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Numerical study on heat transfer characteristics of Pb-Li flow in horizontal square duct

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Molten Pb-Li is a promising candidate to be considered as the breeder and/or coolant in the upcoming magnetically confined nuclear fusion reactors [1]. It has high thermal capacity allowing it to extract more heat for a given volume. Apart from magnetically confined fusion reactor, Pb/PbLi is also proposed as a candidate material in magneto-inertial type nuclear fusion reactors [2]. Where Pb-Li will be used to compress the low density plasma up to fusion conditions. In these applications, the molten Pb-Li will be circulated in a closed loop system starting from the reactor vessel to outside heat exchanger and other sub-systems. This loop system would have several components like heat exchanger, cold trap, recuperator etc. To design such components, it is essential to know about the heat transfer coefficient or Nusselt number (*Nu*) of Pb-Li.

Numerical simulation of turbulent heat transfer is challenging especially for the low Prandtl number fluids as is the present case. This is because the thermal boundary layer in liquid metals are higher compared to momentum boundary layer [3, 4]. This leads to a difference in the momentum diffusivity and thermal diffusivity scales. Therefore, considering the same diffusivity scale (Reynolds analogy), may not be applicable for liquid metals which otherwise has worked well for other fluids like water and gases. In Reynolds Averaged Navier Stokes (RANS) based codes, this problem is tackled by the introduction of turbulent Prandtl number (Pr_t). Over the years, several expression for Pr_t has been proposed, some suggest bulk flow dependent Pr_t and some suggest local flow dependent Pr_t. Direct Numerical Simulation (DNS) studies have been found to predict the heat transfer phenomenon with high accuracy, however, their application to practical geometries are computationally expensive and may not be feasible always. Therefore, several researchers have tried suitable combination of Pr_t with RANS equation with suitable turbulence modelling to predict heat transfer coefficients.

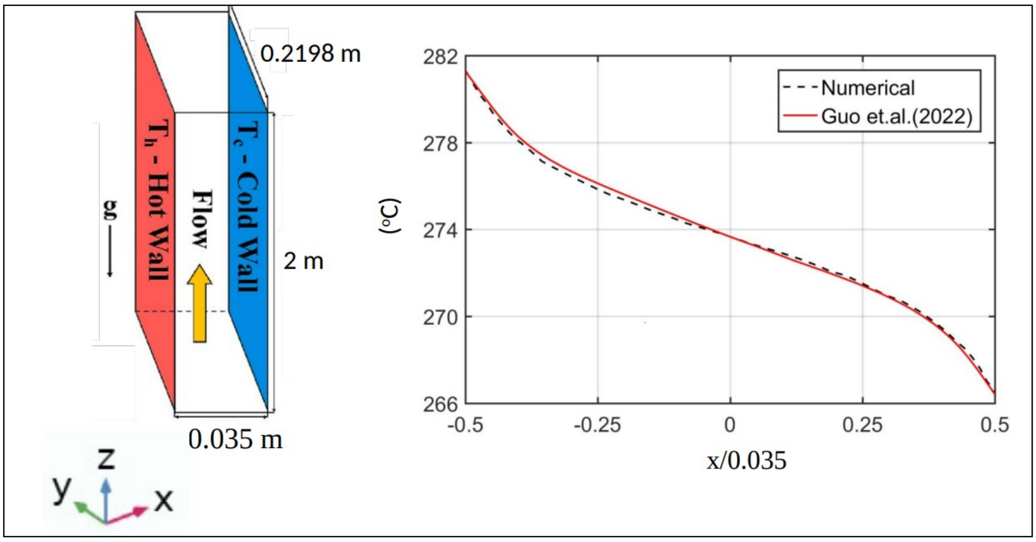


Fig-1. The flow geometry and the heating scheme considered for the validation of the numerical tool (left). (b) The comparison of time averaged temperature across the heated wall at the duct vertical and horizontal centre between the numerical data and literature (right).

