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RAYLEIGH-BENARD PATTERN DISTURBED BY A LATERAL FORCED ROLL

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ABSTRACT

An experimental and numerical study is carried out to describe the competition between Rayleigh-Bénard roll pattern and a roll induced by a lateral heating in a rectangular box. The wavenumber can vary only in a narrow bandwidth. Therefore when the induced roll size increases the mechanical coupling between rolls provokes disappearance of a roll pair.

1. INTRODUCTION

Convection in a two layer system displays a wide variety of dynamical behaviours. Two types of coupling exist between the two convecting liquid layers : the "mechanical" and the "thermal" coupling. In the first one, rolls turn in opposite senses, in a gearlike fashion, in both layers, so as to minimize the shear between rolls of the same liquid layer and at the interface. In the thermal coupling, the rolls have opposite senses of rotation in each layer (for the reason above) but, in the opposite, two facing rolls turn in the same sense on both sides of the interface : for instance warm uprisings in the top layer correspond to warm uprisings in the bottom layer. Nataf *et al.* [1988,1991] have shown that mechanical coupling is the preferred mode when the viscosities of the two fluids are of the same order. At the opposite, when the viscosities are very different, the thermal coupling occurs.

In this paper, we focus on the coupling existing between two horizontal systems of rolls in the same liquid. The first system is the classical Rayleigh-Bénard roll pattern in a rectangular box. The second system is, in fact, a unique roll imposed by the heating of a lateral short wall parallel to the roll axis. The questions of interest are : when the imposed roll size increases is there disappearance of Bénard rolls or decrease of their size ? (This problem can be also considered as a study of Bénard convection with a movable side wall but the boundary conditions on this "wall" are not that of a solid plane). What does happen when the Bénard roll neighbouring the forced roll and the latter have opposite directions on their interface? When they have same direction ?

2. EXPERIMENTAL SET-UP

The vessel (Fig.1) is a rectangular cavity (12x3x1 cm^3) made of polycarbonate "Lexan" which has about the same thermal conductuvity (0.22 W/m.K) than the silicone oil (0.16 W/m.K). At 25°C the Prandtl number is Pr=800). A vertical temperature gradient is applied owing to two liquid flows at controlled temperatures in contact with the lower (C) and the upper (C') limiting plates (thickness = 3 mm). The thickness of lateral walls is 1 cm. In each small lateral wall, a copper element is set in the central part in contact with the oil. These elements allow us to impose the sense of rotation of each roll near A (the wall on the right) and near A' (the wall on the left) with an adjusted very weak heating or cooling. The temperatures in C,C', A and A' are measured using fourteen thermocouples embedded in the walls.

3. EXPERIMENTAL PROCEDURES

Three series of experiments have been carried out :

1/ Series 1 - It is the classical Rayleigh-Bénard convection but between moderately thermal conducting horizontal boundaries : a vertical temperature gradient is applied to the liquid layer (The Rayleigh number R=3.1 Rc, where the subscript c stands for the critical value). A roll pattern parallel to the small side vessel A appears in the fluid (Fig.2).
2/ Series 2 - It is the convection in a box with a vertical heating wall. The two horizontal limiting surfaces C and C' are at the same temperature. That of the wall A (TA) is increased step by step. A roll is induced near A.
3/ Series 3- We successively superpose the two heatings : when a stable roll pattern is established, the wall A is heated, the induced roll (IR) close to A disturbs the roll pattern. The size of the roll near A, which is pointed out by L, increases whereas the number of rolls decreases.

Except very close to the large lateral walls, the structure is 2-D. For each series, the steady state being reached, the sizes of the rolls and the temperatures of C and C' are measured.

4. NUMERICAL ANALYSIS

4.1. Governing equations

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}=-\frac{1}{\rho_0}\frac{\partial P}{\partial x}+\frac{\mu}{\rho_0}\left(\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}\right) \quad (1)$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}=-\frac{1}{\rho_0}\frac{\partial P}{\partial y}+\frac{\mu}{\rho_0}\left(\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}\right)-\frac{\rho}{\rho_0}g \quad (2)$$

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}=0 \quad (3)$$

where U, V, P, t, μ are respectively the horizontal and vertical components of the velocity, the pressure, the time, the dynamical viscosity; ρ_0 is the density at the reference température T_0. The density as a function of temperature is written :

$$\rho=\rho_0\left[1-\beta\left(T-T_0\right)\right] \quad (4)$$

The heat transfers in the fluid and the walls are described by the thermal equation :

$$\frac{\partial T}{\partial t}+U\frac{\partial T}{\partial x}+V\frac{\partial T}{\partial y}=\frac{k}{\rho_0 C_P}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \quad (5)$$

where k and Cp are respectively the thermal conductivity and the specific heat at constant pressure of the medium. In the walls this equation is reduced to a pure conduction equation.

4.2. Finite elements model

Our finite element model is formulated in primary variables (u,v,p,T). Furthermore it uses the standard Bubnov-Galerkin approach which consists in discretizing the weak form of the equations (2). Using a segregated algorithm to solve the thermo-mechanical problem we separately built each integral by the weighted residual method.

