Spatial limitation and gravity effects on the Taylor-Couette flow

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Abstract

The problem studied here is the laminar – turbulent transition in two coaxial rotating cylinders under certain conditions such as height limitation H and inclination α of the system of the flow with the vertical axis. In that case the structure of the flow may become unstable leading to, possibly, new instabilities and modifications regime. According to $\alpha = 0$ the type of instabilities is commonly known as the classical Taylor – Couette flow, and a large body of literature on this topic has developed over a century in both experimental and theoretical works. Yet surprisingly, this literature appears to be unknown for a given inclination α in the game $0 \leq \alpha \leq 90$ as Taylor number Ta is increasing. Using visualisation techniques, observations indicate the existence of the three regimes (WVF, MWVF and Chaos) and consequently different modification on α. Of particular importance is the aspect ratio $\Gamma = H/d$ which is also discussed. When the system is completely filled $H = H_{Max}$, the angle of inclination α has no effect on the flow. Otherwise, the most significant result concerns the relaminarization of the flow when Γ decreases and α is increasing for a given value of Taylor number Ta.

I.INTRODUCTION

Usually, rotating flow systems have known a considerable development and very rapid since more than one century. This is due in particular to the deepening of acquired knowledge and various applications related to the rotating machines (Viscosity, Tribology, crystal growth, Cryogenics……)

The important case of Taylor-Couette flow, defined by the movement of a confined fluid between rotating coaxial cylinders gives place with a very complex in stabilities phenomena ***[1] [2]*** which require a study aiming at the determination of its properties and comprehensive insight of mechanisms in action.

Actually, considering the great interest and the richness which this configuration has on the hydrodynamic, the researchers are also interested in mechanisms related to this type of movement to study the laminar turbulent transition regime including various modes of instabilities in order to give some explanation to the phenomena of chaos and turbulence under the influence of several effects. For examples, one may mention :*) *Geometrical effects* (effects of the edges and the boundary conditions***[3],[4],[5, 6]***, Effect of annular gap and δ and axial limitation aspect factor Γ ***[4], [7], [8], [9] [10]***) , **) *Heating effects* ***[11], [12], [13]*****.....**, ***) *Dynamic effects* (effect of acceleration ***[14], [15]***, ***[16],*** effect of magnetic field ***[17], [18], [19], [20]*** …),…

Up to now one did not record the work devoted to the effect of the Taylor – Couette bending flow on the conditions of appearance of instabilities. Our objective consists in seeking a generalization of different positions (vertical and horizontal) used to date in situations realistic where the system of flow can arise spatially in one unspecified orientation neither vertical position, nor position horizontal; in other words it acts to analyze the effects of the inclination of the apparatus which can involve possible modification of behaviour of the flow such as structure and evolution of this type of movement in the case of small gap configuration.

II EXPERIMENTS

II.1. Dispositif Expérimental

II1. Experimental apparatus

In view of conceiving and carrying out one experimental setup able to find the main results already established by different authors in the case of a vertical system $\alpha = 0$. Thereafter, one extends our tests to the description of the effects of the inclination α of the system according to a configuration defined by two coaxial cylinders within transition regime framework of the observations to be carried out the laminar-turbulent. Under the experimental conditions

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that us let us have create, the evolution of the flow is analyzed by means of a technical visualization by reflexion and optical transmission. These visualizations are carried out in natural light and by *He* laser *(*P = 1 *mwatt)*.

The device consists of two coaxial cylinders made out of insulating and transparent materials (Plexiglas). The system is planned for the use of several interchangeable cylinders and designed for to facilitate the operations of assembly and disassembling. Therefore we are aiming to realize a systematic observations of the flow through four hydrodynamic modes:TVF, WVF, Fluctuation and Chaos regimes in function of inclination α. Also, we considered four rates of filling *H*max = 200 mm, H = 185 mm , H = 155 and H = 100 mm corresponding to the value of factor $\Gamma = \frac{H}{d}$; $\Gamma = 40$, $\Gamma = 37$, $\Gamma = 31$ and $\Gamma = 20$ with $d = R_2 - R_1$ = 5mm annular space used. **Figure.1**

