Temperature measurements during heat-up of a contained homogeneous fluid

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Laboratory measurements of the evolution of temperature field of a fluid contained in a square cavity during heat-up are reported. At the initial state, the fluid is motionless and at uniform temperature. Flows are induced by changing abruptly the boundary wall temperatures to a vertically linear profile. The transient adjustment process of the thermal structure is described. Experiments were performed using water as the working fluid at large system Rayleigh numbers. The Mach-Zehnder interferometry technique was used to portray the evolving thermal field. The results clearly disclosed the formation of boundary layers at very early times. In the intermediate stages, the presence of the vertically propagating temperature front is discernible. Ahead of the temperature front, the fluid remains unstratified, retaining the original uniform temperature. The adjustments of the global thermal structures are substantially accomplished over the convective time scale $O(\mathrm{Pr}^{1/2}\mathrm{Ra}^{1/4}N_f^{-1})$. The transient process is shown to proceed faster at a lower Ra because of the enhanced role of the diffusive effects. These observational findings are consistent with the previous analyses and numerical predictions.

Keywords: convective time scale; Mach-Zehnder interferometry; square cavity; thermal stratification process

Introduction

The transient thermal convection in a closed cavity has been investigated by many authors (e.g., Hyun 1984; Jischke and Doty 1975; Ostrach 1972; Sakurai and Matsuda 1972) because it conveys a fundamental interest in understanding how a stratified fluid system is achieved with the passage of time in an enclosure. However, for the benchmark flow configuration of instantaneously raising and lowering the side wall temperatures in a rectangle, only recently have there been serious experimental efforts (Ivey 1984; Patterson and Imberger 1980; Yewell et al. 1982). Because of the inherent difficulties in constructing realistic practical systems, these investigations have been mostly theoretical or numerical in nature as reviewed subsequently.

Sakurai and Matsuda (1972) studied the transient stratification process in which the fluid was initially in a state of linear stratification and the onset of the fluid motion was due to a small perturbation in the wall temperature distribution. They employed the linearized analysis and revealed that the global adjustment process is achieved over the convective time scale $O(\mathrm{Ra}^{1/4}N_f^{-1})$ rather than the diffusive time scale $O(\mathrm{Ra}^{1/2}N_f^{-1})$. Their arguments were expanded and reinforced by Jischke and Doty (1975) in a more generalized and systematic manner. An interesting, dynamical analogy between the heat-up of a stratified fluid and the spin-up of a rotating fluid was identified by Veronis (1970).

A schematic diagram for the problem considered here is drawn in Figure 1. As is shown there, a Boussinesq fluid is filled inside a rectangular cavity of height H and width W. Initially, the whole system is at a uniform temperature T_0, and the fluid is stagnant. At time $t = 0$, a linear temperature profile is impulsively imposed on the vertical walls such that $T_f(y) = T_0 + 2\Delta T(y/H - 0.5)$. A main issue to be studied is the evolution pattern of the transient thermal structure in the cavity and the relevant characteristic time scales. Obviously, when a steady state is attained at large times, the fluid motion ceases and the liquid is linearly stratified in accord with the externally imposed temperature profile $T_f(y)$. Although the formation of the internal circulation (induced by the buoyant boundary layers on the vertical side walls) is still a dominant aspect of the transient process, this problem differs from that of Sakurai and Matsuda (1972) because of the existence of a vertically propagating temperature front.

Hyun (1985a, b; 1986) formulated the previously specified heat-up problem by extending a linearized model of Sakurai and Matsuda (1972), and presented the numerical results for the typical flow configuration associated with the transient

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Received 13 October 1992; accepted 4 October 1993

