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Numerical analysis of MHD effects resulting from spatial variations of high magnetic fields applied to a rectangular duct flow

C. Stelian

SIMAP-EPM, 1340 Rue de la Piscine, BP 75, F-38402 Saint Martin d'Hères, France

Corresponding author: carmen.stelian@simap.grenoble-inp.fr

Abstract

A fully three dimensional numerical analysis is performed in order to study turbulent flow of liquid metals in rectangular ducts under the influence of high magnetic fields. The goal of this analysis is to improve the level of understanding MHD effects in liquid metal cooled fusion reactor. The turbulent flow is computed in the case of uniform and non-uniform high magnetic fields. The flow computations for a duct in a non-uniform magnetic field, show M-shaped velocity profiles in the upstream region of the longitudinal plane of the flow, and respectively low intensity wall jets in the downstream region. This flow pattern is explained by the induced electrical currents which are closed in both the longitudinal and transversal planes, generating Lorentz forces acting parallel and, respectively, perpendicular to the flow. When the applied magnetic field is uniform, the velocity distribution is slightly affected by the Lorentz forces. The results show flattened velocity profiles in the core region, and no jet flow emerging near the walls. This result is explained by the closure path of eddy currents only in the transversal plane of the flow. By introducing some variation of the axial magnetic field in the computation, no significant changes are observed in the velocity profiles. The velocity profiles are significantly affected by the axial gradient of the magnetic field, only at the entrance and, respectively, at the exit of the rectangular duct from a uniform magnetic field. The flow damping in the core region is much stronger at the entry and, respectively, at the exit side from an extended zone with uniform magnetic field, as compared to the case of a liquid metal flowing through a narrow magnetic system.

Key words: Turbulent duct flow, high magnetic fields, magnetohydrodynamics

Introduction

The analysis of turbulent duct flow under the influence of high magnetic fields is of great interest in the development of liquid metal blankets for fusion reactors. Magnetohydrodynamics (MHD) in duct flows has been extensively studied in theoretical, experimental and numerical works [1-7]. In a previous work [8], numerical modeling has been used to study turbulent duct flows under high uniform and nonuniform magnetic fields. Numerical computations performed in the case of nonuniform magnetic fields produced by two permanent magnets, have shown M-shaped transversal velocity profiles in the upstream region of the flow, and, respectively low intensity wall jets in the downstream region. These results are explained by accounting the pattern of induced eddy currents which are closed in both the longitudinal and the transversal planes of the channel. Eddy currents which are closed in the transversal plane produce Lorentz forces acting parallel to the flow direction. The formation of the M-shaped velocity profiles at the entrance to the magnetic field region was explained as result of these parallel Lorentz forces acting in opposite directions. The interaction between the eddy currents closed in the longitudinal plane and the applied magnetic field generates Lorentz forces acting perpendicular to the flow direction. These forces enhance the effect of the accelerating parallel Lorentz forces, producing wall velocity jets at the exit of the magnetic system. Numerical computations performed in the case of uniform magnetic fields ($B_{\max} = 1.5T$) have shown that eddy currents are closed only in the transversal plane. The effect of the electromagnetic forces on the flow is significantly reduced in this case. The transversal velocity profiles are flattened in the core region, and no jet flow was emerging near the sidewalls.

In the present work, numerical computations are conducted in order to analyze the effect of spatial variations of high magnetic fields on the velocity profiles in rectangular duct turbulent flow. MHD effects appearing at the entry and, respectively the exit side of a zone with uniform magnetic field are also investigated.

Numerical results

Numerical modeling is performed by solving the coupled Navier-Stokes and Maxwell's equations with COMSOL Multiphysics. The nonuniform magnetic field is produced by two permanent magnets having the dimensions $x_M = 0.02\text{ m}$ and $y_M = z_M = 0.04\text{ m}$ (Fig.1). The rectangular channel, with electrical non-conducting walls, has the

dimensions: $x_c = z_c = 0.04 \text{ m}$ and $y_c = 1 \text{ m}$. The mean velocity imposed at the flow inlet is $v_0 = 0.5 \text{ m/s}$ (Reynolds number $Re = 48000$). The physical properties of aluminium (density $\rho = 2370 \text{ kg/m}^3$, viscosity $\eta = 0.001 \text{ N}\cdot\text{s/m}^2$ and electrical conductivity $\sigma = 3 \cdot 10^6 \text{ }\Omega^{-1}\cdot\text{m}^{-1}$) have been used for the simulation. The longitudinal section of the simulation domain and the computed magnetic field distribution along the channel are shown in the Fig.1. The maximum intensity of the magnetic field is $B_x = 1.8 \text{ T}$. B_y and B_z components of the magnetic field are negligible ($B_{y,z} = 0.005 \cdot B_x$).

