Transition to turbulence in confined flow over a cylinder with low aspect ratio

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Abstract. We report on Large-eddy simulations (LES) of a flow around a cylinder in a narrow duct channel at the Reynolds number of 2 000, 3 000 based on the bulk velocity and diameter of the cylinder. We investigate a mechanism of the transition occurring from steady laminar flow at \( Re = 2 000 \) to turbulent flow at \( Re = 3 000 \) with attached recirculation zone and thin sinusoidal far wake.

1. Introduction

Variety of flow structures behind the bluff bodies confined between two impenetrable walls with a distance significantly lower than characteristic size of an obstacle is significantly higher than in deep wake flows. Such flows are of practical use and can be encountered in a wide range of Reynolds numbers in industrial applications and environmental flows like cooling systems, heat exchangers, building sections, junctions in wing-body, bridge piers and etc. Such configurations feature a few well-known vortical structures.

In front of a bluff body the horseshoe vortex system is present due to adverse pressure gradient resulting in increased local heat transfer, acoustic noise and shear stress [1]. Then depending on \( Re \) flow can exhibit different regimes. Behind the body quasi-periodic vortex shedding appears due to Kelvin-Helmholz instability in separated shear layer resulting in a recirculating zone which can lead to the Kármán vortex street with large-scale vortical structures. The recirculating bubble is known to exhibit low-frequency motion featuring the fluctuation of the recirculation zone length and Reynolds stresses intensity [2-4]. In shallow wake geometries such low-frequency modulations are represented as large dominant spanwise vortical structures in a near wake, which strongly affect the heat and mass transfer characteristics downstream of the cylinder [5, 6]. The interaction of the Kármán vortex street and walls creates additional streamwise vortices in the far wake region, similar structures were earlier detected in slot jets [7,8].

In the classical flow around infinite cylinder the transition to non-stationary turbulent regimes occurs around \( Re = 200 \) [9], in case of shallow flows, rigid walls provide additional stabilization effect and transitional \( Re \) is significantly higher. In this paper we investigate the flow around the cylinder in a rectangular duct with the ratio of the channel height to the cylinder diameter equal to 0.4. At \( Re = 2 000 \) flow remains absolutely steady and laminar, while at \( Re = 3 750 \) the Kármán vortex street and streamwise vortices in the far wake region appear [10, 11]. The exact mechanism how this transition occurs is not fully clear and in this paper we investigate this process.
2. Computational details

We use unstructured finite-volume T-Flows computational code [12, 13] with the cell-centered collocated grid structure to solve the spatially filtered Navier–Stokes equations for incompressible fluid and a transport equation for the temperature field acting as a passive scalar within Large-eddy simulation framework. These equation are closed with Smagorinsky subgrid-scale model based on Boussinesque hypothesis [14, 15]. The code implements the second order accuracy discretization in space and time. The SIMPLE algorithm is used to couple pressure and velocity fields to preserve mass in the computational domain. For all simulations the Prandtl number is set to $Pr = 6.13$ corresponding to water at room temperature, while $Pr_t$ is assumed to be constant ($= 0.9$).

The computational domain represents a rectangular duct. The total domain dimensions are $29D \times 20D \times H=0.4D$ in $x \times y \times z$ (streamwise, spanwise and wall-normal direction). A circular cylinder of diameter $D$ is placed at $14D$ from the inlet boundary ($x = 0, y = 0$) and fixed between two parallel walls at $z = 0$ and $z = H$ as shown in Fig. 1. The following boundary conditions are used for the domain boundaries: no-slip boundary conditions are set at all walls, i.e. $z = 0$ and $z = H$ as well as for side boundaries with $y = -10D$ and $y = 10D$ and the surface of the cylinder. At the inlet ($x = -14D$) we impose laminar steady parabolic velocity profile, while the convective outflow condition is set at the outlet ($x = 15D$). The temperature on the cylinder and duct surfaces is also set to be $z$-linear, varying from hot to cold as $T(z) = T_{min} + (T_{max} - T_{min})(1 - z/H)$, where $T_{min}$ and $T_{max}$ - temperature set on the upper and lower walls respectively.

Further all physical quantities are non-dimensionalized with cylinder diameter $D$, bulk velocity at inflow $U_b$ and temperature difference $\Delta T$. A computational mesh consists of $16.6 \times 10^6$ hexahedral cells. As shown in [11] mesh resolution satisfies the near-wall resolution criteria for $Re = 3750$: $\Delta r^+ < 0.3$, $(R\Delta \phi)^+ < 2.3$, where $R = D/2$, measured at midspan of the domain and $\Delta z^+ < 2.4$ at the bottom wall. The mesh has also the constant cell size in $x$ direction starting from $x = 2.5$ and until the end of the computational domain to ensure satisfactory resolution in the far wake to investigate streamwise vortical structures.

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3. Turbulent wake development

In order to observe a transition from laminar steady flow with steady bubble wake detected at $Re = 2000$ to turbulent flow with unsteady vortex street shedding at $Re = 3000$, a series of instantaneous $Q$-criterion surfaces captured at different time instances are shown in Fig. 2. The starting point for this simulation is time instance $t = 0.00$, which corresponds to velocity and temperature fields obtained at $Re = 2000$. Then, we set the inflow velocity of increased magnitude to ensure that Reynolds number is $Re = 3000$. At $t = 1.25$, it is clearly seen that the rolls are formed symmetrically in the shear layer from both side of the cylinder, which caused by Kelvin-Helmholtz instability. At $t = 2.50$, these vortices interact with the legs of horseshoe vortex system and start to loose symmetry. Further downstream they propagate and disturb streamwise structures at the far wake, which is elongated because of increased velocity. At $t = 25.00$, we observe a turbulent flow with attached recirculation zone with long streamwise wake and small turbulent structures appearing in the shear...
layer. It is not the Kármán vortex street, but rather a transitional regime, which is inherent only to shallow flows, previously observed experimentally by Carmer [10].

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\begin{align*}
  t &= 0.00 & t &= 1.25 & t &= 2.50 \\
  t &= 3.75 & t &= 5.00 & t &= 11.25 \\
  t &= 20.00 & t &= 15.00 & t &= 25.00
\end{align*}
\]

**Figure 2.** Isosurfaces of instantaneous $Q$-criterion colored with the temperature field for few time instances.

**Conclusion**

We performed Large-eddy simulations of the wake flow in a narrow duct walls to study the transition from steady laminar regime at $Re = 2000$ to turbulent at $Re = 3000$ with relatively high numerical resolution. The transition to turbulence occurs in separated shear layer, however the near wall recirculation zone remains symmetric and attached to the cylinder wall unlike in the Kármán vortex street.

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