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Influence of Convection on the Piston Effect[1]

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This paper answers some recent questions posed by heat propagation mechanisms in near-supercritical pure fluids under normal gravity conditions. The role of microgravity experiments in the discovery of a fourth temperature equilibration mode in hypercompressible fluids, called the piston effect, is described, as well as its basic mechanisms that are responsible for temperature equilibration on a much shorter time scale than heat diffusion. The question whether this mechanism still exists on the ground is then approached. The results of the numerical calculations which answer this question and the basic references are presented. It is emphasized, in particular, that, although the piston effect has been demonstrated by microgravity experiments, this effect appears to be the temperature equilibrating mechanism on ground, also leading to the striking evidence of a quasi-isothermal convection. Recent modeling in connection with experiments that suggested that the piston effect could be killed by convection shows, on the contrary, that a cooling piston effect, triggered by thermal plumes, prevents the bulk increase in temperature.

KEY WORDS: convection; finite volume methods; hypercompressible fluids; numerical hydrodynamics; piston effect; supercritical fluids.

1. INTRODUCTION

The experimental evidence of intense convection in near-critical fluids when heated led to the interpretation of the observed fast temperature equilibration process as due to convective transport; this transport mode is the only one remaining since heat diffusivity is vanishing in the vicinity of the critical point. This was consistent with the fact that the strength of the observed convection could be explained by the huge density gradients due to the

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diverging isothermal compressibility. However, at the beginning of the 1980s, experiments performed under microgravity conditions suggested that the thermalization process could be very fast even in the quasi-convection-free environment of space [1, 2]. Several teams then explained this observation [3–5], under the form of the prediction of the existence of a fourth new temperature equilibration mechanism due to a thermoacoustic process we called the piston effect. After this mechanism was checked under microgravity conditions [6, 7] and widely accepted, there remained the question of why a strong convection should exist on the ground if temperature is equilibrated: Is the piston effect killed by convection? A negative answer has been given by numerical simulations. In the same way, a very special property of thermogravitational convection in near-critical fluids has been put forward, namely, the existence of quasi-isothermal convection. Recent experiments performed on the ground in a cell with conducting walls [8] added a new question. Why was a local heat source immersed in the near-critical fluid unable to raise the temperature of the bulk fluid? Additional modeling answered this question by showing that the piston effect is not killed but, on the contrary, is enhanced by thermoacoustic interaction of the thermal plume rising from the source with the thermostated wall. Section 1 presents general considerations on the piston effect; Section 2 is devoted to the study of the piston effect heating under normal gravity conditions in the case of a side-heated, square cavity. Section 3 describes what happens when heat is brought into a cavity from a heat source and focuses on the interaction between a hot plume and the upper thermostated wall.

2. THE PISTON EFFECT

In March 1989, the question of heat transport in near-critical fluids was addressed at a workshop, Thermal Equilibration Near the Critical Point, organized at the National Bureau of Standards by Michael Moldover under the auspices of NASA. A set of recent experiments performed under microgravity conditions [1, 2] had suggested fast thermal equilibration in near-critical fluids under microgravity conditions, and they needed explanation. Was this due to convective transport remaining in microgravity? Since the Raleigh number diverges near the critical point, perhaps very small vibrations could homogeneize the bulk phase. Was this due to a misinterpretation of the role of the specific heats in the energy balance? Was it due to some adiabatic effect, as proposed by Onuki and Ferrel at the workshop, the mechanism of which needed to be identified?

Our approach to the question [3] was based on our ability to perform numerical calculations of compressible flows at low Mach numbers. We replaced the ideal equation of state (EOS) by that of van der Waals.

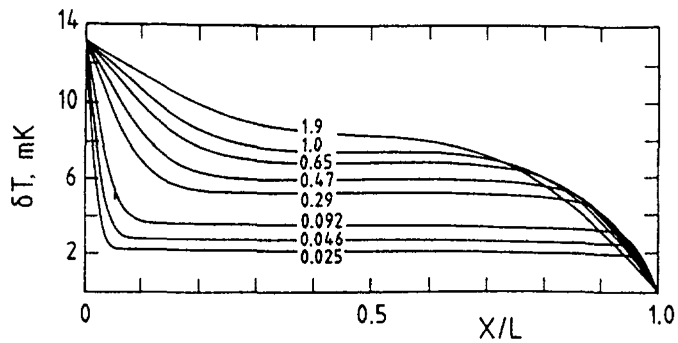

Fig. 1. Temperature in a 10-mm 1-D slot for different times expressed as a percentage of the heat diffusion time ($T_C + 1$ K, critical pressure) (from Ref. 2).

