COMSOL CONFERENCE
2017 BOSTON

Validation of COMSOL Multiphysics® for Magnetohydrodynamics(MHD) Flows in Fusion Applications

Y. Yan, S. Smolentsev, M. Abdou
Fusion Science and Technology Center, University of California, Los Angeles, CA, USA

UCLA FUSION
SCIENCE & TECHNOLOGY

Introduction

- •MHD instabilities in liquid metal(LM) flows in a fusion reactor blanket associated with the mixed-convection phenomena have recently been recognized to be dominant, critically important to any LM blanket concept.
- •Understanding and quantifying these effects is absolutely necessary to design a feasible LM blanket.
- •The existing MHD codes lack the ability to capture such phenomena at high Ha, Re and Gr numbers or this ability has not been demonstrated.
- •Therefore, we initiated an effort to build and test a new computational methodology (physical/mathematical model, boundary conditions, numerical methods) to particularly address a class of time-dependent MHD flows with volumetric and surface heating.
- •We selected COMSOL as the starting code for building 3-D MHD capability because it is a commercial 3-D multi-physics solver with many advanced capabilities.

Governing equations and Dimensionless parameters

•Flow equations: $\nabla \cdot (\mathbf{u}) = 0; \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f}$

where $\mathbf{f} = \frac{1}{\rho}\mathbf{J} \times \mathbf{B} + \mathbf{g}\big(1 - \beta(T - T_0)\big)$

•Electric potential equation: $\nabla^2 \phi = \nabla \cdot (\mathbf{u} \times \mathbf{B})$;

•Ohm's law: $\mathbf{J} = \sigma(-\nabla\phi + \mathbf{u} \times \mathbf{B})$;

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

Validation procedure and Results

- •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 the analytical Shercliff [2] and Hunt [3] 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 [4].
- •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 [5] and (2) periodic MHD flow in conducting duct with thin electrically conducting walls [6].