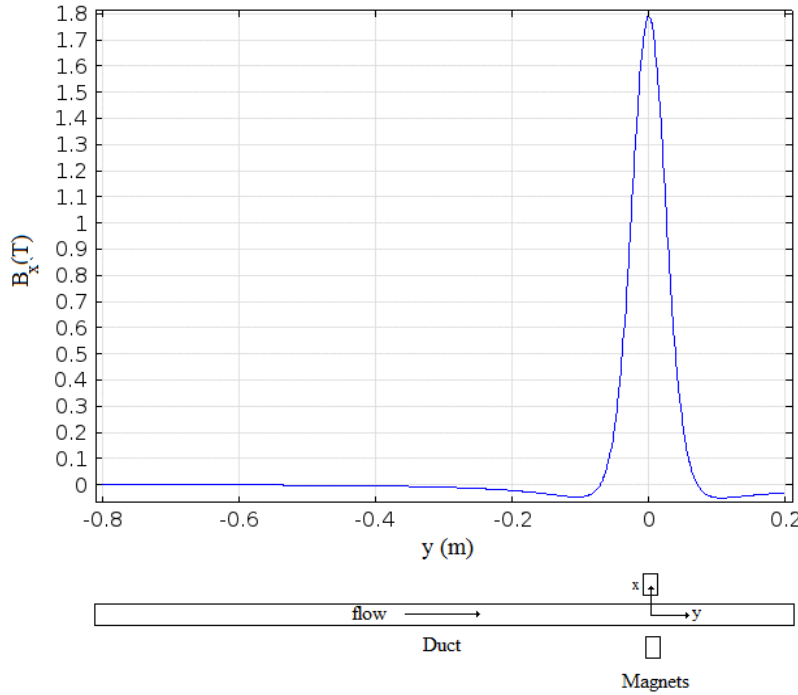


Fig. 1: Longitudinal section (x-y) of the simulation domain and the computed magnetic field (B_x) distribution along the channel.

The velocity distribution in the longitudinal plane (y-z) and the transversal plane (x-z) is shown in Fig.2. Eddy currents which are closed in the transversal plane produce damping parallel Lorentz forces in the core region and, respectively accelerating forces in the wall boundary layers. The interaction of these opposite forces with the flow results in M-shaped transversal velocity profiles at the entrance in the magnetic field region. The centerline velocity plotted in Fig.2a shows a fluctuating profile with a maximum in the center of the magnetic system ($x = y = z = 0$). This result is explained by accounting the electrical currents flowing parallel to the sidewalls, which interact with the applied magnetic field and produce Lorentz forces acting perpendicular to the flow direction. These forces are located at the entry and the exit side of the magnetic system, having a compressive and, respectively an expansive effect on the flow (Fig.2a). The increase of the centerline velocity at the center of the magnetic system is explained as an effect of the compressive Lorentz forces. The expansive forces, acting at the exit of the magnetic system, produce the sidewall velocity jets observed in the downstream region.

The velocity distribution in the longitudinal plane (y-z) and the transversal plane (x-z) computed in the case of high intensity uniform magnetic field ($B_x = 2 \text{ T}$) is shown in the Fig.3. The magnetic field has a small variation on x and z directions ($\Delta B \cong 0.05 \cdot B_{\max}$). In this case the longitudinal and the transversal velocity profiles are slightly affected by the electromagnetic forces. No wall velocity jets have been obtained in this simulation. By introducing a small variation in the longitudinal distribution of the magnetic field, no significant changes have been observed in the velocity profiles. Figure 4 shows the results obtained by introducing a low spatial variation of the magnetic in the longitudinal direction ($dB_x / dy = -4.5 \text{ T/m}$). A small damping effect is observed in the transversal velocity profile, which is flattened in the core region.