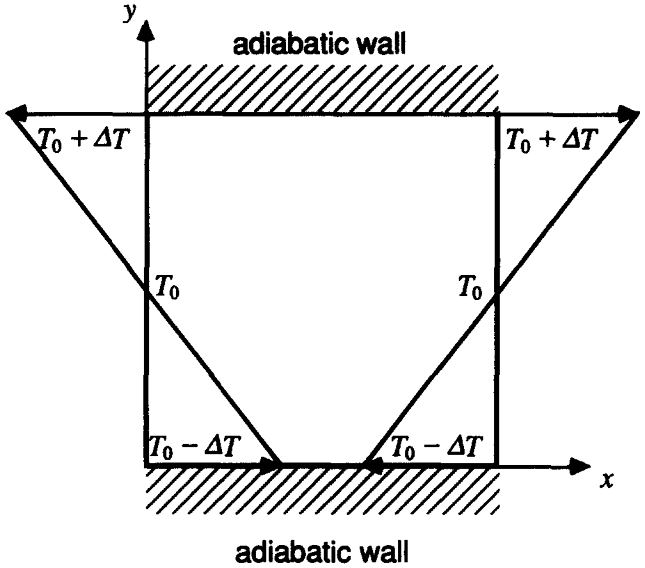

Figure 1 Problem configuration and boundary conditions

thermal convection. He also asserted that the overall transient process was accomplished over the convective time scale $O(\mathrm{Pr}^{1/2}\mathrm{Ra}^{1/4}N_f^{-1})$.

In the present work, experimental measurements were undertaken to provide validations of the predicted behavior of the thermal field during the heat-up process in the laminar flow regime. The temperature field data were found to be very meaningful to determine the characteristic time scales and to validate the presence of the propagating temperature front.

Experiment

For the experiment to be carried out with moderate success, it turned out essential to use a high-quality, versatile-purpose cavity. Therefore, a square-sectioned cavity ($W = 8$ cm, $H = 8$ cm, $D = 32$ cm) was carefully manufactured and precision machined. The depth D of the cavity was selected to be sufficiently long in anticipation that the fluid flow in the cavity would be in effect two-dimensional. For the high degree of thermal insulation, the horizontal walls ($y = 0$ and $y = H$) were made of acryl and polystylene foam. The transparent optical-glass windows were used on the end walls not only to enclose the test cell but also to allow for an easy access to flow visualization. Of central importance in the present experiment was the material chosen for the (vertical) side walls ($x = 0$ and $x = W$). This was because the side walls should have high thermal conductivities so as to simulate faithfully the sudden temperature jump at the wall. For this purpose, thin copper plates having a wall thickness of 1.5 mm were used on the side walls (see Figure 2). However, there still remained a key step to introduce a linearly varying instead of constant-temperature profile at the side walls. This task to be undertaken required an innovative procedure and constituted a core part of our experiment that will be described later.

First, it was a premise that the test liquid should not be thermally disturbed while a linear temperature profile was being established along the side walls. Therefore, the desired temperature profile was first imposed on two auxiliary copper blocks located far away from the test cell, as illustrated in Figure 2. The top/bottom of each copper block was heated/cooled for a sufficient duration of time by means of circulating water issued individually from the hot/cold constant-temperature bath. It was found that for all the experimental runs the steady-state, linear temperature profile was established in each copper block approximately 10 minutes after the hot/cold water was forced to circulate within the system. This steady-state, linear temperature profile was carefully checked per each run by reading the temperatures of the five thermocouples implanted along the copper block. Then, at time $t = 0$, these two copper blocks were instantly brought into contact with the outer surfaces of both the side walls, and the main experiment was commenced. The success of this elaborately designed procedure was heavily dependent on two factors: one is the size of the copper block, and the other is the contact condition between the copper block and the side wall.

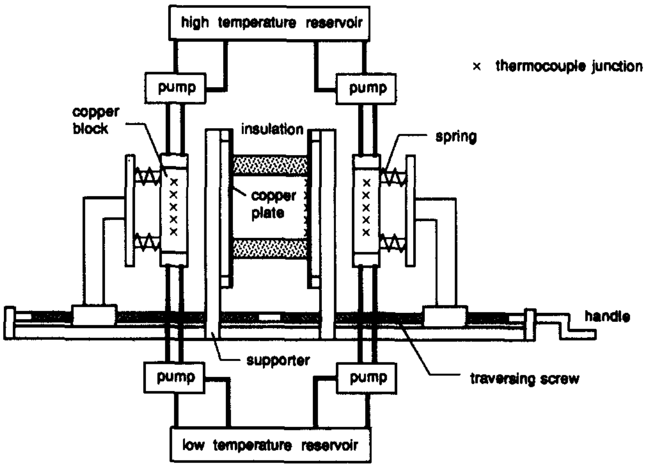

Figure 2 Schematic diagram of experimental apparatus

Notation

D	depth of container
g	gravitational acceleration
H	height of container
N_f	Brunt-Väisälä frequency of the final-state fluid system, $(g\beta\Delta T/H)^{1/2}$
Pr	Prandtl number, ν/α
Ra	Rayleigh number, $g\beta\Delta T H^3/\nu\alpha$
T_f	boundary wall temperature
T_0	initial temperature of boundary wall and fluid
ΔT	temperature difference
t	time
t_h	convective time-scale
t_r	response time of the side wall temperature change
W	width of container
x	horizontal coordinate
y	vertical coordinate

