Characterizing Liquid Metal Performance in Tokamak Plasma-Facing Components (PFCs) Through Lorentz Force-Applied Turbulent Channel Flow and Stuart Number Analysis

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Characterizing Liquid Metal Performance in Tokamak PFCs Through Lorentz Force-Applied Turbulent Channel Flow and Stuart Number Analysis

Outline:

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2. Lorentz force control method - DNS

3. Results of Direct Numerical Simulations

4. Liquid Metal Application

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Motivation

PFCs made from solid materials are tend to be replaced by liquid-metal (LM) PFCs.

Challenges:

- Keep free-surface LM flows attached to reactor surfaces (M.G. Hvasta et al 2018 Nucl. Fusion 58 016022).
- Liquid metal pile-up (Z. Sun et al 2023 Nucl. Fusion 63 076022)

Therefore the investigation of the potential of electromagnetic control for LM-PFCs, are crucial.

Aim

Control the LM flow by leveraging Lorentz force.

Through Stuart Number define the characteristics of the liquid metal.

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- **The Method:**

1) Solve Navier Stokes and Maxwell Equations:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = \hat{\mathbf{e}}_1 \cdot \tilde{\mathbf{I}} - \frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \frac{1}{\rho}(\mathbf{J} \times \mathbf{B}), \qquad (1)$$

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

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \qquad (3)$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}_s, \qquad (4)$$

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B}), \qquad (5)$$

$$\nabla \cdot \mathbf{B} = 0, \qquad (6)$$

$$\nabla \cdot \mathbf{J} = 0. \qquad (7)$$

Here,**u** is the velocity vector, p is the pressure, ρ is the fluid density, μ is the kinematic viscosity, **B** is the magnetic flux density vector, **J** is the current density vector, J_s is the electrode source current density vector, **E** is the electric field vector, μ_0 is magnetic permeability and σ is the electric conductivity of the fluid.

Assumptions:

1. Neglect the time variation of the magnetic field, then Eq. (3) reads:

$$\nabla \times \mathbf{E} = 0, \qquad (8)$$

2. Re_m << 1.
Then Eq. (5) reads:

$$\mathbf{J} = \sigma \mathbf{E} \qquad (9)$$

Maxwell Equations Solution:

The dimensional form of the solution is Laplace equations for both potential ϕ

$$\nabla^2 \phi = 0. \qquad (10)$$

and for magnetic field, **B :**

$$\nabla^2 \mathbf{B} = 0. \qquad (11)$$

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- **Potential and Magnetic field equations to solve (dimensional):**

$$\nabla^2 \phi = 0. \qquad (10)$$

$$\nabla^2 \mathbf{B} = 0. \qquad (11)$$

- **BCs:**

$$J_y\big|_{\text{wall}} = J_0 \sin\left(\frac{\pi}{2a}x\right) = -\sigma \frac{\partial \phi}{\partial y}\bigg|_{\text{wall}}, \qquad (12)$$

$$B(x,y)_{y=0} = B_0 cos(\frac{\pi}{2a}x) \qquad (13)$$

A method: Spanwise applied Lorentz force

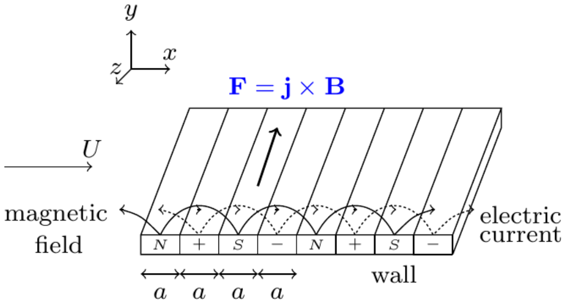

Fig.1 Arrangement of magnets and electrodes for generating a Lorentz force along the spanwise direction.