Although not exact, this EOS was expected to provide at least a phenomenologically correct description.We were surprised to find that the temperature in the bulk was homogeneous and that equilibration was effectively completed after only a few percent of the characteristic time for heat diffusion (Fig. 1). We were led to the thermoacoustic interpretation of the numerical calculations by the work of Kassoy [9]. In an investigation of the response of an ideal gas to a thermal disturbance, Kassoy had found

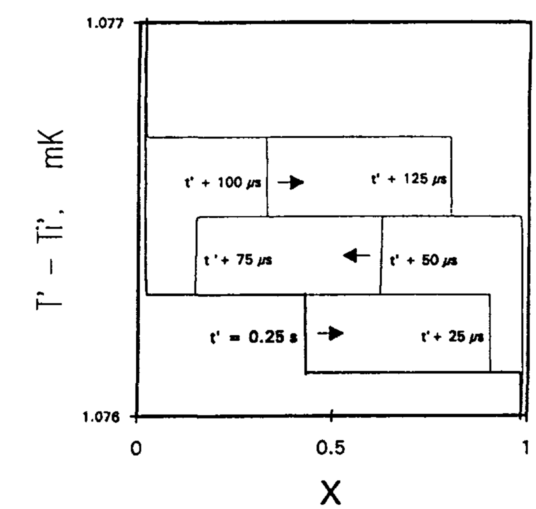

Fig. 2. Two-times-scale asymptotic solution showing the heating of the bulk by acoustic wave propagation (from Ref. 6).

a negligibly small phenomenon which he had named the piston effect [9]. The numerical simulation was consistent with results obtained by our colleagues [4, 5] with the use of totally different methods. More sophisticated analysis with multiple time scales [10] then allowed us to give a complete thermoacoustic description of the process. Compression waves emitted at the edge of the thermal boundary layer that flash back and forth in the cavity provoke an adiabatic increase in temperature which is much faster than diffusion (see Fig. 2). This is why our colleagues working not with hydrodynamics and acoustics but with more global descriptions [4, 5] called this effect adiabatic equilibration, since it corresponds to an adiabatic temperature increase of the bulk phase.

These first interpretative descriptions have been followed by asymptotic analysis attempting to describe the critical behavior of the hydrodynamic field variables as a function of the distance to the critical point [11, 12]. In the meantime, some other striking properties of acoustic wave propagation and reflection have been proposed [13, 14], together with a description of the saturation of the piston effect which occurs close to the critical point [15]. In such situations, the temperature should equilibrate as fast as the speed of sound (see Fig. 3).

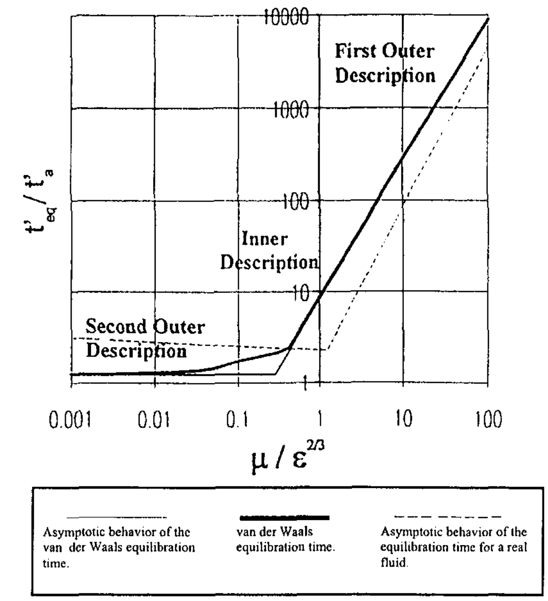

Fig. 3. Heat equilibration time as a function of the reduced distance μ to the critical point; ε is the ratio of the acoustic characteristic time to the heat diffusion characteristic time for an ideal gas (from Ref. 11).

