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NEW MEANS OF VORTEX BREAKDOWN CONTROL

Miguel A. Herrada [1] and Vladimir Shtern[2]

[1] Universidad de Sevilla, 41092 Sevilla, SPAIN
[2] University of Houston, TX 77204-4006, USA

Vortex breakdown (VB) is an intriguing effect of practical and fundamental interest, occurring, e.g., in tornadoes, above delta-wing aircraft, and in vortex devices. Depending on application, VB is either beneficiary or harmful and therefore requires a proper control. This study shows that VB can be efficiently controlled by an additional near-axis swirl, temperature gradients, and their combination. To explore the underlying mechanism, we address a flow in a cylindrical container driven by a rotating bottom disk. This model flow has been extensively studied being well suited for understanding both the VB mechanism and its control. Our numerical analysis explains experimentally observed effects of control co- and counter-rotation (with no temperature gradient) and reveals some flaws of dye visualization. Next, we explore the effects of temperature gradients with no additional swirl on VB enhancement and suppression. Finally, we apply both the temperature gradient and additional swirl and demonstrate that a moderate negative (positive) axial gradient of temperature can significantly enforce (diminish) the VB enhancement by the counter-rotation. A strong positive temperature gradient stimulates the centrifugal instability and time oscillations in the flow with counter-rotation. A new efficient time-evolution code for axisymmetric compressible flows has facilitated the numerical study.

We use the Navier-Stokes equations for an axisymmetric flow of an ideal viscous and heat conducting gas. The parameters of the base flow—$h = H/R$, $\mathrm{Re} = \rho_0\Omega R^2/\mu$, $\mathrm{Ma} = \Omega R(\rho_0 R_g T_0)^{-1/2}$, $\mathrm{Pr} = \rho_0 c_p/\lambda$, and $\gamma = c_p/c_v$—are the aspect ratio, the Reynolds, Mach and Prandtl numbers, and specific heat ratio, respectively. Here H and R are the cylinder height and radius (Fig. 1), ρ_0 and T_0 are the reference density and temperature, Ω is the angular velocity of the rotating disk, $R_g = (c_p - c_v)$ is the gas constant. Viscosity μ, thermal conductivity λ, and the specific heats, c_p and c_v, are kept constant in our analysis. We take Pr = 0.72 and $\gamma = 1.4$ as values typical of gases.

The base flow is controlled by a rotation of the central rod and the axial gradient of temperature. The control rotation is characterized by the Reynolds number $\mathrm{Re}_i = \rho_0\Omega_i R_i^2/\mu$ based on the radius, R_i, and on the angular velocity, Ω_i, of the rotating rod. The thermal control is characterized by the dimensionless temperature difference, $\varepsilon = (T_{bot}-T_{top})/(T_{bot}+T_{top})$, where T_{bot} and T_{top} are temperature of the bottom and top disks; $T_0 = (T_{bot}+T_{top})/2$.

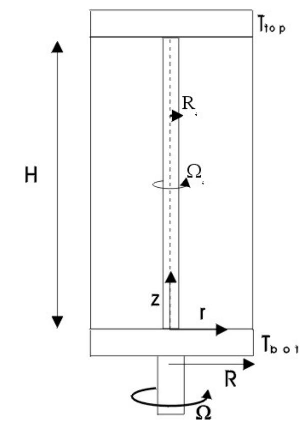

Figure 1.

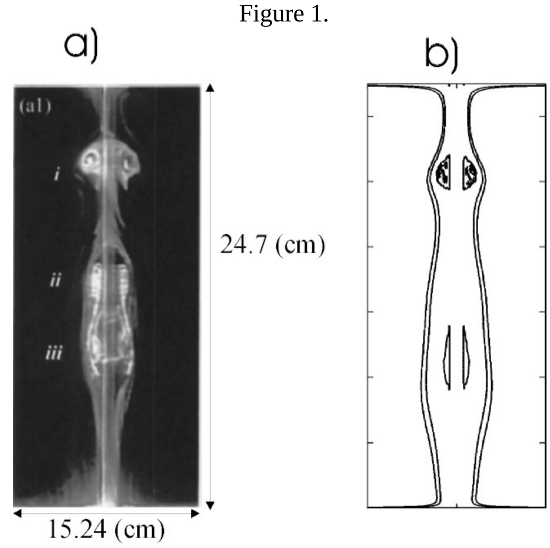

Figure 2.

Figure 2 shows streamline patterns by (a) flow visualization [1] and (b) numerical simulations of the flow where the rod is at rest ($\mathrm{Re}_i = 0$). A minor difference is that the visualization seems to show three vortex rings (Fig.

