

Numerical simulation of a submerged liquid metal jet flow in a longitudinal magnetic field using a hybrid large Eddy simulation method

© M.A. Sokolov¹, N.G. Razuvaev^{1,2}, O.N. Polyanskaya²

¹ Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, Russia

² National Research University „Moscow Power Engineering Institute“, Moscow, Russia

E-mail: maximsokolov1997@mail.ru

Received February 16, 2026

Revised March 15, 2026

Accepted March 19, 2026

The results of numerical simulation of a submerged mercury jet flow in a circular pipe under the influence of a longitudinal magnetic field are presented, using the KDES hybrid large eddy simulation method. The flow regime is considered at a Reynolds number of 10^4 and magnetic fields corresponding to Hartmann numbers in the range from 0 to 125. Under the influence of a longitudinal magnetic field at $Ha = 125$, the maximum deviation in the mean axial velocity from the DNS data does not exceed 25%. It is found that the longitudinal magnetic field alters the structure of secondary flows: eight steady vortices uniformly distributed around the main jet emerge. The critical Hartmann number at which this effect occurs is $Ha \approx 80$.

Keywords: liquid metals, magnetohydrodynamics, submerged jet, numerical simulation

DOI: 10.61011/TPL.2026.06.63803.20655

Liquid metals (LM) are one of the most promising thermonuclear reactor (TNR) coolants used for blanket and divertor cooling [1–3]. TNR blanket has a complex design consisting of channels with diverse shapes. Thus, for example, a submerged coolant jet typically occurs in flow conditions during sudden expansion.

Complexity and diversity of magnetohydrodynamic interactions are most pronounced in transverse magnetic fields. As shown in [4,5], flow can exist in two qualitatively different modes depending on the Stuart number N : as a central jet (at moderate N) or as an asymmetric macroeddy (at high N). These results emphasize the need for methods capable of detecting such nonsteady-state dynamics.

Study [6] performed experimental investigation of the velocity field in a round mercury jet flowing into the cocurrent flow and exposed to uniform longitudinal magnetic field with the Reynolds number $Re = 10\,000$ and Stuart number $N = 0–1$. Experimental results have shown that with jet flow in a longitudinal magnetic field (LMF), transfer of momentum perpendicular to the field direction decreases, turbulence intensity on the jet axis, where velocity gradients are small, decreases. With sufficiently high magnetic inductions, low-frequency components of turbulent motion in the jet and high-frequency pulsations in the second cocurrent flow are damped (cocurrent flow has a mean velocity equal to 0.1 initial jet velocity).

LM submerged jet flow in LMF was studied in sufficient detail in [7]. The study made the main focus on direct numerical simulation (DNS). DNS adequately simulates LM flows in complex mass force conditions, however, requires extremely high computational efforts due to stringent requirements for computational grid resolution, which makes it poorly suited for engineering calculations

within a limited timeline. In turn, the RANS (Reynolds-averaged Navier–Stokes) approach used for investigating a submerged jet in LMF as shown in [8] doesn't provide agreement with experimental data. This mismatch is due to insufficient consideration of the LMF effect on the averaged flow within RANS because this method doesn't include direct impact of a field on the longitudinal velocity component. Moreover, the RANS approach doesn't allow the LMF effect on velocity pulsation components to be correctly considered, which is one of the key factors.

Unlike previous studies [7,8], this work focuses on detailed simulation via the hybrid large eddy method (KDES). The main purpose of this work is to perform numerical simulation of a submerged liquid metal jet in LMF using the KDES method, analysis of simulation data by comparing with the experimental and DNC data, method feasibility assessment for magnetic hydrodynamics tasks, and identification of new effects affecting the submerged jet hydrodynamics in LMF conditions.

In this problem statement (Figure 1), mercury flows (mass-average flow velocity at the computational domain inlet V_0) from a $d_1 = 5$ mm tube into a $d_2 = 25$ mm tube. A jet is formed in a steady-state, spatially uniform longitudinal magnetic field $\mathbf{B} = (0, 0, B_z)$. Magnetic field is applied only to a tube with a larger diameter. Liquid metal is defined as electrically conducting, incompressible, viscous Newtonian fluid with constant physical properties (density $\rho = 13\,530$ kg/m³, kinematic viscosity coefficient $\nu = 1.125 \cdot 10^{-7}$ m²/s, and conductivity $\sigma = 1.04 \cdot 10^{-6}$ (Ω · m)^{−1}). The study was performed in the Hartmann number range $0 \leq Ha = B_z d_1 \sqrt{\frac{\sigma}{\nu \rho}} \leq 125$ with a fixed Reynolds number $Re = \frac{V_0 d_1}{\nu} = 10\,000$.

