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Rotating gas flow past stationary cylinder

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Abstract

Rotating flows past stationary blunt bodies are quite different from linear (non-rotating) flows. In case of rotating compressible flows the body faces its own wake and flow slowdown caused as a consequence affects the flow inside the domain. This paper investigates rotating compressible viscous flow past a rigid circular cylinder placed in a rotating annulus using a Kinetic Flux Vector Splitting (KFVS) based Finite Volume Method (FVM) solver. Flow simulations for different Reynolds numbers are performed and corresponding results are presented. Thresholds of various flow regimes observed are shown in terms of Rossby number versus Ekman number plot. Our simulations reveal that the flow unsteadiness observed at $Re = 500$ disappears beyond $Re = 1000$. This new feature, which is not observed in linear flows, is due to flow slowdown in the wake faced by the body in this rotating flow case. The third vortex, which appears in front of the body at $Re = 1000$, is also not found in linear flows. This vortex is due to baroclinic term which arises because of entropy gain as pressure and density no longer remain isentropically related.

Keywords: rotating compressible flow, KFVS, Ekman number, Rossby number, Kármán vortex street

1. Introduction

Rotating flows are of considerable interest and vital importance for a number of engineering design applications where fluid flow happens inside rotating machines such as centrifugal separators, turbo-machinery, etc. In rotating flows the centrifugal force is balanced by the inward pressure gradient. In case of high speed rotating compressible flows, this force balance produces a strong (exponential) pressure variation of pressure and density fields in radial direction. Numerical modeling of high speed rotating flows has been a challenge as the regime changes from continuum at the periphery, to slip, transition and non-continuum in the central core.

Flow past a rigid circular cylinder has been one of the most basic and classical problem of fluid dynamics. Linear flows (without rotation) past such blunt bodies have been extensively studied and reported in literature. However, there is scant amount of research reported on the study of rotating flows past blunt bodies. Rotating flow past stationary blunt bodies is different from linear flow in many ways. In case of rotating flow as the body faces its own wake, flow slowdown caused by the presence of the stationary body strongly affects the flow inside in domain. At high speeds of rotation heated wake further increases body temperatures. Researchers [1,2,3] have studied incompressible flow past a circular cylinder in a rotating frame. Here, as seen from a rotating reference frame (rotating with angular velocity Ω), there is a linear flow of speed U past a stationary cylinder of diameter D_0. These studies, carried out in context of geophysical marine flows, have identified three main flow regimes: i) a fully attached flow, ii) a steady double asymmetric eddy regime forming on the downstream side of the cylinder, and iii) an eddy shedding regime similar to Kármán vortex street. It should be noted that, in the present study a stationary cylinder is placed in a non-rotating frame in comparison with the studies [1,2,3] where stationary cylinder is in the rotating frame of reference.

In this paper we present computational fluid dynamics (CFD) studies of flow of Argon gas past a stationary circular cylinder placed in a rotating annulus as shown in Fig. 1. Flow simulations for different Reynolds numbers (different annulus rotational speeds) are performed and corresponding results are presented.

2. Computational Method

In our simulations we have used a FVM solver which uses KFVS for invicid split flux evaluation [5]. Solution is updated in time using a two step operator splitting procedure. In the first step, explicit time update is performed for the conserved variables using the invicid KFVS split fluxes. Second step then solves an implicit time correction for the primitive variables using the viscous terms. The NS solver developed is validated for the test case of flow between two eccentric cylinders reported by Socio et. al. [6] and our flow solutions compare well with the Direct Simulation Monte Carlo (DSMC) results given in this reference.