The velocity profiles are significantly affected by the spatial variation of the magnetic field only at the entrance and the exit side of the region with uniform magnetic field. Figure 5 shows the M-shaped velocity profile with very low core velocities obtained at the exit side of the region with uniform magnetic field ($dB_x / dy = -20 \text{ T/m}$).

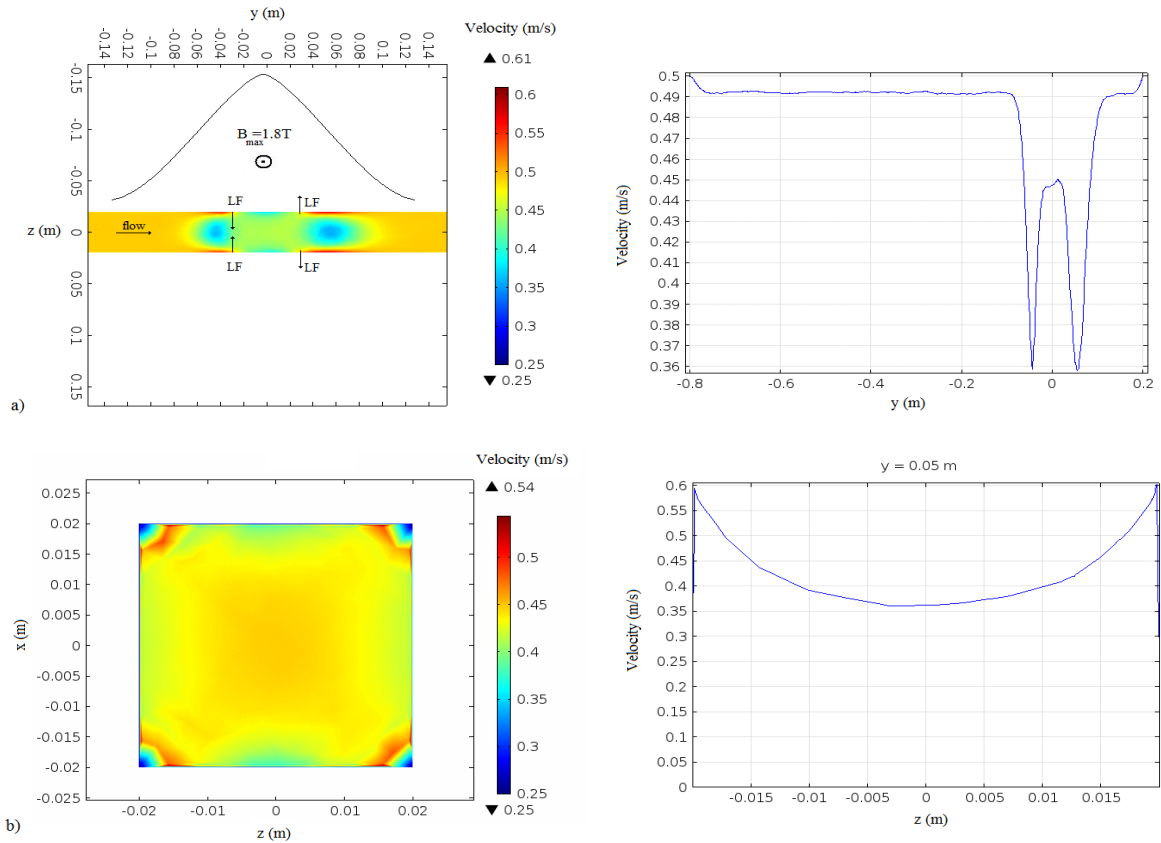


Fig. 2: Color map of velocities and the velocity profiles obtained in the case of nonuniform magnetic field: a) longitudinal plane (y-z); b) transversal plane (x-z). $Re = 48000$, $Ha = 3950$.