2. IS THE PISTON EFFECT KILLED BY CONVECTION? THE 2-D CAVITY PROBLEM WITH SIDE HEATING AND ADIABATIC WALLS

As explained in Section 1, it was natural to see whether temperature is equilibrated on the ground since strong convective motion is observed, or, in other words, Does the piston effect still exist in the presence of convection? Experiments by Gammon and co-workers [16], reporting that temperature could be equilibrated very rapidly on the ground and thus, in the presence of convection, could not in fact give a complete answer to the question, is the observed fast temperature equilibration due to convection or to the piston effect? This question is of prime importance to the wide majority of scientists working with near-critical fluids on the ground since the understanding of any nonisothermal experiment on the ground needs the knowledge of the properties of convective motion in hypercompressible fluids. We describe here the main features of the results reported in a recent paper [17] devoted to the simplest situation to consider this question, namely, a side-heated square cavity filled with a supercritical fluid set at 1 K above its critical temperature. Other situations involving possible unstable situations, such as the Rayleigh–Benard or Raleigh–Taylor ones, for example, are too complex for exploring the basic properties of thermogravitational convection in near-critical fluids. These situations are currently under study [18, 19]. The situation that has been already been computer simulated is the following. A square cavity (2-D problem) is filled with CO_2 set at 1 K above its critical temperature. The fluid is initially at rest and at thermodynamic equilibrium. The upper, bottom, and right-hand side boundaries are adiabatic. The temperature of the left-hand side boundary is increased linearly by 10 mK in 1 s and then kept constant. The simulation consists of solving the 2-D unsteady Navier–Stokes equations in order to study the transient between the initial and the final equilibrium temperatures in the cavity. These equations are written for a Newtonian, viscous, heat-conducting van der Waals gas. The governing equations thus have the following form:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \tag{1}$$

$$\frac{D(\rho \mathbf{v})}{Dt} = -\gamma^{-1} \nabla \mathrm{P} + \varepsilon \left[\nabla^2 \mathbf{v} + \frac{1}{3} \nabla(\nabla \cdot \mathbf{v}) \right] + \frac{1}{F_r} \rho \mathbf{g} \tag{2}$$

$$\frac{\mathrm{D}(\rho \mathrm{T})}{\mathrm{Dt}} = -(\gamma - 1)(\mathrm{P} + \mathrm{a}\rho^2)(\nabla \cdot \mathrm{v}) \frac{\varepsilon \gamma}{\mathrm{P_r}} \nabla \cdot [\lambda \nabla \mathrm{T}] + \Phi \tag{3}$$

where $\Phi = \varepsilon\gamma(\gamma - 1)[v_{i,j}v_{j,i} + v_{i,j}v_{i,j} - \frac{2}{3}v_{i,i}v_{j,j}]$ is the viscous dissipation rate and ε is a small parameter defined by $\varepsilon = P_r t'_a / t'_d$ where t'_d is the characteristic heat diffusion time for the ideal gas and t'_a is the characteristic time of acoustic phenomena. The quantity P_r is the Prandtl number for an ideal gas and F_r is the acoustic Froude number. Additional properties were modeled as follows:

$$\lambda = 1 + A(T-1)^{-0.5}; \qquad C_v = 1; \qquad \tilde{\mu} = 1$$

where λ, C_v, and $\tilde{\mu}$ are, respectively, the thermal conductivity, the specific heat at constant volume, and the dynamical viscosity divided by their ideal-gas values. These expressions, of course, do not describe the real critical behavior of a critical fluid, but they correspond to a mean field theory, which is correct enough to study phenomenology, although not to perform quantitative comparisons with experimental results.

The van der Waals equation was written with the following nondimensional form:

$$P = \frac{\rho T}{1 - b\rho} - a\rho^2 \tag{4}$$

where $a = 9/8$ and $b = 1/3$ are given by the expression of the critical parameters. The fluid is initially at rest and stratification is neglected since the distance to the critical point is not smaller than 1 K.