Greek symbols

α	thermal diffusivity
β	thermal volumetric expansion coefficient
Θ	dimensionless temperature
ν	kinematic viscosity

For the settlement of the former problem, each copper block was manufactured to have a dimension of 24 cm × 5 cm × 35 cm so that its heat capacity was at least two orders of magnitude larger than that of the thin copper plate. The latter problem was efficiently resolved by using the mechanical springs together with bolt assemblies attached to four corners of the block (to promote uniform thermal contact) and by painting a silicon oil (Toshiba Silicon YG6111) on the contact surfaces (to reduce thermal resistance between the contact planes). In addition, care was taken to ensure the symmetry with respect to the centerline (i.e., $x = W/2$); this was accomplished by the precision control of the pumps regulating the water circulation.

To capture the transient evolution of the isotherms, the Mach-Zehnder interferometer system containing two mirrors (diameter, 20 cm) was put to use in conjunction with the beam splits (diameter, 20 cm). The concave mirror had a diameter of 25 cm and a focal length of 2 m. The monochromatic He-Ne laser of 5 mW rating (Uniphase Company) was used. A diffusing lens was placed in front of the laser beam, which was diffused and, after reaching the concave mirror, became a parallel beam. A convex lens with a diameter of 10 cm and focal length of 30 cm was mounted ahead of the camera so that the image of the object accurately fell on the surface of the camera film. A Nikon F-3 camera was used to take photographs and its shutter speed was controlled with a motor drive unit (Nikon MD-4).

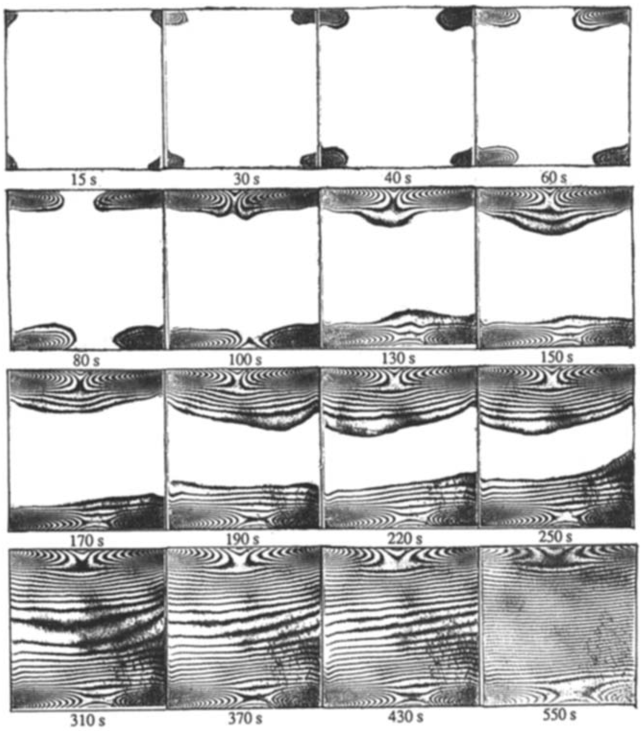

Figure 4 Sequential patterns of interferograms of isotherms, $Ra = 6.4 \times 10^6$

Results and discussion

As was mentioned earlier, the imposition of the desired temperature profile on the side walls, more specifically on the fluid side of the walls, was the key step of our experiments. On the thermal contact between the copper block and the side wall plate, the fluid-side temperature of the walls was monitored by five T-type thermocouples embedded along the height of the side walls (see Figure 2). Displayed in Figure 3 is the transient response of the fluid-side wall temperature at various heights of the side wall. Admittedly, the fluid-side wall temperature does not vary in a perfect step-like mode, but it undergoes initially a steep variation and then asymptotically approaches its desired value. Defining the response time t_r as the time required for the fluid-side wall temperature to attain 90 percent of its desired value, a typical magnitude of t_r is found to be about 20 s, as can be seen in Figure 3. It is a necessary prerequisite that this response time scale t_r should be much smaller than the characteristic convective time scale t_h (of the fluid motion) which is known to be $t_h \approx O(Pr^{1/2}Ra^{1/4}N_f^{-1})$ (Hyun 1986). The convective time scale t_h observed in the present experiments is found to be an order of several hundred seconds, thereby leading to $t_r \ll t_h$; this fact validates the adequacy of the range of physical parameters pertaining to our experiments.

