FLUID TRANSPORT INDUCED BY A FLEXIBLE OSCILLATING FLAPPER IN CREEPING FLOW

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Summary In this investigation, we study the fluid motion induced by a flexible flapper in the creeping flow regime. In this type of flows, the momentum conservation equation is time-reversible. Therefore, a simple reciprocal motion is not is not sufficient to induce mixing or propulsion. We introduce two aspects that can add a time dependence to the flow: a flexible flapper and a non-Newtonian liquid. Using a particle image velocimetry technique, we measure the amount of liquid motion induced in the fluid by a reciprocal flapper. As expected, when the flapper in rigid and the fluid is Newtonian, no net motion is produced for small Reynolds numbers. When the flapper is made of a flexible material (rubber), a net fluid motion is observed near the tip of the impeller. Likewise, when the fluid is viscoelastic, a remanent motion is observed. These results and their implication to biological systems are presented and discussed.

INTRODUCTION

In this biological world, which includes motile bacteria (prokaryotes), spermatozoa, algae and protozoa (eukaryotes), the Reynolds numbers are very small (typically between $\Re \approx 10^{-4}$ and $\Re \approx 10^{-2}$) and viscous forces dominate over any inertial effects. To achieve locomotion or to induce fluid transport in this flow conditions, two strategies can be considered: the organisms must posses a more that one-degree-of-freedom swimming strategy[1]; or, time-reversal breaking mechanism must be introduced to the problem[2]. In this investigation, we analyze two ways to introduce an additional time scale to the problem: we consider a flexible flapping element and we consider viscoelastic materials. Both options are relevant for biological problems.

EXPERIMENTAL SETUP

We have built an experimental setup to observe the fluid motion around a rectangular flapping impeller is moved in a reciprocating manner, immersed in a viscous fluid (Fig.1,left). In a rectangular transparent container, a rectangular impeller is placed. The impeller flaps reciprocally, with angle of ± 30 degrees from the vertical. A standard particle image velocimetry (PIV) technique is used measure the velocity field around the the flapper. Fig 1 (center) shows a typical PIV image, while Fig. 1 (right) shows a typical velocity field obtained when the flapper is moving in the clock/wise direction. When the flapper moves in the counter-clock-wise direction the flow field is identical to that shown in the figure, but in reversed direction.

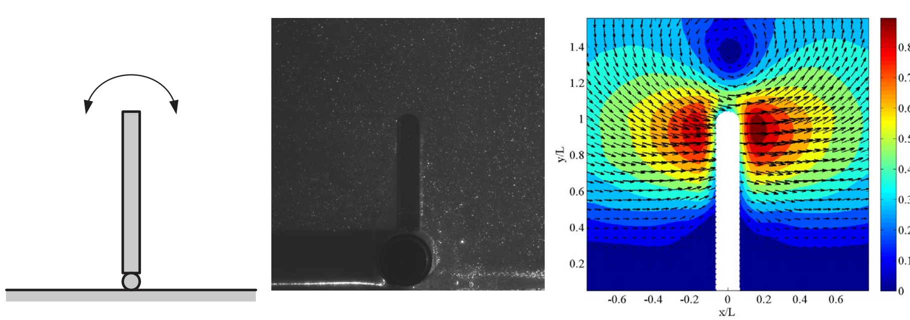

Figure 1. Scheme of the flapping experiment (left). Implementation of the PIV technique to measure the velocity field induced by the flapper (center). Typical result: flow field around the flapper (moving clock-wise); the arrows are fluid velocity vectors, the colors show the normalize magnitude of the fluid velocity (U_{fluid}/U_{tip}).

Two water-glucose solutions were used, a Newtonian and a viscoelastic one, both with a shear viscosity of 62 Pa s. For the viscoelastic fluid, small amount of Polyacrilamide was added to make it elastic. Care was taken to ensure that the fluids had constant viscosities (Boger-type fluids). By varying the rotational speed of the flapper, both the Reynolds ($Re = \omega L^2 \rho/\eta$) and Weissenberg number were varied ($We = \lambda\omega$). L is the flapper length, ω is the angular velocity of the flapper; ρ,η and λ are the fluid density, viscosity and relaxation time respectively. For the fluid considered here a value of $\lambda = 0.45$ s was obtained (via rheological characterizations).

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The flexibility of the flapper was varied by changing the thickness and material. Rigid (acrylic) and flexible (neoprene) flappers were used. The flexibility of the flapper was characterized by:

$$F_N = \frac{L}{I^{1/4}} \left(\frac{\omega\eta}{E}\right)^{1/4} \tag{1}$$

where I is the second moment of inertia of the flapper cross-sectional area and E is the elastic Young modulus of the flapper. This number compares the flexibility of flapper with the viscous forces around it; it is similar to the so-called sperm number used to characterize the locomotion of flagellated organisms[3].

To measure the amount of fluid transport we obtain a net velocity field by adding the velocity field in the clock-wise and counter-clock-wise directions when the flapper was in its vertical position. If the flow is reversible, the net flow is null. Otherwise, a remanent can be observed which can be quantified considering a pumping capacity number:

$$Q_V^* = \frac{\int_{x_{left}}^{x_{right}} v dx}{\omega L^2} \tag{2}$$

where v is the vertical velocity component of the net velocity field and x is the horizontal coordinate.

RESULTS AND DISCUSSION

Figure 2 shows the pumping capacity as a function of the flapping number for all the experiments conducted in this study. Clearly, when the impeller is flexible ($N_F > 0$) a net flux is produced: the flow reversibility is broken by the flexibility of the foil. As the flapping number is increased, the pumping capacity increases. Arguably, the pumping capacity must reach a maximum value for as the flapping number continues to increase. If N_F is too large, for instance, for a very soft flapper, one could expect to observe a reduction of the induced flow. We are currently conducting experiments for larger values of the flapping number.

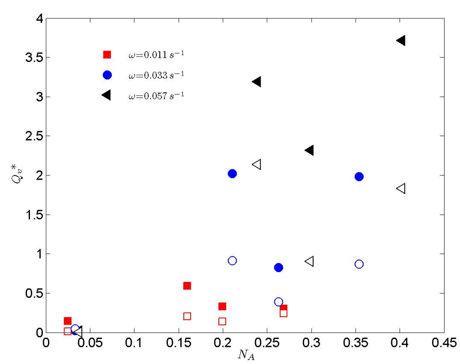

Figure 2. Pumping capacity as a function of flapping number. Newtonian (filled symbols) and non Newtonian results (empty symbols). The different symbols show the results obtained for different angular velocities (different Re and We numbers).

Interestingly, when we consider a non Newtonian liquid no net flow is observed for a rigid flapper. This behavior results, most likely, from the small value of We considered here ($We < 0.025$). When both non Newtonian and flapper flexibility effect are considered, the pumping capacity appears to be slightly smaller that than measured for the Newtonian fluid. In this case, we can argue that viscoelastic character of the fluid tends to hamper the fluid transport induced by the flapper flexibility.

CONCLUSIONS

We have studied the effect of the flexibility of a membrane to induce fluid transport in creeping flow. We observed that it is possible to break the time-reversibility of the flow by introducing an elastic time to the problem. We observed that the problem can be characterized by flapping number (Eqn.1). Although viscoelastic effects alone were not able to break the flow time-reversibility (we considered only small values of the Weissenberg number), when combined with the flexibility of the flapper, the induced fluid transport was observed to be smaller for the non Newtonian liquid (in comparison with the Newtonian case).

References

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