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Technical Note

Natural convection driven in CO_2 near its critical point under terrestrial gravity conditions

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Nomenclature

g gravitational acceleration
P pressure
T temperature
T_c critical temperature.

Greek symbols

α_P coefficient of volume expansion
κ_T isothermal compressibility
ρ density.

1. Introduction

The specific heat and the isothermal compressibility increase greatly as a fluid system approaches its critical point and, therefore, the thermal diffusivity becomes very small. It had been believed that thermal energy cannot be transferred near the critical point because of this small thermal diffusivity. However, a fast heat transfer was observed even under microgravity conditions in which buoyancy convection was suppressed [1]. This problem was analysed by Onuki et al. [2] and Boukari et al. [3] from a thermodynamical point of view and by Zappoli et al. [4], Zappoli [5], and Zappoli and Carles [6] from a thermofluid mechanical point of view. It is now known that temperature propagates as acoustic waves near the critical point. Ishii et al. [7] analysed the temperature propagation near the critical point theoretically and made clear the effect of the direction of gravity and the wave number of perturbation on the temperature propagation mode. However, the convective mode induced in near-critical fluids under gravitational conditions has not yet been investigated either experimentally or theoretically.

In this paper, we investigate natural convection driven in near-critical CO_2 experimentally under $1g$ conditions. In Section 2, the experimental apparatus and procedure are described. In Section 3, the result of the experiment is shown and the effect of the gravitational direction and the system temperature on the convective mode is discussed. In the final section, the result of the experimental analysis is summarised.

2. Experimental apparatus and procedure

The outline of the experimental system is shown in Fig. 1. The cylindrical test cell, 60 mm in diameter and 40 mm long, was made of aluminium. A cylindrical cavity, 27 mm in diameter and 40 mm long, was made in the cell and sandwiched between two glass windows, 20 mm in diameter and 10 mm thick. CO_2 was introduced into the test cell until the density reached the critical value [8] and the system temperature was raised to the set value by a precise temperature controller. The system temperature was controlled to an accuracy of 0.001 K and the fluid temperature was measured by a thermistor. Another thermistor was set at the centre of the test cell and heated for 2.0 s by circulating an electric current. The heated part of the thermistor is shown in Fig. 2. The thermistor was covered with a polyimide film, the length and diameter of which were, respectively, 4 mm and 0.38 mm. The

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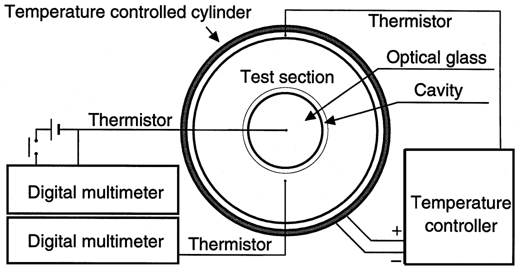

Fig. 1. Schematic diagram of the experimental system. CO_2 was introduced until the density reached the critical value. The system temperature was controlled by a heater. One spot in the test cell was heated by a thermistor set at the centre. The temperature field was visualised by the shadowgraph method.

power of heat input was 0.5 mW. The temperature field was visualised using the shadowgraph technique and recorded on a video tape. Experiments were carried out in both supercritical and subcritical regions near the critical point.

3. Result and discussion

The temperature field visualised by the shadowgraph method is shown in Fig. 3. When the difference between the initial system temperature and the critical temperature, $T-T_c$, was -0.025 K (Fig. 3(a)) and 0.037 K (Fig. 3(d)), buoyancy convection was driven in the anti-gravitational direction and no convection was induced in the gravitational direction. On the other hand, when $T-T_c = -0.012$ K (Fig. 3(b)) and 0.004 K (Fig. 3(c)), convection was driven in both anti-gravitational and gravitational directions. The temperature propagation in the anti-gravitational direction is due to the buoyancy effect. Convection in the gravitational direction was observed only when $-0.012\ \mathrm{K} < T-T_c < 0.015\ \mathrm{K}$.

