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Numerical simulation of swirling flow in the pipe under non-uniform magnetic field

S. Dong¹, D. Krasnov², Yu. Kolesnikov², C. Karcher² and X. Wang³

¹Department of Power Engineering, North China Electric Power University,
071003, Baoding, China

²Institute of Thermo- and Magnetofluidynamics, TU Ilmenau
98684 Ilmenau, Germany

³College of Materials Science and Optoelectronic Technology,
University of Chinese Academy Sciences, 100049, Beijing, China

Corresponding author: yuri.kolesnikov@tu-ilmenau.de

Abstract

The flow in a circular pipe subjected to a non-uniform magnetic field is considered. The flow is set into rotation at the inlet section. The non-uniform transverse magnetic field with strong leading and front gradients is imposed at a certain offset from the inlet. We apply direct numerical simulation (DNS) to study the flow transformation, including transition to turbulence at a subcritical Reynolds number for pipe flow. This process is studied for various intensities of the swirling and the magnetic field.

Key words: direct numerical simulation, pipe flow, swirling flow, flow instability

Introduction

The study of swirling flow in the pipe under non-homogeneous magnetic field is conducted. Our particular interest is the processes of flow instability and development of turbulence considering the magnetic field as a tool for flow control. Swirling flows are widespread in industrial and engineering applications, as, e.g., in the case of molten metals flowing from large containers through a pipe or a hole. The effects associated with these processes are analyzed by applying fully-3D numerical simulations [1]. The results obtained will also serve for the experiment, which is, too, considered as a perspective for studying swirling flow in the pipe. The approximation of low magnetic Reynolds numbers, corresponding to liquid metal flows, is used. The swirling of different intensities is imposed at the entry section of the pipe flow. It is analyzed the averaged and fluctuating characteristics of axial, radial and azimuthal velocity components, their cross correlations before and behind magnetic field to identify the regions of generation and dissipation of the turbulent kinetic energy. We describe the structure of the turbulent flow in a broad range of parameter space, including the effects of Reynolds and Hartmann numbers, as well as the swirling amplitude. In particular, we analyze the changes of spatial scales of turbulent structures, their turbulent intensity and energy spectrum under the action of the imposed magnetic field. Changes in these quantities, given they are put into a fully controlled manner, can significantly affect the solidification phase and, therefore, the quality of the final product.

Equations

We consider the flow of an incompressible electrically conducting fluid in a long straight pipe. The walls are perfectly electrically insulating. The flow is driven by an imposed streamwise pressure so that the flow rate is constant. A uniform and constant magnetic field is applied in the vertical direction. The magnetic Reynolds number is assumed to be very small, which simulates the typical liquid metal flow in laboratory. As a result, the induced magnetic field can be neglected with the quasi-static approximation. The non-dimensional equations are:

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \frac{1}{Re} \nabla^2 \mathbf{u} + N(\mathbf{j} \times \mathbf{e}), \quad (1)$$

$$\nabla \cdot \mathbf{u} = 0, \quad (2)$$

$$\mathbf{j} = -\nabla \phi + \mathbf{u} \times \mathbf{e}, \quad (3)$$

$$\nabla^2 \phi = \nabla \cdot (\mathbf{u} \times \mathbf{e}), \quad (4)$$

The non-dimensional parameters in the above equations are the Reynolds number Re and the magnetic interaction parameter N . The boundary conditions at the wall are, correspondingly, no-slip (velocity) and perfectly insulating (electric potential):

