Journal of Engineering and Applied Sciences 2 (6): 1048-1053, 2007

Experimental Study of Rayleigh-Bénard Convection Destabilized by Heated Side Wall

[1]M. Zeroual, [2]P. Cerisier and [1]M. Zereg
[1]Département de Physique, Faculté des Sciences, University of Batna,
Rue Boukhlouf Med el Hadi , Batna 05000 Algerie
[2]Polytech Marseille, Mécanique Energétique, UMR CNRS 6595,
University of Provence, 5 rue Fermi, 13453 Marseille Cédex 13, France

Abstract: A study of the influence, in addition to the effect of the vertical and horizontal heat gradient, of higher and lower walls, on the natural convection in a cavity was made. We studied the behavior of the induced roll (rI) in contact of the heating side wall, as well as Benard rolls (rB) number and the evolution of the convective structure according to the heating side. This study concerns two different values of the horizontal walls conductivity (polycarbonate and glass). The vessel is a parallelepipedic cavity filled with silicone oil (Pr 880 at 25°C) and which comprises three walls subjected to different temperatures (higher and lower walls as well as small with dimensions side). According to the small side wall temperature the observed structure is a network of transverse rolls (Rayleigh-Bénard convection), in case of the side heating absence and network of transverse rolls with induced roll (rI). The dilation of the (rI) as well as the process of rB destruction are a function of the heat flow on the level of the side wall.

Key words: Cavities, heat transfer, instabilities, natural convection, silicone oil, visualisation

INTRODUCTION

A significant number of works was the object of the natural convection, also called in the theoretical studies thermoconvective instabilities, in cavities heated by the top and bottom. The importance given to these research tasks was justified by its importance in the fundamental domain (heat transfer, selection of the wave number, spatio-temporel behavior, structural disorder, transition towards chaos, etc.) and by the large variety applicability domains of this particular configuration. The solar and nuclear energy production and its storage mechanism, meteorology, astrophysics, geophysics, the crystalline growth, the metal electrochemical refining, the electronics components production and their cooling, to quote only these cases solely, are thermal system examples where the convective flow is met.

For the Rayleigh-Bénard convection in a horizontal cavity where the lower wall is brought up to a higher temperature than that limiting the liquid on top, in the majority of the studied cases, once the threshold is exceeded, the known convective structure for a fluid with high Prandtl number is a network of parallel rolls with the small side wall. They correspond to a mechanical coupling whose adjacent rolls turn in opposite directions.

Three results, related to the convection in a traditional horizontal rectangular box heated by bottom and cooled by the top, are well-known. One generally observes:

- In a horizontal cavity, a network of rollers transverse, i.e. parallel with small with dimensions of the box (convection known as of Rayleigh-Bénard) (Busse and Whitehead, 1991; Stork and Muller, 1972; Normand *et al.*, 1977; Daniels and Wang, 1994; Cerisier *et al.*, 1998 a, b; Akihiro *et al.*, 1998; Calcagni *et al.*, 2005; Wu *et al.*, 2006; Lee and Ha, 2005; Sharif and Mohammad, 2005).
- For small inclination, rollers longitudinal, i.e. perpendicular to small with dimensions of the cavity (Mazuoka and Shimizu, 1987; Shadid and Goldstein, 1990; Sundstrom and Kimura, 1999; Orazio *et al.*, 2004; Schluter *et al.*, 1965).
- In vertical vessel, a single transverse roller (Buhler *et al.*, 1979; Yahata, 1999; Aydin *et al.*, 1999).

In this study we try to understand how the various ratios between thermal conductivities of the horizontal walls and those of oil affect the convective structure evolution in the case of the horizontal enclosure.

Corresponding Author: M. Zeroual, Département de Physique, Faculté des Sciences, University of Batna,
Rue Boukhlouf Med el Hadi , Batna 05000, Algerie

What does it occur in the structure when one small side wall is heated or cooled, in other words, when three walls of the enclosure (two horizontals and one side) are brought up to different temperatures? In this research, two series of investigation were carried out for horizontal walls (C) and (C') cases of having simultaneously conductivities κ_1=0.22 W/m.K and κ_2=0.18 W/m.K. The experimental results obtained for this exploration are exposed.

MATERIALS AND METHODS

The experimental device is composed of a common part for all experiments, a heating and control system and an used enclosure for each experiment. The enclosure is a rectangular cavity (12×3×1 Cm^3) filled with Rhodorsil 47V100 silicone oil (Fig. 1). The physical properties of oil are indicated in Table 1.