In our simulations presented in Ref-[5], RANS equation is used to conserve the momentum and mass. Shear Stress Transport (SST) model has been utilized for turbulence mechanism. To solve the conjugate heat transfer and buoyancy phenomenon energy conservation equation following Boussinesq approximation has been used. In our study, the Pr_t value as shown in Eq-1 has been considered. The expression is initially proposed by Lie et. al.(2022), which is found to work well for most liquid metals with a deviation of 5 % [6]. The wall has been treated with Low Reynolds number wall condition. This treatment allows the computation to be carried out all the way to viscous boundary layers. The transient simulations are carried out using the backward differentiation formula, with adaptive step size method.

Where, $$Pr_t = 0.85 + \frac{2.5}{Pe_t} \quad \text{Eq. (1)}$$

$$Pe_t = \frac{\mu_t}{\mu} Pr \quad \text{Eq. (2)}$$

All the simulations have been performed in ANTYA cluster facility of Institute for Plasma Research, Gandhinagar. COMSOL multiphysics software has been used for the numerical work. It utilizes finite element discretization to solve the governing equations of conjugate heat transfer problem solved in the present study. The validation of the numerical tool has been performed by replicating the DNS study conducted by Guo and Prasser (2022) for the flow condition with Ri =1 [7]. The comparison of time averaged temperature across the heated wall at the duct vertical and horizontal centre between the numerical data and literature has been plotted in Fig-1. It can be observed that there exists a good matching between the present simulation and the DNS study by Guo et. al. (2022). This ensures that methodology opted in our numerical simulation is reliable. The same methodology has been continued for all the computations.

The computational domain used for our simulation has been shown in Fig-2. The computational domain has Pb-Li fluid flowing inside a SS 304 duct. A heater is placed to provide the heat in the system. 2 inch cerawool insulation surrounds the SS 304 duct. In the computational model, the heat from the heater is conducted in the SS 304 duct and then convected by the Pb-Li fluid. Some amount of heat gets lost to the environment through the cerawool to the ambient still air.

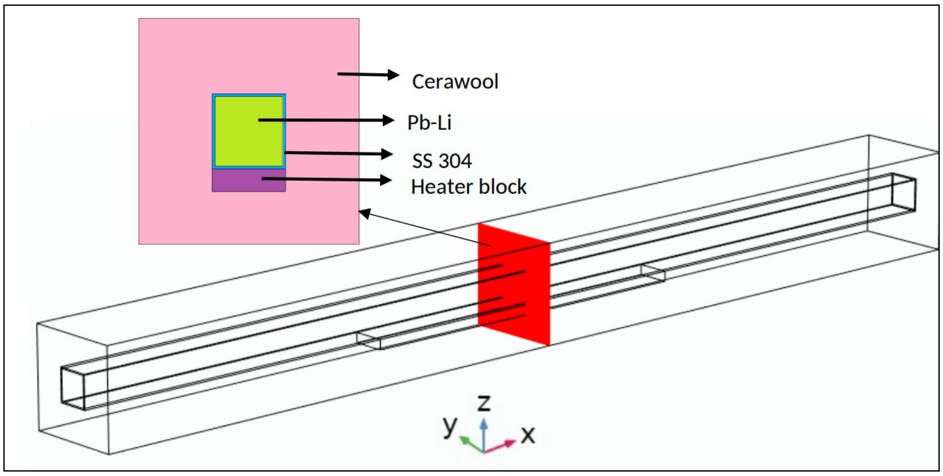


Fig-2. The computational domain used in our simulation showing a cross-sectional view having different materials.

