TRANSITION IN ROTATING ANNULUS WITH THERMAL GRADIENT

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Summary The transition to turbulence in a differentially rotating annulus with a radial temperature gradient has been investigated both in experiments and in numerical simulations. We have shown that for an intermediate radius ratio and a large aspect ratio, the base flow with 2 velocity components bifurcates via a Hopf transition to a state of traveling vortices with a frequency related that depends on temperature gradient. For a large temperature gradient, the bifurcation leads to a modulated spiral pattern. Numerical simulations and experiments using thermochromic liquid crystals technique allow for discrimination of different modes by measuring simultaneously the temperature and the velocity fields, but also for the determination of the Nusselt number that characterizes the heat transfer in the flow.

INTRODUCTION

The present work focuses on the study of heat transfer within a vertical Couette–Taylor system with a radial temperature gradient. Such a configuration is encountered in many industrial applications, such as cooling systems of rotating machinery or electronic circuitery. In this system, there is a coupling between the centrifugal force and the torque induced by the radial stratification of density. In case of natural convection with fixed cylinders, the fluid is only influenced by the radial temperature gradient in the gap between the two coaxial vertical cylinders. As soon as a small temperature gradient is applied to cylinder walls, radial stratification of the density induces a torque which produces a large convection cell. Fluid particles near the heated wall move upwards while those near the cooled one move downwards. When the temperature difference exceeds a critical value, the large convection cell (base flow) becomes unstable and traveling axisymmetric rolls occur in the middle of the system giving rise to a finite extent pattern.

FLOW PARAMETERS

The flow configuration consists of annulus formed of two coaxial cylinders of radii a and b. The annular gap of width $d = b-a$ and length L is filled of liquid of density ρ, kinematic viscosity ν and thermal expansion α and thermal diffusivity κ. The inner cylinder is maintained at a fixed temperature T_a and rotates at angular frequency Ω. The outer cylinder is fixed and its temperature is $T_b = T_a + \delta T$. The flow dynamics depends on the geometry parameters, i.e. the radius ratio $\eta = a/b$ and the aspect ratio $\Gamma = L/d$; it depends also on physical control parameters : the Prandtl number $Pr = \nu/\kappa$, the Taylor number $Ta = Re\ \delta^{1/2}$ where $Re = \Omega a d/\nu$ and the Grashof number $Gr = \alpha \delta T g d^3/\nu^2$. The threshold of the instability depends on the geometrical parameters, and the nature of the working liquid (Pr). The base flow has two velocity components: an azimuthal velocity component due to the rotation and the axial velocity component.

PREVIOUS WORKS

While many scientific works have been performed for the isotherm Couette-Taylor flow [1], relatively little work has been devoted to the case of non-isothermal Couette-Taylor flow [2-4]. In 1964, Snyder and Karlsson [5] experimentally studied the effect of small temperature differences [-10 °C, 10 °C] on the circular Couette flow for glycerol and water mixtures. A detailed linear stability analysis investigation including non-axisymmetric modes was performed by Weidman and Ali [6]. Some experiments in the air have been reported by Ball and Farouk [7] together with numerical simulations of Kuo and Ball [8] which have shown the effects of fluid nature for $\eta = 0.5$ and $\Gamma = 10$. The experiments of Ball and Farouk [7] have underlined the importance of centrifugal and buoyancy forces. They observed that when increasing the radial temperature gradient, the buoyancy forces become predominant and leads to the appearance of the rolls similar to those observed in natural convection.

EXPERIMENTAL AND NUMERCAL RESULTS

We have revisited this problem using the up-to-date techniques of flow visualization and metrology (PIV and TLC). The gap between the cylinders has a width $d = 0.5$ cm and the length of working liquid is $L = 57$ cm. Hence the system has a radius ratio $\eta = 0.8$ and an aspect ratio $\Gamma = 114$. The working fluid is water to which we have added Kalliroscope suspension for visualization or thermochromic liquid crystals for temperature and velocity measurement. The addition of the Kalliroscope particles or thermochromic liquid crystals in a small amount does not affect in a significant way the viscosity of the liquid so the Prandtl number Pr varies between 5 and 7 for all covered values of temperature gradients.