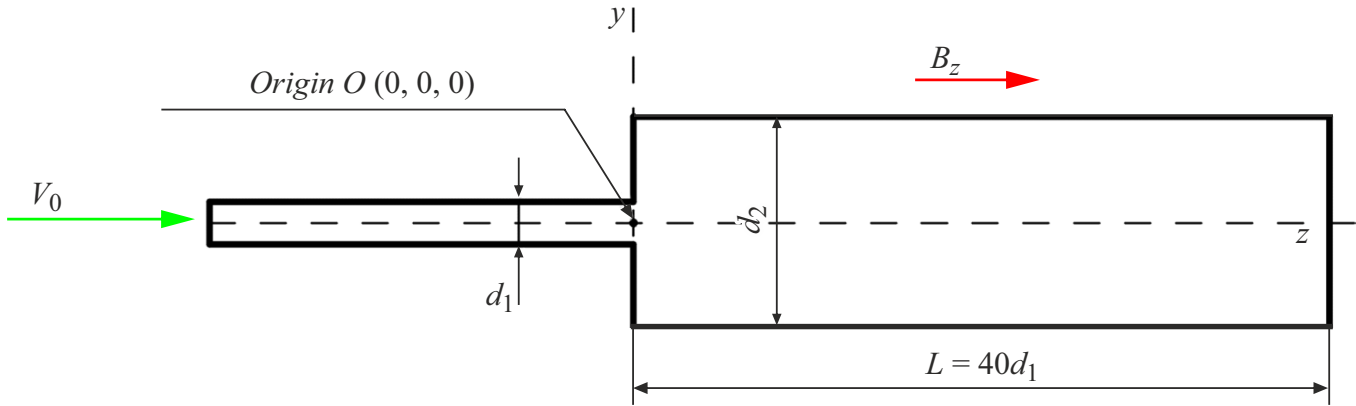


Figure 1. Graphical problem statement in the O_{yz} plane.

For turbulence simulation, this work uses a hybrid KDES model (k-based Detached Eddy Simulation) with ANES computer code [9,10] that combines the benefits of the RANS and LES (Large Eddy Simulation) approaches. The fundamental KDES principle is in using an effective RANS model to calculate thin near-wall layers (where it is well established) and in switching to the LES-mode for resolution of large transient eddies in detached flow zones and flow core.

The model is based on a two-layer $k-\varepsilon$ turbulence model [11]. Near the walls where the turbulent Reynolds number $R_k = \frac{\sqrt{k_{sgs}} y_w}{\nu} < 200$ (y_w is the distance to the nearest solid wall [m]), only an equation for subgrid turbulent energy k_{sgs} is solved. For electromagnetic field description, the equation of preservation of electric field potential φ is solved in ANES. Simulation uses noninductive approximation.

Thus, the system of equations of the KDES model is as follows

$$\frac{\partial \bar{u}_k}{\partial x_k} = 0, \quad (1)$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_k} \left(\bar{u}_k \bar{u}_i - (\nu + \nu_{sgs}) \frac{\partial \bar{u}_i}{\partial x_k} \right) = -\frac{1}{\rho} \left(\frac{\partial \bar{p}}{\partial x_i} + F_i \right), \quad (2)$$

$$F_i = \varepsilon_{ijk} j_j B_k, \quad (3)$$

$$j_i = \sigma (E_i + \varepsilon_{ijk} \bar{u}_j B_k), \quad (4)$$

$$\tau_{ik}^{sgs} = \rho \bar{u}_i \bar{u}_k - \rho \bar{u}_i \bar{u}_k, \quad (5)$$

$$E_i = -\frac{\partial \varphi}{\partial x_i}, \quad (6)$$

$$\frac{\partial k_{sgs}}{\partial t} + \frac{\partial}{\partial x_k} \left(\bar{u}_k k_{sgs} - (\nu + \nu_{sgs}) \frac{\partial k_{sgs}}{\partial x_k} \right) = \nu_{sgs} G - \varepsilon, \quad (7)$$

