Thermal Hydraulic Study For Heavy Liquid Metal Flows Using COMSOL Multi-physics

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Abstract

Liquid metals are the extensively used as coolants in nuclear reactors. Heat removal by liquid metal is the prime factor determining efficiency of the reactor. However, the heat transfer mechanism differs significantly in low Prandtl number heavy liquid metals (HLM's) than those observed in common fluids. It is crucial to have an accurate heat transfer correlation for the liquid metal to estimate the heat removal efficiency. The present paper describes the use of Comsol Multi-physics tool for analysing the heat removal phenomena for a circular pipe with molten Lead Bismuth as the process fluid. A the Nusselt number have been obtained under a fully developed turbulent flow approximation and is compared with various empirical and experimentally validated liquid metal Heat Transfer Correlations (HTCs). After successful comparison, the same procedure can be applied to estimate the heat transfer correlation for similar heavy liquid metals for fusion reactor applications. This analysis shows the feasibility of using numerical tools in comparing the performance of various liquid metal as a coolant in reactor grade application. The details of the physical problem associated numerical model, analysis procedure and the preliminary analysis results will be discussed in this paper.

Keywords: LBE, Nusselt number, Numerical analysis, Liquid metals, Prandtl number, Peclet number,HTC's.

1. Introduction

Liquid metals are foreseen as the efficient coolants in modern nuclear reactors. Since decades a lot of research is being done on the coolants like molten sodium, flibe, Lead Bismuth (LBE) and more recently Lead Lithium (LLE) in fusion applications. Liquid metals are preferred as coolants owing to their have high thermal conductivity 'K', passive safety features and excellent natural circulation capability. Heat transfer plays an important role in determining the efficiency of the reactor, the choice of the coolant for a particular application is a major aspect of design.

LBE has been chosen as the coolant in Acceleration Driven System (ADS) for both sub critical reactor and spallation target [1]. It is also the coolant considered in the design of Compact High Temperature Reactor (CHTR) in BARC[3]. On the other hand LLE is preferred as the coolant in Indian LLCB TBM planned for testing in ITER, Cadarche[2]. Thermal Hydraulics of liquid metals have to be studied before the process design.

2.1 Thermal Hydraulics of HLM's

A lot of progress is made in the thermal hydraulics studies of LBE for various purposes. The TALL facility [4] have been constructed to study thermal hydraulic behaviour of LBE and also to validate a 1-D code TRAC-AAA. Research is going on HLM's in Karlsruhe ,Germany on LBE flows[4]. Significant efforts have been made to develop physical models, validate computer codes and to support ADS components [1]. A test loop HANS is installed at BARC for thermal hydraulic study and validate LE-BANC code [3]. There are no experiments carried out using LLE.

In designing an experiment, it is necessary to carry out in-detail analysis to test the performance of HLM by CFD tools and validated experiments. It is well agreed that reliable physical models are still missing [1], especially related to turbulent prandtl number and heat transfer at turbulent conditions

2.2 Present Work

In this paper, the applicability of heat transfer correlations in turbulent heat transfer regimes is studied, nusselt number is computed by CFD tool using LBE as fluid and the results are compared with the experimental LBE values available and other HTC for liquid metals in circular pipes. After successful comparison, the same procedure can be applied to estimate the HTC's for liquid metal LLE in fusion applications.

This analysis would be of great use in designing heat transfer related experiments using HLM's.

3. Liquid metal heat transfer

Liquid metals are the specific class of coolants whose basic advantage is high thermal conductivity which enhances heat transfer and low prandtl number (Pr<0.4) which implies that heat transfer by molecular conduction is significant not only in the near wall layer but also in the fully developed turbulent flow [5].

Nusselt number (Nu) physically describes the extend of heat transfer

$$Nu = \frac{(ts-t)/y}{(ts-t\infty)/l} = \frac{\Delta t \text{ surface}}{\Delta t \text{ overall}}, \quad (13)$$

Where, t_s-temperature of the solid wall,

t_∞-temperature of the free stream

y- Distance normal to the surface,

T-Temperature at a distance of y from the solid surface,

y- Distance normal to the surface,

l- Characteristic length.

Dittus Boelter equation (2) is generally used for calculation of Nusselt number in conventional fluids with Pr >0.7. Since the Prandtl number of HLM's is very low, the above equation cannot be employed as HTC.

Dittus Boelter HTC correlation [6]

$$Nu= 0.023Re^{0.8}Pr^{0.4} \text{ (for heating)} \quad (2)$$

$$Nu= 0.023Re^{0.8}Pr^{0.3} \text{ (for cooling)} \quad (3)$$

There are various HTC's proposed by different authors for the fully developed turbulent flows in circular pipes using liquid metals in single phase, which are compared below. The purpose of this comparison is to see the applicability to a liquid metal system [6] .