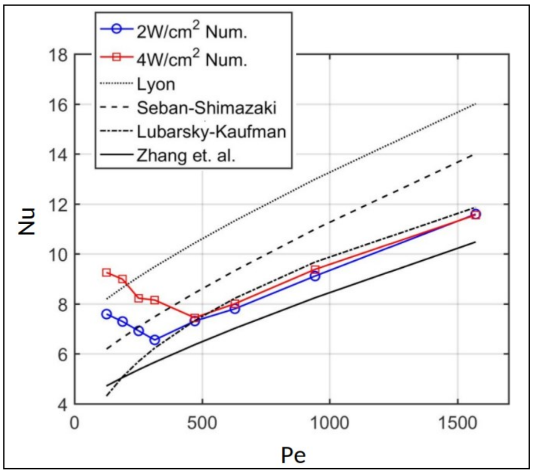


Fig-3. Variation of numerically computed Nusselt number (Nu) with Peclet number (Pe) and its comparison with existing expressions in literature

The global value of Nusselt number is estimated using the expression Eq.(3).

$$Nu = \frac{hD}{\kappa} \qquad \text{Eq. (3)}$$

where, h is the heat transfer coefficient, which is calculated from the logarithmic mean temperature difference defined by Eq.(4). D is the hydraulic diameter of the duct and κ is the thermal conductivity of the fluid.

$$h = \frac{q''}{\Delta T_{lmtd}} \qquad \text{Eq. (4)}$$

where, ΔT_{lmtd} is given in Eq.(5). q'' is the surface heat flux provided to the fluid.

$$\Delta T_{lmtd} = \frac{\left(\overline{(T_{hw})_{avg}} - \overline{(T_o)_{avg}}\right) - \left(\overline{(T_{hw})_{avg}} - \overline{(T_\iota)_{avg}}\right)}{\ln\left(\left(\overline{(T_{hw})_{avg}} - \overline{(T_o)_{avg}}\right) / \left(\overline{(T_{hw})_{avg}} - \overline{(T_\iota)_{avg}}\right)\right)} \qquad \text{Eq. (5)}$$

Here, $\overline{(T_{hw})_{avg}}$ is the average of time averaged bottom wall temperature. Numerically, the spatial averaging done over the area of heater (i.e. 0.046 m ´ 0.55 m) at 1 mm below fluid wall interface. The time averaging is done for 60 seconds. $\overline{(T_o)_{avg}}$ is the average of the time averaged temperature at the outlet of heated duct (x = 0.3 m) and $\overline{(T_\iota)_{avg}}$ is the average of the time averaged temperature at the inlet of heated duct (x = -0.3 m). Numerically, the spatial averaging done over the duct cross section (i.e. 0.046 m ´ 0.046 m) and time averaging is done for 60 seconds.

Fig-3 shows the variation of Nu against Peclet number (Pe) obtained numerically. For $Pe > 500$, it has been observed that Nu is increasing with increase in Pe and follows the expression provided by Lubersky&Kaufman. It is nearly ~ 20 % lower than the famous Lyon-Martinelli correlation. The increase in Nu with increase in Pe may be because of the increase in turbulent intermixing of hot and fluid particles, leading to higher heat transfer. Here, the $Ri < 0.1$, hence the buoyancy forces may not be that high compared to the inertia forces. For $Pe < 500$, the Nu is increasing with decrease in Pe. In these cases, the values of Ri lies within $0.3 < Ri < 3$, hence the role of buoyancy cannot be neglected. The earlier reports don't show such observation, probably because the ducts were provided with uniform heat flux, which don't allow significant velocity alteration due to buoyancy forces. The horizontal fluid flow in our experiment and only bottom wall heating allows buoyancy forces to significantly alter the velocity profile. Hence, there is greater chances of mixing of hot and fold fluid particles in the duct vertical cross section due to convective rolls resulting in high value of Nu.

Reference:

[1] Federici G., Bachmann et. al., 2019, Nuclear Fusion, 59, 066013

[2] Alexander N., Bromley B.P., et. al., FUSION 2030: A roadmap for CANADA to develop fusion energy, 2017, 37th Annual Conference of the Canadian Nuclear Society and 41st Annual CNS/CNA Student Conference Sheraton, June 4 -7, Niagara Falls, ON, Canada

[3] Grötzbach G., 2023, *Nuclear engineering and design,* 264, 41-55.