$$\frac{\partial^2 \varphi}{\partial x_k \partial x_k} - \frac{\partial}{\partial x_k} (\varepsilon_{kij} \bar{u}_i B_j) = 0, \quad (8)$$

where $\bar{u}_k$, $\bar{u}_i$, $\bar{p}$ are the filtered (averaged) velocity and static pressure less the hydrostatic head, x_k are the radius vector components [m], t is the time [s], τ_{ik}^{sgs} are the undergrid

stresses, F_i are the electromagnetic force components (conducting fluid ($\sigma \neq 0$) without volumetric charges is addressed) [N/m³], j_i are the current density components [A/m²], E_i are the electric field strength components [V/m], B_k are the magnetic field induction components [T], ε is the dissipation rate, $\nu_{sgs} = \mu_{sgs}/\rho$ is the dynamic undergrid eddy viscosity [m²/s], $G = 2\bar{S}_{ij}\bar{S}_{ij}$ is the dissipation function, $\bar{S}_{ij}$ is the strain rate tensor.

Dissipation rate ε and undergrid viscosity ν_{sgs} for the KDES model are calculated as follows

$$\nu_{sgs} = C_\mu^{1/4} f_\mu(R_k) \sqrt{k_{sgs}} L_{des},$$

$$\varepsilon = C_\mu^{3/4} f_\varepsilon(R_k) \frac{k_{sgs}^{3/2}}{L_{des}},$$

$$f_\mu = 1 - \exp\left(\frac{-R_k}{A_\mu}\right),$$

$$f_\varepsilon = \left[1 - \exp\left(\frac{-R_k}{A_\varepsilon}\right) \right]^{-1},$$

$$R_k = \frac{\sqrt{k_{sgs}} y_w}{\nu},$$

where $L_{des} = \min\{L_{rans}, L_{les}\}$; $L_{les} = C_{sgs} \Delta_{les} \psi_L$, $\psi_L = \frac{f_\mu^{1/4}}{f_\mu^{3/4}}$; $L_{rans} = \kappa y_w$; $A_\mu = 70$, $A_\varepsilon = 5.1$, $\kappa = 0.41$, $C_\mu = 0.09$ are the model constants [10]; f_μ , f_ε are the damping functions; R_k is the modified turbulent Reynolds number; y_w is the distance to the nearest solid wall [m]; Δ_{les} is the filtration scale in the LES method.

For generation of nonsteady-state fields of the velocity vector components and turbulent characteristics at the computational domain inlet, a PIG (Periodic Inlet Generator) model implemented in ANES was used. The idea of PIG is in the fact that a circular channel fragment with the diameter d_1 is added upstream of the main computational domain segment, with periodic boundary conditions set at the channel inlet and outlet. Whilst the main computational domain segment doesn't affect the PIG zone and the PIG outflow boundary serves as the inflow boundary for the