As explained in Ref. 17, the van der Waals EOS is used for the same reasons as those considered for the transport coefficients. The governing equations are discretized on a nonuniform staggered mesh by means of a finite volume method; the obtained equations are then solved by a AIMPLE-type algorithm [20] associated with an acoustic filtering procedure. [21].

2.1. Piston Effect Is Not Killed by Convection

Figure 4 plots the temperature field at $t = 4.5$ s after heating has been stopped. We observe that temperature equilibrium in the cavity is almost achieved through the piston effect, while the effect of buoyancy is restricted to a low-density thermal plume visible at the hot wall and top-left part of the cavity. The perfect gas thermal field, which is shown in Fig. 5, for the same time and heating conditions exhibits a typical, not yet homogeneous, diffusion-driven profile together with weak convection. In Fig. 4, the temperature field in the bulk is homogeneous at a time much shorter than the thermal-diffusion time. This is the signature of the piston effect, and it

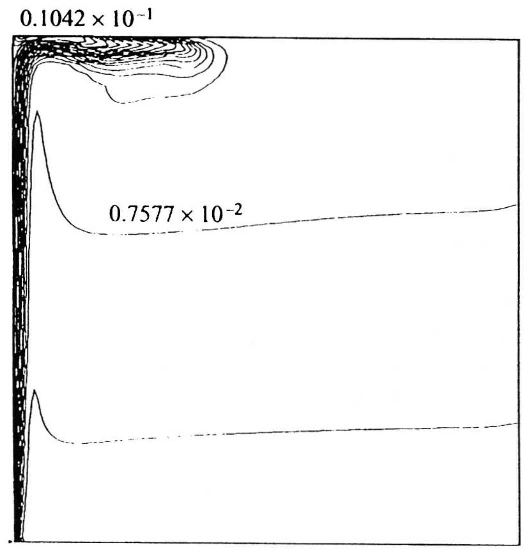

Fig. 4. The temperature field (K) in a side heated (left hand wall) square cavity 4.5 s after a 1-mK increase in temperature has been completed.

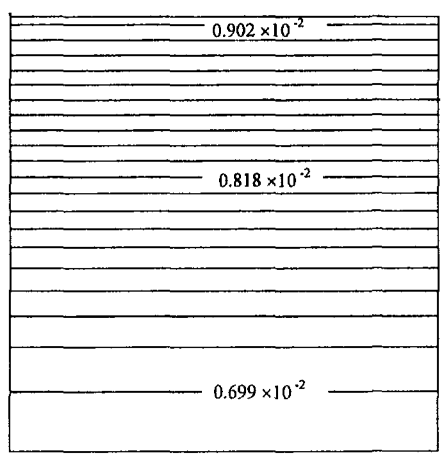

Fig. 5. The temperature field (K) at the same time as in Fig. 4 and under the same conditions in a ideal gas.

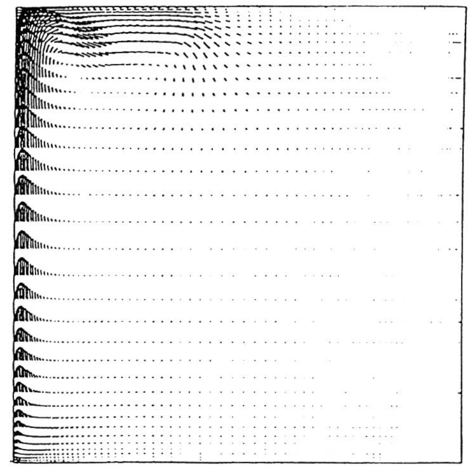

Fig. 6. The velocity field in the cavity (the max. vector plot is $2.24 \times 10^2\ \mu m \cdot s^{-1}$, 4.5 s after a 1-mK increase in temperature has been completed.

shows that there is no significant interaction between the buoyant convection and the piston effect. This comes from the fact that the strong upward velocity near the heated wall is parallel to the isotherms and thus does not affect the thermal structure of the thermal boundary layer and thus that of the piston effect. Figures 6 and 7 show the convective motion at $t = 4.5$ s