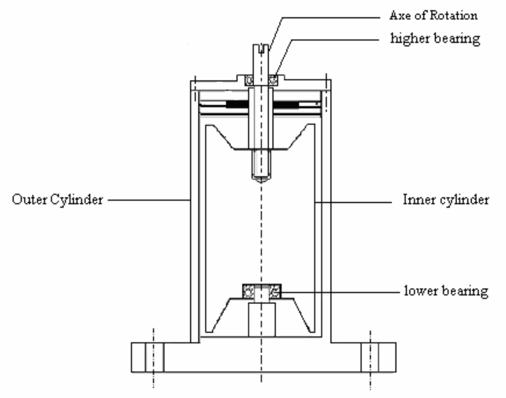


Figure.1: apparatus Taylor – Couette flow

II. 2. Procedure:

The procedure of visualization of the flow was implemented according to two procedures:

- Visualization by reflexion of the light: This mode of observation proceeds by reflexion of a pencil of light diffused by front an outside source on the flow in order to show the mode and the structure associated with the movement.

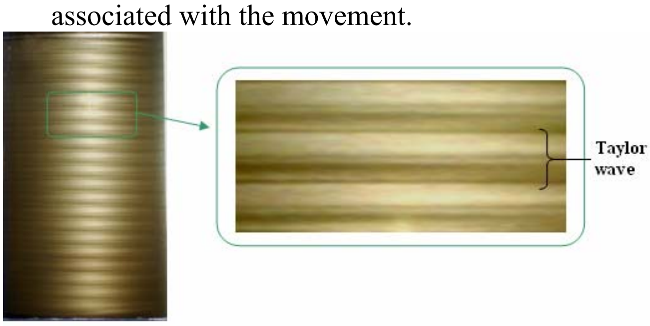


Figure 2: Visualization of a state of flow by means of optical reflexion

- Visualization by transverse optic transmission: Here, visualization is based on the optical transmission of a beam luminous coming from a source placed contrary to the observer and crossing the whole of the flow. This mode of lighting makes it possible to visualize the in-depth structure of the movement related to the shape of the cells.

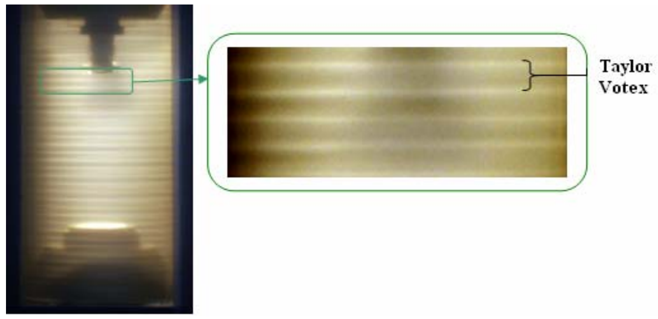


Figure 3: Visualization of a state of flow by mean of optical Transmission

We worked in natural light to study the total structure of the flow and in light coherent (Laser *He*, 1mW) to examine the local structure of movement, in particular detailed configuration of the vortices of Taylor and Wavy mode, etc.…

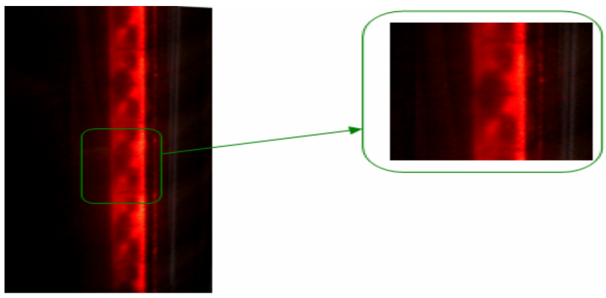


Figure 4: Visualization of a state of flow by mean of Helium Laser

II.4. Condition of setting in mode of speeds

The geometrical characteristics are fixed and move neither in space nor in time, the value of the parameter of control (*Ta*) depends of the velocity rotating cylinder $\Omega_{1,}$ annular space (*d*) as well as viscosity of the fluid used. Consequently, the value of a number of Taylor *Ta* is given by

$$Ta = Re\sqrt{\delta} \quad and \quad Re = \frac{V_1 d}{\nu}$$

Where *Re* indicates the Reynolds number, $\delta = d/R_1$ indicates the radial aspect factor, $V_1 = R_1\Omega_1$ the linear velocity of the inner cylinder, ν kinematic viscosity of the fluid considered.

