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# Numerical simulation of a round jet in the presence of an axial magnetic field

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## Abstract

We report numerical simulations of a submerged round jet of conducting liquid issuing into a square duct in the presence of a uniform axial magnetic field. Starting from a quiescent initial condition, the spatial development of the jet is simulated until the transition or breakup zone is no longer evolving in space or the jet has reached the outlet while remaining intact. By increasing the magnetic field strength, the transition length of the jet grows and breakup can eventually be completely suppressed within the computational domain. For even stronger fields the laminar jet becomes unsteady again, which is presumably caused by a MHD pinching mechanism.

**Key words:** direct numerical simulation, jet flow, flow instability

## Introduction

Jet flows through nozzles occur in a number of metallurgical processes, e.g. in continuous casting machines. Electromagnetic brakes that are routinely applied in these machines also serve to control the jets from the submerged entry nozzle and the resulting flow pattern in the mold. How jets behave in the presence of magnetic fields is therefore not only of fundamental interest but also of practical importance.

Generally, a magnetic field leads to flow anisotropy due to selective damping of flow structures. In a parallel flow, a transverse field gives rise to electromagnetic boundary layers on the walls, i.e. the Lorentz force modifies the mean flow directly. A streamwise or axial field in a parallel flow only affects the fluctuations but not the mean flow. In particular, the formation of such electromagnetic boundary layers is avoided. In the present work we, therefore, focus on a streamwise (axial) field in a duct geometry. Specifically, we study the evolution of a jet that issues into a duct with initially quiescent liquid by means of direct numerical simulations. We are interested in the stabilizing effect (suppression of shear instability) of the magnetic field and in the behavior in a strong field.

Theoretical and experimental investigations on submerged jets with an axial magnetic field have already been performed during the 1960s. However, they only give limited information. The theoretical investigations [1-3] deal with the laminar flow and the behavior of small perturbations. Experiments [4,5] are limited by the problematic flow measurement in the opaque and chemically aggressive liquid metals. Although simulations cannot reach the high Reynolds and Hartmann numbers of experiments, they provide full details on the flow structure and evolution. This information should be valuable for a better understanding of the complex dynamics of turbulent jet breakup and its modification by the magnetic damping.

## Numerical procedure and parameters

We consider the flow of an incompressible, electrically conducting fluid (e.g. liquid metal) in a square duct subjected to a uniform magnetic field  $B$ , applied in the streamwise direction  $x$ . MHD effects are considered in the limit of small magnetic Reynolds number, i.e. the quasi-static approximation [6] is applied. The governing non-dimensional equations are the Navier-Stokes equations with an additional Lorentz force term, which are given in details in [7]. The non-dimensional parameters are the Reynolds number  $Re_a = U_q a / \nu$  and the magnetic interaction parameter  $N = Ha_a^2 / Re_a$ , where  $Ha_a = Ba(\sigma/\rho\nu)^{1/2}$  is the Hartmann number. Here  $U_q$  is the mean flux velocity,  $a$  is the half-height of the duct,  $\sigma$  is the electrical conductivity,  $\rho$  and  $\nu$  are, correspondingly, the density and kinematic viscosity. The governing equations are solved numerically by our in-house DNS solver, implemented for rectangular geometry and based on finite-difference method described in [8]. The spatial discretization of 2<sup>nd</sup> order is performed on a rectangular structured grid, the time integration uses projection-correction procedure to satisfy incompressibility constraint. The computational grid is uniform in the streamwise  $x$ -direction and can be clustered in the wall-normal  $y,z$ -directions. The walls are considered perfectly insulating, i.e. the electric potential  $\partial\psi/\partial n = 0$  at the walls.

To address specific problems of jet flows, the non-periodic solver [7] has been modified. First, the inlet conditions have been set to form a laminar round jet with the parabolic Poiseuille velocity profile that enters the computational domain. In our simulations the jet diameter  $d$  at the inlet is fixed and amounts to 1/8 of the full duct height. The jet is centered on the square inlet boundary. To characterize the jet we define additional Reynolds and Hartmann numbers

$$Re = \frac{U_j d}{\nu}, \quad Ha = Bd \sqrt{\frac{\sigma}{\rho \nu}}$$

based on the jet mean velocity  $U_j$  and jet diameter  $d$  as characteristic scales. These values are commonly accepted in studies of jet flows and will be used further in the text. The second modification concerns boundary conditions at the exit. The unsteady convective outflow boundary condition  $\partial u/\partial t + U_q \partial u/\partial x = 0$  used in [2] was found to produce numerical artefacts (e.g. „zig-zag“ or piling-up behavior) once the jet reached the exit section. The outflow condition has been replaced by a simplified form  $\partial u/\partial x = 0$ , which has been tested and shown to produce numerically stable and smooth solutions of the velocity field.