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- **Lorentz force (dimensional):**

$$F_z = B_y J_x - B_x J_y, \qquad (14)$$

$$\begin{aligned} B_y J_x &= -B_0 J_0 cos^2(\frac{\pi}{2a}x)[cosh(\frac{\pi}{2a})y - \frac{sinh(\frac{\pi}{2a}y}{tanh(\frac{\pi}{a}\delta)}] \\ &\frac{1.0}{tanh(\frac{\pi}{a}\delta)}[cosh(\frac{\pi}{2a})y - tanh(\frac{\pi}{a}\delta)sinh(\frac{\pi}{2a}y)], \end{aligned} \qquad (15)$$

$$\begin{aligned} B_x J_y &= B_0 J_0[\frac{sin^2(\frac{\pi}{2a}x)}{tanh(\frac{\pi}{a}\delta)}sinh^2(\frac{\pi}{2a})y - sin^2(\frac{\pi}{2a}x)\frac{sinh(\frac{\pi}{2a}ycosh(\frac{\pi}{2a}y}{tanh(\frac{\pi}{a}\delta)} - \\ &sin^2(\frac{\pi}{2a}x)cosh(\frac{\pi}{2a}y)sinh(\frac{\pi}{2a}y) + \frac{sin^2(\frac{\pi}{2a}x)cosh^2(\frac{\pi}{2a}y)}{tanh(\frac{\pi}{a}\delta)}], \end{aligned} \qquad (16)$$

result force is:

$$F_z = J_0 B_0[sinh(\frac{\pi}{2a}y - \frac{cosh(\frac{\pi}{2a}y}{tanh(\frac{\pi}{a}\delta})][cosh(\frac{\pi}{2a}y - \frac{sinh(\frac{\pi}{2a}y}{tanh(\frac{\pi}{a}\delta})] \qquad (17)$$

For the case $\frac{\delta}{a} \rightarrow \infty$ then $tanh(\infty) \rightarrow 1.0$ then,

$$F_z = J_0 B_0 \exp^{-\frac{\pi}{a}y} \quad \text{(N/m}^3\text{)} \qquad (18)$$

A method: Spanwise applied Lorentz force

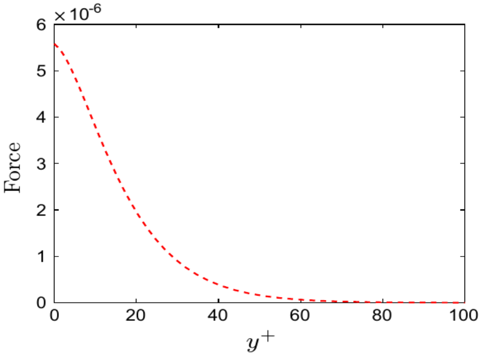

Fig.2 Force decays in wall-normal direction.

Non-dimensional force is:

$$f_z^+ = St\ exp(-\frac{\pi y^+}{a^+})sin(\frac{2\pi t^+}{T^+}). \qquad (19)$$

$$St = J_0 B_0 \delta/[\rho u_\tau^2] \qquad (20)$$

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- **Non-dimensional N-S equations:**

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = -\nabla\mathbf{p} + \frac{1}{Re_\tau}\nabla^2\mathbf{u} + St\,(\mathbf{J}\times\mathbf{B}), \qquad (21)$$

$$\nabla\cdot\mathbf{u} = 0 \qquad (22)$$

Seawater properties :

- electric conductivity σ : 2.5 - 5.0 Siemens/m.
- ρ : 1.020 - 1.029 kg/m^3.
  The flow field variables :
- u_τ : 0.0025 m/s.
- δ : 0.04m.

In this situation if we apply EM width (a) = 0.1 m. Apply a voltage to the electrodes 3 V. The current density we have is :

$J_0 = \frac{\pi}{4a}\sigma V_0$ = 94.2 A/m^2.

The magnet power equal (B$_0$)= 0.023 T

Then we got the St number;

$St = B_0 J_0 \frac{\delta}{\rho u^2{}_\tau}$ = 36.

$$\left(\frac{St\;T^+}{Re_\tau\;\pi}\right)_{opt} = 20. \qquad (23)$$

(Berger et. al. Physics of Fluids 12, 631–649 (2000))

For Re_τ=180

$St = 36\pi$ for $T^+ = 100$

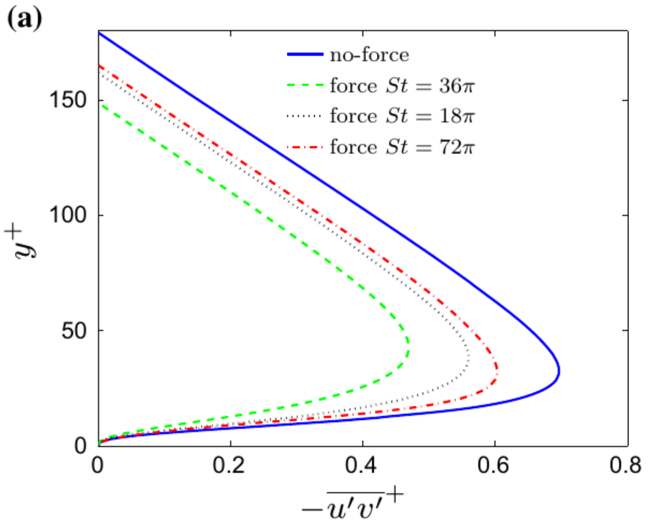

Fig.3 Reynolds shear stress.