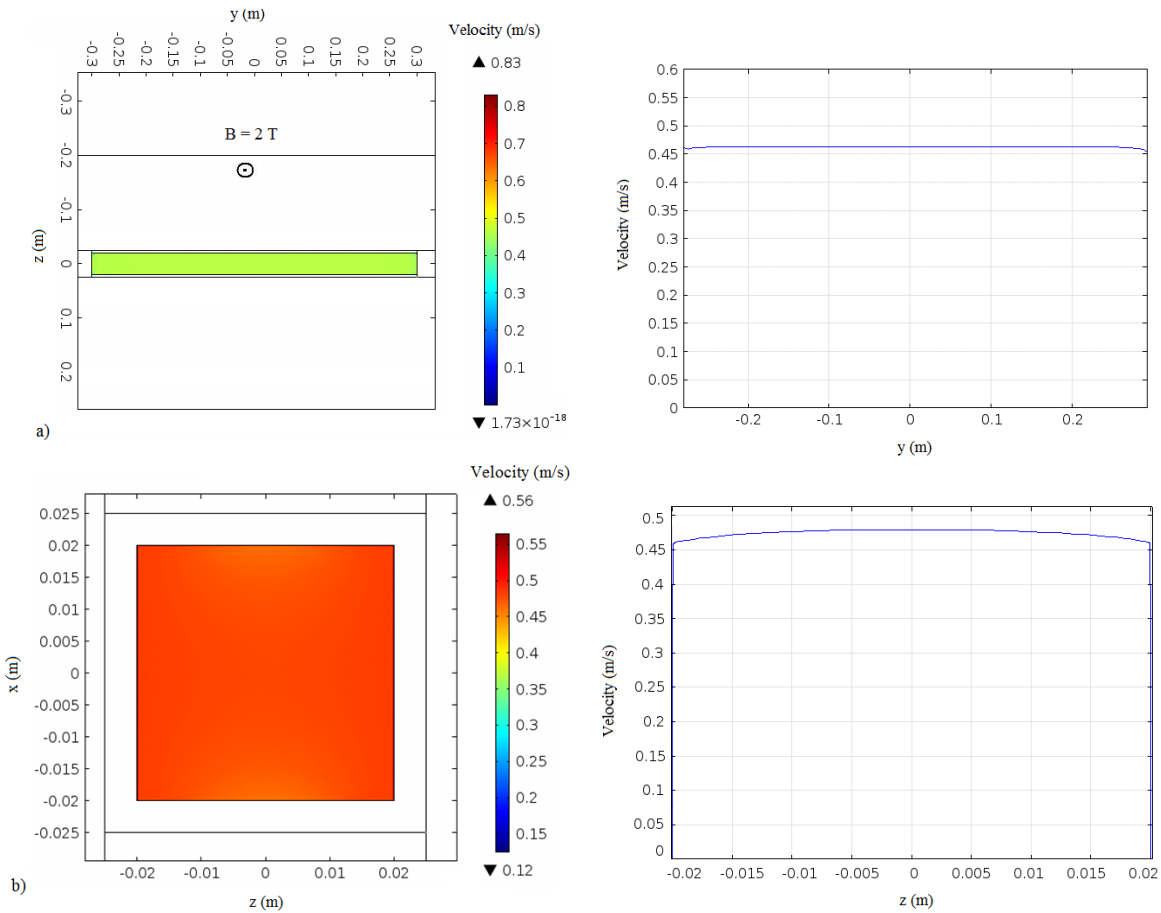


Fig. 3: Color map of velocities and the velocity profiles obtained in the case of a uniform magnetic field: a) longitudinal plane (y-z); b) transversal plane (x-z). $Re = 48000$, $Ha = 4380$.