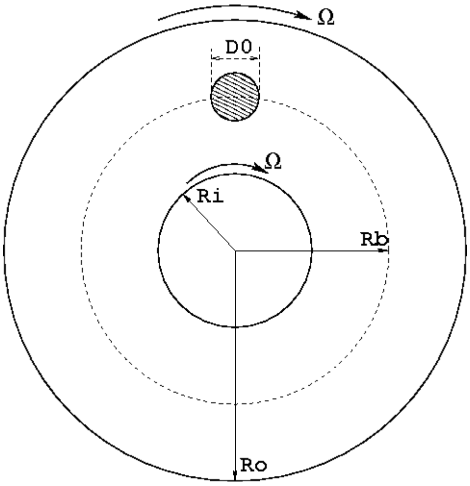
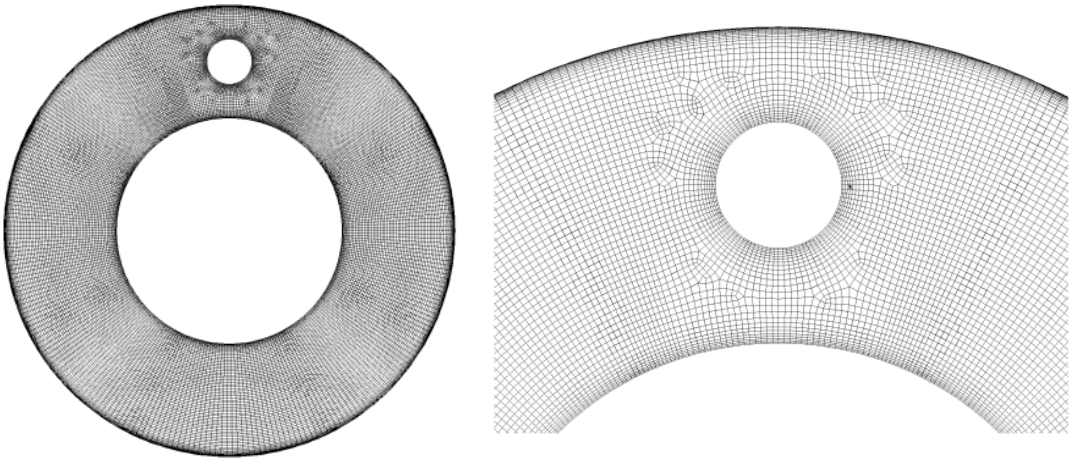


Fig. 1. Domain geometry.


(a)

(b)

Fig. 2. (a) Computational mesh, (b) enlarged view of mesh near stationary cylinder.