A maximum of approximately 40% drag reduction achieved.

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- **DNS Results:**

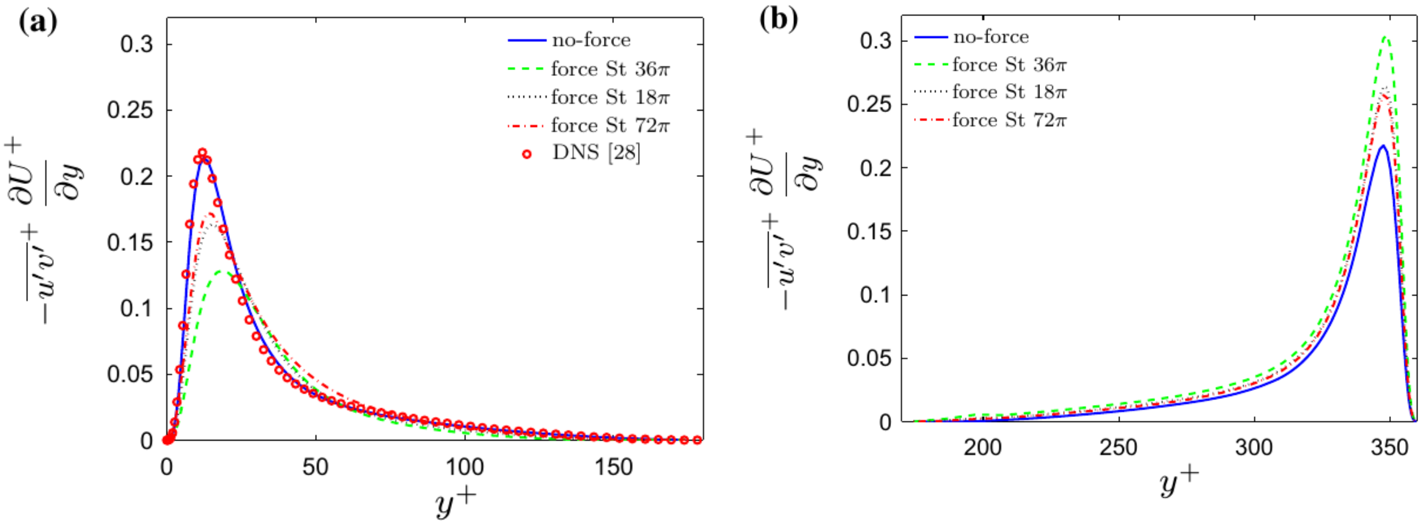

Fig.4 Turbulence production, (a) is force applied wall, (b) is upper wall.

Lower Reynolds shear stress compared to the no-force case shows that the Lorentz forcing gives a turbulence drag reduction.

This is also seen by the fact that the bulk velocity increases with forcing by 18% (St = 36π) compared to the no-force case.

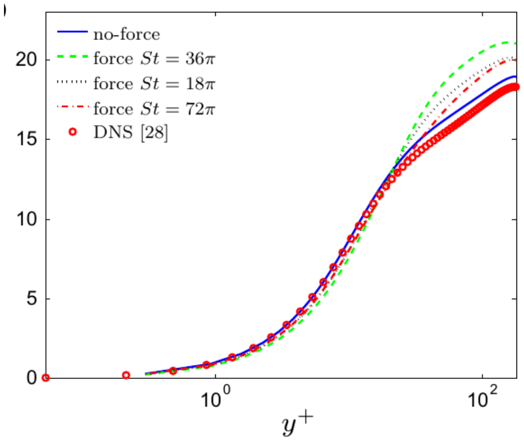

Fig.5 U^{+}, mean streamwise velocities.