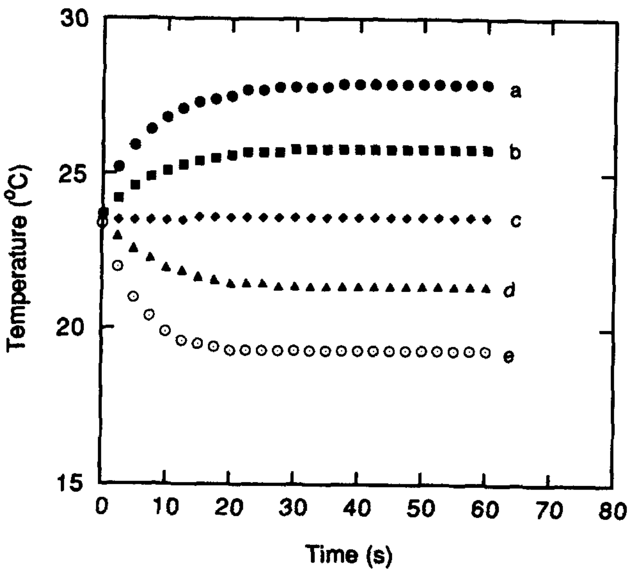

Figure 3 Time response characteristics of the copper plate side wall. The heights are a, $y = 4$ cm; b, $y = 8$ cm; d, $y = 12$ cm; e, $y = 20$ cm.

To obtain some frozen shots of the transient thermal field inside the cavity during the stratification process, the Mach-Zehnder interferometer images were photographed in a sequence of time, the interval of which was computer-controlled interfacing with an IBM PC. Figure 4 shows a series of 16 chronologically arranged interferograms of isotherms for the case of $Ra = 6.4 \times 10^6$. The "white-sea-like" region in the figure is occupied by the unstratified fluid at its initial-state uniform temperature T_0, whereas the "seashore-like" frontier isotherm represents the temperature front, which is almost at T_0. Each isotherm shift in Figure 4 stands for the temperature difference of approximately 0.02°C. The flow configuration is nearly symmetric with respect to the centerplane ($x = W/2$) and nearly antisymmetric with respect to the mid-height ($y = H/2$). Therefore, discussion hereafter will be made referring only to the lower left quarter of the cavity. Although the desired thermal forcings on the side walls were not completed up to the time $t \sim t_r$ (i.e., about 20 s; see Figure 3), the experimental results during this incipient period were also included in Figure 4 to exhibit an entire gamut of the transient stratification process considered here. One point worthy of special attention is to see how the temperature front advances with time. The frontier isotherm continues to elongate horizontally until it reaches to the center plane. Subsequently, the frontier isotherm, hand in hand with its mirror part, migrates vertically toward the mid-height position at which it will settle down permanently. Note that during the upward marching period the distribution of isotherms tends to be almost one-dimensional (1-D), as indicated by horizontally stacked isotherms. Further examination of Figure 4 reveals that the full stratification is accomplished in the bulk of the cavity over the convective time scale $t_h \approx O(\mathrm{Pr}^{1/2}\mathrm{Ra}^{1/4}N_f^{-1})$, which is estimated to be about t_h (615 s for Ra = 6.4×10^6; therefore, the experimental confirmation to the existing analytical theory is rendered in this study.

The transient evolution of the isotherm distribution for the case of a higher Rayleigh number (Ra = 1.7×10^7) is shown in Figure 5. The convective time scale evaluated from the theory turns out to be $t_h \approx 485$ s for this case. This is also consistent with the experimental data. Regarding the results shown in Figure 5, further discussion is omitted here because much of the qualitative physical description remains the same as in Figure 4.