A non-uniform grid with a modified Gauss-Lobatto clustering of points  $z = \sin(\eta\pi/2)^2 \text{sign}(\eta)$  has been applied, where  $\eta$  and  $z$  are the uniform and wall-normal coordinates, correspondingly. Such type of grid-stretching provides tight clustering of the points not only at the walls, but also in the middle of the duct, where the jet is specified. In our grid-sensitivity study we have identified that this refinement of the core flow is really essential for the accurate resolution of the jet. The simulations have been conducted for the streamwise domain length  $L_x = 16\pi$  and the resolution of 2048x96x96 points. Further increase of the resolution did not change the results within considered  $Re$  and  $Ha$ . Finally, we remark that at each time-step the inlet jet-profile was perturbed with random noise with the amplitude  $10^{-3}$  in respect to the mean jet-velocity. This procedure has helped to regularize the process of jet instability. Otherwise, given the idealized numerical conditions, the jets could extend very far and remain laminar, which would require extremely long domain sizes and, correspondingly, computational time.

## Results and discussion

In the absence of a magnetic field, jets are unstable already at fairly low Reynolds numbers (on the order of  $Re \approx 10$ ) [9]. In our study the Reynolds number  $Re = U_j d/\nu = 1800$  exceeds such values significantly, and one observes a rapid transition to turbulence (Fig. 1a). At  $Ha=0$ , growing perturbations can already be observed at a distance of 2 diameters. Further downstream, these perturbations are destabilized and the jet expands rapidly. At the distance of 16d it has become fully turbulent and occupies the entire area of the duct. Further downstream, the flow reverts to the laminar state on account of the low global Reynolds number  $Re_a \approx 90$ , where turbulence in a duct flow cannot be sustained.

In contrast to Fig. 1a, which shows a developed state of jet breakup after initial transients, Fig. 1(b-d) show the temporal evolution of the jet at  $Ha=25$ . The injection of the jet leads to a rapid development of a turbulent region (length of about 10-12d), which is advected downstream (Fig 1b). Behind it, the magnetic field suppresses instabilities. As time progresses, the turbulent region is increasingly damped and advected further (Figs. 1c,d) while it largely retains its length. The damping is apparent by the loss of small-scale features. In the final developed state of the jet, the turbulent region persists close to the exit.