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- **DNS Results:**

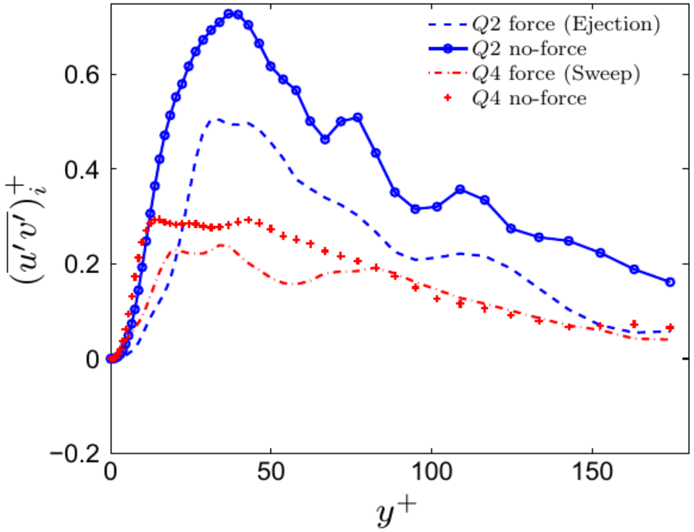

Fig.6 Fluctuation velocity quadrant analysis.

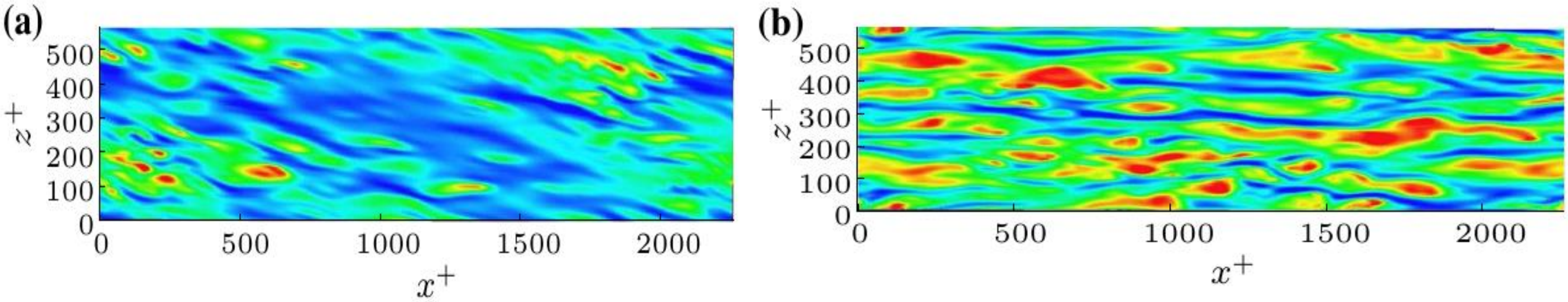

Fig.7 Streamwise velocity (u) contours for the same instant for lower and upper wall, y+ = 10. St = 36π. Applied force case. Blue color indicates low-speed streaks, yellow-red high-speed streaks. a Lower wall, b upper wall.

