Control of Vortex Breakdown in a Closed Cylinder with a Rotating Lid

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The vortex breakdown within a closed cylinder with a rotating lid has been controlled successfully in numerical simulations, using the LIMSI/CNRS finite-difference code (Sørensen and Loc 1989), for varying parameter values by the introduction of a thin rotating rod along the center axis. In contrast to an earlier study (Jørgensen, Sørensen and Brøns 2003) concerned with control of the transition to unsteady flow, we here focus on the fact that breakdown bubbles are prevented by co-rotation and promoted by counter-rotation of the rod. Husain *et al.* (Husain, Shtern and Hussain 2003) performed an experimental investigation by using LIF and presented an analytical model, arguing that the rod co-rotation decreases the unfavorable pressure gradient along the axis, thus suppressing the breakdown bubbles. This explanation is based on assumptions regarding the behavior of the pressure related to the presence of the rod. In the present work, we seek a general fundamental control mechanism, applicable to the rotating rod as well as other types of control devices, including e.g., the suppression of breakdown bubbles through the counter-rotation of a small disk opposite to the driving lid, as reported by Mununga *et al.* (Mununga, Hourigan, Thompson and Leweke 2004).

The basic configuration, shown in Fig. 1a, consists of a closed cylinder with a rotating lid and a rotating rod. While the main effect of the rotating lid is to set the fluid into a rotating motion around the center axis, it also causes a meridional circulation. The fluid rising along the center axis forms a strong swirling vortex core. This vortex may experience a vortex breakdown which manifests itself by one or more bubble-like zones of recirculating fluid, referred to as breakdown bubbles, that are located along the center axis.

It was found that rotating the rod results in a local generation of negative vorticity near the bottom and positive vorticity near the lid, see Fig. 1b. This local generation of vorticity can be derived from the source term of the vorticity transport equation. Inspired by previous work on control of vortex shedding (Tang and Aubry 1997) (Tang and Aubry 2000), we found that the effect of preventing vortex breakdown can also be achieved by adding a negative vorticity source close to the center axis near the bottom of a cavity flow which tends to move the breakdown bubbles up in the direction of the bulk flow. Likewise, the effect of promoting vortex breakdown can be obtained by adding a positive vorticity source close to the center axis near the rotating lid, which tends to move the breakdown bubbles down against the bulk flow. It is demonstrated that the competition between these two mechanisms controls the streamline topology when the rod rotates. This behavior can be explained by the vorticity sources generating an induced axial velocity according to the induction law of Biot-Savart (subject to the boundary conditions of a confined domain). To gain insight into the mechanisms at play, consider the transient between two equilibrium states. The steady flow with a fixed rod was calculated for $\mathrm{Re}_{lid} = 2200$. The breakdown bubbles were visualized numerically by injecting tracing particles near the rod close to the fixed bottom, with an image of tracing particles appearing in the core of the flow, see Fig. 2. When suddenly starting a co-rotation of the initially fixed rod, at the time $t = 0$, the breakdown bubbles moved up and dissipated in the boundary layer of the rotating lid.

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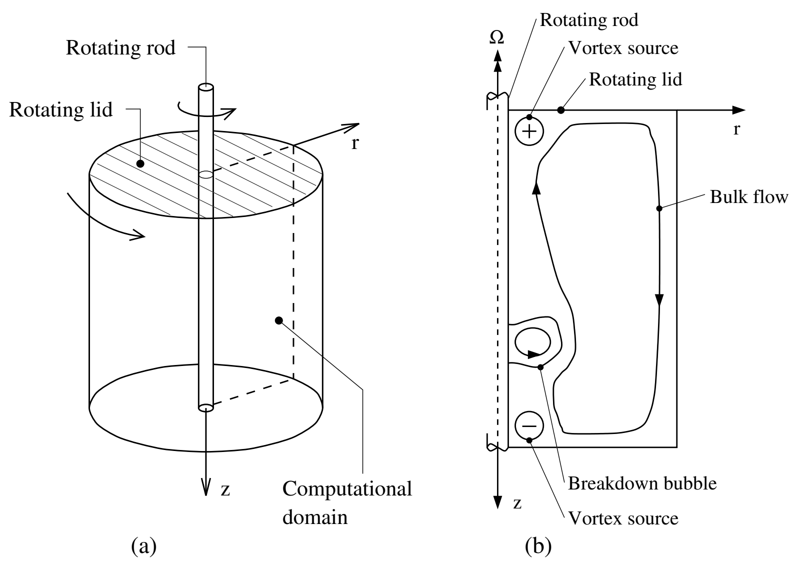

Figure 1: (a) Cylindrical cavity with rotating lid and rotating rod. (b) Sketch of the flow in the computational domain. The vorticity sources generated by the rotation of the rod are indicated near the top and near the bottom of the cavity.

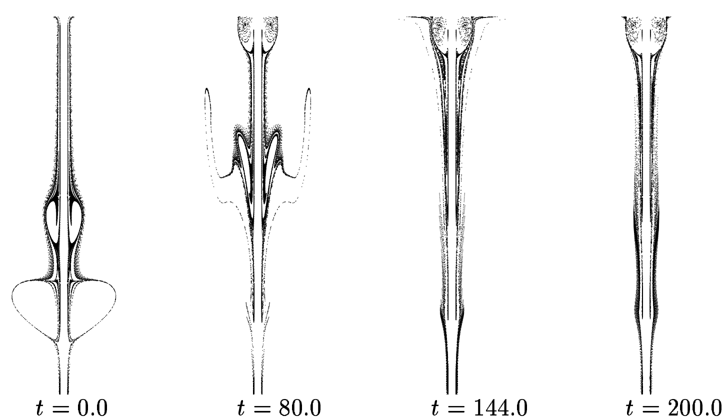

Figure 2: Simulated visualization of the transient flow at $\mathrm{Re}_{lid} = 2200$ for a sudden rotation ($\gamma = 0.008$) of an initially fixed rod. The breakdown bubbles move up and dissipate in the boundary layer of the lid.