For that, one adopted a drastic procedure for each test while proceeding systematically by increasing speed and according to a condition of setting in satisfactory mode the following inequality:

$$\frac{\Delta\Omega_1}{\Omega_1} \leq 1\% \qquad (*)$$

Where Ω_1 represent the angular velocity of the inner rotating cylinder.

This condition also appears necessary for the good reproducibility of measurements which is besides enough near to experimental uncertainty on the angular velocity Ω_1: for about $\frac{\Delta\Omega_1}{\Omega_1} \approx 1\%$

Adopted procedure for the various tests is as follows:

From the rest, one puts the Taylor – Couette system moving by increasing angular speed Ω_1 gradually by respecting the preceding inequality *(*)*. One stops a few minutes so to allow the flow to stabilize itself then one observes the appearance of phenomena.

For Ω_1 chosen, characterizing the appearance of a given phenomenon, we notice measurements characteristic of the structures considered and taking a picture of the state of the flow. The way thus described corresponds to a rigorous method in what they call a quasi-static thermodynamics process allowing observing the conditions of reversibility associated with the movement.

III Results and discussion

The processing of photometric data led to establish the law of variation of the number of critical Taylor Ta_c dependent on the appearance of instabilities according to the inclination α of the systeme.

The observations carried out show that if the system is completely filled $H = H_{max}$ or $\Gamma = \Gamma_{max} = 40$, the inclination α is then without influence on appearance of instabilities **Figure 6**. On the other hand, for a system partially filled $\Gamma < \Gamma_{max}$; *and* the inclination α play a part important. The examination of the experimental results allowed us to analyze the effect of the rate of filling Γ and of the inclination α, allowing to determine phenomenological laws, obeying expressions linear or exponential, that one presents in the general form following:

- Laws of the linear type:
  - $Tc(\alpha) = A \qquad (1)$

  Relation valid for $\Gamma_{max} = 40$ (completely filled)
- Laws of the exponential type:
  - $Tc(\alpha) = Tc_0 + B\exp[\alpha/C] \qquad (2)$

  Relation valid for $\Gamma < \Gamma_{max}$ (partially filled)

The whole of the constants *A, B, C and* Tc_0 are determined by filling on the experimental curves (**figure 5**).

The laws of the linear type are valid for one weak slope which is in the following angular interval:

With regard to the laws of the exponential type the criterion of appearance of the preceding structures is valid in the field of the angles complementary, namely:

$15° \leq \alpha \leq 60°$ in the case of Tc_1 and Tc_2. in the case Tc_3 and Tc_4 the range is extended to 80° .

The axial wave or Taylor vortex flow disappear thank to the relaminarization according to α.

It is also noted that there are critical angles α_c or angle of relaminarization which waves Taylor disappear; in the case $\Gamma = 37$ $\alpha_c = 70$ *to* $Ta = 44.5$, for $\Gamma = 31$ $\alpha_c = 60$ to $Ta = 44.3$. The wavy mode or azimutal wave are progressively attenuated according to α total disappearance; for $\Gamma = 37$, $\alpha = 35$ to $Ta = 56$ and has $\alpha = 25$ for $\Gamma = 31$.

One notices the appearance of a laminar zone on the side the free surface. This is due to the disappearance of the vortices or cells of Taylor close to the higher part of the flow. It is noted, as, as the part which find just below the laminar zone consists of vortex of Taylor inclined, this field of flow is characterized by a size of the vortices which is variable on the same circumference. This situation is physically remarkable in the sense that one notes on a side a phenomenon of compression of waves and on the opposite side a dilation of those for the same value of *Ta* Figure 6.

