Flow regimes in a Taylor-Dean system with a superimposed Poiseuille flow

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ABSTRACT

1. Introduction

The purpose of this study is to investigate experimentally a Taylor-Dean open system where three different flows may be produced as shown in fig1. and fig 2:

1. The flow is obtained by pumping a fluid around the annulus while the cylinders are at rest. The flow obtained is commonly called the Dean problem. Many studies were concerned by this problem since the first theoretical analyse of Dean [1].

2.The fluid is driven by the inner cylinder which rotate clockwise or counter-clockwise. The fluid induced is forced to reverse by a diaphragm. A similar system was first considered by Brewster and Nissan [2]. During the last twenty years the so called Taylor-Dean system was investigated again by Mutabazi and al. [3] and Chen and al. [4].

3.Pumping fluid around the annular space is combined with the flow induced by the rotation of the inner cylinder. Since the experimental and theoretical analyses of Brewster, Grosberg and Nissan [5], the few contributions concerned by this flow were theoretical. Most of them were interested only by the critical conditions for the formation of the vortices [6 – 8].

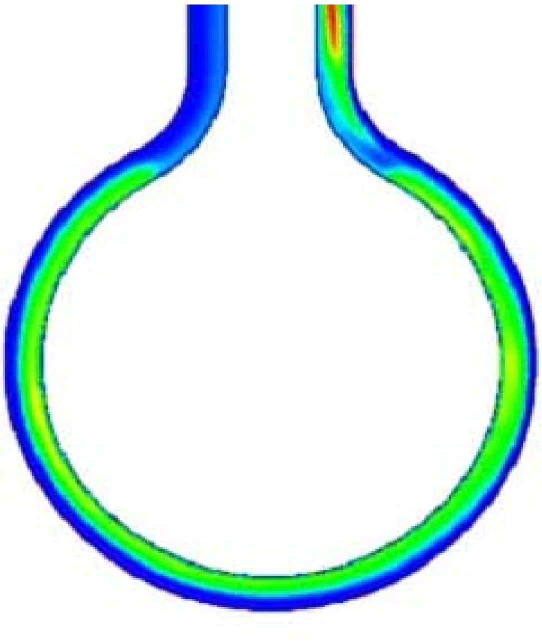

Fig.1 Simulated Open Taylor-Dean flow

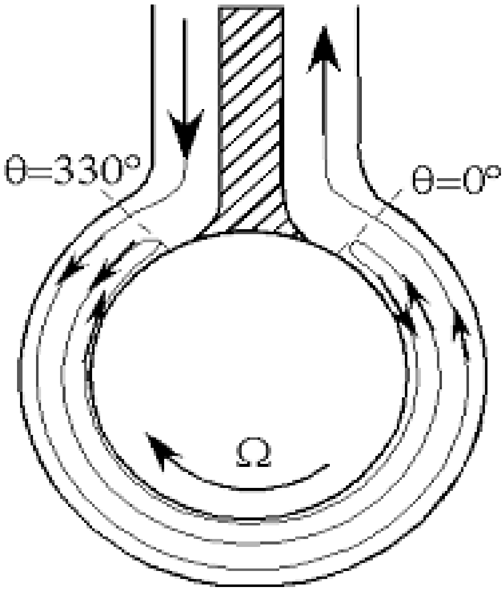

Fig.2 Sketch of the flow system

2. Device and experimental procedures

The system considered consists of a curved rectangular channel connected to a pumping circuit by two superimposed straight rectangular channels, one for the inlet and the other for the outlet of the flow. The curved section consists of two cylinders with an inner rotating cylinder of R_1 = 38,5mm, a gap d =R_2–R_1=6mm, a radius ratio η=0,865 and an aspect ratio Γ = L/d = 16,6. The straight section dimensions are 100mm x 180mm x 6mm. The device is shown by the fig.1. We make our observations in a cell delimited axially between $0<z<10$cm and azimuthally between $0°<\theta<330°$. The inner cylinder can cover the range of speeds $-17<\Omega<17$ rd/s. The flow net, which varies from 0 to 1000 dm^3/h, is provided by a pump and controlled by an electromagnetic flowmeter. It is recycled from a receptacle. Used fluid is a mixture of water and Emkarox with added Iriodin for the visualisation. Experiences are accomplished with different viscosities to produce the first instability and the high turbulence at rotation speeds which allow easy observation. The viscosity is varied in the range $10^{-6}<\upsilon<5.10^{-6}m^2s^{-1}$.

