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Validation Of COMSOL Multiphysics® For Magneto-hydro-dynamics (MHD) Flows In Fusion Applications

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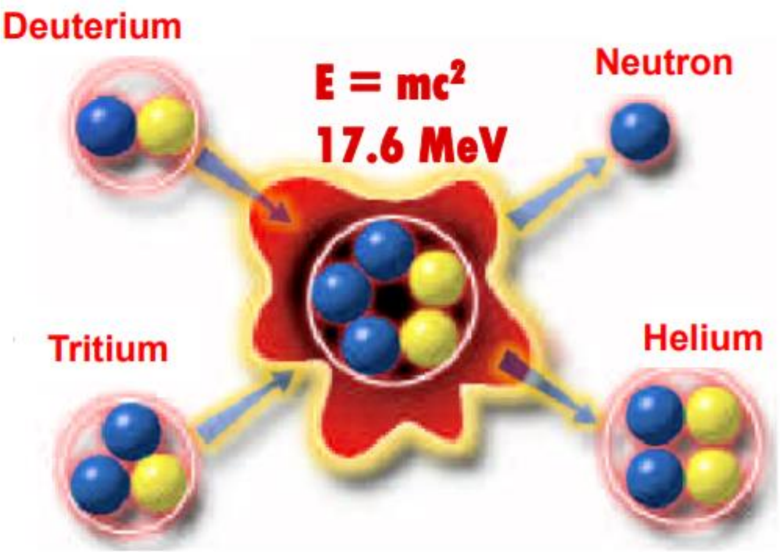
Introduction

What is Nuclear Fusion?

- **Fusion powers the sun and stars:** Fusion is the energy-producing process taking place in the core of the sun and stars.
- Two light nuclei combine to form a heavier nuclei, converting mass to energy through **$E = mc^2$.**
- Deuterium-Tritium Cycle is the easiest to achieve: attainable at lower plasma temperature because it has the largest reaction rate and high energy output.



80% of energy release (14.1 MeV) → Used to breed tritium and close the DT fuel cycle

$Li + n \rightarrow T + He$

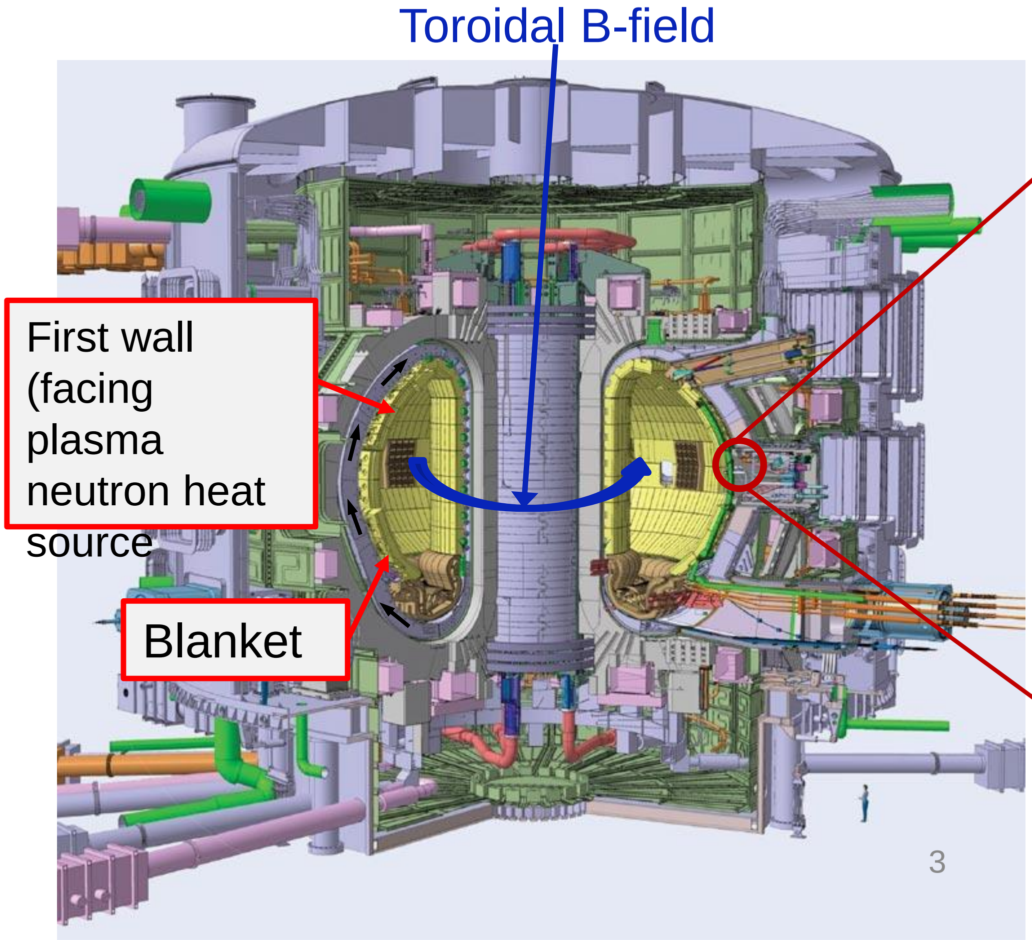
Li in some form must be used in the fusion system