The vertical temperature gradient is applied due to the liquid flows at controlled temperature in contact with lower (C) and higher (C') horizontal walls (4 mm thickness). The side walls (A, A', B and B') are made of polycarbonate with 1 cm thickness and of thermal conductivity κ_1=0.22 W/m.K. Two types of material are used for the higher and lower (C and C') walls. The glass thermal conductivity is κ_2=0.18 W/m.K and transparent polycarbonate conductivity is κ_1=0.22 W/m.K. One of the two small side walls is made of copper which is in contact with oil. The role of this element is to impose a temperature to generate an induced natural convection.

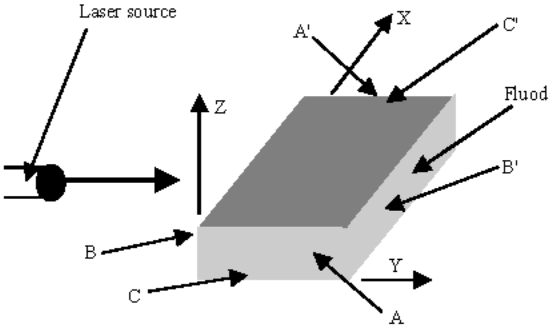

Fig. 1: Experimental device

The convection appears in an enclosure with moderate aspect ratio (Γ_x=12, Γ_y=3) between walls with average thermal conductivity. Under these conditions, the theoretical critical Rayleigh number in the case of the Rayleigh-Bénard convection is roughly Rac=1420 (Cerisier *et al.*, 1998a) , which corresponds to ΔT=1.55 °C for used oil at 30 °C.

$$Ra = \alpha g H^3 \Delta T/\nu\kappa \qquad (1)$$

Where:

α: Coefficient of isobaric expansion (1 K^{-1}),
g: Acceleration of gravity (m s^{-2}),
H: Thickness of oil (m),
ΔT: Vertical gradient temperature (°C),
ν: Kinematics viscosity ($m^2\ s^{-1}$),
κ: Thermal conductivity (W/m.K).

The temperatures in the horizontal walls and copper are measured using embedded thermocouples (diameter = 0.5 mm, precision±0.05 °C). The flow is visualized in the horizontal and vertical planes using a laser seet. The streamlines and the trajectories are observed using small reflective aluminium balls dispersed in the liquid. The photographic exposure time is 45 sec.

The stability of the structure is observed using a laser line crossing the enclosure and is projected on a screen (Fig. 2). The permanent (continuity) of the position and the form of this projection translates the stability of the structure; in the contrary case, the structure is unstable or not permanent, the projected laser line undulates and changes of position.

We established the temperature gradient between walls (C) and (C') ; the temperature of the side wall (A) is the ambiant one. Once the flow is established, we destabilize it by a temperature applied to the side wall (A). After stabilization of the convective structure, we increase the (A) temperature further.

The experiments were carried out for horizontal walls (C) and (C') cases of having simultaneously conductivities κ_1=0.22 W/m.K and κ_2=0.18 W/m.K. An example of structures thus formed, for the two cases, the same value of the side heating, are shown using the threads of current on Fig. 3-5.

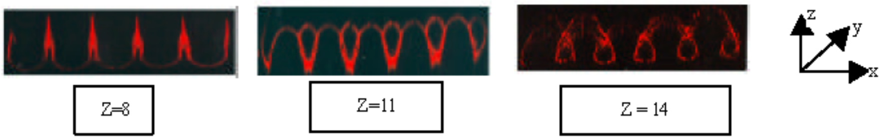

Fig. 2: Laser line projected in various heights Z case of the stable horizental structure

Fig. 3: Experimental streamlines observed for the Rayleigh-Bénard traditional flow in the two cases κ_1 and κ_2, (10 rB). ΔT=6.5 °C, Y=1.5

Fig. 4: Experimental streamlines observed for the destabilization of the Rayleigh-Bénard traditional flow, (1rI + 9rB). T_A = 42 °C; ΔT = 6.5 °C and κ_2 = 0.18 W/m.K, Y=1.5

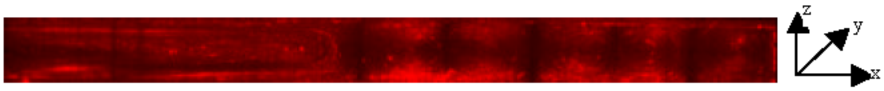

Fig. 5: Experimental streamlines observed for the destabilization of the Rayleigh-Bénard traditional flow, (1rI + 5rB). T_A=42 °C; ΔT=6.5 °C and κ_1 = 0.22 W/m.K, Y=1.5