3. Experimental results

3.1. Visualisation of the Dean flow

We realised a photographic study which allows us to notice the changes which occur when following the flow from laminar until the chaos. The photos are taken at nearly 330° from the entry. The flow is parameterised by the Dean number : $D_e = \frac{V_q d}{\upsilon}\sqrt{\frac{d}{R_1}}$ where V_q is the mean velocity of the flow. The photographic sequence chosen shows rise and growth of Dean cells. The cells appear first between $280°<\theta<330°$ and $7<z<10$cm, just before the flow leaves the curved channel. They are not stationary but move slightly in the axial direction. We notice that the cells are alternately inclined right and left. However, the pictures taken in continue, during 1s, by [9] in a curved channel, suggest a radial oscillation which modulate the cells ; this can explain their temporary disappearance. The cells, which are not present in the core of the flow till De=52, fill the gap at De=58. We consider this last value as critical. [9] observed the first signs of cells at $\theta=85°$ for De=64. The theoretical value obtained by Dean for a closed system is equal to 36. Beyond $De_c=58$, the cells split and merge alternately. This cellular mutation was described by [10] as a bifurcation which arise when, for a fixed Ta, the wavelength diminishes. At De=1,3 De_c, the cells undulate. Beyond De=1,7 Dec, the cells split into wavy rolls which merge into flat cells and then split again. This mixed regime corresponds to the "twisting vortices" obtained numerically by [10] who indicates a possible transition to undulating Dean cells for a flow making more than one circumference turn. The mixed regime we observed is characterised by two sets of cells which wavelength are in a ratio 5/3. The flow then undergoes the same transitions observed in the Taylor-Couette flow even the subsequent regimes are not so well established: modulated travelling waves, turbulent bursts, ripples at the cells boundaries and the fully developed turbulence where the cells are present till De=17 De_c , the highest number of Dean our system reached.

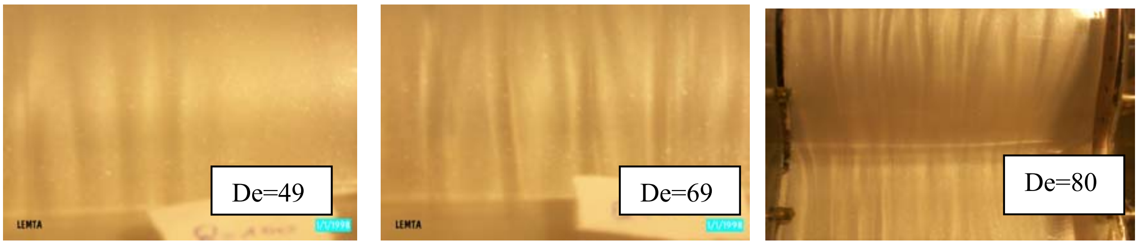

Fig.3 Photographic sequence showing rise and growth of Dean cells**.**

3.2 Visualisation of the Taylor-Dean flow

For De=0, we increase the Taylor number $Ta = \frac{\Omega_1 R_1 d}{\upsilon}\sqrt{\frac{d}{R_1}}$ where Ω_1 is the inner cylinder rotational velocity. The fluid layers dragged by the inner cylinder make a 180° turn at the exit and then flow back towards the entry where the flow is reversed again. End cells appear at the entry and the exit, the exit one being more larger. Flow structures observed simultaneously at the entry, where the rotating cylinder enter in the gap, the core and at the exit of the flow are different as shown in fig.4. Photos shown illustrate: 1) sinks vortex at the entry and cells around them 2) diagonally propagating rolls on the core 3) “necking” cell and inclined wavy rolls at the exit 4) fully developed turbulence. The structures at the entry did not receive so much interest than those developing in the exit. To our knowledge, they are reported here for the first time.