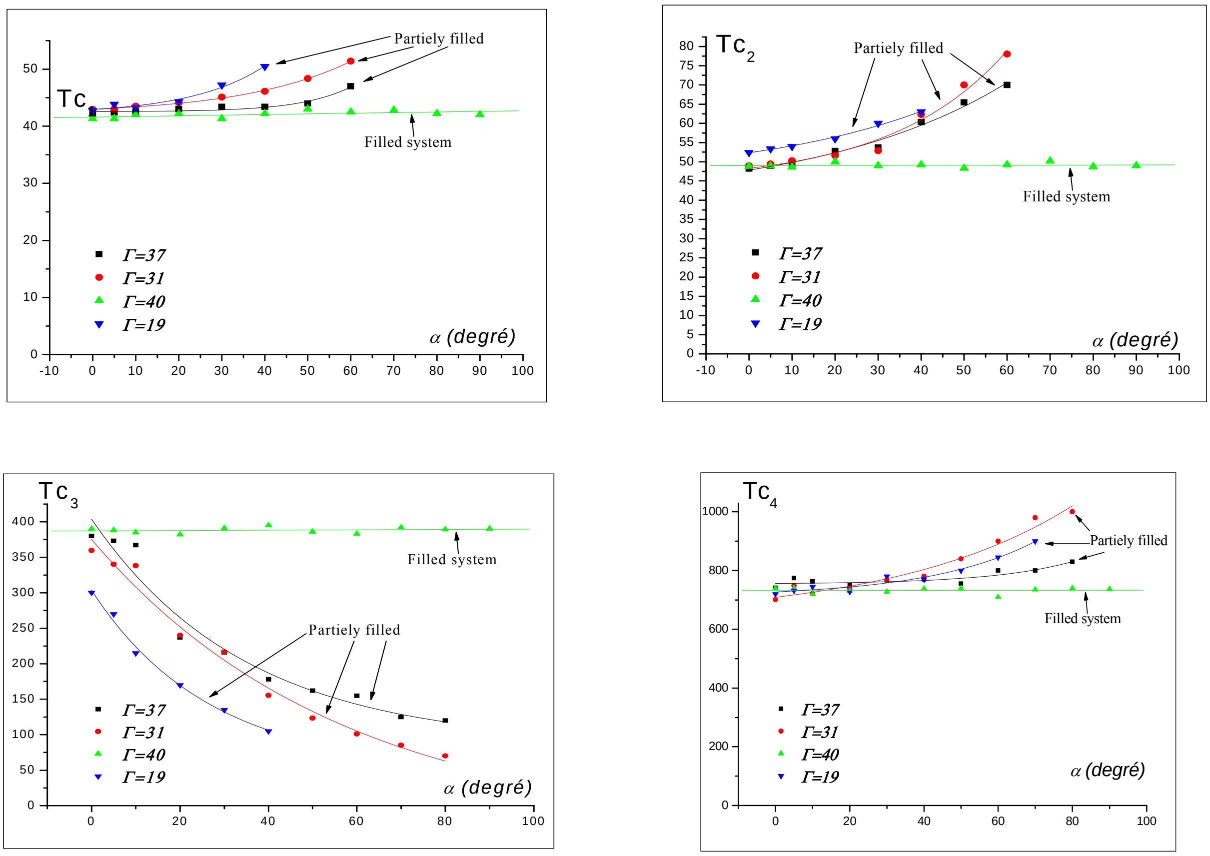


Figure 5: Variation of the critical numbers of Taylor Tc_1, Tc_2, Tc_3, Tc_4 versus angle of inclination α for a given aspect factor Γ

Ta_c / Γ	Tc_1	Tc_2	Tc_3	Tc_4
40	linear Laws $A = 41.62$	linear Laws $A = 48.89$	linear Laws $A = 387.27$	linear Laws $A = 732.03$
37	Exponential law $Tc_0 = 42.54$ $B = 0.025$ $C = 11.59$	Exponential law $Tc_0 = 39.85$ $B = 8.08$ $C = 44.77$	Exponential law $Tc_0 = 86.05$ $B = 317.64$ $C = -34.87$	Exponential law $Tc_0 = 754.13$ $B = 1.99$ $C = 21.19$
31	Exponential law $Tc_0 = 42.01$ $B = 0.86$ $C = 25.34$	Exponential law $Tc_0 = 44.61$ $B = 3.67$ $C = 85$	Exponential law $Tc_0 = -35.96$ $B = 411.27$ $C = -56.11$	Exponential law $Tc_0 = 637.93$ $B = 71.97$ $C = 43.83$
20	Exponential law $Tc_0 = 42.12$ $B = 0.82$ $C = 17.12$	Exponential law $Tc_0 = 45.79$ $B = 6.56$ $C = 0.33$	Exponential law $Tc_0 = 50.48$ $B = 252.92$ $C = -26.53$	Exponential law $Tc_0 = 710.86$ $B = 16.63$ $C = 28.84$