Table 1: The physical properties of Rhodorsil 47V100 silicone oil at 25 °C are

Kinematic viscosity	$\nu = 1.10^{4}$ m^{2} s^{-1},
Density	ρ = 0.965,
Thermal conductivity	κ = 0.16 W/m.K,
Heat capacity	C_p = 1.46 KJ/Kg.K
Coefficient of isobaric expansion	α=9.45.10^{4} 1/K
Prandtl number	Pr = 880

RESULTS AND DISCUSSION

The principle of the Rayleigh-Bénard convection destabilization by superposition, with the vertical heat gradient of a side heating, was initiated by Cerisier *et al.* (1998b) where only the effect of the disturbance by the horizontal temperature gradient was taken into account. The dilation of the induced roll as well as the process of rB destruction is a function of the heat flow on the level of the side wall.

We present the results of a complementary study of the same process by taking into account, in addition to the effect of the horizontal temperature gradient, the effect of horizontal walls and the vertical temperature gradient.

Influence of vertical gradient temperature: The process of destruction per pairs of the rB (Benard Rolls) by the dilation of rI (Induced Roll) is always preserved. For κ_2= 0.18 W/m.K, the convective structure is made of, 1rI + 9rB up to a value of T_A(max) = 79 °C (Fig. 4 and 6) and of 1rI + 7rB for T_A(max) =88 °C if ΔT = 6.5 °C and of 1rI + 9rB up to a value of T_A(max) = 84 °C and 1rI + 7rB for T_A(max) = 89 °C if ΔT = 8.2 °C (Fig. 6). The corresponding maximum lengths of rI are, respectively 47.5; 54; 45 and 51.5 mm (Fig. 7).

On Fig. 7 are represented the results of this influence over the length of rI, for two different values of the thermal horizontal walls conductivity. For κ_1=0.22 W/m.K or κ_2=0.18 W/m.K, the rI length is slightly affected by the vertical ΔT variation; it increases when vertical ΔT decreases.

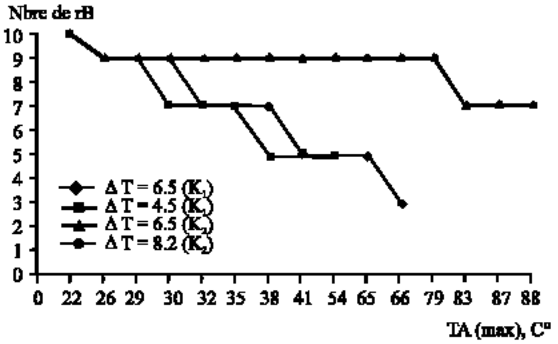

Fig.6: Variation of the rB number according to the temperture T_A (max)

We can conclude that, for this variation of the vertical temperature gradient, the maximum rI length increases with the increase in ΔT and the convective structure is preserved when ΔT increases. This is for κ_1 or κ_2 and for two different values of vertical ΔT (ΔT=4.6; 6.5°C first case and ΔT=6.5; 8.2°C second case), the shape of the representative curves is strictly the same.

Influence of the horizontal wall conductivity: Figure 7 shows clearly the difference on rI dilation according to T_A for two different values of thermal horizontal wall conductivity (κ_1= 0.22 and κ_2= 0.18 W/m.K). For the same T_A value, the length of rI, for κ_1 = 0.22 W/m.K, is almost the double for κ_2=0.18 W/m.K. This rI length is never reached in the κ_2 case, even for a value of T_A= 79 °C which is almost the double of that corresponding to the κ_1 case