The time variation of the displacement of the temperature front in both gravitational and anti-gravitational directions after the heat input is shown in Fig. 4. The front of buoyancy convection moves in the anti-gravitational direction and the effect of the initial system temperature on the speed of the temperature front is not significant. On the other hand, the initial system temperature has a strong effect on the speed of the temperature front and the time delay of the onset of convection in the case of convection driven in the gravitational direction.

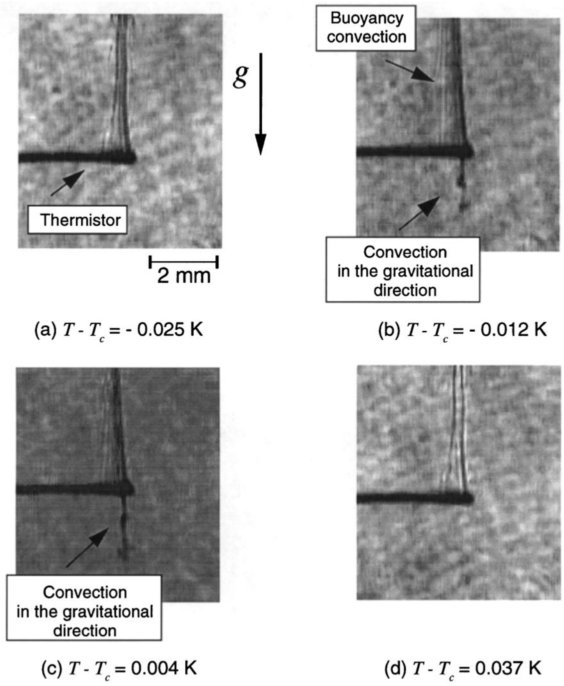

Fig. 3. Temperature field visualised by the shadowgraph method. (a), (d): Buoyancy convection was driven in the anti-gravitational direction. (b), (c): Convection was driven in the gravitational direction when the system temperature was very close to the critical temperature.

The temperature propagation speed was calculated from Fig. 4 and the dependence of the speed on the initial system temperature is shown in Fig. 5. The temperature propagation speed in the anti-gravitational direction is higher than that in the gravitational direction. The temperature propagation speed in the gravitational direction becomes maximum at the critical temperature, while the speed in the anti-gravitational direction is almost uniform.

Another significant feature is that the temperature front does not start moving in the gravitational direction immediately after the heat input. The dependence of the

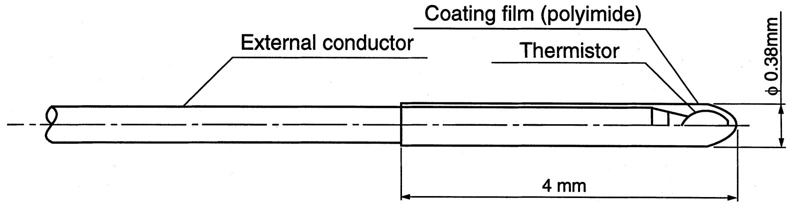

Fig. 2. Heated part of thermistor.

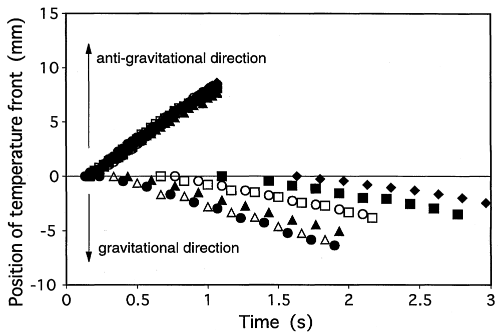

Fig. 4. Displacement of temperature front. ■, $T-T_c = +14$ mK; □, $T-T_c = +11$ mK; ▲, $T-T_c = +5$ mK; △, $T-T_c = +2$ mK; ●, $T-T_c = 0$ mK; ○, $T-T_c = -7$ mK; ◆, $T-T_c = -11$ mK. A thermistor set at the centre of the test cell was heated when the time was zero. There is no significant effect of the system temperature on buoyancy convection. The onset of convection in the gravitational direction is delayed and the propagation speed is different depending on the system temperature.

