasan and Farouk also studied the thermoacoustic waves generation under different boundary heating rate using a real-fluid CFD model [20]. The results provided details regarding the thermal transport mechanisms at near-critical and pseudo-critical state fluids, and showed that the heating rate and the initial reduced temperature (i.e. $\varepsilon = (T_0 - T_c)/T_c$, where T_0 and T_c are initial and critical temperature) are key factors in the generation of acoustic waves.

The interplay between buoyant convection and PE has also been an active research topic. Zappoli et al. conducted a series of two-dimensional [21–23] and three-dimensional [24] numerical simulations for near-critical van der Waals fluid by a finite volume method together with an acoustic filtering procedure. A similar problem was further studied by Shen and Zhang [25,26]. Notably, an unexpected temperature oscillations at the convection onset in terms of the PE were found by Amiroudine and Zappoli [27]. The Rayleigh-Taylor-like gravitational instability and thermovibrational instability in near-critical fluids were also studied by Amiroudine et al. [28,29]. A monograph by Zappoli et al. [30] and a review by Shen and Zhang [31] give a detailed summary of previous researches on this topic.

In this paper, the PE in spherical cells filled with near-critical fluids under zero gravity condition is studied numerically to identify how some key factors influence the PE. The thermodynamic model presented by Boukari et al. [3] is used, and an explicit finite difference method using a central difference scheme for the spatial discretization is developed to solve the model iteratively. The NIST database [32] is used to obtain the ρ–P–T relations for near-critical fluids.

The important factors we study in this paper are the specific heat ratio, the characteristic length and the boundary condition. As for the specific heat ratio, some previous studies [33,34] have revealed the relationship between it and the bulk temperature increase. However, their conclusions are drawn from the PE for one near-critical fluid. In the present study, the PE for different near-critical fluids is further studied to show how the specific heat ratio influences the PE. In order to make different fluids be able to be compared with each other, a nondimensionalization method is particularly developed. Regarding the characteristic length, it is an important geometrical factor that changes the physical model. The PE under different characteristic lengths must differ greatly. With regard to the boundary condition, previous studies only focused on the influences of boundary condition on the thermoacoustic process. Thus, it is also significant to study the problem on a longer timescale and deepen our understandings from a macroscopic view. The last two factors are studied for near-critical CO_2, so it is not necessary to nondimensionalize variables.

Besides, it should be mentioned here that small thermal disturbance is considered only in the present study, because under strong thermal disturbance, the initial reduced temperature (i.e. ε, which can be seen as the distance to critical point) will be altered during the PE. As a result, the nature of a near-critical fluid will change dramatically and the controlled variable is altered. For example, when we study the influences of the characteristic length on the PE, the strong thermal disturbance will change the specific heat ratio considerably too. As a result, it is difficult to distinguish the dominant factor.

In Section 2, we introduce the problem formulation and the numerical method used in simulations. An explicit finite difference method using a central difference scheme for the spatial discretization is relied on solving the governing equations, whose validity is also discussed. In Section 3, related definitions of physical quantities are presented. In Section 4, how the specific heat ratio, the characteristic length and the boundary condition, influence the PE is shown and discussed. The paper is finally concluded in Section 5.

2. Physical and numerical model

2.1. Physical model

As shown in Fig. 1, the physical model is a spherical cell filled with near-critical fluid under zero gravity condition. R is the radius of the cell and the origin O is placed at the surface of the sphere. Being highly symmetrical, the spherical cell was adapted by Straub et al. [12,35,36] in their space experiments, which certified the presence of the PE both in one-phase and two-phase region, and evaluated the isochoric heat capacity measurements at the critical isochore of SF_6. On the other hand, the critical pressure for most fluids are much higher than standard atmospheric pressure. Owing to good pressure bearing ability, many pressure vessels are designed as spherical geometry. Thus a spherical cell filled with one near-critical fluid is a reasonable configuration in experiments and applications.

Initially, the fluid is in thermodynamic equilibrium. The density and temperature are uniform throughout the whole cell. The initial conditions are

$$\rho_0 = \rho_c, \tag{1}$$

$$T_0 = (1 + \varepsilon)T_c, \tag{2}$$

with T_c the critical temperature, ρ_c the critical density, ε the initial reduced temperature and $\varepsilon = (T_0 - T_c)/T_c$. At $x = 0$, the boundary conditions used in this study are of the Dirichlet type:

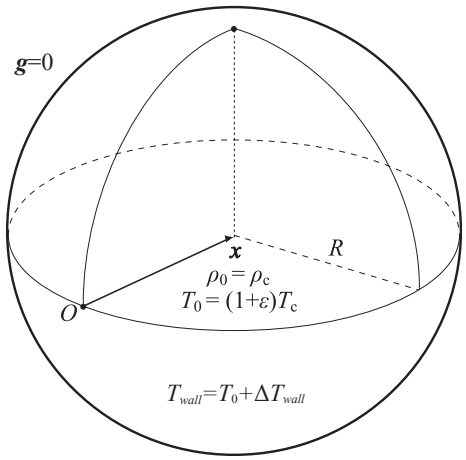

Fig. 1. Physical model. R is the radius of the cell and the origin O is placed at the surface of the sphere.