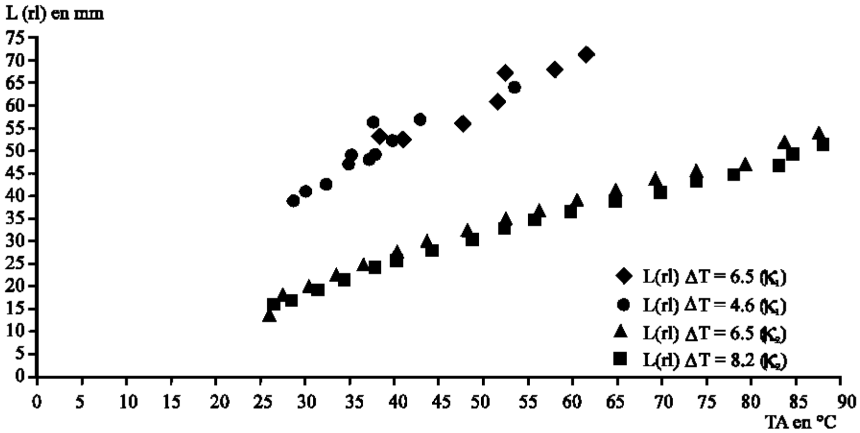

Fig.7: Variation of the rI length according to T_A temperture

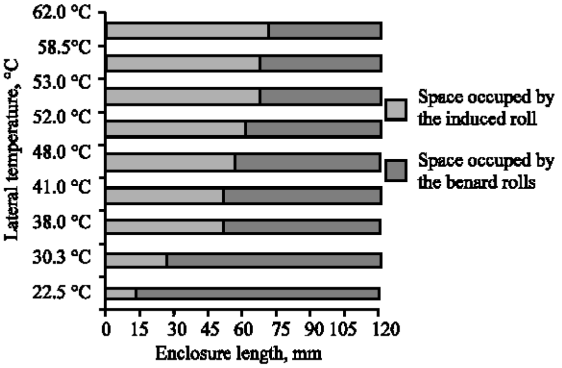

Fig. 8: Invasion of the enclosure by rI according to the lateral temperture. ΔT = 6.5 °C and κ_1 = 0.22 W/m.K

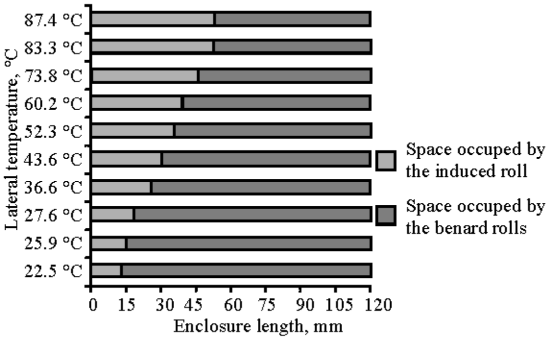

Fig. 9: Invasion of the enclosure by rI according to the lateral temperture. ΔT = 6.5 °C and κ_2 = 0.18 W/m.K

(T_A= 42 °C), (Fig. 7). Thus, the rI length according to the side wall flow, increases with the increase in the thermal horizontal walls conductivity.

The influence of the wall conductivity on the threshold of the Rayleigh-Benard convection is shown. The horizontal walls conductivity does not influence the principle of the destruction process per pairs of the (rB) by the dilation of (rI). On the other hand, it clearly influences the convective structure and the maximum length of rI. The structure is of 1rI + 9rB with T_A= 79 °C (Fig. 4 and 6) and 1rI + 7rB with T_A = 88 °C for κ_2= 0.18 W/m.K (ΔT=6.5 °C), whereas it is of 1rI + 5rB with T_A = 42 °C for κ_1 = 0.22 W/m.K (ΔT = 6.5 °C) (Fig. 5 and 6). The corresponding maximum lengths of rI are respectively 47.5; 54 and 49.5 mm (Fig. 7). It is noticed that the structure 1rI+5rB for κ_1 is preserved until T_A = 62 °C and the length of rI varies from 49.5-71 mm.

Figure 8 and 9 represent the spaces occupied in vessel of convection by the induced roll (rI) and the Bénard rolls (rB) according to the side temperature, for the two cases κ_1 = 0.22 W/m.K and κ_2 = 0.18 W/m.K simultaneously.

This phenomenon can be explained in the following way: The increase in the temperature side and wall conductivity contributes to more heat, which leaves much more time the fluid particles in suspension and falls down possibly further away from the small heating wall.

CONCLUSION

The structural composition of the tritherme horizontal convection is not only a function of the disturbance by the side heating, but in addition depends on thermal horizontal walls conductivity. The evolution of the convective structure of a liquid of high Prandtl number (Pr) in a rectangular enclosure with three walls heated differentially was examined experimentally. The influence of the thermal conductivities fluid-wall ratio was highlighted. Compared with the study made on the convective structure with another thermal conductivity of the walls (Calcagni *et al*., 2005) a clear difference exists on the level of the convective structure. We think that the competition between the two convective modes present in this problem, as well as the range of variation in the length of waves of the phenomenon also depend on the thermal conductivity of the horizontal walls.

We also have confirmed as it was found by Cerisier *et al.* (1998b) that the convection is three-dimensional, as opposed to what he was always considered. The phenomenon depends on thermal conductivities of the walls and the physical characteristics. To determine the influence, of one or other of the physical parameters, power of the side heating on the convective structure, an experimental study (determination of temperature fields and heat transfer measurement) and also a more general and complete numerical study of the phenomenon are necessary.

ACKNOWLEDGEMENT

The I.U.S.T.I, UMR CNRS 6595, University of Provence is gratefully acknowledged.