1. Simulation of Shercliff, and Hunt flows

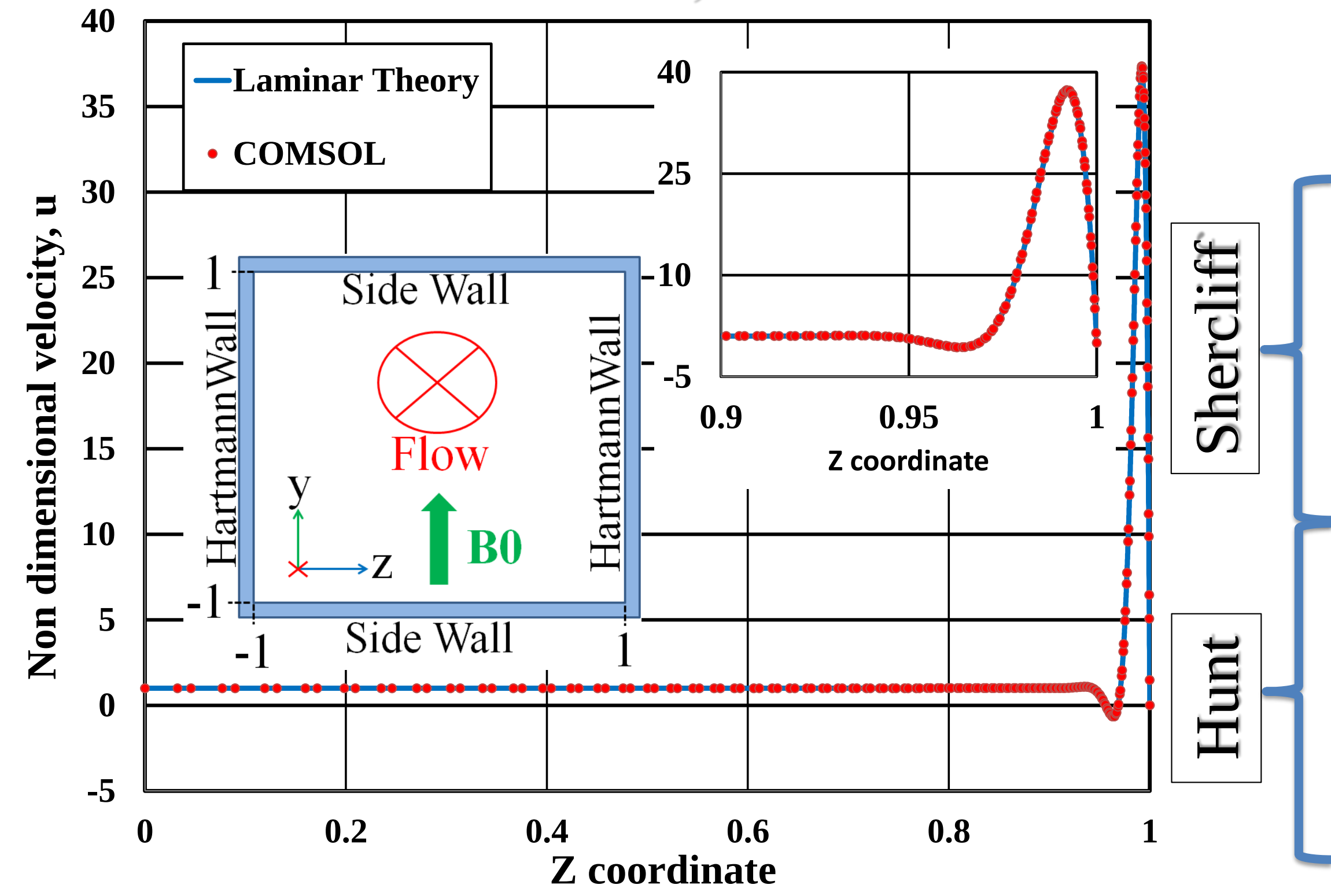

Fig.1 Velocity distribution for Hunt flow at Ha = 15000 with electrically insulating on side wall and 0.01 of conducting ratio on Hartmann wall

	Ha	**Non-dimensional flow rate**		**Relative Error**
		Analytical	**COMSOL**	
Shercliff	500	7.6790e-3	7.6655e-3	0.1761%
	5000	7.9018e-4	7.8715e-4	0.3839%
	10000	3.9654e-4	3.9521e-4	0.3372%
	15000	2.6479e-4	2.6384e-4	0.3596%
Hunt	500	1.4050e-3	1.4057e-3	0.0501%
	5000	1.9070e-5	1.9014e-5	0.2948%
	10000	5.1690e-6	5.1445e-6	0.4675%
	15000	2.4250e-6	2.4133e-6	0.4859%

Table 1 Numerical comparison between analytical and COMSOL solutions with same set up parameters in Fig. 1

- •Good agreement between COMSOL results and analytical solutions with less than 0.5% difference for flow rate at Hartmann number up to 15000.