Table 1 : value of constants of the phenomenological law of the evolution of the critical Taylor number $Tc_I(i=1..4)$ according to the inclination α

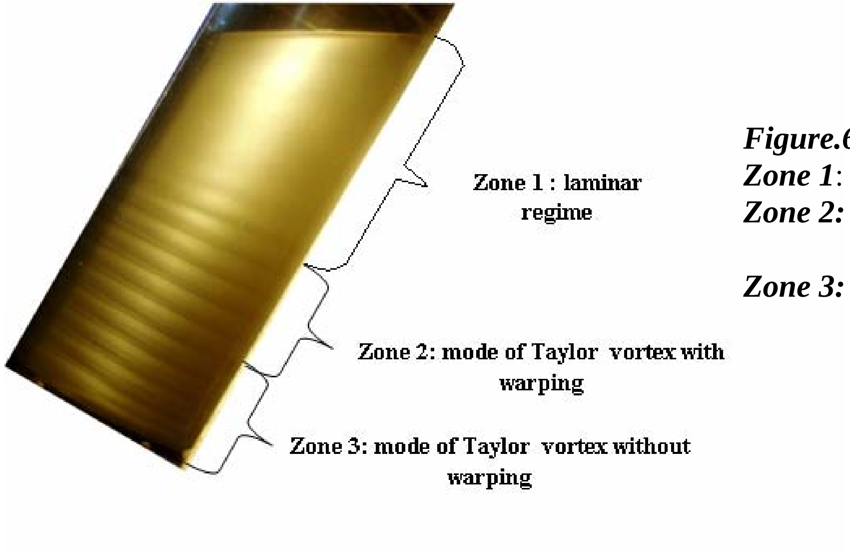
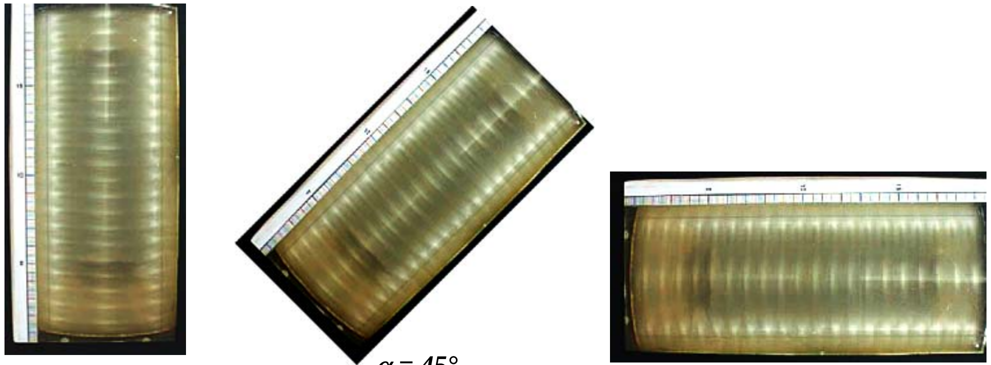
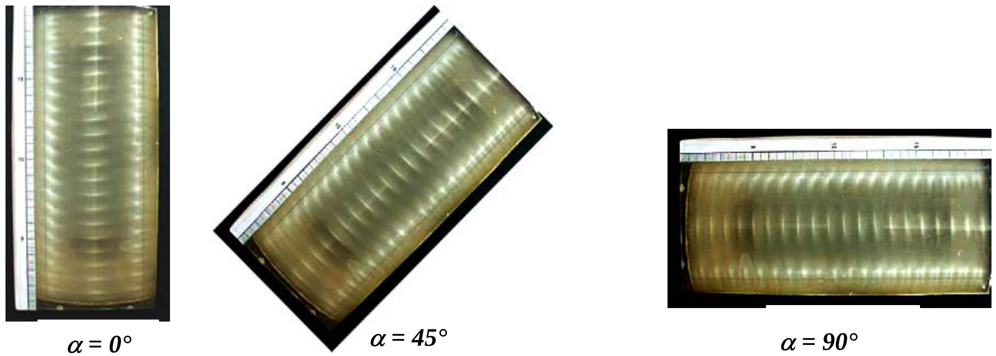