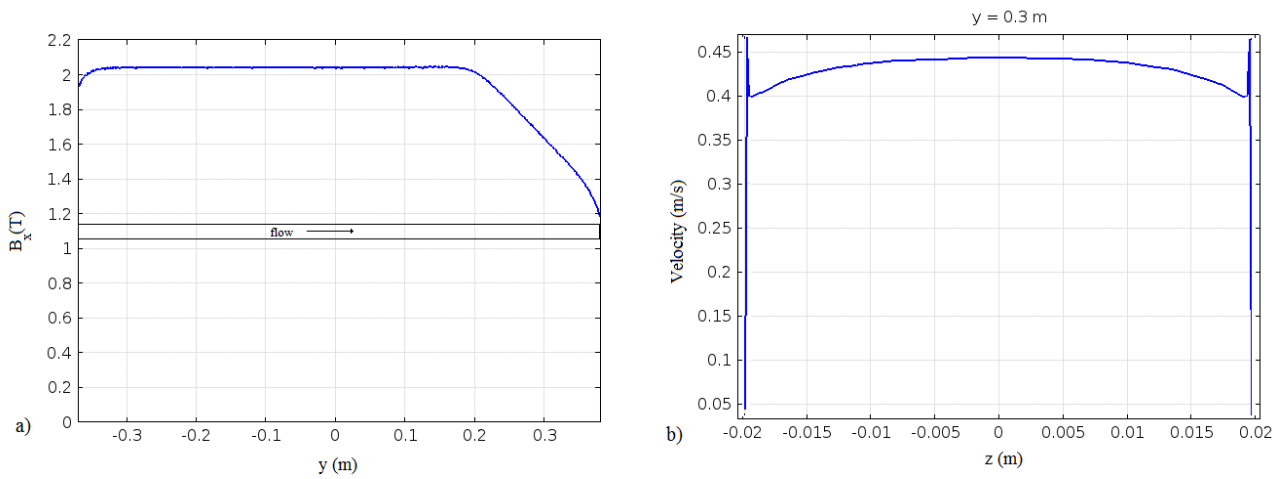


Fig. 4: Results obtained in the case of small spatial variation of the magnetic field $dB_x / dy = -4.5 T / m$: a) Magnetic field distribution along the channel; b) Transversal velocity profile at location $y = 0.3 m$. $Re = 48000$, $Ha = 4380$.

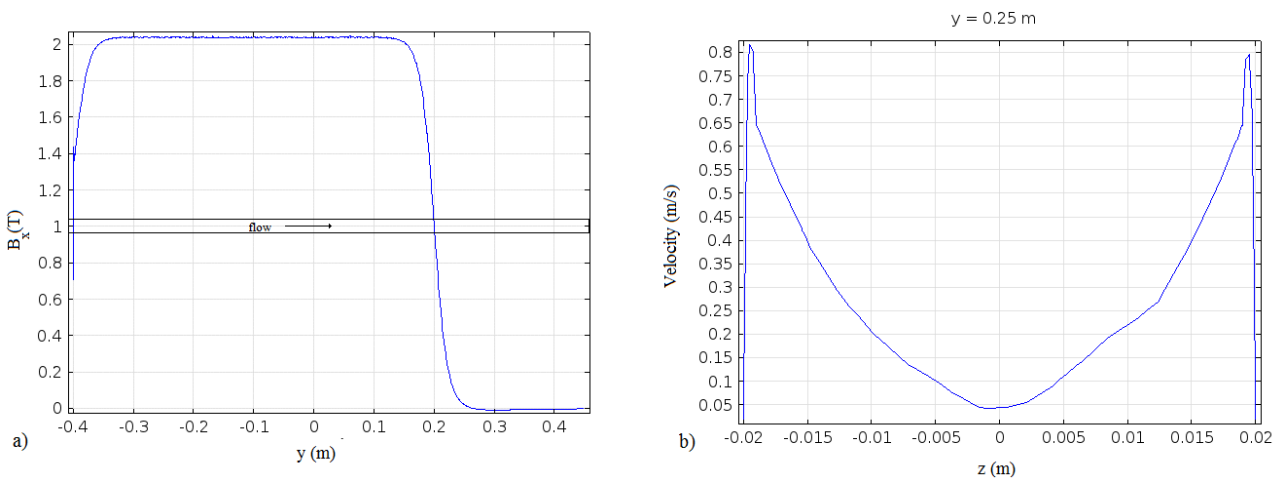


Fig. 5: Results obtained in the case of high spatial variation of the magnetic field $dB_x / dy = -20 T / m$: a) Magnetic field distribution along the channel; b) Transversal velocity profile at location $y = 0.25 m$. $Re = 48000$, $Ha = 4380$.

Conclusions

Numerical analysis of spatial variations of high magnetic fields influence on the turbulent duct flow shows that the velocity profiles are affected only by high longitudinal gradient of the magnetic field. The flow damping in the core region is much stronger at the exit side of an extended zone with uniform magnetic field, as compared to the case of a liquid metal flowing through a narrow magnetic system.

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