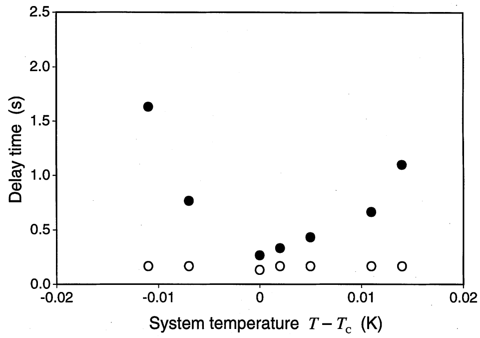

Fig. 6. Delay time of the onset of convection. ○, The delay time of the onset of convection in the anti-gravitational direction. ●, The delay time of the onset of convection in the gravitational direction. The delay time of the onset of convection in the gravitational direction becomes minimum at the critical temperature, whereas that in the anti-gravitational direction is almost constant.

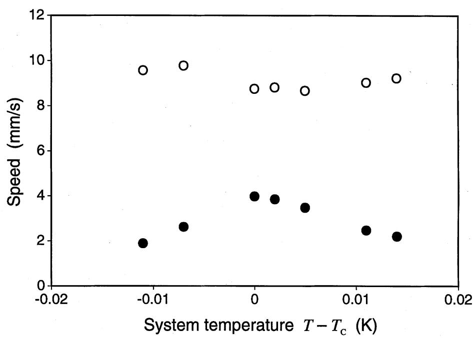

Fig. 5. Speed of temperature front. ○, The speed of the temperature front in the anti-gravitational direction. ●, The speed of the temperature front in the gravitational direction. The propagation speed of the temperature front in the gravitational direction becomes maximum at the critical temperature.

delay time on the initial temperature of the system is shown in Fig. 6. The delay time of the onset of convection in the gravitational direction becomes minimum at the critical temperature and longer as the system temperature deviates from the critical temperature, whereas the delay time of the onset of buoyancy convection is almost constant. We carried out various experiments altering the power of the heat but the basic characteristics of convection driven in the gravitational direction was the same as those explained above

A volumetric force ρg acts on fluid under $1g$ conditions, where ρ is the density of fluid and g is the gravitational acceleration. Density change $\Delta\rho$ is dependent on both temperature and pressure changes, ΔT and ΔP.

$$\Delta\rho = \left(\frac{\partial\rho}{\partial T}\right)_P \Delta T + \left(\frac{\partial\rho}{\partial P}\right)_T \Delta P = -\rho\alpha_P\Delta T + \rho\kappa_T\Delta P \qquad (1)$$

where α_P and κ_T are, respectively, the coefficient of volume expansion and the isothermal compressibility. When fluid is heated, both temperature and pressure rise and therefore buoyancy force $\rho\alpha_P\Delta Tg$ acts in the anti-gravitational direction and compression force $\rho\kappa_T\Delta Pg$ acts in the gravitational direction. When a fluid system is very close to its critical point, the isothermal compressibility becomes very large and therefore convection may possibly be driven in the gravitational direction.

The mechanism of the onset of convection in the gravitational direction is an open question. The dependence of the speed of convection and the delay of the onset of convection on the system temperature must be explained. A more detailed theoretical investigation of the mechanism of the convection based on eqn (1) will be carried out in the future.

4. Conclusion

We investigated natural convection induced in CO_2 near its critical point under 1 g conditions experimentally. Through this study, the following results were obtained; (1) convection was driven in the gravitational direction when the system was close to the critical point, (2) the temperature propagation speed in the gravitational direction was lower than that in the anti-gravitational direction, (3) the temperature propagation speed in the gravitational direction became maximum at the critical temperature and (4) the onset of convection in the gravitational direction was delayed after the heat input. The delay time became minimum at the critical temperature.

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