The experimental data shown in Figures 4 and 5 are manipulated to obtain a collective picture of the marching pattern of the temperature front. As such, the obtained results are redrawn in Figure 6 for the lower left quarter of the cavity. In Figure 6a corresponding to the low Ra number case, it can be noted that the temperature fronts at t = 130 s and 150 s are a bit tilted upward away from the side wall. Such may be explained as follows. The downward fluid motion along the vertical wall, after impinging on the bottom plate, makes a 90° turn and flows horizontally adjacent to the bottom wall. While traveling horizontally, the fluids are exposed to the heat supply from the hot unstratified core fluid and thus are getting so light as to rise up slightly. Although the qualitative behavior portrayed in Figure 6b for Ra = 1.7×10^7 is similar to that of Figure 6a, it can be noted that as Ra increases the thickness of the boundary layer becomes small. Further comparison

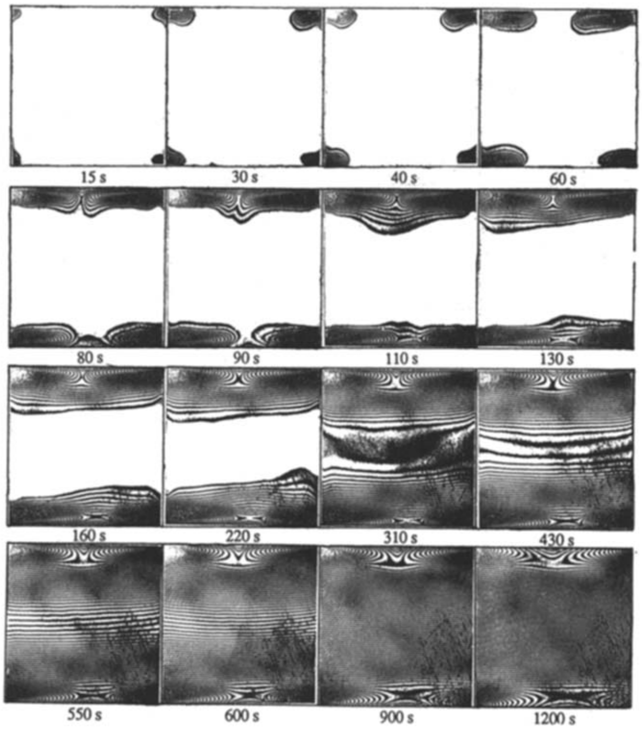

Figure 5 Sequential patterns of interferograms of isotherms, Ra = 1.7×10^7

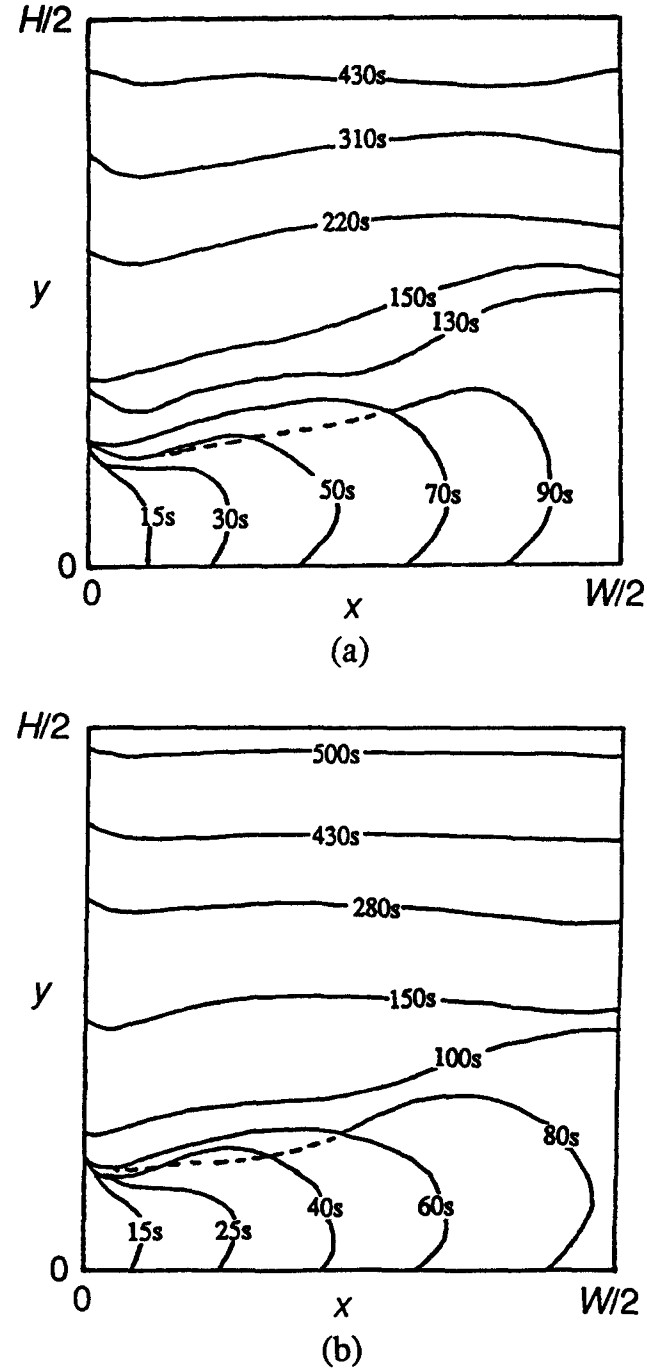

Figure 6 Evolution of temperature front: (a) Ra = 6.4×10^6, (b) Ra = 1.7×10^7

between two different Ra cases reveals that during an intermediate period (say t = 100 s or t = 150 s) the temperature fronts tend to remain more stably horizontal at a higher Ra owing to the increasing role of the buoyancy. The general character of the temperature front, as disclosed by the present experimental observations, is qualitatively in good agreement with the earlier numerical predictions (Hyun, 1985c).

The data on the temperature field are reorganized to render the position-time plots for specific isotherms. Figure 7 depicts the temporal locations of two isotherms traced vertically along the mid-width $x = W/2$: one is $\Theta = 0$ (corresponding to the temperature front), and the other is $\Theta = 0.2$ [the scaled