$$\mathbf{u} = 0 \text{ at } r = 1, \quad (5)$$

$$\frac{\partial \phi}{\partial n} = 0 \text{ at } r = 1. \quad (6)$$

Numerical procedure and parameters

This problem is solved numerically with our in-house DNS code for circular geometries. The second-order finite difference scheme with collocated grid arrangement is employed. The scheme is nearly fully conservative in respect to mass, momentum, energy and electric charge conservation principles. The explicit 2nd-order backward-difference/Adams-Bashforth scheme is applied for time integration. The computational domain has the dimensions of $40R \times 2\pi R \times R$ in the streamwise, azimuthal, and radial directions, respectively. The computational grid consists of $1024 \times 128 \times 32$ points, which are distributed uniformly in the streamwise and azimuthal directions and clustered toward the walls using the coordinate transformation $r = \tanh(A \zeta) / \tanh(A)$ with $A = 1.5$ and $\zeta = 0 \dots 1$ being the uniform coordinate. A more refined mesh with $2048 \times 256 \times 32$ grid points was examined, the relative error in integral parameters, e.g. total friction and wall stresses, was found within %1.

Results and discussion

In first series of simulations we realized a swirling flow in pipe at the different degree of spiraling γ without influencing the magnetic field at fixed the Reynolds number $Re = 1000$. As shown in Fig. 1a for small $\gamma = 0.1$, streamwise velocity component undergoes no changes along the pipe, i.e. typical as in ordinary pipe flow. The azimuthal component decreases with distance from the place of swirl in the initial section of pipe (in picture for azimuthal component in Fig.1a the left and right areas have negative and positive signs).