Figure.6 coexistence of three modes regimes in bending Taylor – Couette Flow
Zone 1: laminar regime with out perturbation
Zone 2: mode of the Taylor Vortices with warping; phenomenon of compression and expansion of the waves of Taylor.
Zone 3: mode of the Taylor vortices without warping.



α = 0° ***α = 45°*** ***α = 90°***

Figure 7 : Effect of inclination on the Taylor vortex *Ta = 44,2* pour *Γ =40*



α = 0° ***α = 45°*** ***α = 90°***

Figure 8 : Effect of inclination on the wavy mode *Γ=40*

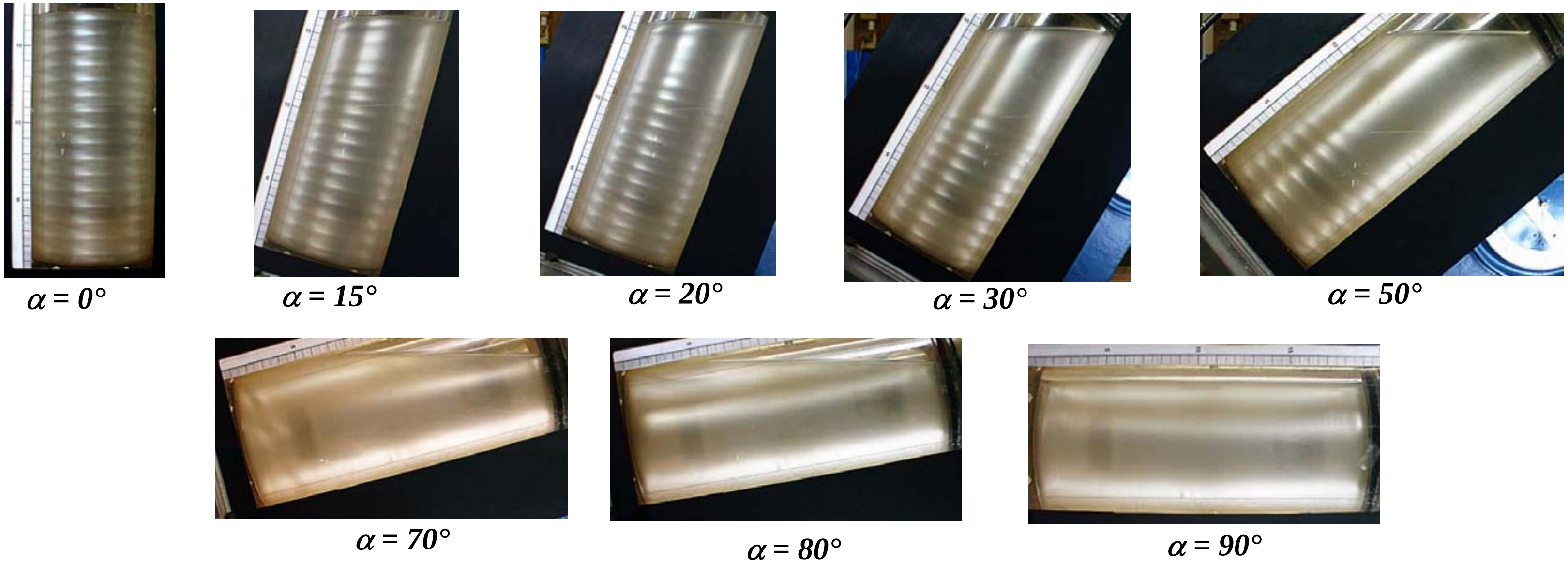


Figure 9: Effect of inclination α on the Taylor vortex $Ta = 46$ pour $\Gamma = 37$