20% of energy release (3.5 MeV)

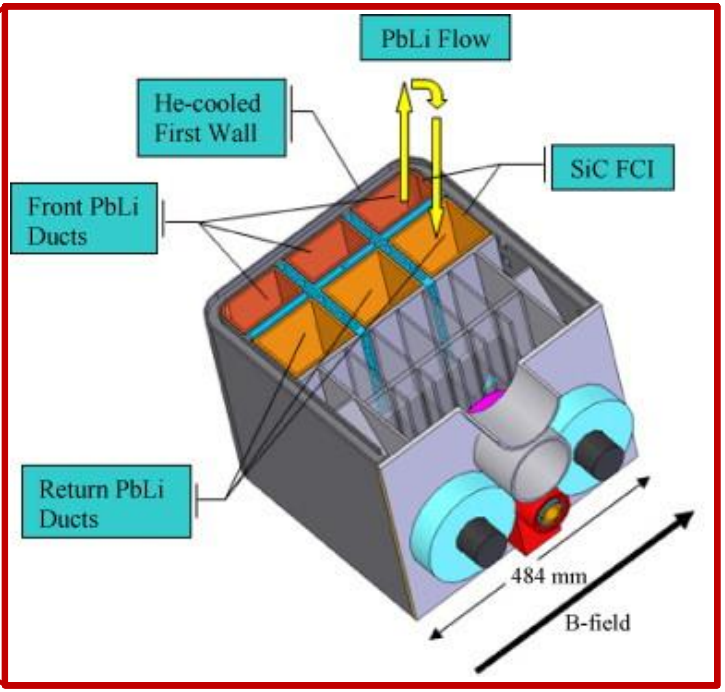
Introduction

Role of Liquid Metal Blankets in Nuclear Fusion Reactor

- Protection of the magnetic coils and vacuum vessel from unbearable radiation doses.
- Absorption of fast neutrons to convert its energy into heat.
- Breeding of tritium, one of Fusion reactants.



Dual Coolant Lead Lithium (DCLL)



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Introduction

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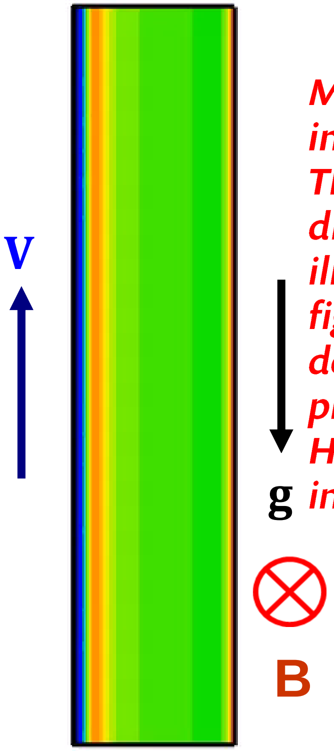
MHD Flows in Fusion Liquid Metal Blankets

- Magneto-hydro-dynamic (MHD) is a study that concerns the dynamics of magnetic field and electric conducting fluid when they are interacted with each other.
  - Generation of electrical currents – Faraday’s law of induction
  - Appearance of induced magnetic field – Ampere’s law
  - Production of Lorentz force – Interaction of electrical current and total magnetic fields.