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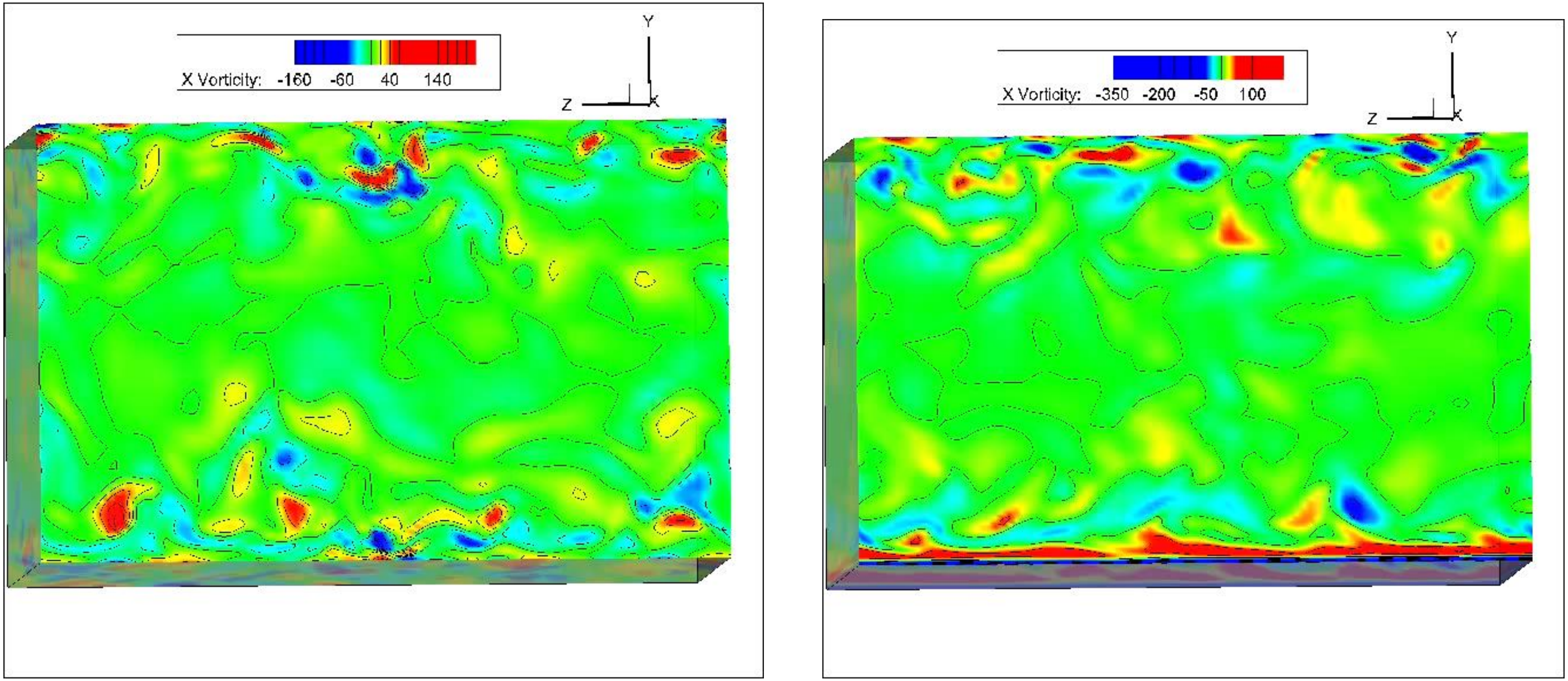

Video 1. Vorticities, left no-force, right applied force case.

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- **DNS Results: Entropy generations**

$$\varepsilon = 0.5\nu\left[\overline{\left(\frac{\partial u_i'}{\partial x_j}+\frac{\partial u_j'}{\partial x_i}\right)^2}\right] \quad \text{(Turbulent dissipation)} \quad (24)$$

$$\varepsilon_{mean} = \nu\left(\frac{\partial U}{\partial y}\right)^2 \quad \text{(Mean dissipation)} \quad (25)$$

$$(S'''(y^+))^+ = \left[\nu\left(\frac{\partial U}{\partial y}\right)^2+\varepsilon\right]\left(\nu/u_\tau^4\right) \quad \text{(Entropy generation)} \quad (26)$$

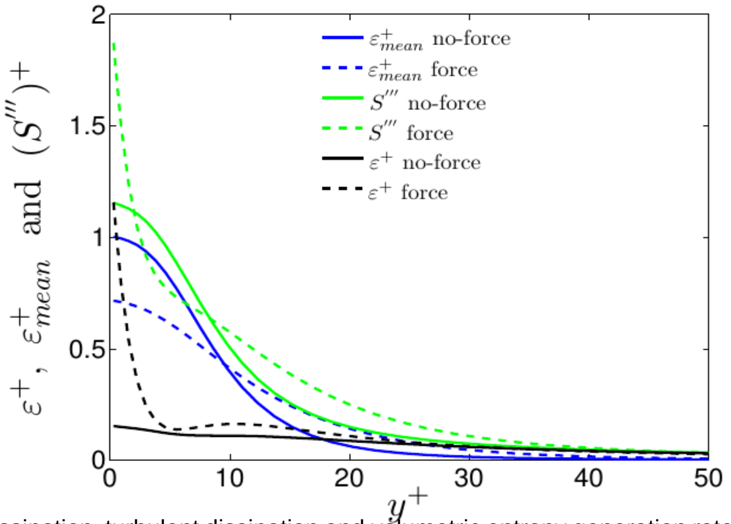


Fig.8 Mean dissipation, turbulent dissipation and volumetric entropy generation rate, for applied force and no-force cases, for lower wall.

Modelling Galinstan and air multiphase model

Laminar flow. Galinstan has been used as operating fluid.