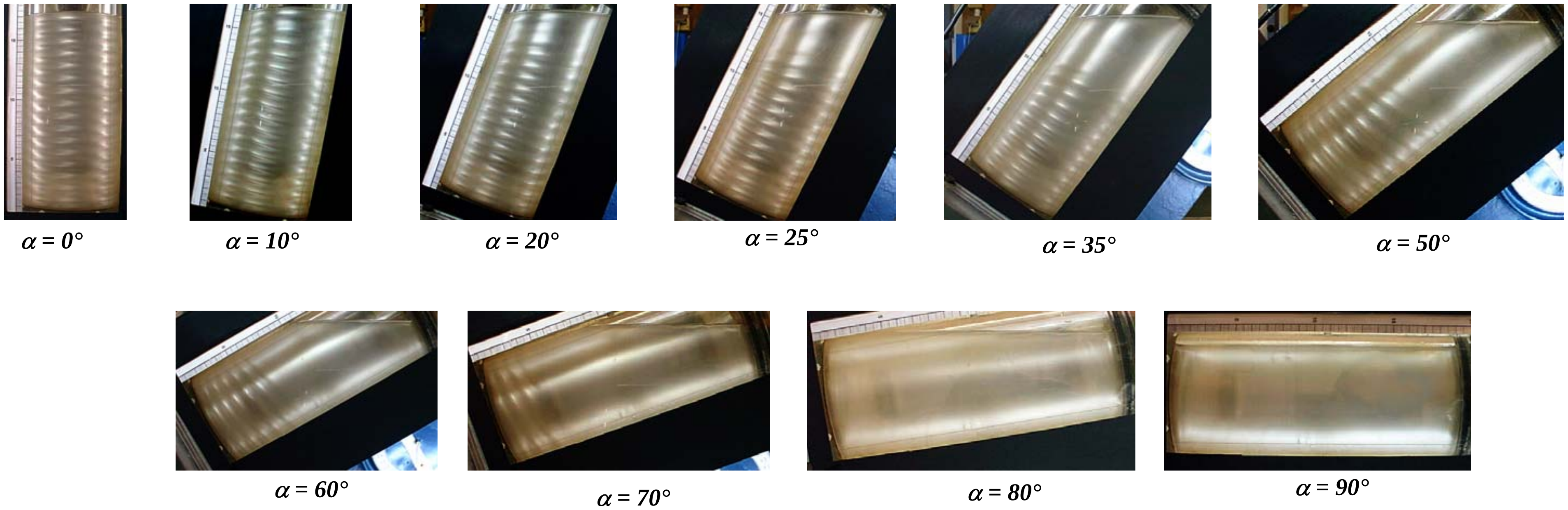


Figure 10 : Effect of inclination on the Taylor vortex $Ta=59,6$; $\Gamma = 37$.

IV. CONCLUSION

La présente étude expérimentale a permis de mettre en évidence l'influence de l'inclinaison α du système d'écoulement sur le déclenchement des phénomènes d'instabilités telles que les ondes de Taylor, Wavy Mode, fluctuation chaotique et chaos etc.…

A ce stade, on peut affirmer que l'angle d'inclinaison α n'a aucun effet sur l'apparition de ces instabilités pour un système totalement rempli (écoulement en charge $\Gamma=\Gamma_{max}$). Par contre, α joue un rôle majeur dans un système partiellement rempli, $\Gamma<\Gamma_{max}$ donnant lieu à diverses modifications significatives du mouvement. En particulier, on a mis en évidence l'effet de relaminarisation de l'écoulement pour des valeurs critiques de l'angle d'inclinaison du dispositif à Γ fixé.

Ces essais appellent à une investigation approfondie pour examiner au cas par cas, chacun des effets ou leurs combinaison sur chaque structure. Egalement, il serait intéressant d'étendre systématiquement les essais au régime de la turbulence complètement développée.

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