[4] Mathur A., Roelofs F., et. al., 2023, Nuclear Engineering and Design, 406, 112241

[5] S. Sahu, A. Prajapati, et. al., International Journal of Heat and Fluid Flow, 2025, 109961

[6] Lei X., Guo Z., et. al., 2022, International Journal of Thermal Sciences, Vol. 171, 107260

[7] Guo, W., Prasser, H.M., 2022, International Journal of Heat and Mass Transfer, Vol. 194, 123013

Interactive Visualization on ANTYA: Best Practices for GUI based Workloads

The ANTYA HPC cluster includes a dedicated visualization node designed to support interactive, GUI-based applications that are not well-suited for batch execution. This node enables users to run applications such as Spyder, MATLAB, ANSYS, COMSOL Multiphysics, as well as interactive Python scripts that generate real-time visual plots. It offers a flexible environment for data exploration, debugging, and development workflows that require graphical output. Users can leverage this resource to prototype algorithms, inspect intermediate results, or work with scientific visualizations in real time.

However, due to the shared nature of the visualization node and the increasing demand from multiple users, overall responsiveness may occasionally vary. In such cases, the expected speedup or interactivity may not be fully realized. This article aims to provide users with practical guidelines for running interactive jobs on the visualization node, focusing on common use cases such as launching Spyder with GUI forwarding, executing Python scripts with matplotlib, and using commercial applications like COMSOL.

For resource-intensive interactive tasks or when the visualization node is under heavy load, users can submit interactive jobs to the compute nodes using the PBS Pro scheduler. This allows users to access allocated compute resources interactively while benefiting from job isolation and dedicated performance. A typical PBS interactive job command might look like:

```
## Interactive PBS Job script
[user@login1 ~] $ qsub -I -X -l select=1:ncpus=40 -l walltime=02:00:00 -q regularq
qsub: waiting for job 362621.ANTYA to start
qsub: job 362621.ANTYA ready
cd /home/user/pbs.362621.ANTYA.x8z
// A node will be assigned by the PBS Scheduler as per the policy and availability
[user@cn230 ~] $
```

Once the job starts, users are dropped into a shell session on the allocated compute node, where GUI applications can be launched. This approach is ideal for longer interactive sessions, larger memory requirements, or parallel workloads that exceed the capacity of the visualization node.

Example Use Cases for Interactive Jobs on ANTYA

1. Running Spyder (Python IDE) Interactively

Spyder is one of the widely used Python IDE for scientific computing. It offers an interactive development environment with a built-in IPython console, variable explorer, and plotting capabilities. To run Spyder on a compute node using a PBS interactive session.

```
## Interactive PBS Job script
[user@login1 ~] $ qsub -I -X -l select=1:ncpus=40 -l walltime=02:00:00 -q regularq
[user@cn220 ~] $ module load anaconda/3
[user@cn220 ~] $ spyder
// A spyder GUI will open, which will use compute nodes' resources.
```

2. Running Interactive Python Jobs

Python users often want to run scripts that show plots interactively using matplotlib. This is fully supported on both visualization and compute nodes, provided that X11 forwarding is enabled.

```
## Run python script after loading anaconda module
[user@cn220 ~] $ python test.py
```