Mixed convection in a vertical duct. The vorticity distribution illustrated in the figure demonstrates the presence of Kelvin-Helmholtz type instability

- For liquid metal flows in Fusion applications, the induced magnetic field is usually negligible with respect to applied magnetic field, which simplifies the system and allows the usage of inductionless approximation of MHD flow.

- MHD instabilities in LM flows in a fusion reactor blanket, critically important to any LM blanket concept, have recently been recognized to be dominant.
  - Understanding and quantifying these effects is absolutely necessary to design a feasible LM blanket.
  - Existing MHD codes have not demonstrated the ability to simulate phenomena in a Fusion Reactor harsh environment (where Ha, Re and Gr numbers are high)

Numerical Modeling

- Governing equations and characteristic parameters:
  - Flow equations: $\rho \nabla \cdot (\mathbf{u}) = 0$; $\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{F}$;
    where $\mathbf{F} = \mathbf{J} \times \mathbf{B_0} + \rho_0 \mathbf{g}\big(1 - \beta(T - T_0)\big)$
  - Electric current equations: $\nabla \cdot (\mathbf{J}) = 0$; $\mathbf{J} = -\sigma \nabla \phi + \mathbf{J_e}$; where $\mathbf{J_e} = \sigma \mathbf{u} \times \mathbf{B_0}$;
  - Heat transfer equation: $\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot (-\kappa \nabla T) = Q_e$

Reynolds number (Re)	Re: Ratio of inertia to viscous force
Hartmann number (Ha)	Ha^2: Ratio of Electromagnetic to viscous force
Grasholf number(Gr) / Rayleigh number(Ra)	Gr or Ra: Ratio of buoyancy to viscous force

- We follow the validation approach proposed in 2014 by Smolentsev et al [1].
  - First, fully developed laminar MHD flows were computed and the results compared with analytical Shercliff and Hunt solutions at high Ha up to 15,000 for electrically conducting and insulating ducts.
  - Second, the COMSOL capability to address developing MHD flows was tested against available experimental data for 3D laminar steady MHD flows in a non-uniform transverse magnetic field.
  - As a final test, two unsteady MHD flows were computed and the results compared against available 3D numerical data: (1) MHD flow in a horizontal cavity with volumetric heating and (2) periodic MHD flow in conducting duct with thin electrically conducting walls.

1. Simulation of fully developed laminar Shercliff [2], and Hunt flows [3]

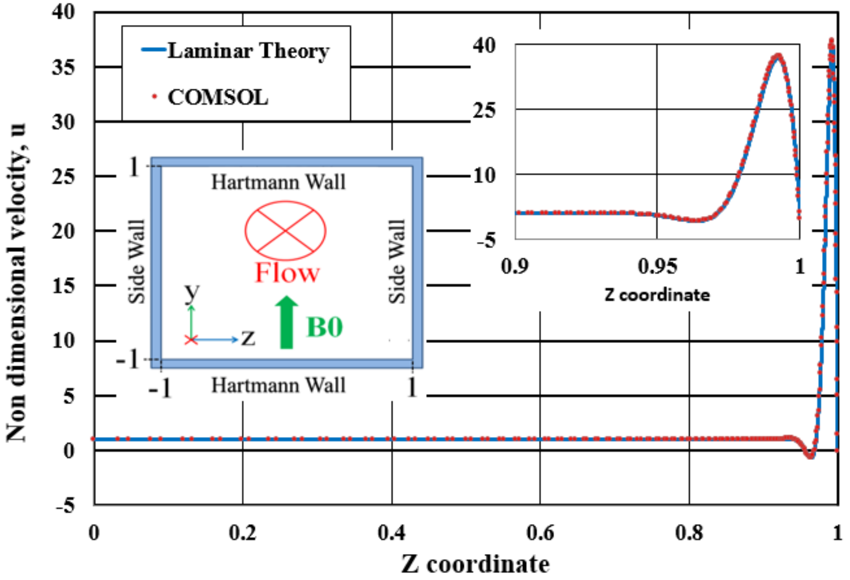


Fig.1 Velocity distribution for Hunt flow at Ha = 15000 with electrically insulating on side wall and 0.01 of conducting ratio on Hartmann wall