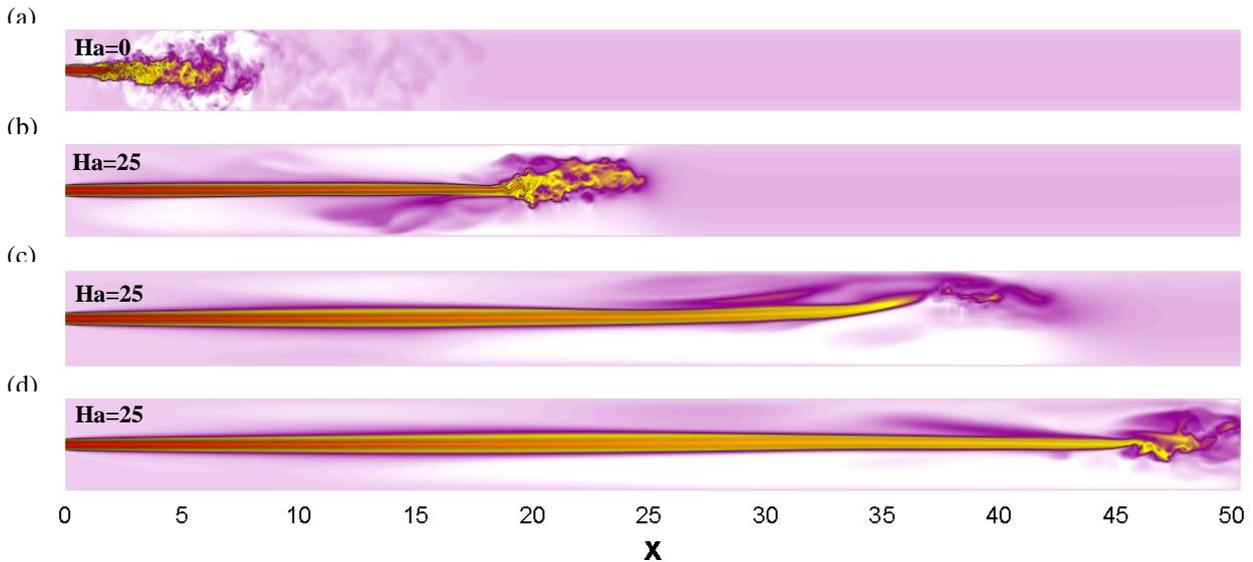


Fig. 1: Results of direct numerical simulations of jet flow at  $Re=1800$  under streamwise magnetic field at  $Ha=0$  (a) and three phases of evolution at  $Ha=25$  (b,c,d). Shown is the streamwise velocity in a  $(x,y)$ -mid-plane at  $z=0$ .

For  $Ha=50$ , the jet becomes fully laminar inside the computational domain in the developed state. The visible undulation in Fig. 2a is a transient feature. At  $Ha=125$ , the jet is stable and straight (Fig. 2b). Upon increasing the Hartmann number further this stable flow structure persists up to a certain value of  $Ha$ . For  $Ha=250$  longitudinal waves appear on the jet as can be seen from the two snapshots of Fig. 2(c, d) that correspond to different times during jet development.

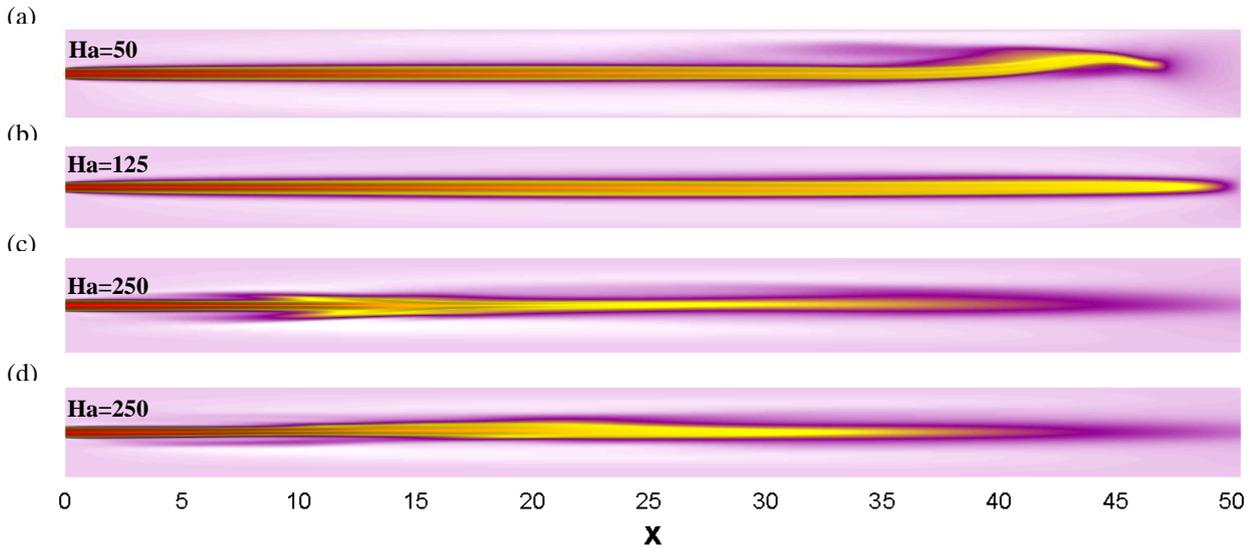


Fig. 2: Results of direct numerical simulations of jet flow at  $Re=1800$  under streamwise magnetic field at  $Ha=50$  (a), 125 (b) and two-phases at  $Ha=250$  (c,d). Streamwise velocity is visualized in a mid-plane, the radial "pinch" instability is visible at  $Ha=250$ .