NOMENCLATURE

A, A’: Small lateral walls
B, B’: Large lateral walls
C, C’: Higher and lower horizontal walls
C_p: Heat capacity, KJ/Kg.K
g: Acceleration of gravity, m/s^2
H: Thickness of the oil layer, m
κ: Thermal conductivity, W/m.K
Pr: Prandtl number
Ra: Rayleigh number
RB: Abbreviation of Rayleigh-Bénard
rB: Benard rolls
rI: Induced roll
Ra_c: Critical Rayleigh number
T_A: Temperature of the side wall (A), °C Y : Height of laser projection along Y axis
Z: Height of laser projection along Z axis

Greek Symbols
α: Coefficient of isobaric expansion, 1/K
Γ_x: Aspect ratio in the X direction dimension along X axis / thickness of oil)
Γ_y: Aspect ratio in the Y direction dimension along Y axis / thickness of oil)
ΔT: Vertical temperature gradient
Φ: Inclination angle of the enclosure
ν: Kinematic viscosity, $m^2 s^{-1}$
ρ: Density, $kg m^{-3}$

REFERENCES

Akihiro N., O. Hiroyuki and S.W. Churchil, 1998. Numerical computation of natural convection for a low-Prandtl-number fluid in a shallow rectangular region heated from below, Chem. Eng. J., 71: 175-182.

Aydin, O., A. Unal, T. Ayhan, 1999. Natural convection in rectangular enclosures heated from one side and cooled from the ceiling, Int. J. Heat and Mass Transfer, 42: 2345-2355.

Buhler, K., K.R. Kirchartz and H. Oertel, 1979. Steady convection in an horizontal fuid layer, Acta Mech., 31: 155-171.

Busse, F.H., J.A. Whitehead, 1971. Instabilities of convection rolls in a high Prandtl number fluid, J. Fluid Mech., 47: 305-320.

Calcagni, B., F. Marsili and M. Paroncini, 2005. Natural convective heat transfer in square enclosures heated from below. Applied Thermal Eng., 25: 2522-2531.

Cerisier P., M. Jaeger, M. Médale and S. Rahal, 1998. Mechanical coupling of convective rolls in a high prandtl number fluid, J. Heat Transfer, 120: 1008-1018.

Cerisier, P., S. Rahal, J. Cordonnier and G. Lebon, 1998. Thermal influence of boundaries on the onset of Rayleigh-Bénard convection, Int. J. Heat and Mass Transfer, 41: 3309-3320.

Daniels, P.G. and P. Wang, 1994. On the evolution of thermally driven shallow cavity flows, J. Fluid Mech., 259: 107-124.

Delgado-Buscalioni, R. and E. Crespo del Arco, 1999. Stability of thermally driven shear flows in long inclined cavities with end-to-end temperature difference, Int. J. Heat and Mass Transfer, 42: 2811-2822.

D'Orazio, M.C., C. Cianfrini, M. Corcione, 2004. Rayleigh-Bénard convection in tall rectangular enclosures. Int. J. Thermal Sci., 43: 135-144.

Lee, J.R. and M.Y. Ha, 2005. A numerical study of natural convection in a horizontal enclosure with a conducting body. Int. J. Heat and Mass Transfer, 48: 3308-3318.

Mazuoka, T. and J. Shimizu, 1987. Convection in an inclined box, Heat Transf. Jap. Res., 16: 82-94.

Normand, C., Y. Pomeau and M.G. Velarde, 1977. Convective instability: A Physicist Approach, Rev. Mod. Phys., 49: 581-624.

Schluter, A., F. Lortz and F.M. Busse, 1965. On the stability of steady finite amplitude convection, J. Fluid Mech., 23: 129-144.

Shadid, J.N. and R.J. Goldstein, 1990. Visualization of longitudinal convection roll instabilities in an inclined enclosure heated from below, J. Fluid Mech., 215: 61-84.

Sharif, M.A.R. and T.R. Mohammad, 2005. Natural convection in cavities with constant flux heating at the bottom wall and isothermal cooling from the sidewalls. Int. J. Thermal Sci., 44: 865-878.

Stork, K. and U. Muller, 1972. Convection in boxes: Experiments, J. Fluid Mech., 54: 599-611.

Sundstrom, L.G. and S. Kimura, 1996. On laminar free convection in inclined rectangular enclosures, J. Fluid Mech., 313: 343-366.

Wu W., D. Ewing and C.Y. Ching, 2006. The effect of the top and bottom wall temperatures on the laminar natural convection in a air-filled square cavity. Int. J. Heat and Mass Transfer, 49: 1999-2008.

Yahata, H., 1999. Stability analysis of natural convection in vertical cavities with lateral heating, J. Phys. Soc. Jap., 68: 446-460