These integrals are then spatially discretized according to a finite element approximation and temporally according to a finite difference scheme (implicit Euler). Spatial discretization of thermal field is obtained through a linear triangular finite element with three nodes. The triangular element with six nodes, developed by Bercovier and Pironneau (1988) is our choice for the flow.

The solution of the formed algebraic systems is executed according to the sequential solution algorithm mentioned down below. It was implemented in the scope of a finite element code architecture/base that we have developed :

Initialisation of variables
Loop on time steps
- Determination of velocity field
- Determination of temperature field

Each system is solved by a direct method. Furthermore, Newton-Raphson method is used to linearize the system related to velocities.

5. RESULTS AND DISCUSSION

5.1. Series 1

The results are displayed for R=3.1 Rc. The observed and computed streamlines and the isotherms are shown in Fig.2. They exhibit the presence of ten rolls which rotate in a gearlike fashion. The agreement between experimental and calculated results is fair. As expected, isotherms go into the blocks C and C' with the same periodicicy that the rolls and in agreement with the local flow direction.

5.2. Series 2

The size of the induced roll as a function of TA is shown in Fig.3. The agreement between experimental and calculated sizes is very good for TA<45 °C. Beyond this value the difference between them increases with TA. This is chiefly due to the hypothesis of a viscosity independant of temperature which is no more valuable when temperature increases (for instance a 20°C variation provokes a decrease of 36 % for μ).

5.3. Series 3

A number (from 1 to 10) is attributed to each roll, corresponding to its position, the origin being the wall A. Three cases must be considered :

5.3.1. Roll 10 is upward on the wall A' and imposed for all the experiment duration, initially roll 1 is upward on the wall A. The Fig.4 shows the steady pattern for TA=44.4 °C. When A is heated, a transient regime occurs. TA progressively reaches a constant value. During that time the velocity increases along A wall and the roll 1 widens. As a consequence it provokes a compression of next rolls. The bandwidth of the selected wavelength in Rayleigh-Bénard pattern is narrow, therefore the rolls cannot be compressed beyond a certain limit. A new size increase of roll 1 needs the disappearance of rolls. So the second roll disappears by integration into the roll 1. Now rolls 1 and 3 have opposite flows creating a strong shear at their interface. Therefore roll 3 is also absorbed. This is achieved in a short time (about 2 mn). Observed and computed sequencies provide a good and comparable description of that successive phases of transient regime.

After this stage, the remaining rolls are generally greater than the preceding ones. Then, there is a new compression and so on. So, due to the the gearlike effect, rolls disappear by pairs (2 and 3, 4 and 5, etc...) following the cycle : compression, disappearance, expansion and so on. Fig.5 shows the observed position of rolls in the box and their disappearance when TA increases.

In Fig.3 IR size variations are shown as a function of the temperature wall TA. As expected this size is smaller in series 3 than in series 2.

The temperatures of C and C' are constant where the roll pattern exists (Fig.6). On the opposite, close to roll 1, they increase when the distance to A decreases. For high TA (= 113.2 °C), the local vertical temperature gradient is inversed (C' is warmer than C)

5.3.2. Roll 10 is downward on the wall A' and imposed for all the experiment duration, initially roll 1 is downward on the wall A. A very weak heating of A provokes the apparition of a thin roll between A and roll 1. It is called roll 0. This induced roll is upward along A, so it satisfies the mechanical coupling. When TA is increased, even weakly, the increase of roll 0 provokes the disappearance of roll 1, then, fastly that of roll 2 because of the gearlike effect. A new increase of the roll 0 size provokes the already described cycle : compression of roll pattern, disappearance of a roll pair, expansion etc.... Now the pairs which disappear correspond to the rolls 1 and 2, 3 and 4, etc...

5.3.3. Rolls 1 and 10 have the same sense (upward for instance) but the flow direction of roll 10 is not fixed during the experiment. It can vary if boundary conditions vary. Generally there is first a disappearance of roll pairs. Then, and when the increase of TA is small, it can be observed that there is disappearance of only one roll. In that case the mechanical coupling leads to a transient state : the Bénard roll pattern is destroyed. Then, after a transient regime, a new permanent convective regime appears : the flow of each roll is reversed to respect the gearlike effect. Now the flow along A' wall is downward.

6. CONCLUSION

For each study, experiments and computations are in agreement. They allow the conclusion that the Rayleigh-Bénard pattern is not very compressible because the wavelength can vary only inside a narrow bandwidth. The size increase of the induced roll provokes the disappearance of rolls so as to respect the mechanical coupling between rolls and the practically constancy of the wavelength.