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RESULTS AND CONCLUSION

In experiments, we fixed the temperature gradient i.e. the value of Gr and then varied the rotation frequency of the inner cylinder i.e the value of *Ta*. The critical values of *Ta* depend on the *Gr*. A complete state diagram has been obtained in the plane spanned by *Gr* and *Ta* (Fig.1). For a fixed value of Gr, when *Ta* increases, the base flow bifurcates to a state of traveling helical vortices with axial and azimuthal wavenumbers that depend on Gr. We found new types of patterns that have not been reported before [9, 10]; for example, we have evidenced the existence of critical corotating vortices and modulated spirals. We have measured the velocity field and temperature field in the vertical cross-section (Fig.2). We have deduced heat transfer properties near the cylindrical walls. The experimental study has been complemented by linear stability analysis and direct numerical simulations; there is a very good agreement between experimental and numerical results.

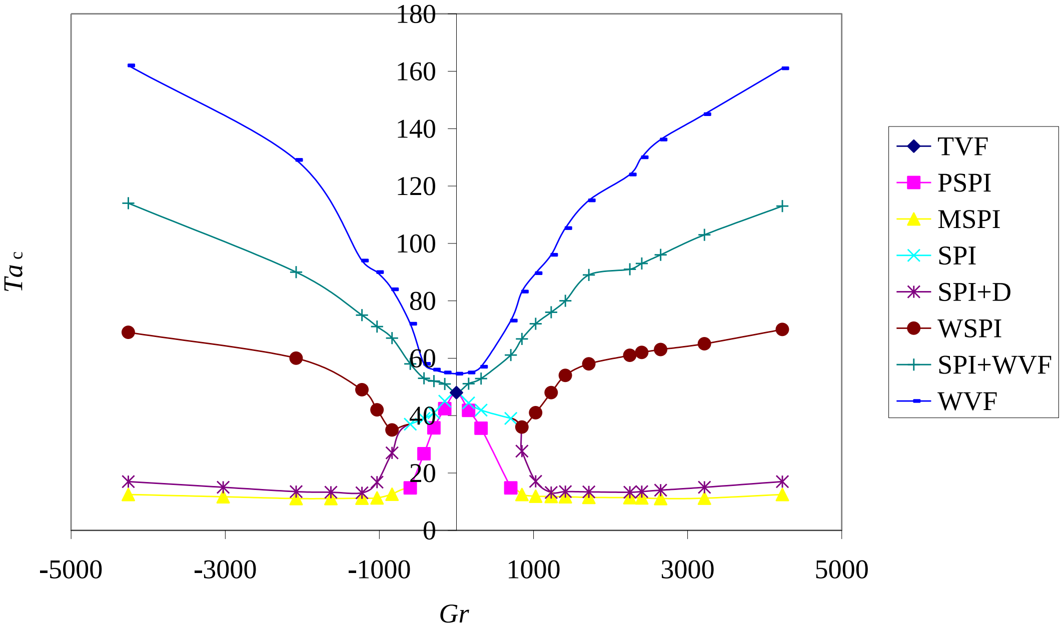

Figure 1 : Diagram of states observed for different values of *Gr* and *Ta*.

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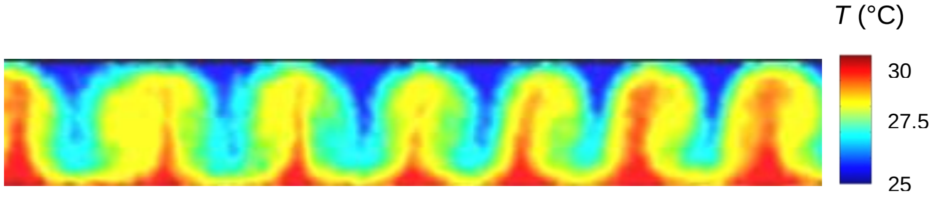

Figure 2 : Temperature field for *Ta* = 30 and *Gr* = 673. The image has a length of 8 cm and a width of 0.5cm which is the size of the annular gap.