	Ha	Dimensionless flow rate		Relative Error
		Analytical	COMSOL	
Shercliff	500	7.6790e-3	7.6655e-3	0.176%
	5000	7.9018e-4	7.8715e-4	0.384%
	10000	3.9654e-4	3.9521e-4	0.337%
	15000	2.6479e-4	2.6384e-4	0.359%
Hunt	500	1.4050e-3	1.4057e-3	0.050%
	5000	1.9070e-5	1.9014e-5	0.295%
	10000	5.1690e-6	5.1445e-6	0.468%
	15000	2.4250e-6	2.4133e-6	0.486%

Table 1 Numerical comparison between analytical and COMSOL for Shercliff, and Hunt flow with same set up parameters in Fig. 1

2. 3D laminar duct MHD flow with a non-uniform magnetic field [4]

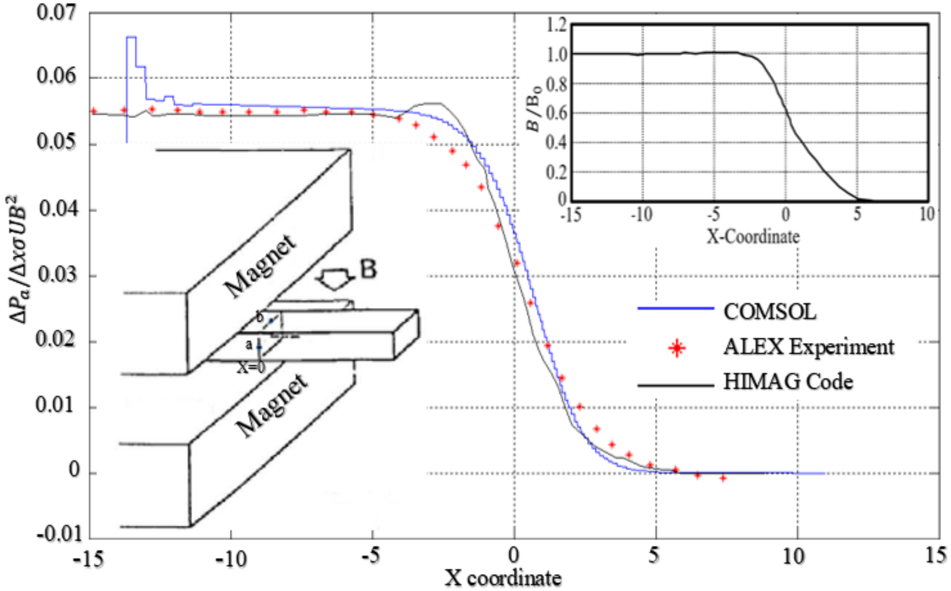


Fig.2 Comparisons of non-dimensional pressure gradient distribution at point a, along flow direction with Ha = 2900 and Re = 15574

[1] S. Smolentsev, S. Badia, R. Bhattacharyay, et al., Fusion Eng. Des. 100 (2015) 65–72
[2] Shercliff, Mathematical proceeding of the Cambridge Philosophical Society, 1953, pp 136-144.
[3] Hunt, J.Fluid Mech. (1965), vol. 21, pp. 577-590
[4] B.F. Picologlou, C.B. Reed, in: JUTAM Sysmposium on LM MHD, Riga, USSR, 1988

3. Unsteady natural convection MHD flow in a cubic enclosure with volumetric heating. All walls are adiabatic except for top isothermal wall.