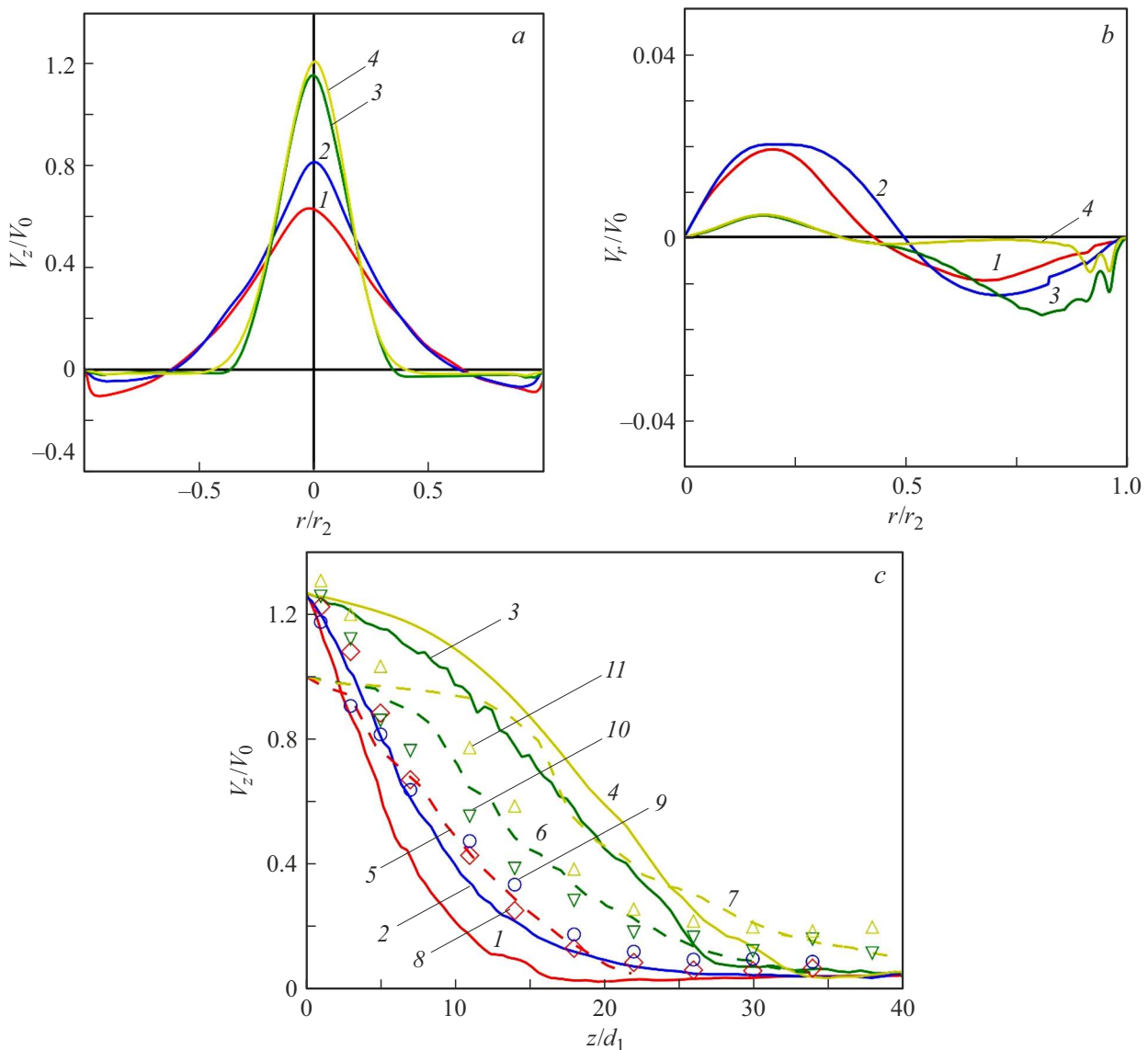


Figure 2. Profiles of time-averaged longitudinal V_z/V_0 (a) and radial V_r/V_0 (b) velocity components vs. the radial coordinate r/r_2 at $Re = 10\,000$ and $z/d_2 = 1.0$, as well as profiles of V_z/V_0 on the axis vs. the longitudinal coordinate z/d_1 at $Re = 10\,000$ (c). $Ha = 0$ (1, 5, 8), 42 (2, 9), 83 (3, 10), 125 (4, 7, 11) and 80 (6). 1–4 — simulation data obtained in this work, 5–7 — DNS calculation data [7], 8–11 experimental data [8].

main domain. No-slip conditions are used as boundary conditions on solids walls. Velocity field and turbulence characteristics from the previous RANS calculation were used for initial conditions. Solution stabilization process was excluded from the following averaging process.

Time-averaged profiles of the longitudinal V_z/V_0 and radial V_r/V_0 (the profile was obtained by averaging, in particular, with respect to angle) components depending on the radial coordinate r/r_2 ($r_2 = d_2/2$) at $Re = 10\,000$ and different Ha numbers (Figure 2, a, b) were obtained. As the Hartmann number grows, considerable change in the velocity profile is observed. LMF suppresses transverse radial velocity pulsations. Submerged jet and surrounding fluid agitation intensity decreases due to friction and eddy

making. As a result, kinetic energy and jet momentum are not spent on dragging the surrounding fluid by the jet in the direction of flow and are maintained at a much longer distance from the cross-section. Consequently, as the Hartmann number Ha grows in the center of jet, the velocity increases and the jet width decreases. This is indicative of an increase in the effective jet length. The previous work of the authors [8] could not reproduce this change in the three-dimensional structure of the jet using the RANS method.