2. 3D laminar pipe MHD flow with fringing magnetic field

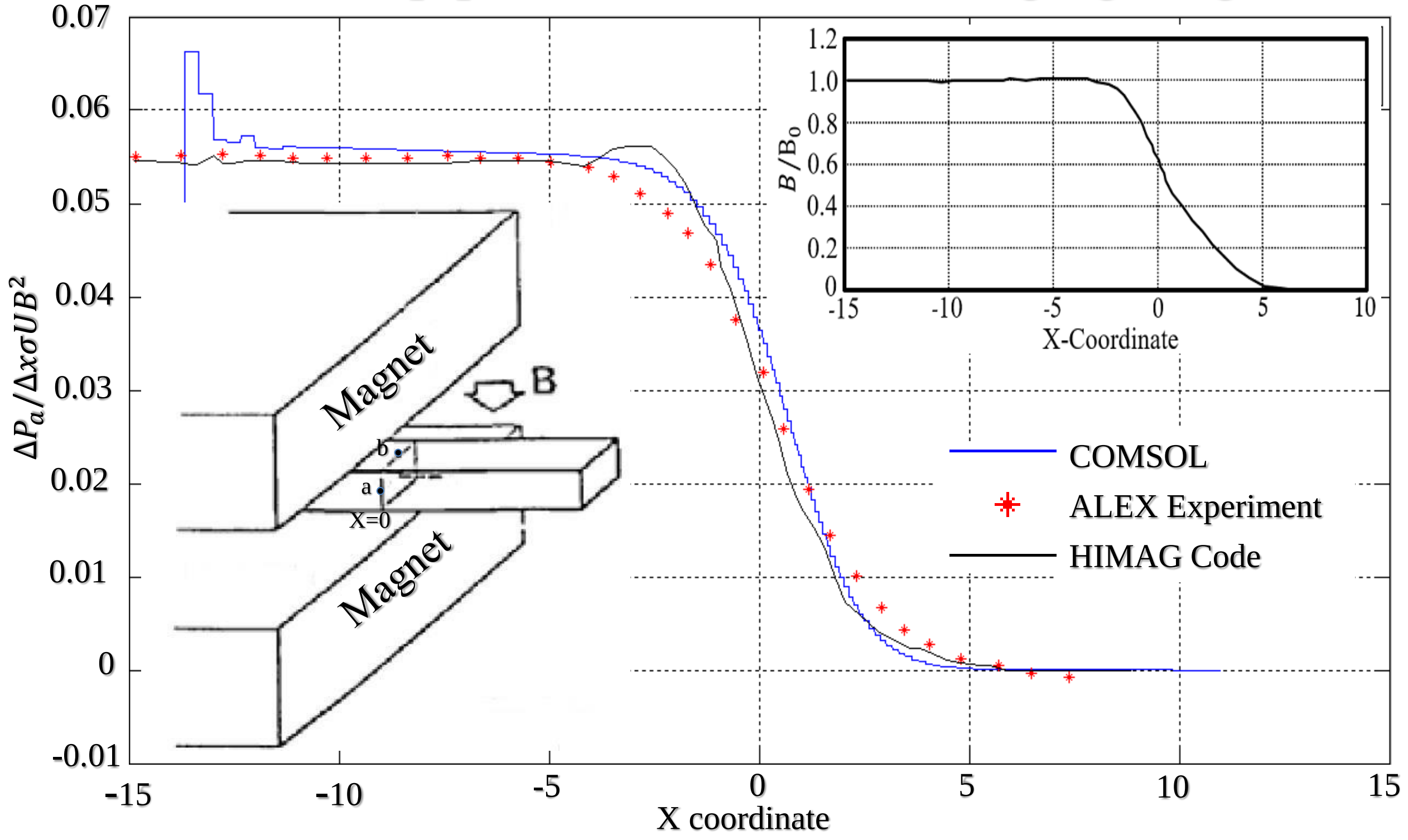

Fig.2 Comparisons of non-dimensional pressure gradient distribution at point a, along flow direction with Ha = 2900 and Re = 15574

- •Qualitative and quantitative agreement with experimental data and HIMAG simulation.