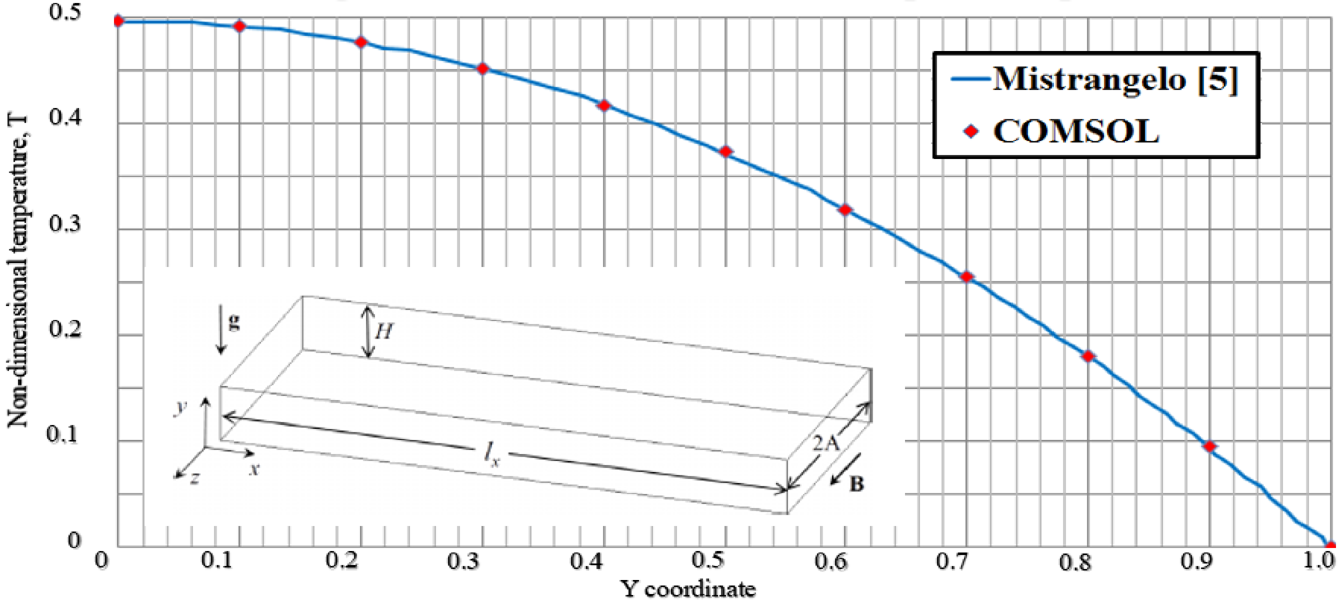


Fig.3 Axially averaged temperature distribution along vertical axis with Ha = 200 and Ra = 1e4 (steady)