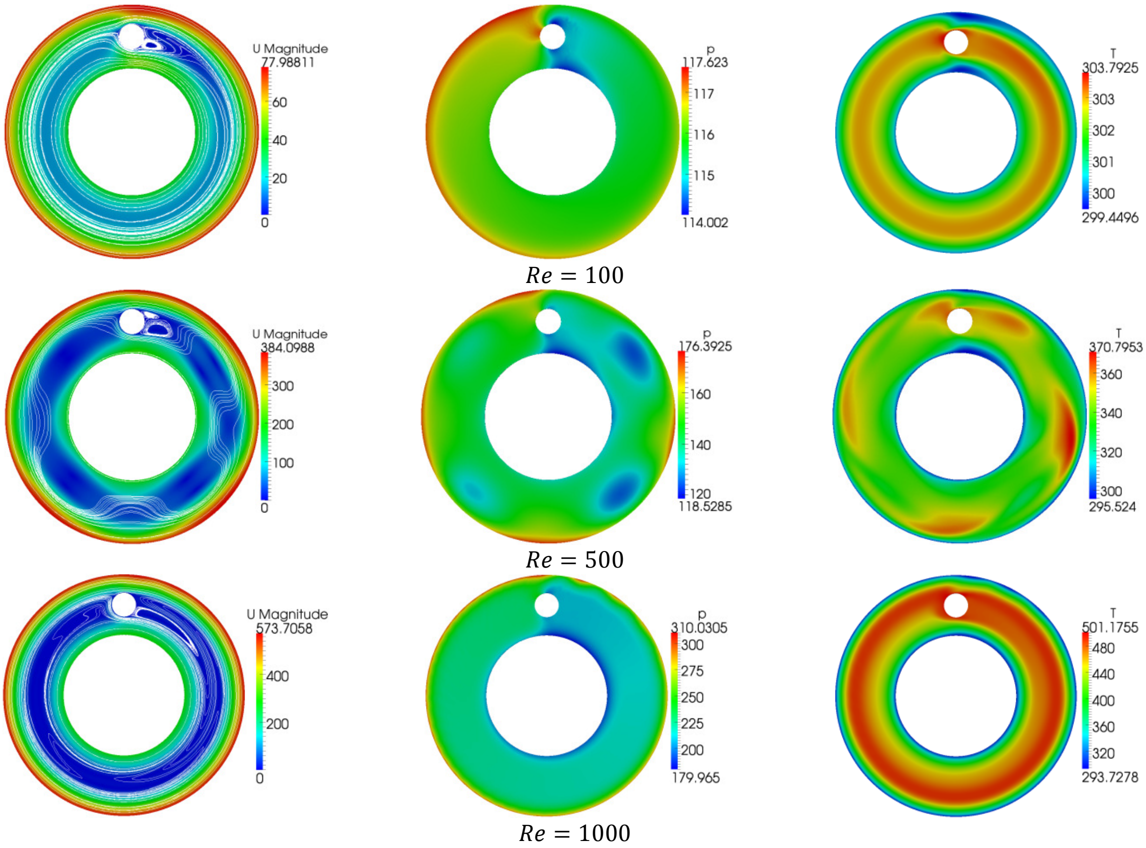
3. Results and discussions

In present investigations we have simulated the flow past the stationary cylinder placed in the rotating annulus for different values of Reynolds numbers. The Reynolds number in present study is defined as $Re = \frac{D_0 U_{AV} \rho_{AV}}{\mu_0}$; where D_0 is diameter of stationary cylinder, $U_{AV} = \frac{\Omega(R_i+R_o)}{2}$ is average angular speed; ρ_{AV} is average gas density and μ_0 is gas viscosity at temperature T_0. Initially the fluid, Argon gas with density ρ_{AV} and temperature $T_0 = 300\,K$, is stagnant in the domain, and then suddenly, the annulus start rotating with frequency Ω. Temperature boundary conditions are fixed value, $T_0 = 300\,K$ for the rotating annulus and adiabatic for the stationary cylinder. Close to the cylinder surface there exists a $E_k^{1/4}$ boundary layer across which the flow is brought to no-slip condition, and in order to resolve this boundary layer mesh has been clustered near the body surface as shown in Fig. 2(b) and 2(c). Streamlines, pressure and temperature plots for three different Reynolds numbers (100, 500 and 1000) are shown in Fig. 3. Wall Mach numbers for these cases are 0.24, 1.18 and 1.76 respectively. In linear flows the nature of the flow solution is decided by the Reynold's number, whereas in rotating flows the flow regimes are classified in terms of Rossby number $R_o = U_{AV}/\Omega D_0$ and Ekman number $E_k = \mu_0/(\Omega D_0^2 \rho_{AV})$. The Reynolds number for rotating flow can be interpreted as the ratio of Rossby to Ekman number, $Re = R_o/E_k$. In general, Rossby number is a measure of perturbation from equilibrium rigid-body-rotation condition and is quantified using different types of perturbation measures (geometric, flow properties etc.). Ekman number is defined as the ratio of viscous forces to Coriolis forces and at small values of Ekman number flow disturbances are able to travel in flow domain before decaying due to viscous effects.