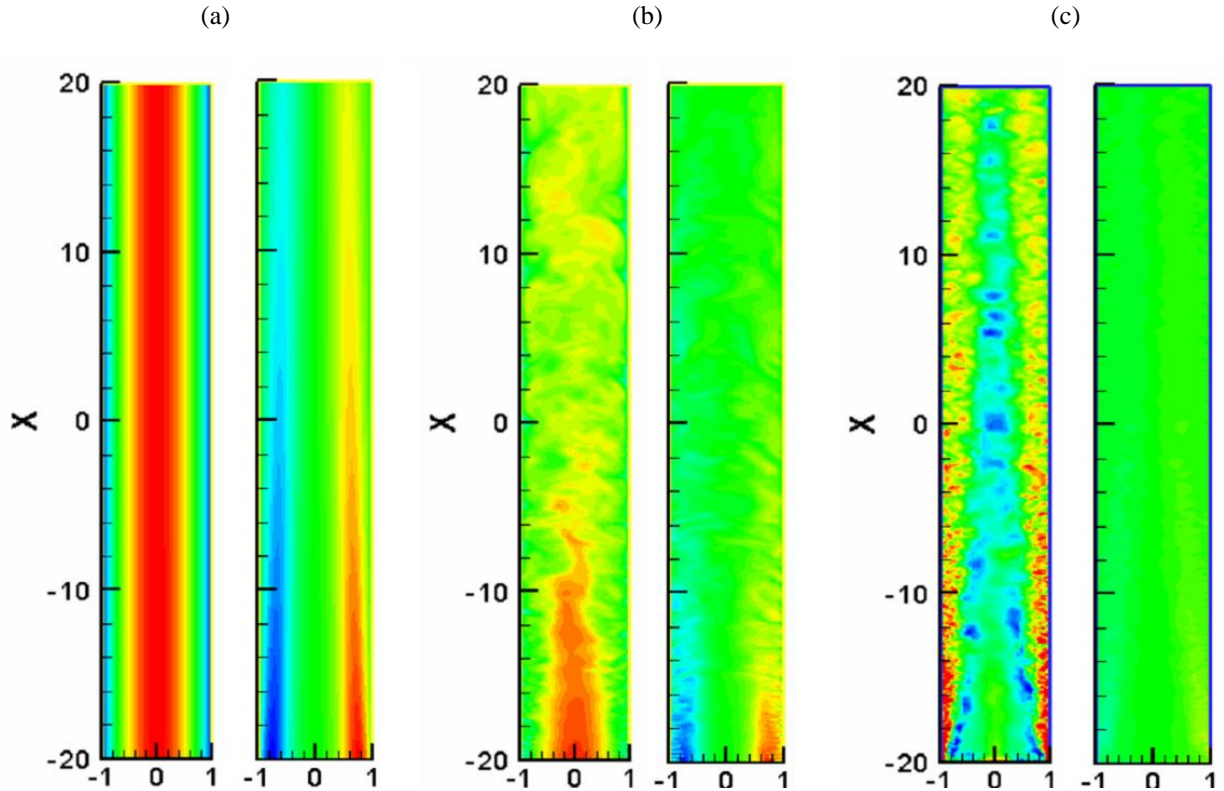


Fig. 1: Results of direct numerical simulations of non-MHD swirling flow in the pipe at $Re = 1000$ and different swirling intensities (from left to right): $\gamma = 0.1$ (a), 1.0 (b) and 10 (c). Shown are the streamwise and azimuthal velocity components u_x and u_θ , correspondingly.

When the degree of spiraling is $\gamma = 1$, in spite of $Re = 1000$ is in two times below a critical threshold of transition to turbulence in ordinary pipe, nevertheless, the flow becomes turbulent (Fig. 1b). The streamwise and azimuthal velocity components are essentially perturbed. Obviously such effect is linked with interaction between both components and

resulting appearance of additional stresses in shear layer near wall where azimuthal velocity maximal, thereby the extension of azimuthal velocity decreases. The core of straight flow is visible in a range of coordinate x between -20 and -10. Behind this range turbulent transfer provides turbulization in further cross-sections of the flow as well as the formation of large scale structures.

At increasing the degree of spiraling $\gamma=10$, turbulization is displaced toward wall in annular shear layer, turbulent perturbations are basically small scale.

In second series we use an inhomogeneous transversal magnetic field in the position and distribution as shown in Fig. 2a. Strong gradient of magnetic field $\partial B/\partial x$ provides impact on the field on small scale perturbations and generation of strong Lorentz force in the flow. Fig. 2b demonstrates influence of magnetic field on the degree of spiraling at different parameter Ha .

As an example, Fig. 3 illustrates the behavior of flow at the small degree of spiraling $\gamma=0.1$ in dependence on magnetic field value. Without magnetic field the distribution of velocity field, shown in Fig. 3a, is axisymmetric (cf. with Fig. 1a). When magnetic field increases, $Ha=10$, the similarity of swirling flow is disturbed in the cross-sections along the pipe (Fig 3b). This disturbance in the form of a transverse flow deformation appears clearly since $x=0$. With further increasing magnetic field, $Ha=50$, the flow structure becomes ordered from section to section (Fig. 3c)