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

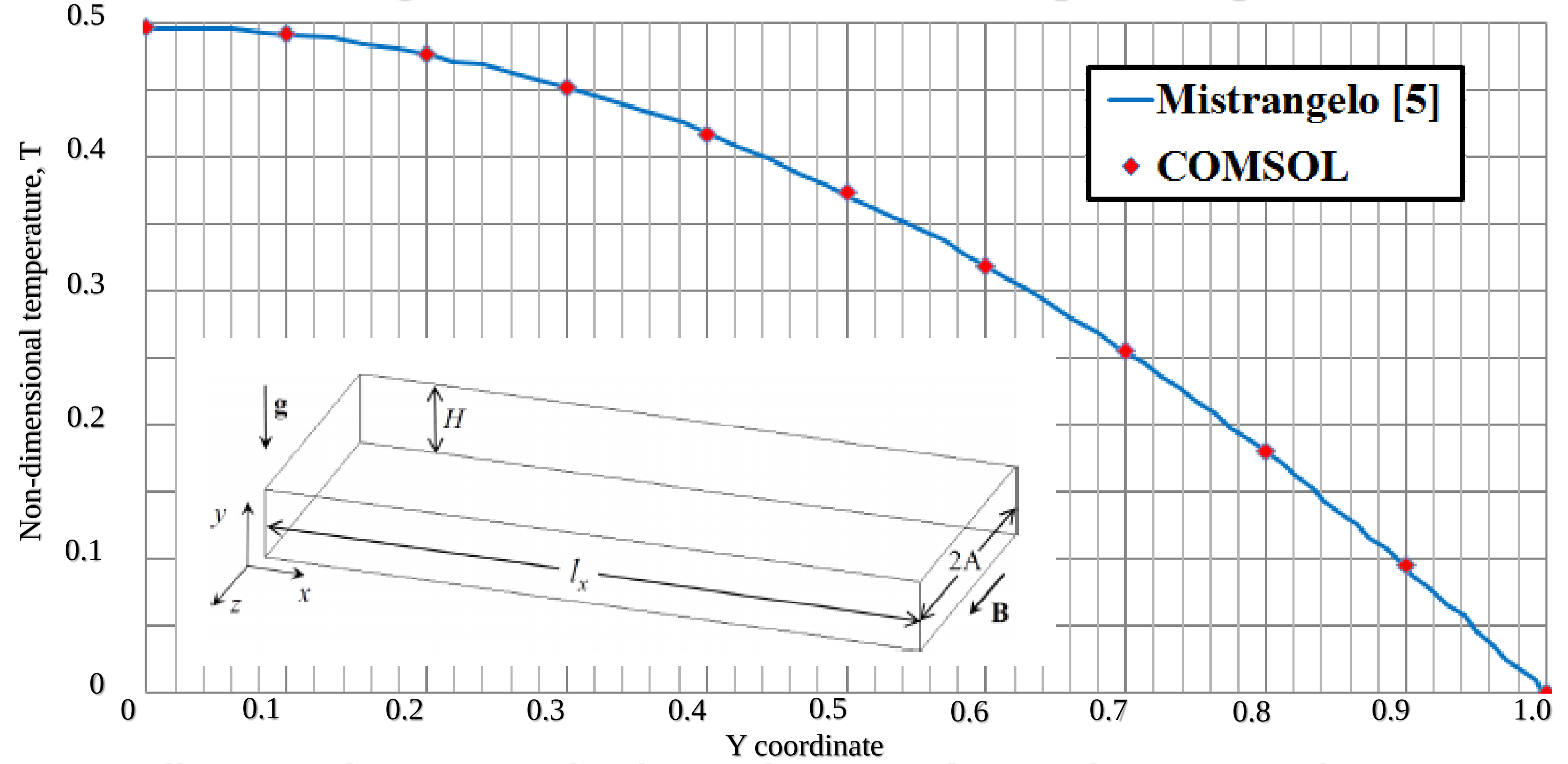

Fig.3 Axially averaged temperature distribution along vertical axis with Ha = 200 and Ra = 1e4 (steady)