At $Re = 100$ the flow is steady and a stationary vortex structure is formed behind the body. Flow is unsteady at $Re = 500$ and a vortex shedding regime similar to Kármán vortex street is present in solution. The solutions in Fig. 3 for $Re = 500$ are snapshots at a given time while the other Re solutions correspond to the steady state. Surprisingly, flow is again steady at $Re = 1000$ and three steady vortices are observed near the body. One of these three vortices is in front of the body while the two other asymmetric vortices are observed behind the body. In linear flows, where the body does not faces its own wake, the flow remains unsteady with increasing Reynolds number. While in this case, as shown in Fig. 4, the flow slowdown caused by the body at $r = R_b$ increases with the Reynolds number and this effect slowdowns the wake at higher values of Re. It is for this reason that flow again becomes steady at $Re = 1000$. Body wake is observed to have higher temperatures with increasing Re value. The vortex in front of the cylinder for $Re = 1000$ case occurs because of baroclinic term. If $\nabla\rho \times \nabla p \neq 0$ then, this baroclinic effect creates the vorticity because of entropy gain as pressure and density remain no longer isentropically related [4]. The baroclinic term χ is derived by taking the curl of the pressure gradient in the Navier-Stokes equation is given as follows:

$$\chi = \nabla \times \left(-\frac{1}{\rho}\nabla p\right) = \frac{1}{\rho^2}\nabla\rho \times \nabla p$$

Thresholds of attached flow and vortex streets obtained from simulations are shown in Fig. 5. Dotted lines show various flow regimes observed in Rossby number versus Ekman number plot while circular symbols show simulation results.



$Re = 100$

$Re = 500$

$Re = 1000$

Fig. 3. Flow past cylinder at different Reynold's numbers.

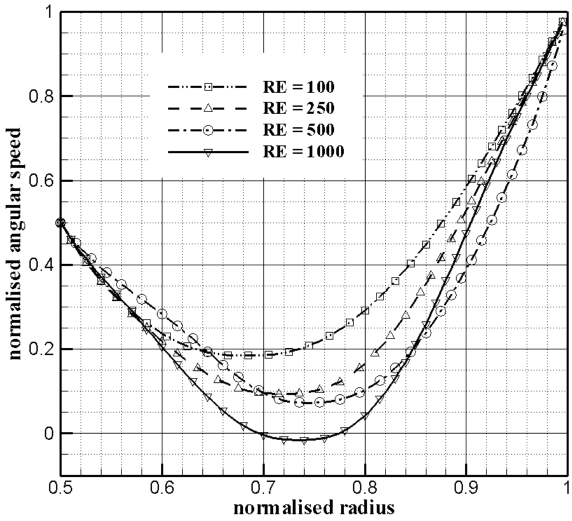


Fig. 4. Flow slowdown for different values of Re at π radian from the stationary cylinder.

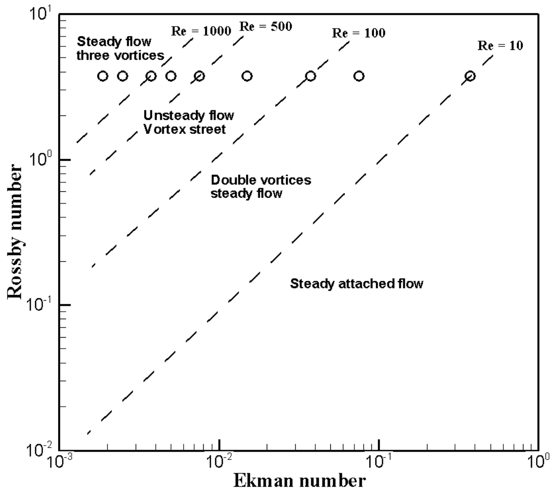


Fig. 5. Rossby number/Ekman number flow regime showing thresholds for attached flow and vortex streets.

3. Conclusions

In our simulations of rotating flow past the stationary cylinder four flow regimes were observed: i) fully attached steady flow for small value of Re, ii) a steady double asymmetric eddy regime forming on the downstream side of the cylinder near $Re = 100$, iii) an eddy shedding regime similar to Kármán vortex street at $Re = 500$, and iv) steady three vortex structure for Reynolds number beyond $Re = 1000$. While there is flow unsteadiness at $Re = 500$, the flow again becomes steady at $Re = 1000$ due to the flow slowdown in the wake faced by the stationary body. The third vortex in front of the body at $Re = 1000$ is also a feature of rotating flows which is not present in linear flows.

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