Figure 2, c shows the profiles of the time-averaged longitudinal velocity component V_z/V_0 along the axis depending on the longitudinal coordinate z/d_1 at various Hartmann numbers. Simulation results demonstrate qualitative and quantitative compliance with the DNS calculation data [7]

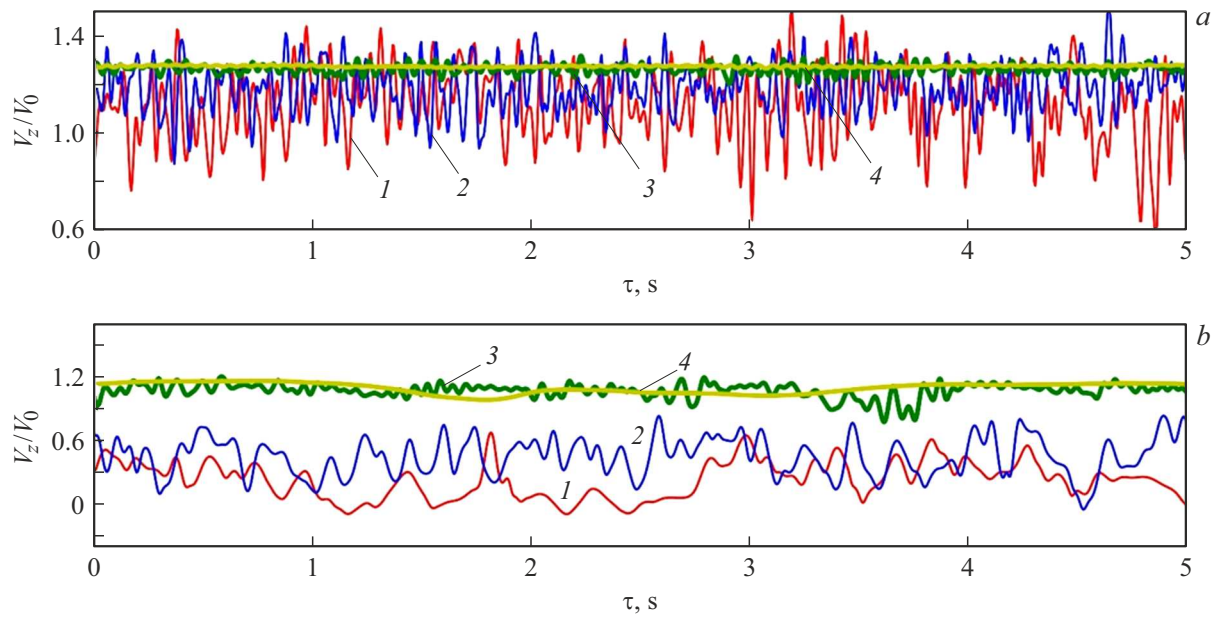


Figure 3. Waveforms of longitudinal velocity component V_z/V_0 at $Re = 10000$. $z/d_2 = 0.2$ (a) and 1.8 (b). $Ha = 0$ (1), 42 (2), 83 (3) and 125 (4).

and experimental data [8] (with $Ha = 125$, relative deviation of V_z/V_0 from the DNS data is max. 25%). In the LMF effect conditions, decrease in the axial velocity with growth of z/d_1 decelerates. Observed quantitative deviations of the calculation and experimental data are caused by different input conditions.

Without LMF, the inertial and turbulent mixing mechanism dominates. Coherent structures induced by detachment of the boundary layer drag the surrounding fluid into the jet core. Thus, the fluid is quickly decelerated. As z/d_1 grows, large-scale eddies are broken. And the difference between the velocity in the jet core and surrounding fluid decreases, which reduces the jet deceleration effect. LMF suppresses the development of transverse velocity pulsations. This causes magnetic jet laminarization near the cross-section and considerable weakening of turbulent mixing. As a result, initial jet deceleration is weakened. Viscous friction at the jet boundary becomes the main deceleration mechanism. As the jet propagates, viscous friction efficiency grows. This increases the jet deceleration effect.

As Ha grows, the absolute pulsation level decreases and the flow is noticeably laminarized. Fluctuation energy decreases when compared with a mode without magnetic field and moves into the jet region where the flow is eddied. Then the downstream flow is eddied in LMF and transformed into channel flow. Thus, as Ha grows, transition to turbulent flow regime moves into the zone of high z/d_1 . Figure 3 shows calculated waveforms of the longitudinal velocity component V_z/V_0 on the axis. Waveform analysis shows that pulsation amplitude and frequency without LMF decrease with distance from the cross-section, and at $z/d_2 = 6.2$ the flow is almost completely laminarized.