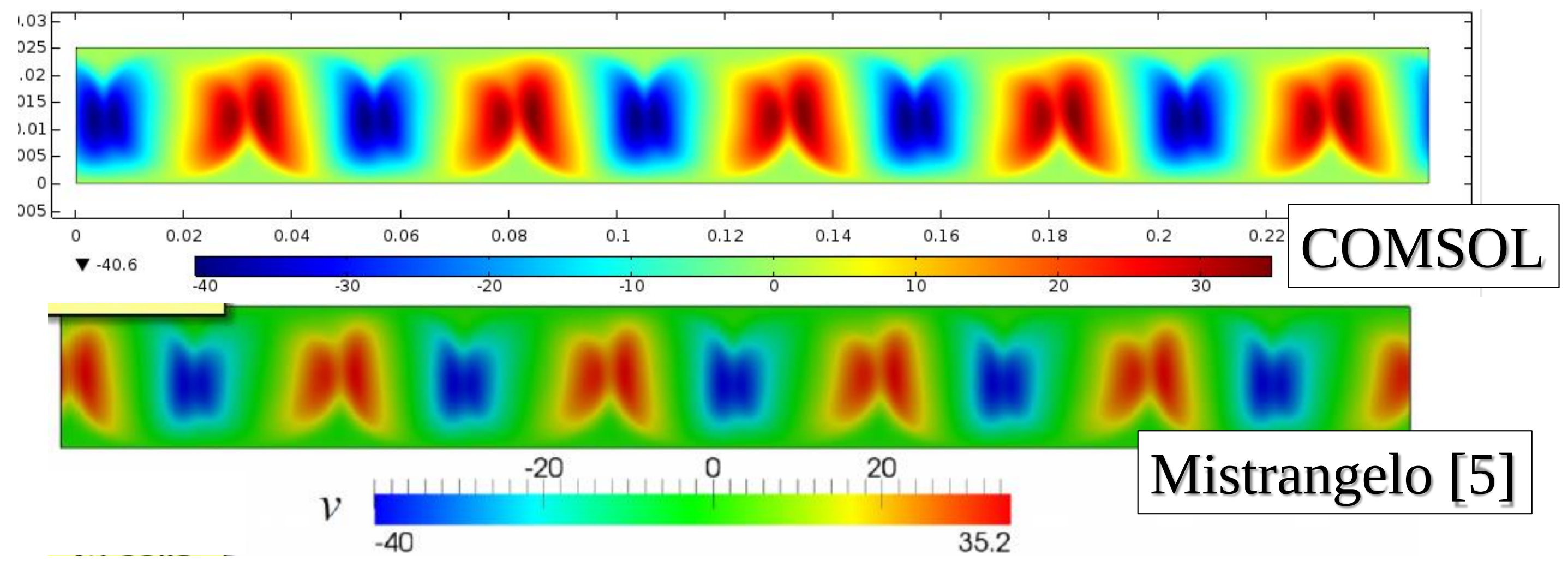

Fig.4 Instantaneous contours of vertical velocity at y-z plane with Ha = 200, Ra = 3e5 (unsteady).

- •Qualitative and quantitative match on steady solution, and qualitative agreement on unsteady solution (No quantitative data in reference [5]).