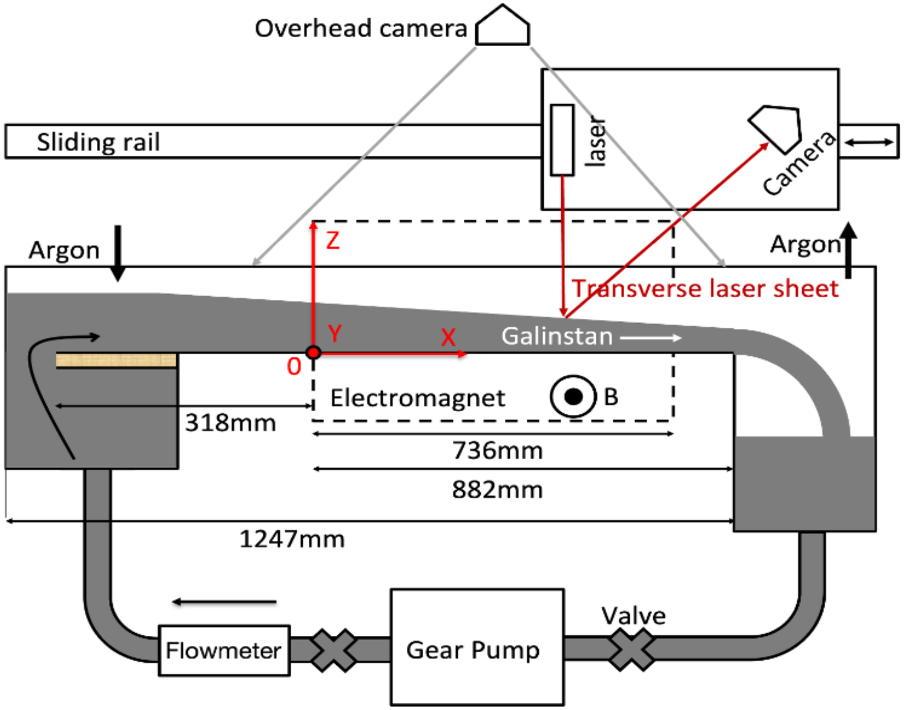


Fig.9 The geometry adapted from Z. Sun et al 2023 Nucl. Fusion 63 076022.

Modelling Galinstan and air multiphase model

- ANSYS Fluent
    - Poly-hex mesh formation ~1e6cells
- Setup1 - Multiphase flow without magnetic fields
- Setup2 - Multiphase flow with magnetic flux boundary condition

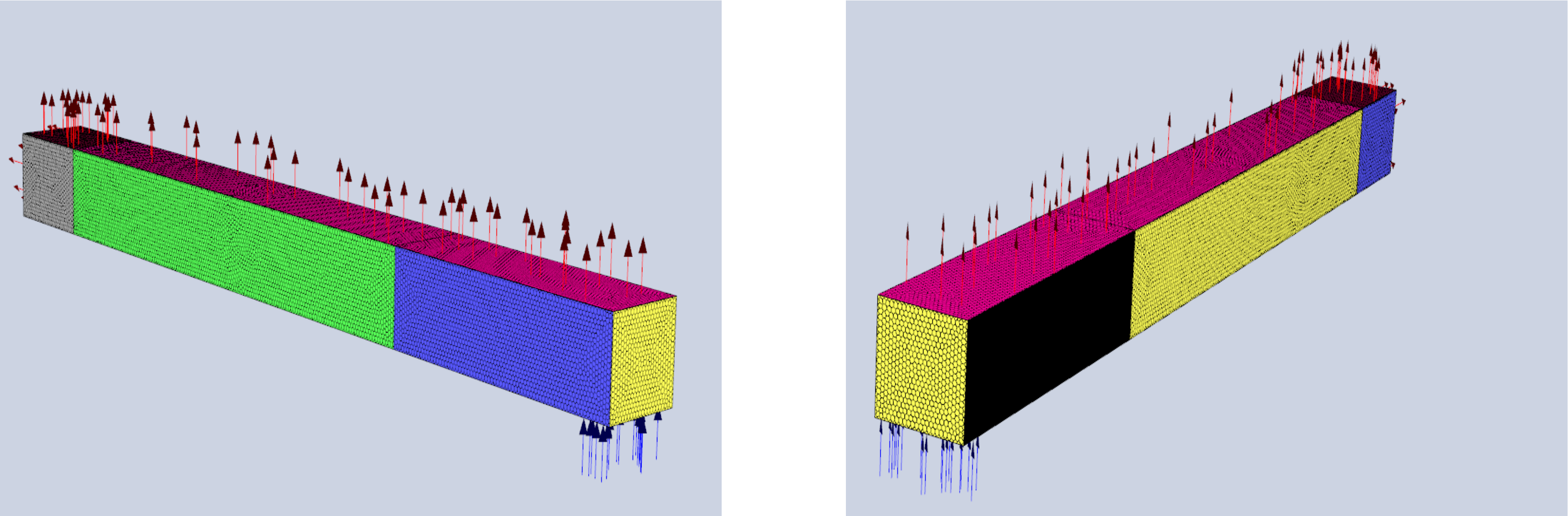


Fig.10 The channel flow, inlet and outlet.