2a) while the numerical results reveal only two vortex rings (Fig. 2b).

Figure 3 and 4 show the flow at $Re_i = 21$ (co-rotating rod) and $Re_i = -12$ (counter-rotating rod). Comparing Fig. 3 (Fig. 4) with Fig 2, we see that the co-rotation (counter-rotation) suppresses (enhances) VB.

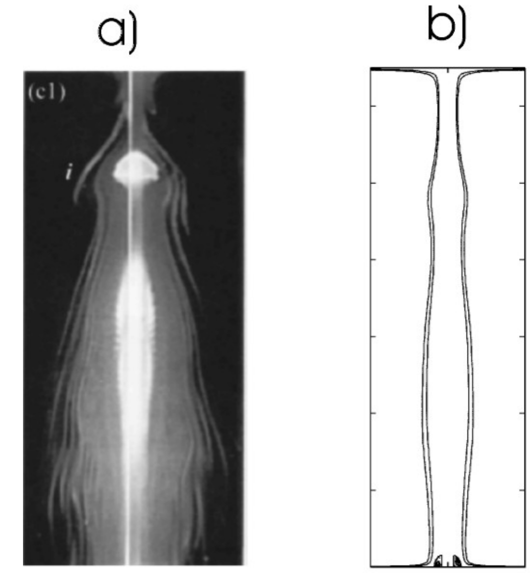

Figure 3.

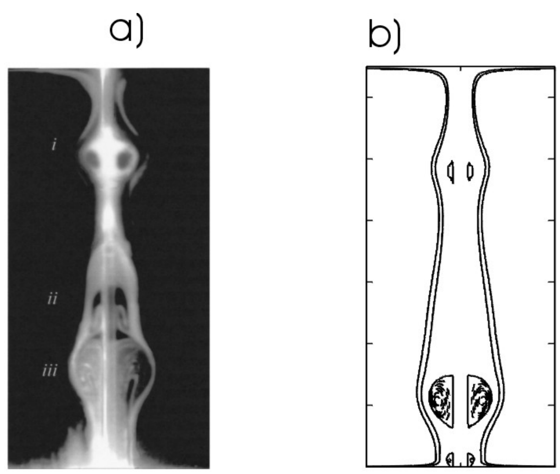

Figure 4.

Figure 5 shows the effect of the temperature gradient in the flow with no rod. VB occurring at $\varepsilon = 0$ (a) is totally suppressed at $\varepsilon = 0.7$ (b).

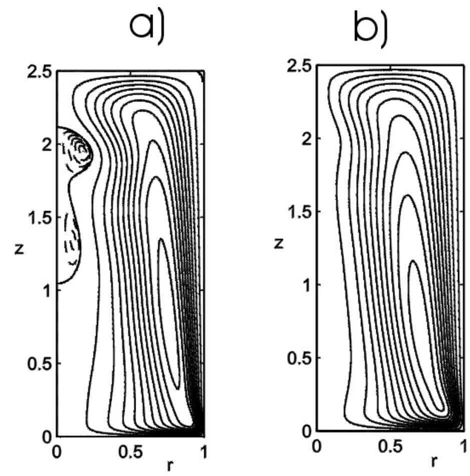

Figure 5.

Figure 6 shows the combined effect of the counter-rotation and the temperature gradient: (a) $Re_i = -12$, $\varepsilon = -0$, and (b) $Re_i = -12$, $\varepsilon = -0.6$. The negative temperature gradient enlarges VB "bubbles" and makes the flow unsteady.

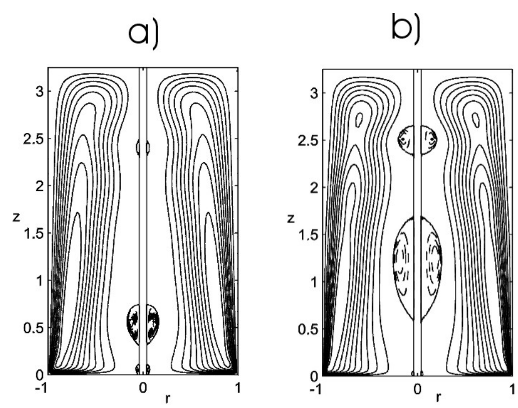

Figure 6.

These results indicate that an additional co-rotating cold (counter-rotating hot) swirling jet can help to suppress (enhance) VB in practical flows, e.g. over delta-wing aircraft and vortex burners.

[1] H. S. Husain, V. Shtern and F. Hussain, Physics of Fluids **15**, 271 (2003).