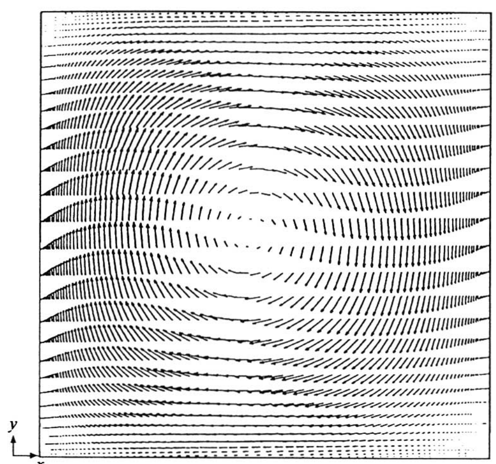

Fig. 7. The velocity field at the same time as in Fig. 6 and under the same conditions as an ideal gas (the max. vector plot is $6.5\ \mu m \cdot s^{-1}$).

in supercritical CO_2 and in CO_2 as an ideal gas after heating is stopped. The difference in the structure as well as in the convective motion is evident.

2.2. The Isothermal Convection

When the temperature has been quite homogenized by the piston effect, the remaining temperature gradients diffuse very slowly on the very long diffusive time scale. Due to the very large compressibility, the associated density gradients are still 6×10^3 larger than those in the perfect gas. This means that, as time goes by, a convective motion fills the cavity which is quite thermally homogenized. For example, at $t = 713$ s, the velocity field plotted in Fig. 8 shows that its magnitude is still 10 times larger than its maximum value in the perfect gas ($t = 4.5$ s, $6.5\,\mu\text{m} \cdot \text{s}^{-1}$), although temperature is homogenized by more than 99%.

2.3. Remarkable Property of Isothermal Convection

Figure 7 shows a secondary roll appearing in the left upper corner of the cavity. This is due to an overheating of the top wall which is a consequence of a very unusual phenomenon at these low velocities. The fluid is

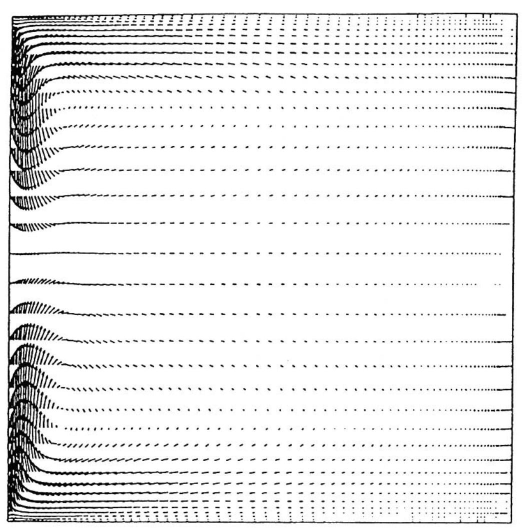

Fig. 8. The isothermal convection: velocity field 713 s after the heating has been stopped (the max. vector plot is $86\,\mu\text{m} \cdot \text{s}^{-1}$).

accelerated during the rise along the heated wall, and its kinetic energy thus increases. When it reaches the upper wall, the direction of the velocity changes from vertical to horizontal and there is thus a point where the velocity is zero: at that point, the kinetic energy that has been "pumped" into the gravity field is turned into internal energy to satisfy the conservation of energy, thus provoking an increase in temperature. Known as the stagnation point effect in normally compressible fluids, this effect needs high-velocity flows (higher than Mach number 0.8) to be noticeable so that the kinetic energy and the internal energy have the same orders of magnitude. In normally compressible fluids, the effect is not noticeable because usual convective motions are not fast enough so that the increase in kinetic energy is negligible. In supercompressible fluids, the increase in internal energy by diffusion through the thermal boundary layer is of the same order of magnitude as the increase in kinetic energy gained during the rise along the heated wall. This effect is thus noticeable in the present situation: the heated wall is colder than the bulk, thus provoking a downward flow corresponding to the secondary roll that increases in size as time goes by (see Fig. 8). This points out the very important role of compressibility in driving the structure of convective flows in supercritical fluids. Considering the formidable difference that exists in the presently studied simple situation, one can imagine the important role played by compressibility in near-critical fluid instabilities.

