Patterns of vortex generation behind a cylinder in a wall-bounded cross-flow during transition to turbulence

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Abstract The paper elaborates on experimental investigation and direct numerical simulation of the wake flow behind a circular cylinder located near the wall of a rectangular channel. The study considers the Reynolds number range that covers transition to turbulence in the wake. Spiral fluid motion directed from the sidewalls to the channel center is revealed behind the cylinder for both positions of the cylinder considered in the study. The paper describes the effect of this motion on the critical Reynolds number corresponding to the onset of Karman vortex street and on the vortex topology. The spiral motion is shown to correlate with the onset of low-pressure regions behind the cylinder near the sidewalls. These regions result from the interaction between the boundary layer on the sidewalls and the separation region behind the cylinder.

1. Introduction
Flow separation behind bluff bodies is a classical problem of fluid mechanics. In addition to their fundamental importance, such flows are often encountered in practice: heat exchangers and cooling systems, heat transfer promoters, chemical reactors, constructions under the wind load, etc. Moreover, this type of flow is a benchmark problem employed for testing of computer codes in computational fluid dynamics.

At moderate Reynolds numbers corresponding to laminar core flow, large-scale vortical structures can form in the wake of a bluff body, and local onset of turbulence can be observed in the flow. If the bluff body is installed on a solid surface (backward-facing step, rib, etc.), then the flow instability and local transition to turbulence in the laminar boundary layer developing on this surface result from the interaction between the boundary layer and the obstacle. If there is a gap between the bluff body and the solid surface, the laminar-turbulent transition in the wake depends mainly on the gap size and the boundary layer thickness at the location of the body. Circular cylinders in cross-flows are usually considered as bluff bodies in such studies.

If a moderate Reynolds number flow past an obstacle is not confined by vertical sidewalls, it is assumed to be two-dimensional (on average) at different stages of transition to turbulence. Sidewalls and boundary layers developing on these walls are the reasons for essentially three-dimensional separated flow behind the obstacle mounted on the wall. This flow configuration was considered in [1], where physical and numerical experiments were employed to show that the principal mechanism behind the formation and regular shedding of large vortices is the interaction of a pair of spiraling corner vortices, formed on the channel sidewalls in the separation region behind a spanwise
The contribution of sidewalls to the vortex generation process and to transition to turbulence in the cylinder wake (when there is a gap between the body and the channel wall) is neglected by most of the authors. The majority of papers dealing with this flow case employed numerical simulation for their research. Some of them utilized two-dimensional flow models [2, 3]. The overwhelming number of numerical studies used three-dimensional models to simulate the flow past a near-wall cylinder but imposed periodic boundary conditions at the lateral boundaries of the computational domain. In this case, the influence of boundary layer developing on these boundaries and its interaction with the separation region behind the body are omitted [4 – 6]. Such studies of flows at moderate Reynolds numbers, even with periodic boundary conditions, are scarce [7 – 8]. The majority of experimental studies of flows past near-wall bluff bodies dealt with flows not confined by sidewalls. Such studies were mainly focused on evolution of cylinder wakes and vortex generation frequency at different gaps between the cylinder and the wall [e.g. 9, 10]. A few authors estimated the effect of spanwise boundary conditions on vortex shedding from cylinders [11, 12]. The present paper studies a circular cylinder in a cross-flow installed at two different distances from the channel wall.

2. Experimental setup and procedure

The geometry and dimensions of the test section were the same as in our previous work [1]. However, the semicircular rib on the bottom wall of the channel was replaced with a circular cylinder with the diameter \( d = 3 \) mm. The cylinder was installed at the same distance from the test section inlet, but it was separated from the bottom wall by a gap \( \delta \). The cylinder diameter is equal to the radius of the semicircular rib [1] in order to maintain the same blockage ratio. Two gaps were considered: \( \delta = 1.5 \) mm and 8.5 mm. In the latter case, the cylinder was located symmetrically relative to the top and bottom walls of the channel.

Smoke-wire visualization and measurements of instantaneous vector fields of velocity using Smoke Image Velocimetry (SIV) technique [13] were performed. The experimental Reynolds number ranged between 60 and 480. Direct numerical simulation (DNS) of three-dimensional unsteady Navier-Stokes equations was carried out for incompressible fluid flow using dimensionless natural variables. No-slip boundary condition was imposed on all of the channel walls, including the sidewalls (spanwise). Uniform unit velocity profile was set at the inlet. Convective boundary conditions were used for the outlet boundary. The computational grid was built using the locally-structured approach [14]. The domain was filled with a set of structured grid segments, which were connected by non-structured insertions. The grid was refined near solid walls and in the wake. The total number of grid cells was approximately \( 1.5 \times 10^6 \). The simulated Reynolds number range was \( \text{Re} = 135 – 480 \). Finite volume technique implemented in ANSYS Fluent 15.0 was employed for simulation.

3. Results and discussion

Flow visualization in the cylinder wake agrees well with DNS in the channel symmetry plane and in the plane of the cylinder axis. SIV and DNS profiles of velocity are also in good agreement. Thus, only the most representative results (experimental or numerical) are shown below.