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

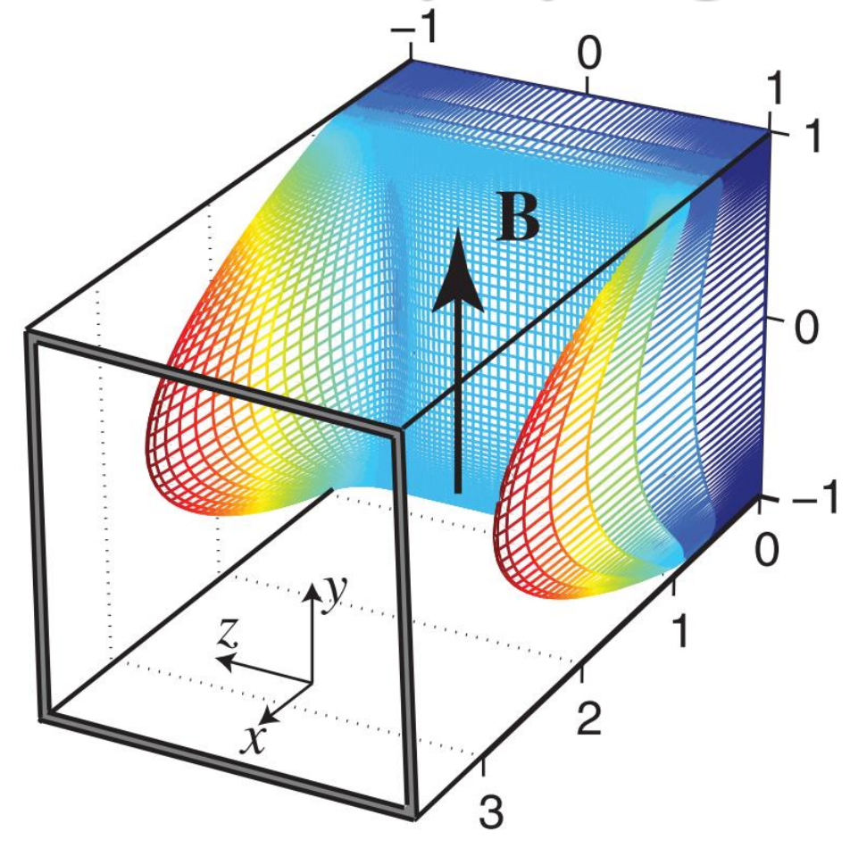

Fig.5 Base velocity profile in a conducting

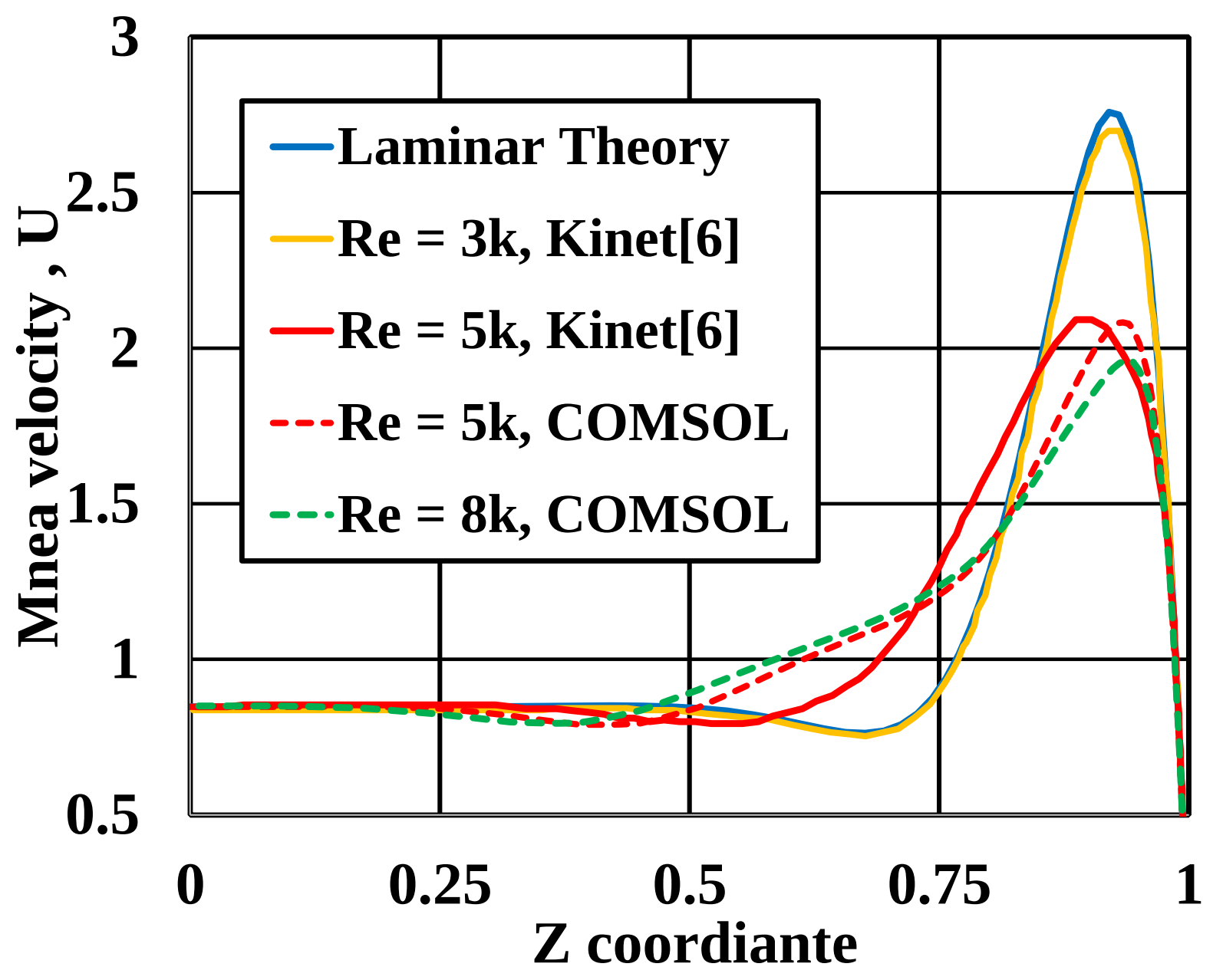

Fig.6 Mean velocity distribution along z axis

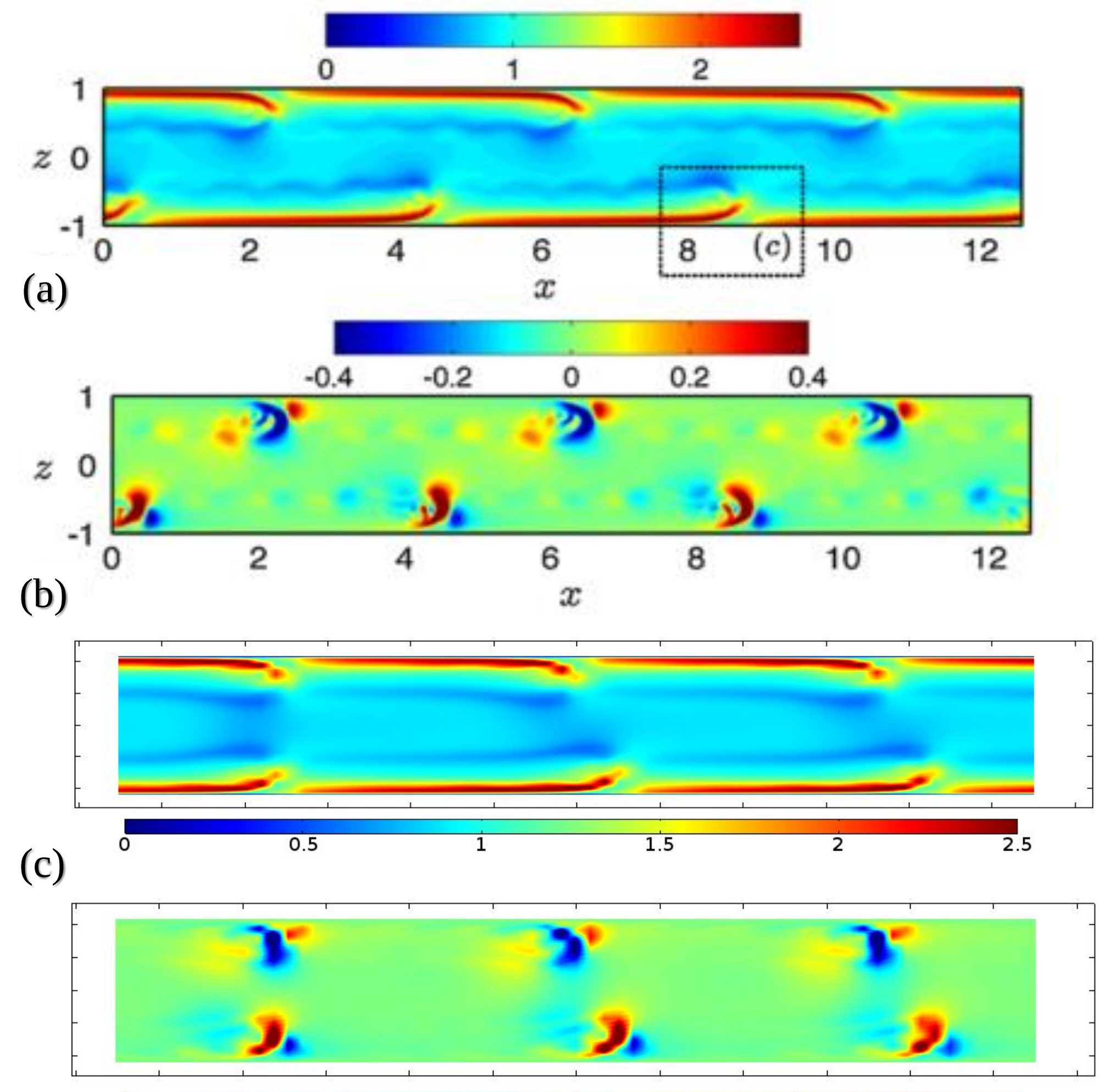

Fig.7 Instantaneous contours of axial component of (a), (c) the total axial velocity u_1 and (b), (d) the transverse disturbance velocity u_3' for Re = 5000 from Kinet [6] and COMSOL respectively

- •Qualitative and quantitative match on mean velocity distribution and flow development patterns comparing with **DNS** code results in reference [6].
- •Higher numerical dissipation on the bulk side of flow jet can be observed in COMSOL, and future tune up will be proceeded.

Concluding Remark and Future Work

- •All computations have demonstrated good qualitative and in most of the cases fair quantitative match with the available experiment, analytical and numerical data.
- •It suggests that COMSOL can serve as a good CMHD tool along to analyze multi-physics effects in MHD flows for fusion applications.
- •As a next step, we will apply our numerical methodology to analyze critical MHD instabilities under experimental and real blanket conditions.

References

[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
[5] Chiara Mistrangelo and Leo Buhler, Physics of Fluids. 28, 024104 (2016)
[6] Kinet, Knaepen, Molokov, Phys Rev Lett. 2009 Oct 9; 103(15):154501.

Excerpt from the Proceedings of the 2017 COMSOL Conference in Boston