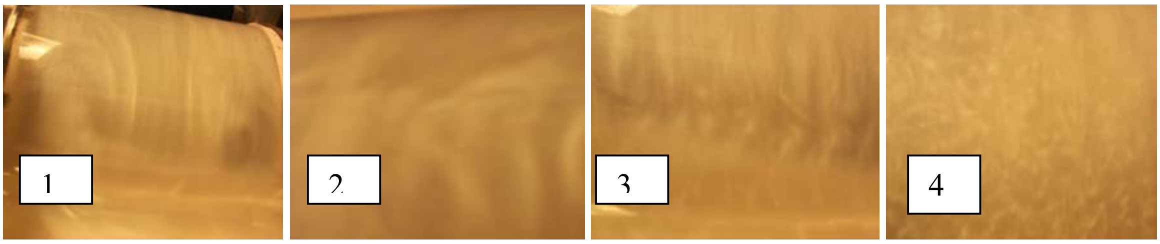

Fig.4 Structures observed at 1) the entry end 2) the core 3) the exit end 4) fully turbulence

On the core, the primary flow is purely azimuthally, Couette flow in a direction and Poiseuille flow in the opposite direction with a zero-crossing point. With increasing Ta, the flow undergoes a series of transitions leading to the turbulence: Taylor cells, Dean cells, split-merging cells, travelling waves, modulated waves, vortex path, diagonally propagating rolls and finally fully developed turbulence where all structures crumble.

2.3 Taylor-Dean flow with superimposed Dean flow

In this case, the flow is parameterised by τ=2Vq/Vc, the ratio of the net flow due to pumping and that due to inner cylinder rotation. Vc is the linear velocity of the inner cylinder. The evolution of the flow is shown in fig.5. Qualitatively, we observe the same phenomena as in Taylor-Dean flow at the entry and exit end. On the core, the primary flow is purely azimuthally with Couette flow in a direction and two Poiseuille flows in opposite direction one due to the reversed flow, the other to pumping; the Poiseuille flows can also be in opposite direction. A succession of transitions lead the flow to turbulence: sinks or sources, “necking cells” at the entry and exit end, Taylor cells in the inner layer, Dean cells in the outer layers, split-merging of the cells, travelling waves with two trains in the same or opposite direction, turbulent bursts, vortex path in opposite direction, diagonally travelling rolls, chaos where the different structures coexist and then the fully developed turbulence where all the structures crumble as in fig.4.4. It is worth noting that the fully developed turbulence, which occurs earlier than in Taylor-Couette flow, propagates from the exit to the entry end. The structures around the sinks at the entry are the last to be destroyed.