Modelling Galinstan and air multiphase model

- Walls are modelled as insulating walls
    - B = - 0.3 Tesla flux is defined from blue surfaces perpendicular to the flow.

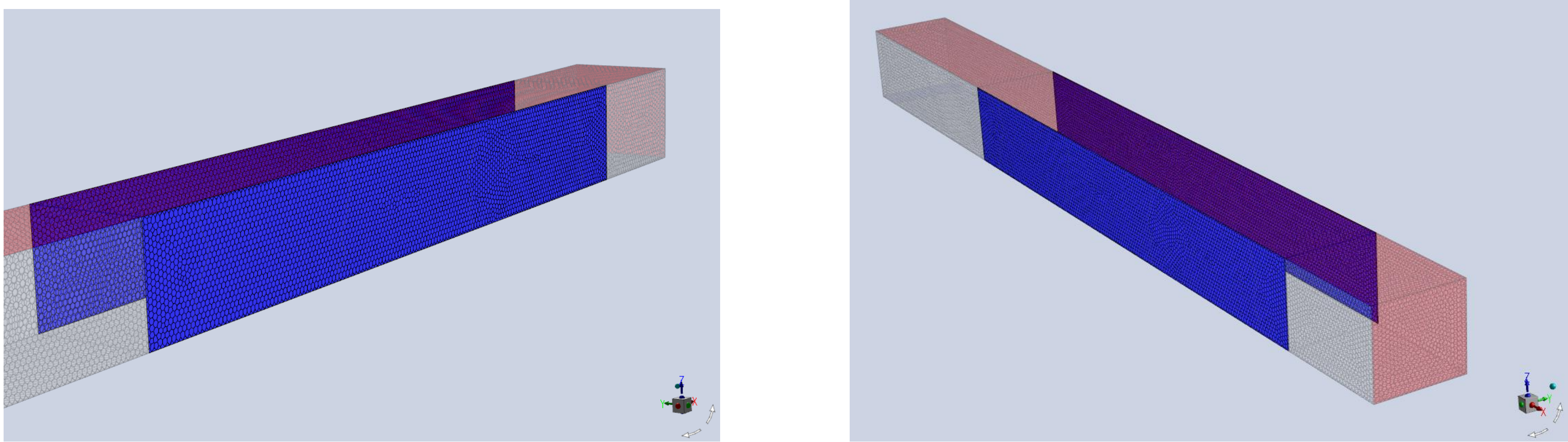


Fig.11 Magnetic field applied in blue areas .