As Ha grows, pulsations of V_z/V_0 near the jet cross-section decrease. Thus, at $Ha = 83$ and 125, laminarization now occurs at the cross-section. Pulsation amplitude near the jet cross-section is much lower than in conditions without magnetic field, which indicates that pulsations of the longitudinal velocity component are suppressed due to a link between the velocity components through the pressure field and to the Lorentz force acting on the transverse motion.

It has been found that after achievement of $Ha \geq 83$ the flow structure in the annular mixing zone around the submerged jet underwent qualitative rearrangement. Discrete eddy formations are observed. The number (eight) of the formations is defined by the channel configuration: diameter ratio (1:5) sets the typical circumference, on which the stable azimuthal perturbation mode falls. Magnetic field in this case suppresses high-frequency chaotic modes and leaves the dominating low-frequency mode with the azimuthal wavenumber equal to eight. This effect is visualized on the current line projections on the pipe cross-section (Figure 4). Note that the described phenomenon was not fixed in [7]. This divergence is probably caused by the computational grid effect: cylindrical topology induces heavily elongated nodes in the near-wall region, which probably neutralizes eddying and masks the real effect.

Thus, the study performed numerical simulation of the submerged liquid metal jet flow in LMF using the hybrid large eddy method. Simulation results were compared with the experimental data and DNS calculation data. The results reflect the main flow characteristics, which have not been obtained before using the RANS approach. In a mode with $Ha = 125$, relative deviation of the averaged axial velocity from the DNS calculation data is max. 25%. Thus, the KDES model has a set of benefits with respect to RANS