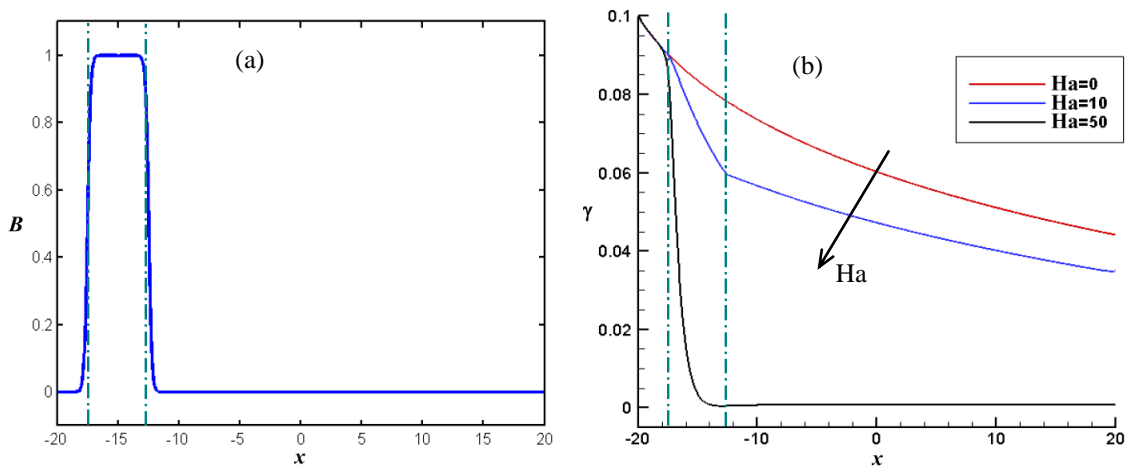


Fig. 2: Spatial distributions of magnetic field (a) and swirling intensity (b) along the streamwise direction. The magnetic field is normalized by its maximum at $x=-15$, the intensity of swirling is $\gamma=0.1$. The effect of magnetic field on the swirling intensity γ is shown for $Ha=0, 10$ and 50 and $Re=1000$.

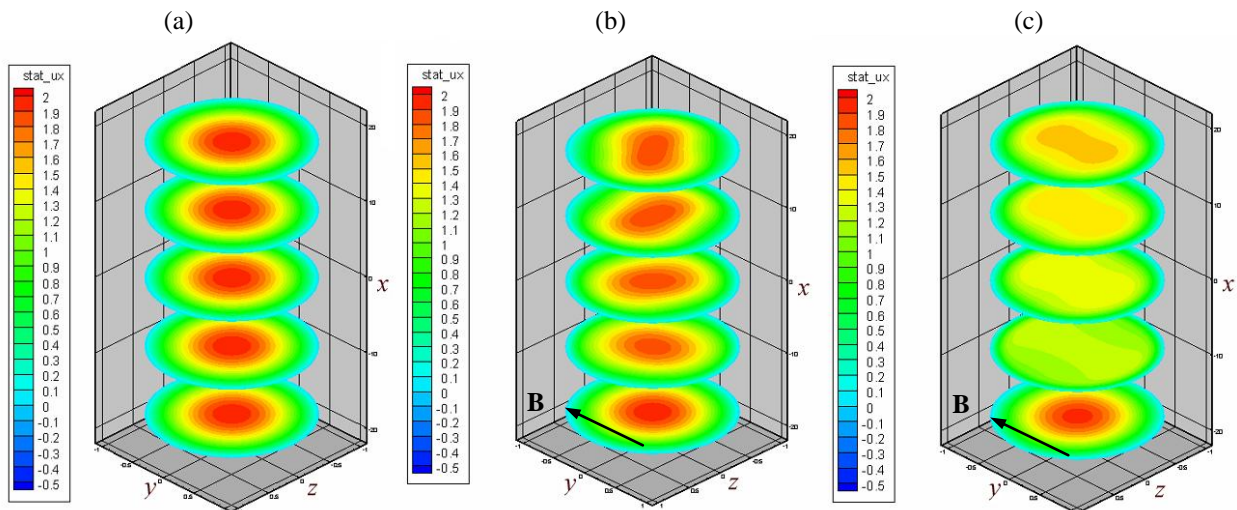


Fig. 3: Results of direct numerical simulations of swirling pipe flow at $Re=1000$ and $\gamma=0.1$. Effect of the magnetic field is shown for $Ha=0$ (a), 10 (b) and 50 (c), the streamwise velocity component u_x is visualized in several circular cross-sections along the pipe. The magnetic field occupies a section from $x=-17.5\dots-12.5$ with its maximum at $x=-15$ (also shown in Fig. 2).

Conclusions

Considered swirling flow has been studied at a fixed Reynolds number $Re = 1000$, which is by factor of 2 smaller than the critical value for transition to turbulence in a pipe. The applying local rotation on the flow periphery makes the flow unstable and evolving turbulent structures. There are investigations of swirling flow: experimental in a straight pipe [2, 3] (in work [3] pipe is with a smooth wall), and by numerical simulation in swirling pipe [4]. However, the magnetic field as an external action has not been considered in these works. In the presented study we demonstrate suppression of the flow rotation by the local magnetic field, as well as its transversal deformation and transition to laminar state.

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