Modelling Galinstan and air multiphase model

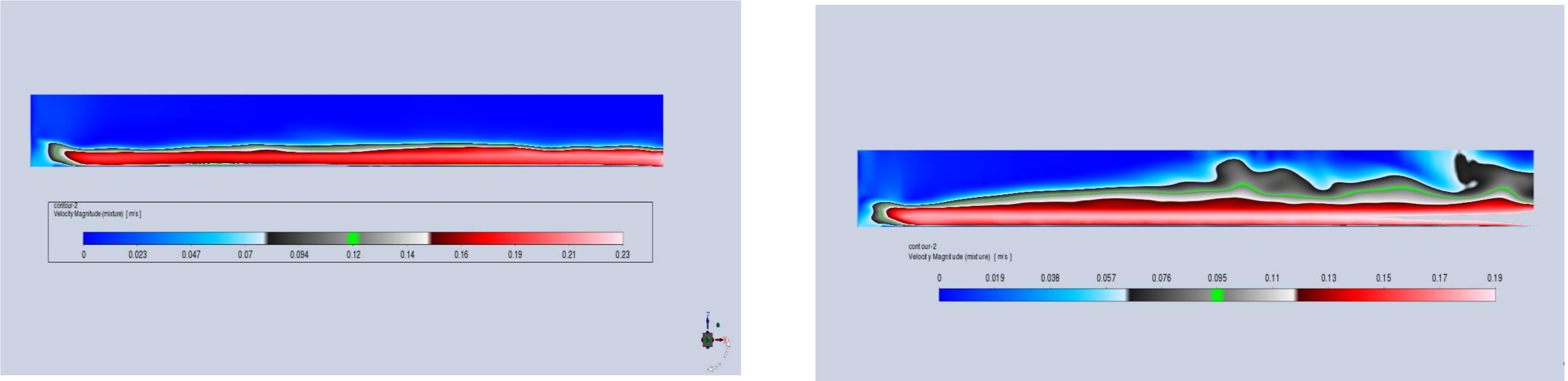
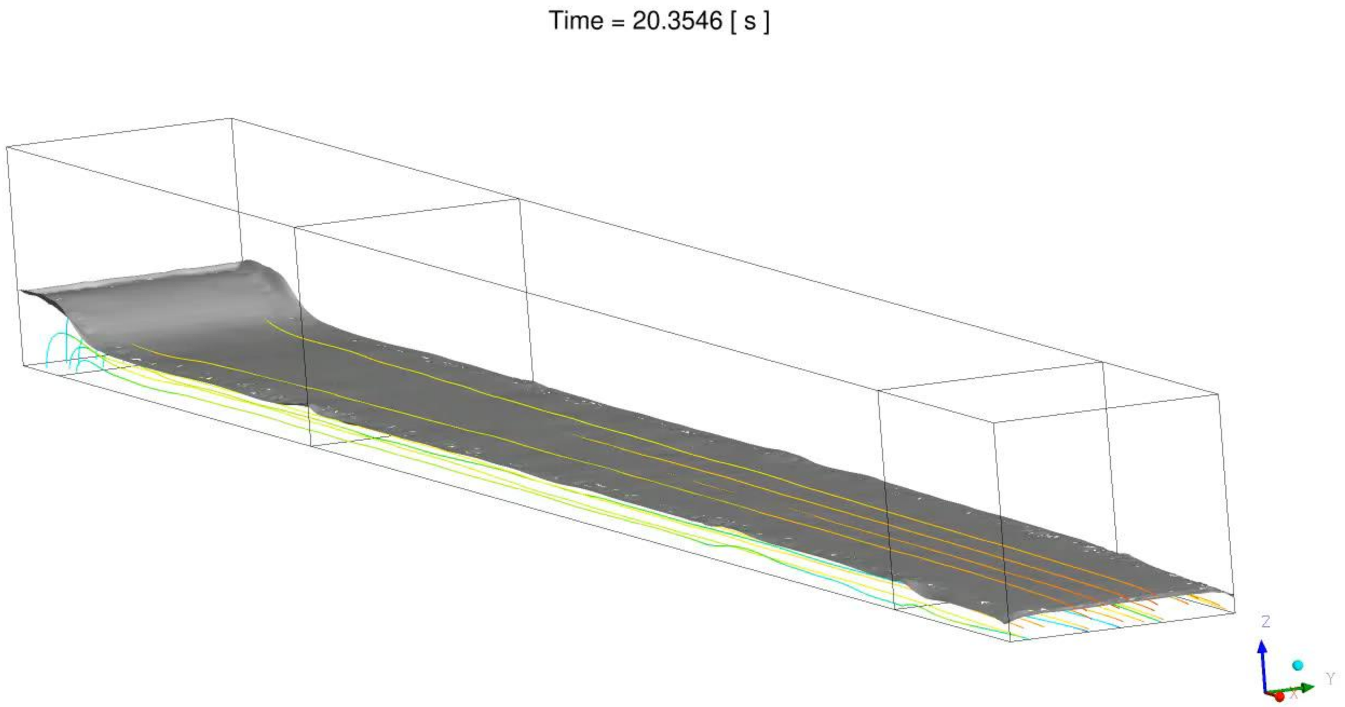


Fig.12 No magnetic field applied at left and distortion on the velocity after magnetic field applied.

Modelling Galinstan and air multiphase model



Video.2 After magnetic field applied.

Conclusion

Working with non-dimensional equations with St number enables:

- To obtain optimum St number for the different applications.
- The external voltage and/or magnetic field to control (slow down or enhance the velocity) for a given liquid metal.
- Obtaining suitable liquid metal for a given magnetic field.

Thank you for your attention.