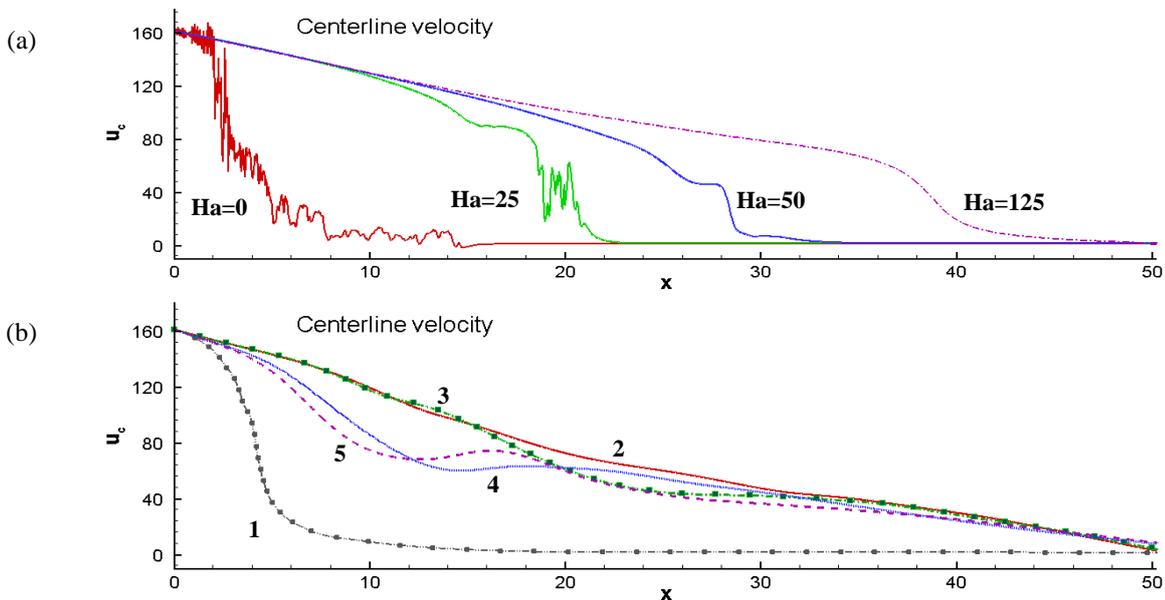


Fig. 3: Variation of the centerline velocity along the streamwise direction for the cases of  $Ha=0, 25, 50$  and  $125$  (a) and  $Ha=250$  (b). The results at  $Ha=250$  show five different phases of temporal evolution denoted by the indices running from 1 to 5 and corresponding to progress in time.

The cause of these waves in a longitudinal magnetic field is related to the action of Lorentz forces. Due to the tendency of jet to expand a radial velocity component develops, which is accompanied by an annular electric current in the cross-section. Direction of the electric current depends on direction of radial velocity component. Interaction of the magnetic field with the current generates Lorentz force that counteracts the expansion or compression of jet cross-section.

The evolution and expansion of the jet is further illustrated by Fig. 3, which shows snapshots of the distribution of axial velocity along the central axis of the jet, which coincides with the central axis of the computational domain. The velocity is displayed in units of the mean velocity  $U_q$ . The curve for  $Ha=0$  in Fig. 3a illustrates the developed state where the jet breaks down rapidly and the velocity reaches a constant value after a certain distance. For the higher values of  $Ha$  in Fig. 3a, the velocity distributions correspond to a transient state with approximately identical times from the beginning of the injection. One can clearly identify the turbulent region at the front at  $Ha=25$ . For  $Ha=50$  and  $Ha=125$  the jet has penetrated increasingly further and its front has become smoother. The front or leading edge visually resembles a running wave of the soliton type [6] for flow regimes at  $Ha=50$  and 125. The spreading of the jet, which is apparent from the decreasing velocity with the distance, is also reduced by increasing  $Ha$  from  $Ha=25$  to  $Ha=125$ .

Fig. 3b displays different snapshots of the axial velocity distribution for different times. One can see an early stage where the jet has only penetrated a certain distance (plot 1) and a later stage where the jet has almost reached the outlet (plot 2). It subsequently develops the oscillatory behavior (plots 3-5) described earlier with stronger variations in velocity for  $x < 20$ .

## Conclusions

Our results are in qualitative agreement with an experimental study of jet stabilization under longitudinal magnetic field that was conducted with the liquid metal alloy Galinstan at  $Re = 3300$  and different Hartman numbers around 100 [5]. In this work it was found that laminarization of the jet also allowed its propagation on large distances. More detailed analyses of the expansion of the jet and its spatio-temporal dynamics for different values of  $Ha$  will be the subject of future work.

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