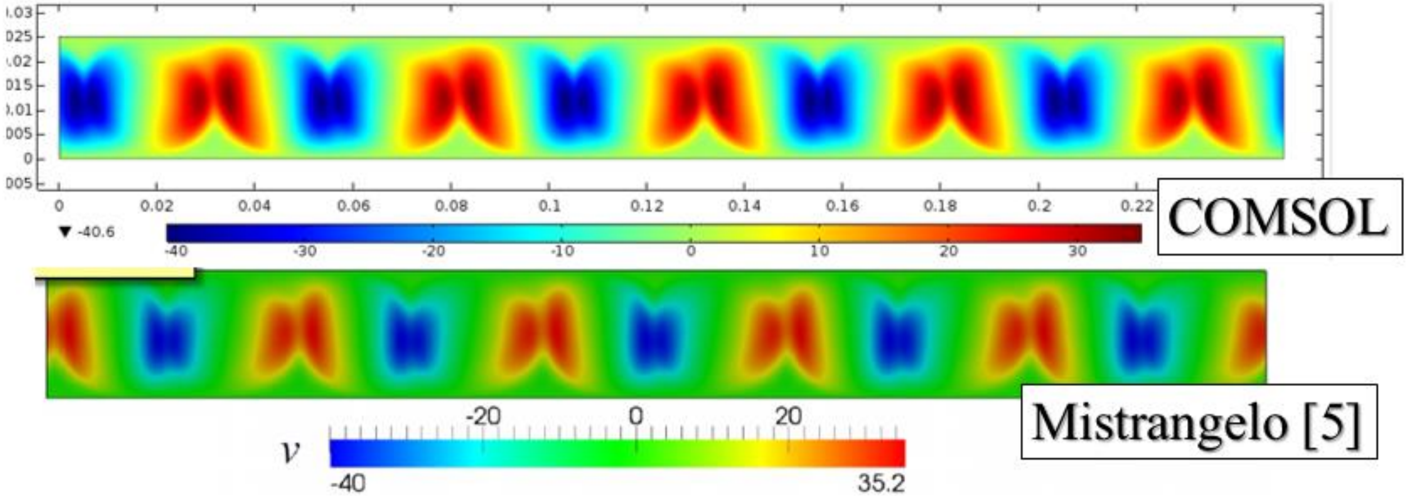


Fig.4 Instantaneous contours of vertical velocity at y-z plane with Ha = 200, Ra = 3e5 (unsteady).

[5] Chiara Mistrangelo and Leo Buhler, Physics of Fluids. 28, 024104 (2016)

4. Simulation of Kelvin-Helmholtz instability on isothermal MHD flow generated naturally by high flow jet in an electrically conducting duct.

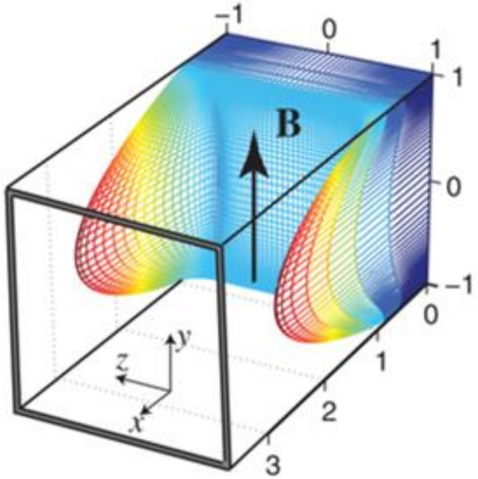


Fig.5 Base velocity profile in a conducting squared duct (conducting ratio = 0.5) with Ha = 200