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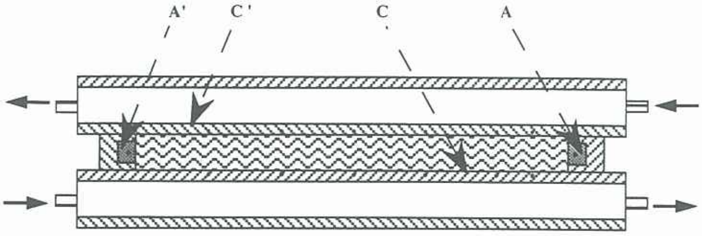

FIG.1 - EXPERMENTAL DEVICE

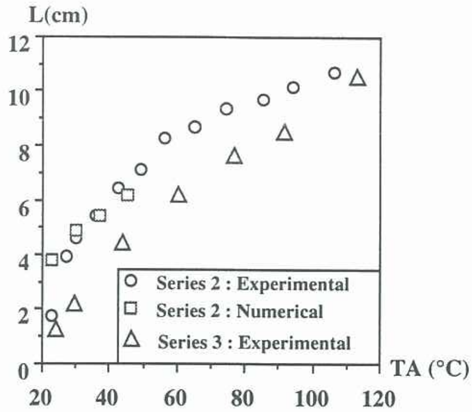

FIG.3 - SIZE OF IR AS A FUNCTION OF TA

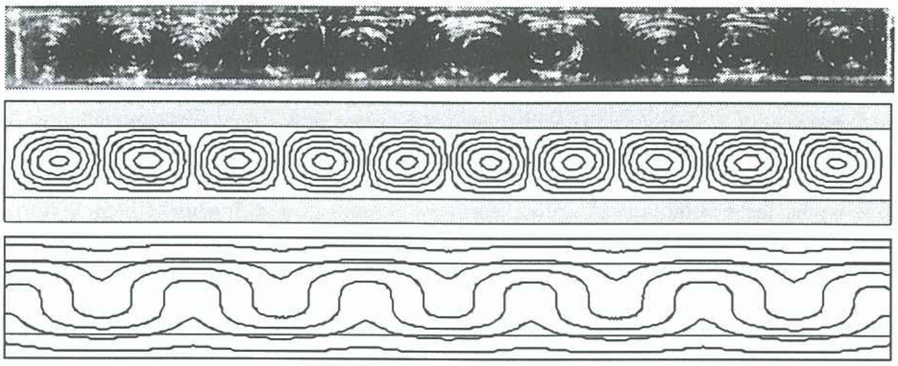

FIG.2 - SERIES 1 : OBSERVED AND COMPUTED STREAMLINES, COMPUTED ISOTHERMS

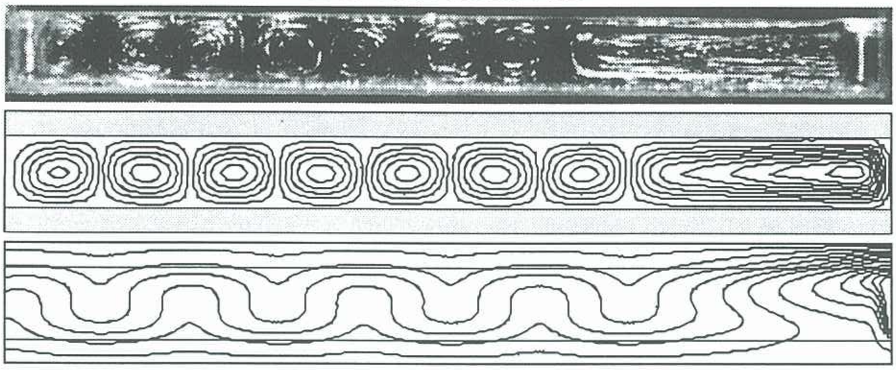

FIG.4 - SERIES 3 : OBSERVED AND COMPUTED STREAMLINES, COMPUTED ISOTHERMS

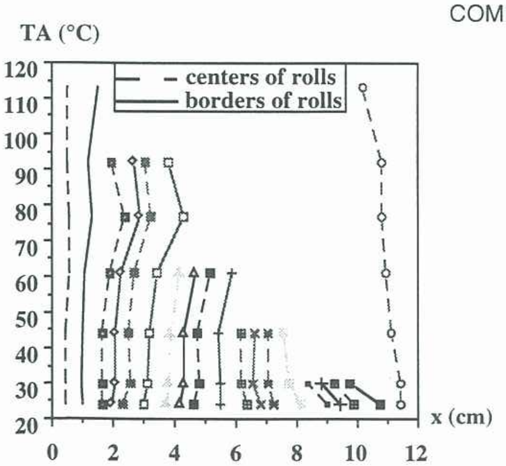

FIG.5 - SERIES 3 : BEHAVIOUR OF THE ROLL PATTERN FOR DIFFERENT TA

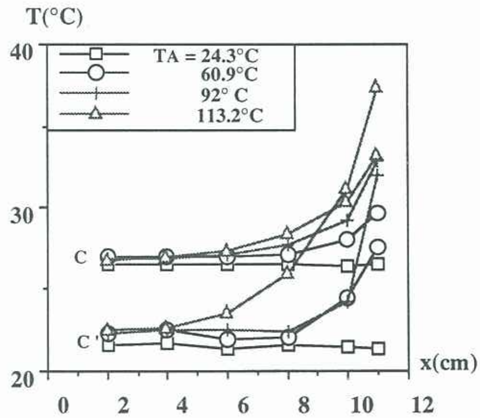

FIG.6 - TEMPERATURES IN DIFFERENT POINTS OF C AND C' FOR VARIOUS TA