3. CAN THE PISTON EFFECT BE KILLED IN OTHER CONFIGURATIONS? THE HEAT SOURCE PROBLEM WITH AN ISOTHERMAL WALL

As suggested by experiments by Beysens and collaborators [8], the piston effect seems not to operate when heat is brought through an immersed heater and when the upper wall is thermostated. We have recently performed a numerical experiment based on the same numerical code as in Ref. 17: a heat flux is set at the central mesh node, while the upper wall of the square cavity is maintained at its initial temperature. The result of the simulation is consistent with the observation in the experiments; after an initial increase, the bulk temperature stops increasing and reaches a constant value, although heat is continuously produced by the heater (Fig. 9). The mechanism that has been demonstrated here is the thermoacoustic interaction between the hot plume rising from the thermistor and the upper thermostated wall. A total correlation has been demonstrated between the thermal evolution and the hydrodynamic events occurring in the vicinity of the upper wall. The mechanism has been analyzed and can be summarized as follows. The hot plume flows upward and brings with it the thermal field

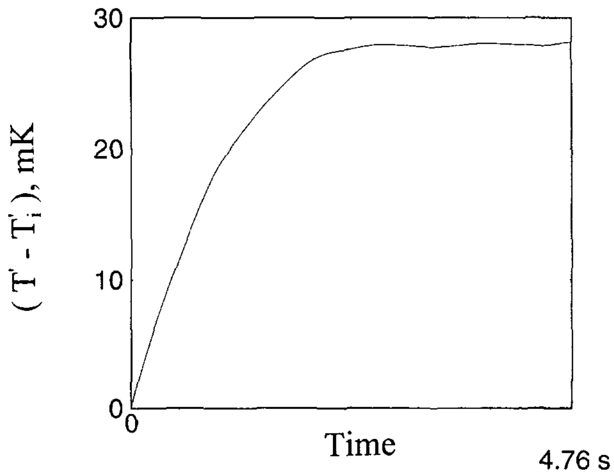

Fig. 9. The bulk temperature evolution as a function of time showing the different changes in the heating rate by the piston effect.

since the convective transport is intense. When this hot fluid impinges on the upper wall (see Fig. 10), a thin thermal boundary layer forms where the plume interacts with the wall. The fluid contained in that layer contracts, and this contraction provokes the enhancement of the cooling piston effect. The cooling piston effect generates the propagation of expansion waves in

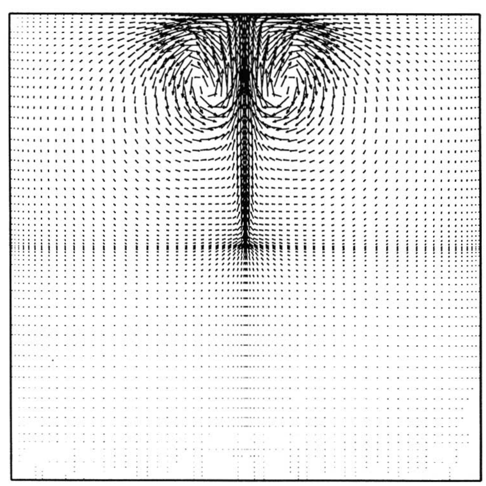

Fig. 10. The first interaction of the hot plume with the upper thermostated wall.

the bulk, while the heating piston effect generates compression waves. This cooling piston effect enhancement corresponds to the first decrease in the overall PE heating rate of the bulk phase (see Fig. 9). The second decrease is due to the interaction with the upper wall of hot "bubbles" that had been first convected downward by the vortex flow. This matter is developed in detail in Ref. 22. Accordingly, the piston effect is not killed by convection but by a different balance between the heating and the cooling piston effects caused by the thermal plume. Before the thermal plume reaches the upper boundary, the resulting temperature evolution is the same as at microgravity conditions. Since only the cooling piston effect has been enhanced, the heating piston effect is quite balanced and the bulk increase in temperature no longer possible.

These studies show that it is most likely that the thermoacoustic heating of a bulk phase still occurs in most of the ground situations and not only under the microgravity conditions where it was first demonstrated. The complexity of the flow fields and the richness of the hydrodynamic phenomena suggest that the critical phenomena and hydrodynamic communities will find here a wide field of common interest. This is supported by recent studies of the unstable configurations of Rayleigh–Benard and Rayleigh–Taylor convection in near-critical fluids [19, 22].

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