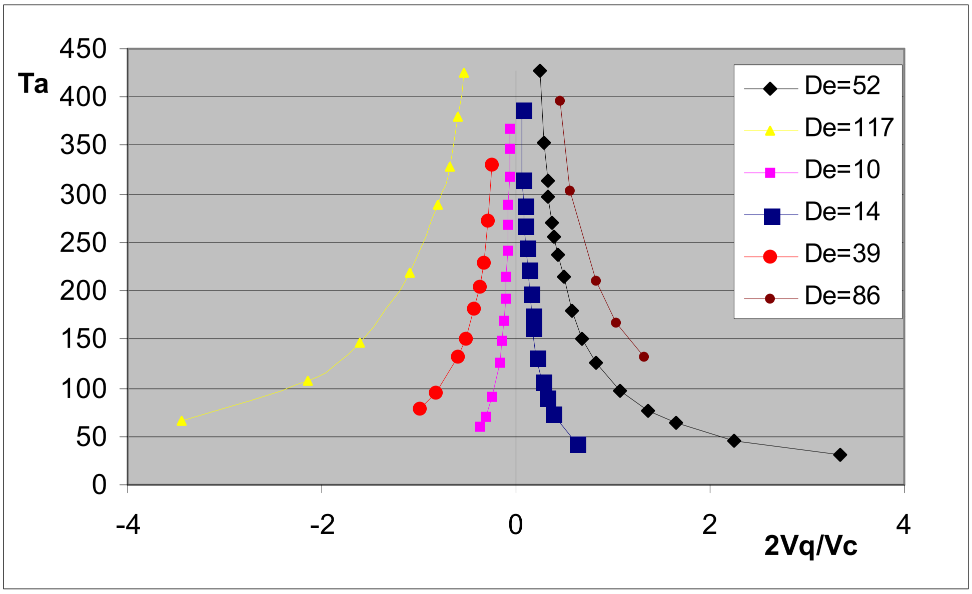

Fig.5 Evolution of the Taylor-Dean open flow when varying Ta for De fixed.

Authors [6],[7] et [8] were interested by the transition occurring at τ = - 1,222 for which the critical wave number changes abruptly. In our experiments, we observed that from τ = -1,22 large stationary cells appear in the outside layer while finest cells are present in the inside layer. Then the two sets of cells seem to be in competition. The flow doesn’t choose its cellular mode. It changes from a state to another by the split merging phenomena..

2.4 Numerical results

The 2D- finite-element method is used to simulate the flow. Freefem ++ and a penalisation method is used to solve the Navier-Stokes equations and Crout method is used to solve the linearised system. From these, the streamlines and velocity distribution are obtained. The simulated flows show clearly three different layers in the gap, those near the cylinders being potentially unstable. The difference between the entry end and the exit end are also noticeable in fig.6.

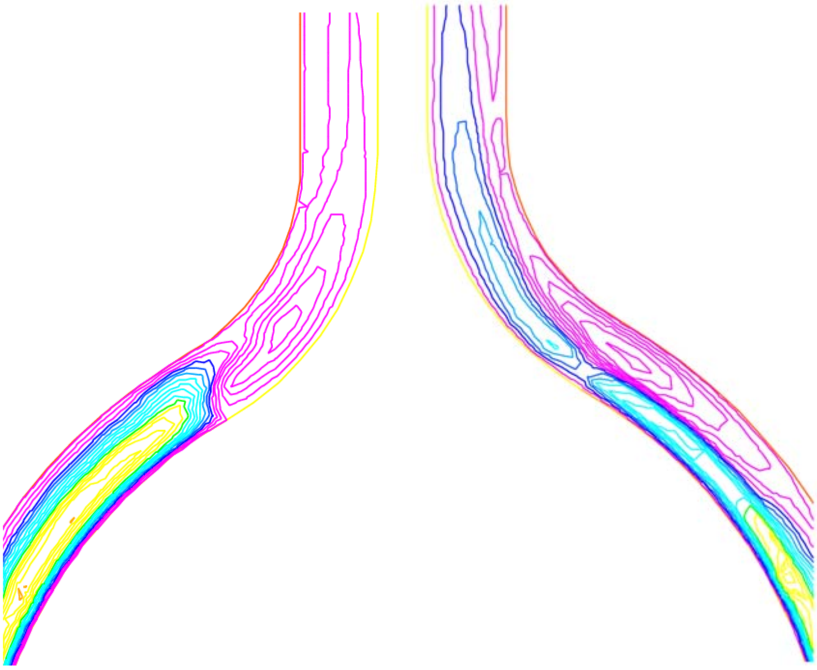

Fig.6 Entry and exit ends

3. Conclusions

The study we presented has revealed a great number of physical phenomena. Some of them agree with previous works devoted to similar flows. Others are new. More investigation is needed for a better understanding of their role in the turbulence rising. That is, while the numerical simulation study of the flow is continued in 3D, local velocity measurement is being done with a laser-Doppler velocimeter.

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