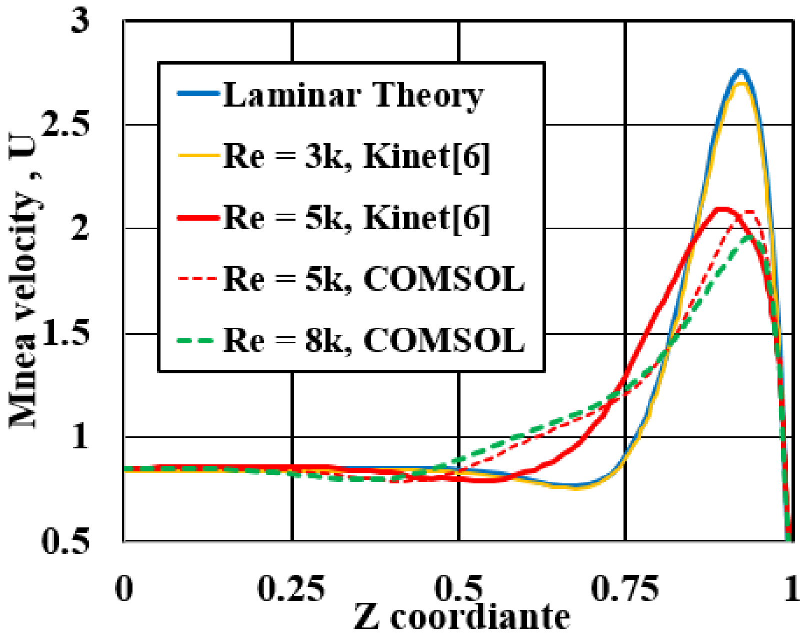


Fig.6 Mean velocity distribution along z axis

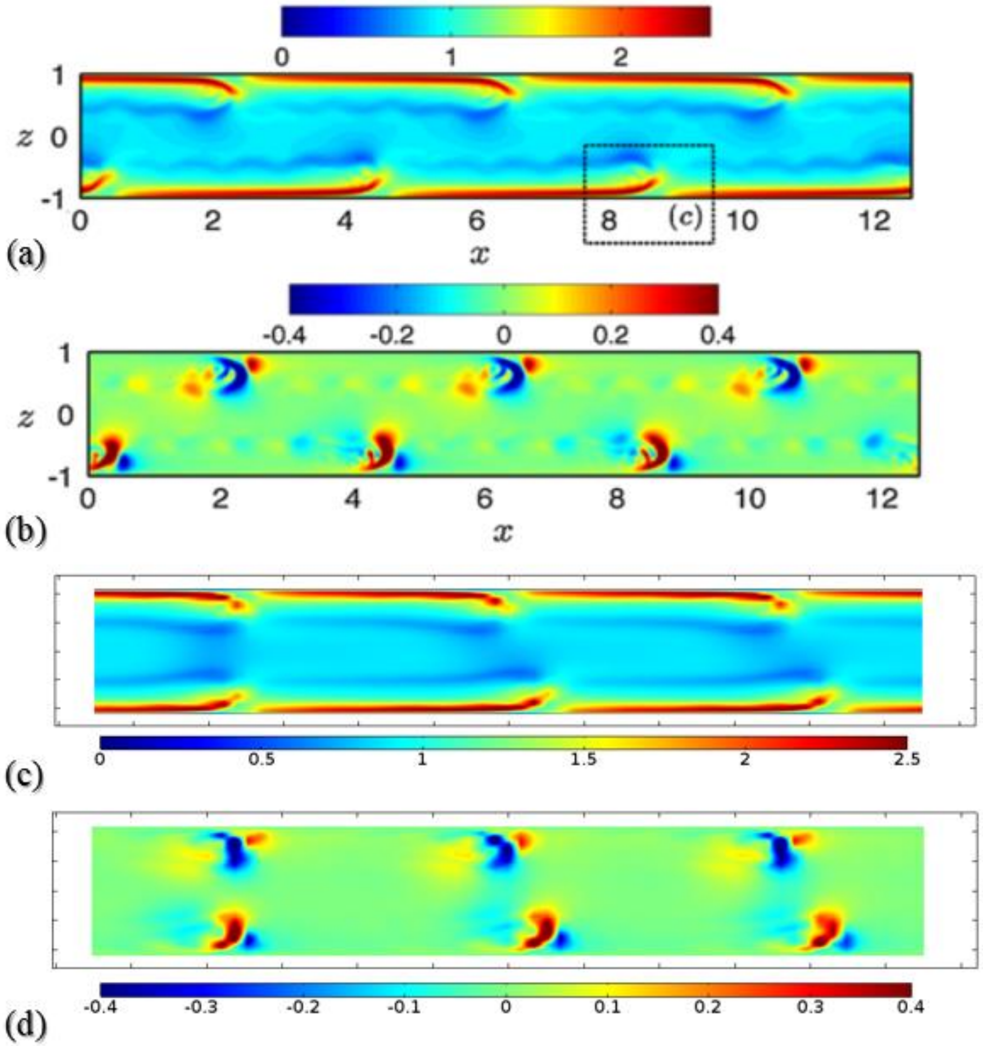


Fig.7 Instantaneous contours of axial component of (a), (c) the total axial velocity u_1 and (b), (d) the transverse disturbance velocity u'_3 for Re = 5000 from Kinet [6] and COMSOL respectively

[6] Kinet, Knaepen, Molokov, Phys Rev Lett. 2009 Oct 9; 103(15):154501.

Conclusion

- All computations have demonstrated good qualitative and, in most cases, fair quantitative match with the available experiment, analytical and numerical data.
- It suggests that COMSOL Multiphysics® can serve as a good computational MHD tool to analyze multi-physics effects in MHD flows for fusion applications.
- As a next step, this numerical methodology using COMSOL Multiphysics® will be applied to analyze critical MHD instabilities under experimental and real blanket conditions.

Q & A