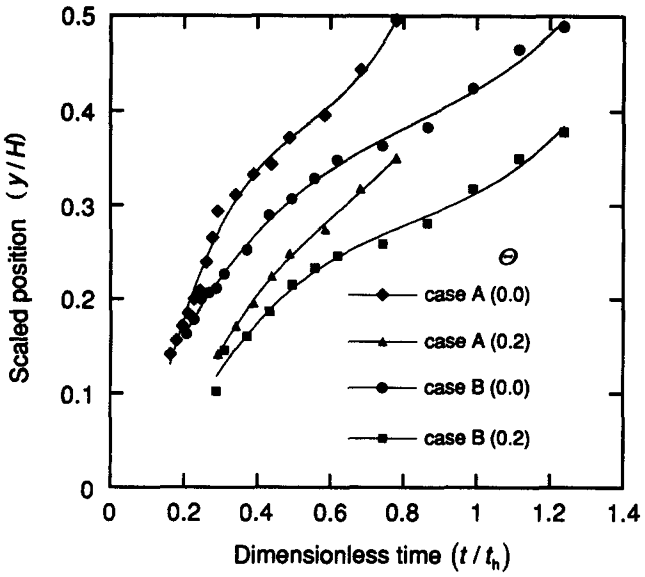

Figure 7 Vertical locations of the temperature front (Θ = 0) and of the isotherm (Θ = 0.2)

temperature is defined as $\Theta = (T - T_0)/\Delta T]$. At early times, the propagation speed of the isotherms has a trend to increase slightly with a decrease in Ra. This is suggestive of the enhanced role played by diffusive effects at a lower Ra. These findings are corroborative of the numerically observed assertions of Hyun (1985c).

Conclusion

The Mach-Zehnder interferometry technique proved to be effective in depicting the transient evolution of the thermal structures during heat-up. The present experimental results clearly validated much of the available predictions based on the numerical and theoretical analyses.

At an incipient phase, the temperature front of boundary-layer type is forming near the corner wall. Then, the temperature front continues to spread horizontally until it reaches to the symmetry line. The next stage, characterized by the vertically propagating temperature front, prevails during the transient stratification process. This final stage may be approximated as a 1-D process because of the development of stacked isotherms. As the Ra number increases, the temperature front tends to evolve with its surface more flattened. Ahead of the front, the fluid remains unstratified at its original uniform temperature.

The temperature field measurements point to the fact that the principal phase of the global transient adjustment process is accomplished over the convective time scale $O(Pr^{1/2}Ra^{1/4}N_f^{-1})$. This finding is consistent with the results of the previous numerical simulations.

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