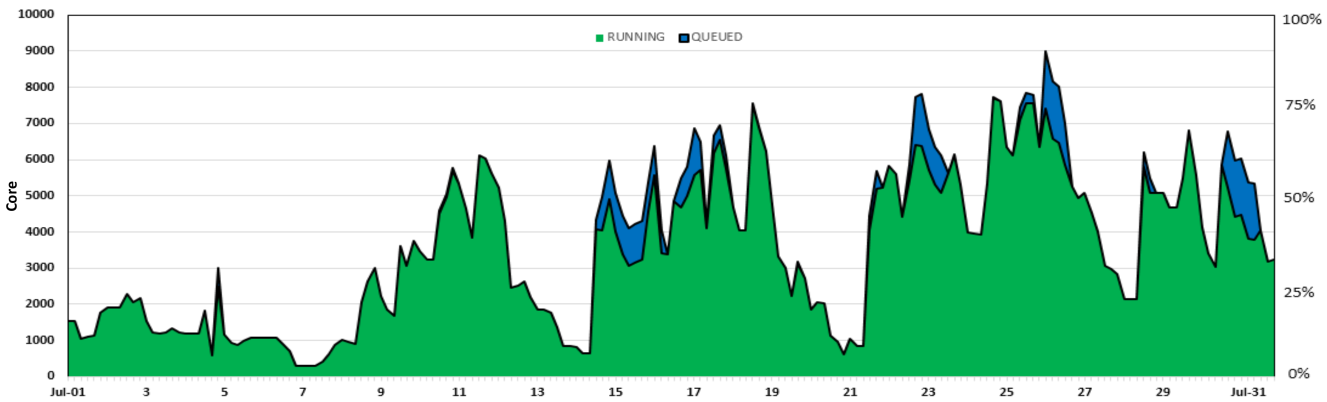
3. Running COMSOL Multiphysics Interactively

COMSOL can be launched in interactive mode on ANTYA for GUI-based model setup, simulation, and visualization. Start a PBS interactive session with X11 forwarding, then run the COMSOL GUI from the terminal.

```
## Interactive PBS Job script
[user@login1 ~] $ qsub -I -X -l select=1:ncpus=40 -l walltime=02:00:00 -q regularq
[user@cn220 ~] $ /home/application/comsol/comsol62/multiphysics/bin/comsol
```

By following the practices outlined in this guide, users can efficiently run interactive applications on ANTYA using both the visualization and compute nodes, enabling seamless graphical and real-time workflows. However, some applications may not support this mode of execution due to licensing restrictions or dependencies on local hardware (e.g., GPU acceleration or floating licenses tied to specific nodes).

ANTYA Utilization: JULY 2025



ANTYA HPC Users' Statistics July 2025

Total Successful Jobs~ 1200

- **CPU Cores** Vinod Saini
- **GPU Cards** Gaurav Garg
- **Walltime** Arzoo Malwal
- **Jobs** Prince Kumar

ANTYA Usage, Updates and News

- **Scheduled Downtime**: There was no downtime of ANTYA for July 2025.
- **Job Submissions:** The highest job loads were observed in the *serialq*, medium, regularq, ansysq and *longq* queues, reflecting sustained user activity across multiple workloads in various queues.
- **Cluster Utilization**: The system maintained an average utilization of ~34.77% and peak utilisation of ~77.12%.

Packages/Applications Installed: No new modules have been installed this month. To view list of available modules.
> module avail

Other Recent Work on HPC

Finite Ion Mobility Effects on Quasi-Longitudinal Whistlers Near the Resonance Cone	Gayatri Bhayyaji Barsagade
Influence of ion-neutral collisions on the impact of edge biasing in a tokamak plasma	Souvik Mondal
Data Adequacy for Deep Learning-Assisted Microwave Plasma Interaction-Based Plasma Density Diagnostics	Dr. Pratik Ghosh
Conceptual Design of Solid Breeder Blankets for Fusion Pilot Plants	Deepak Sharma
Modelling and Analysis of Multi-stage Acceleration Grid Power Supply Controllers for Neutral Beam Injectors	Ashok Daulatram Mankani
AI-Driven Ensemble Model for Comprehensive Chest X-Ray Abnormality Detection and Deployment	Agraj Abhishek
Status of the Progress of Fabrication of High Power Ion Extractor Grid for NBI System	Mukti Ranjan Jana
Enhancement of Short Wavelength Branch of ITG in the Presence of Non-Monotonic q Profiles	Gopal Krishna M
Design, Fabrication and Performance Testing of a Cold Bore Vertical Cryostat for HTS magnets	Mahesh M Ghate
Simulation and Experimental Analysis Of RF Helicon Antenna for Plasma thruster system	Prashant Kumar
Benchmarking of IPREQ Equilibrium Code Against CORSICA for Multiple Devices	Deepti Sharma

Acknowledgement

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