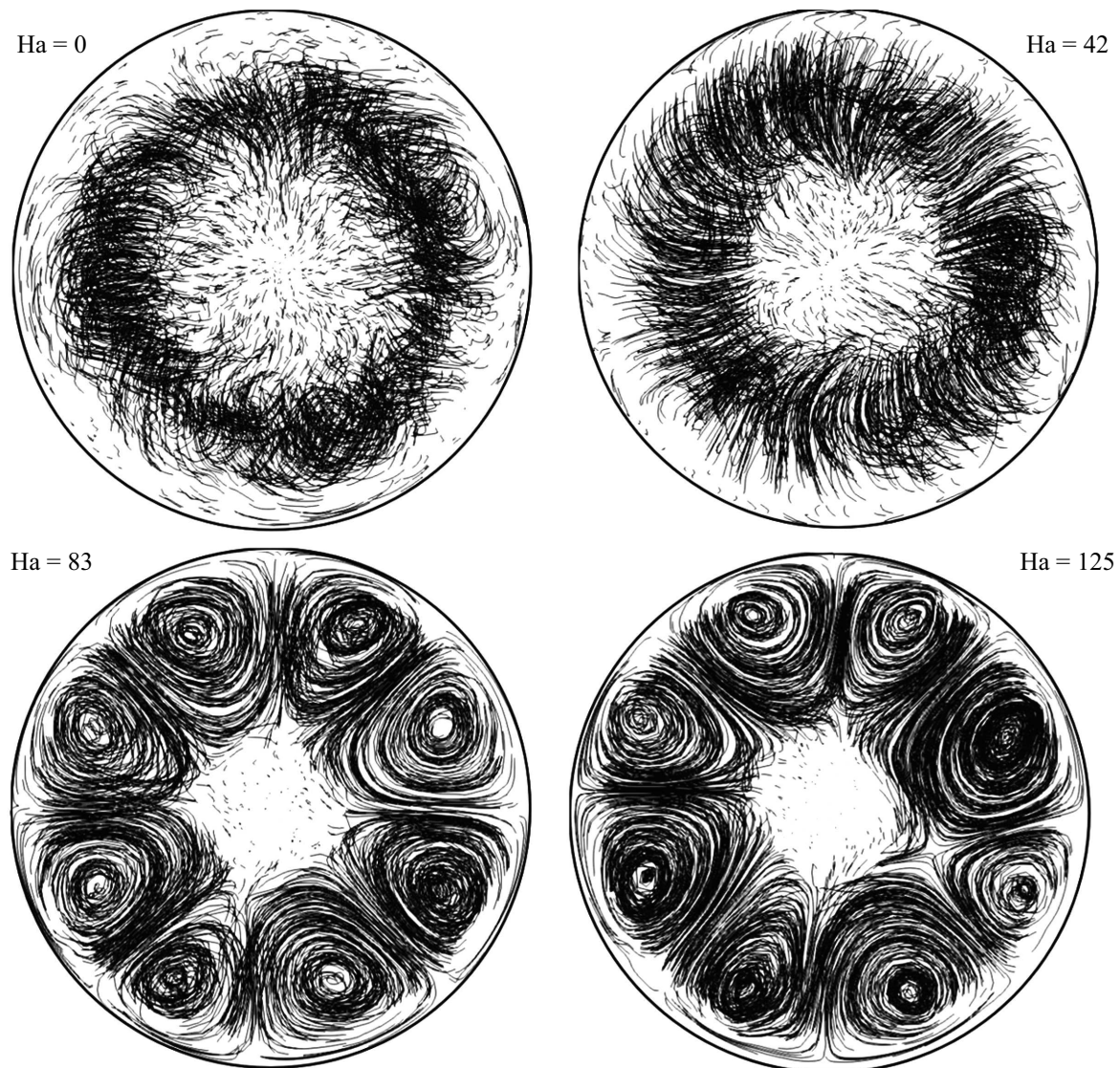


Figure 4. Current line projections on a cross-section at $z/d_2 = 1.0$ and $Re = 10000$.

(sensitivity to the LMF effect on the flow) and DNS (lower computational efforts) and, therefore, can be recommended for simulation of LM flows in LMF.

It has been found that at $Ha \geq 83$ the jet was laminarized already at the cross-section. It is first shown that at $Ha \geq 83$ self-induced flow arrangement into a stable eight-eddy structure is possible in the annular mixing zone, which has not been reported in the literature earlier.

Acknowledgments

The authors would like to express gratitude to G.G.Yankov's scientific group for creating ANES20XE, a numerical simulation software package, and personally to V.I. Artemov for the first-line support of the code and computational recommendations.

Funding

The study was supported by the Ministry of Science and Higher Education of the Russian Federation (state order No 075-00270-26-00).

Conflict of interest

The authors declare no conflict of interest.

References

- [1] G. Federici, W. Biel, M.R. Gilbert, R. Kemp, N. Taylor, R. Wenninger, Nucl. Fusion, **57** (9), 092002 (2017). DOI: 10.1088/1741-4326/57/9/092002
- [2] A.V. Tananaev, Nauch.-tekhn. vedomosti SPbGPU. Nauka i obrazovanie, No 1, 84 (2012) (in Russian).
- [3] M. Abdou, N.B. Morley, S. Smolentsev, A. Ying, S. Malang, A. Rowcliffe, M. Ulrickson, Fusion Eng. Des, **100**, 2 (2015). DOI: 10.1016/j.fusengdes.2015.07.021

- [4] M. Sajben, J.A. Fay, J. Fluid Mech., **27**, 81 (1967).
DOI: 10.1017/S0022112067000060
- [5] I.A. Belyaev, I.S. Mironov, N.A. Luchinkin, Ya.I. Listratov, Yu.B. Kolesnikov, D. Krasnov, O. Zikanov, S. Molokov, J. Fluid Mech., **953**, A10 (2022). DOI: 10.1017/jfm.2022.879
- [6] Ya. Listratov, D. Krasnov, O. Zikanov, Yu. Kolesnikov, S. Molokov, I. Belyaev, Phys. Fluids, **37** (10), 107144 (2025).
DOI: 10.1063/5.0289071
- [7] Ya.I. Listratov, N.G. Razuvanov, I.A. Belyaev, E.V. Sviridov, Vychislitel'naya mekhanika sploshnykh sred **15** (4), 495 (2023) (in Russian). DOI: 10.7242/1999-6691/2022.15.4.37
- [8] M.A. Sokolov, N.G. Razuvanov, Teplovye protsessy v tekhnike, **17** (6), 247 (2025) (in Russian).
<https://tptmai.ru/publications.php?ID=185571>
- [9] V.I. Artemov, G.G. Yan'kov, V.E. Karpov, M.V. Makarov, Therm. Eng., **47** (7), 632 (2000).
- [10] Kod ANES [Electronic resource].
<http://anes.ch12655.tmweb.ru/>
- [11] A.V. Garbaruk, M.Kh. Strelets, M.L. Shur, *Modelirovanie turbulentnosti v raschetakh slozhnykh techenii* (Izd-vo Politekhn. un-ta, SPb., 2012) (in Russian).

Translated by E. Ilyinskaya