The cylinder wake remains laminar at low Reynolds numbers for both gaps considered in the study. A stationary pair of vortices is observed immediately behind the cylinder in the channel symmetry plane. The vortices are nonsymmetrical at \( \delta = 1.5 \) mm, the dividing line deviates away from the wall. When the cylinder is located at the channel center (\( \delta = 8.5 \) mm), the vortex pair is symmetrical. As soon as the Reynolds number reaches some \( \text{Re}_{\text{crit}} \), the dividing line becomes unstable, and regular Karman vortex street emerges behind the cylinder. The critical Reynolds number for a near-wall cylinder is \( \text{Re}_{\text{crit}} \approx 160 \). When the cylinder is located at the channel center, the critical Reynolds number is \( \text{Re}_{\text{crit}} \approx 90 \) because of the blockage. Note that \( \text{Re}_{\text{crit}} \approx 190 \) if an obstacle is mounted on the channel wall [1].

Spatial pattern of flow behind the cylinder is more complex: spiral motion of fluid from the channel sidewalls emerges as in [1], where a semicircular obstacle on the channel wall was considered. This
motion is observed at both positions of the cylinder and affects the critical Reynolds number, \( \text{Re}_{\text{crit}} \) and the topology of the cylinder wake. Fig.1 shows experimental and numerical results in the cylinder wake (fig.1, a, c, and e – cylinder at the channel center; fig.1, b, d – near-wall cylinder) at \( \text{Re} \approx \text{Re}_{\text{crit}} \). As can be observed from the figure, the shape of Karman vortices is far from cylindrical despite the fact that the aspect ratio of the cylinder in both cases is 16.7, i.e. far exceeds the ratio recommended to provide almost two-dimensional flow in the central part of the wake. Besides, the bottom wall impedes free development and shedding of vortices from the bottom generatrix of the cylinder if the cylinder is placed near the wall (fig.1, b), unlike the cylinder located at the channel center (fig.1, a).

Figure 1. Formation and topology of Karman vortex street in the wake of a cylinder installed at the channel center (a, c, e) at \( \text{Re} = 100 \) and near the bottom wall with the gap \( \delta = 3 \text{ mm} \) (b, d) at \( \text{Re} = 160 \): a, b, e – experiment; c, d – DNS.

The flow pattern behind the near-wall cylinder changes significantly with the increase in the Reynolds number. At \( \text{Re} = 235 \), the spanwise size of the region occupied by spiral vortices decreases, the region of the onset and shedding of vortical clouds is shifted upstream. The size of vortical clouds in the vortex street and the distance from the street to the bottom wall somewhat increase (fig.2).
Turbulent features emerge in the flow, which is confirmed by the onset of velocity fluctuations occupying 10d long region downstream of the cylinder.

The same pattern is observed for the cylinder located symmetrically relative to the top and bottom walls of the channel. Starting from Re ≈ 250, vortices, moving downstream, split into smaller ones, and the flow is turbulized.

![Figure 2](https://example.com/fig2.png)

**Figure 2.** Smoke visualization (a) and contours of velocity fluctuations (DNS) (b) behind the near-wall cylinder in the vertical symmetry plane at Re = 235.

Fig. 3 demonstrates pressure distributions at the distance of x = 1.83 from the cylinder axis for two positions of the cylinder. Low-pressure regions exist near the sidewalls, which agrees with the spiral motion of fluid from the sidewalls to the channel center in the separation region behind the cylinder. The low-pressure regions are probably associated with the interaction between the boundary layers on the sidewalls and the separation region.

![Figure 3](https://example.com/fig3.png)

**Figure 3.** Pressure distribution behind the cylinder at the distance x = 1.83 from its axis:

- a – cylinder near the wall;
- b – cylinder at the channel center

**Conclusions**

Experiments and direct numerical simulation of the wake flow behind a circular cylinder located in a rectangular channel at different distances from the channel wall have been performed. The Reynolds number based on the cylinder diameter ranged between 60 and 480. Spiraling motion of fluid directed from the sidewalls to the channel center has been revealed behind the cylinder for both positions of the cylinder in the whole range of the Reynolds number considered in the study. It has been shown that Karman vortex street emerges at \( Re_{\text{crit}} = 90 \) instead of \( Re_{\text{crit}} = 160 \), if the gap between the cylinder and the wall grows from \( \delta = 1.5 \text{ mm} \) to \( \delta = 8.5 \text{ mm} \). Large-scale vortices in their early development stages are almost horseshoe-shaped due to the spiral motion. When the Reynolds number exceeds \( Re_{\text{crit}} \) and keeps growing, the spanwise size of the regions occupied by spiraling fluid shrinks, and the onset of
vortex generation shifts towards the cylinder. Further downstream, the vortices disintegrate into several smaller vortical clouds, and the regions with pronounced turbulence are formed. Spiraling motion is induced by the interaction between the boundary layers on the sidewalls and the separation region behind the cylinder. This interaction results in low-pressure zones formed near the channel walls.

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