Lyon [7] showed that for low prandtl no. fluids like liquid metals nusselt no. for a fully developed single phase flow in a tube with constant flux can be expressed in terms of peclet number (Pe=Re*Pr) by a relation

$Nu= a +b* Pe^c$ and found that,

$$Nu= 7.0 + 0.025Pe^{0.8} \quad 300 <Pe< 10^4 \quad (4)$$

R. A. Seban and T. T. Shimazaki [6] for turbulent tube flow with constant wall temperatures.

$$Nu=5.0 + 0.025Pe^{0.8} \quad Pe< 4*10^3 \quad (5)$$

Lubarsky and Kaufman [8] using 4 and 5 they corrected the equation to

$$Nu=0.625Pe^{0.4} \quad (6)$$

Sleicher et al (1973) investigated the local heat transfer coefficient's in NaK flows [1]

$$Nu=6.3+0.0167Pe^{0.88} Pr^{0.08} \quad (7)$$

Kirillov and Ushakov [1], recommended following correlation for LBE flows

$$Nu=4.5+0.018Pe^{0.8} \quad (8)$$

Stromquist [1], considered the effect of wetting of liquid metals and recommended

$$Nu=3.6 + 0.018 Pe^{0.8} \quad 88<Pe<4000 \quad (9)$$

Above correlation's, constant heat flux condition from the wall is considered which is the most encountered engineering application.

4.1 Thermo-physical Properties of liquid LBE

Temperature dependence LBE properties have been given to COMSOL as input in piece wise functions, properties are taken from the LBE handbook [9]. these properties are needed to calculate Pr and Re for HTC's.

$$\text{Density (kg/m}^3\text{)}, \rho= 11096- 1.3236T \quad (10)$$

Dynamic Viscosity(Pa.s),

$$\eta=4.94\times10^{-4} \times \exp(754.1/T) \quad (11)$$

Specific heat (J/Kg K),

$$C_p = 159 - 2.72\times10^{-2}T + 7.12\times10^{-6}T^2 \qquad (12)$$

Thermal conductivity (W/m K),

$$K = 3.61 + 1.517\times10^{-2}T - 1.741\times10^{-6}T^2 \qquad (13)$$

4.2 LBE parameters for study in COMSOL

The heat transfer phenomenon of LBE is studied in a test section having the dimensions and characteristics given below Table 1 . The same parameters are used for modelling the test section in COMSOL.

Table1. The list of the parameters used in the simulation

Parameter	Value range
Inlet temperature	300 °c
Heat flux from the wall	24.509 KW
Velocity	0.5-2.0 m/s
Mass flow rate	2-3 kg/s
Total length	1.5495
Reynolds number	60000-100000
Prandtl number	0.01-0.02
Peclet number	600-2000
Turbulent prandtl number	0.9-3.0
Turbulence model	k-ε model

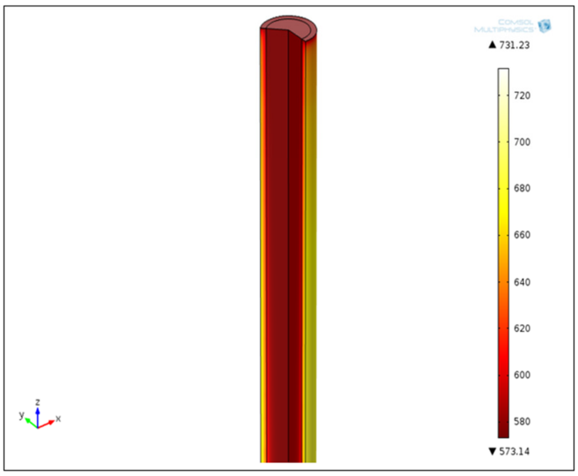

Figure 1. Model of LBE Test section in COMSOL.

Since the HTC's are valid over fully developed turbulent conditions, the choice of the turbulent physical model in CFD is an important aspect. In the present study a vertical circular tube with inner and outer radius 20.93 and 26.67 mm respectively.

6.1 Plots for various HTC's

Comparison of Nusselt number for various HTC's is shown below. HTC's from equation 4-9 are plotted against different velocities

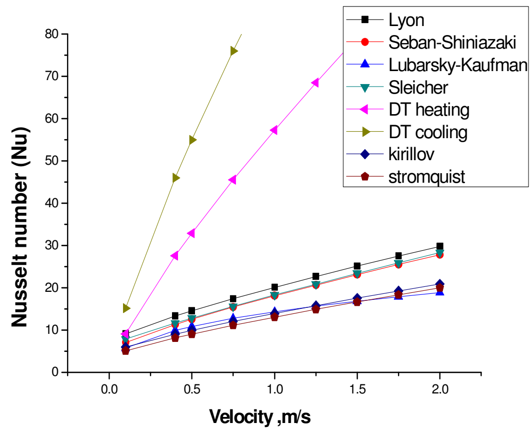

Figure 2 - Nu vs Velocity

In figure 1, We can see the deviation of Dittus Boetler equations from the others.

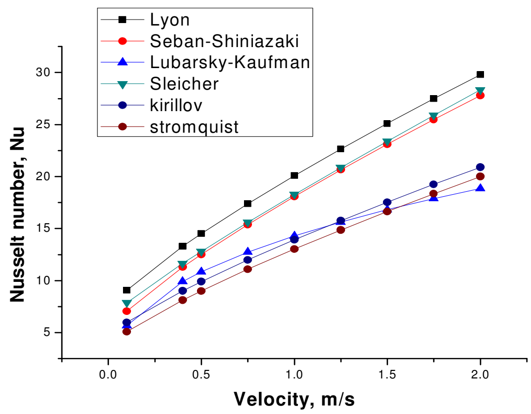

Figure 3- effect of velocity on Nusselt number, Nu

At the same velocity, HTC's proposed by Kirillov and Stromquist Nusselt numbers are lower than others. Lyon gives the highest Nusselt number at the same conditions.

In figure 3, the experimental values calculated by Johnson et al (1953) are lower than the values of Nusselt number predicted by HTC's.

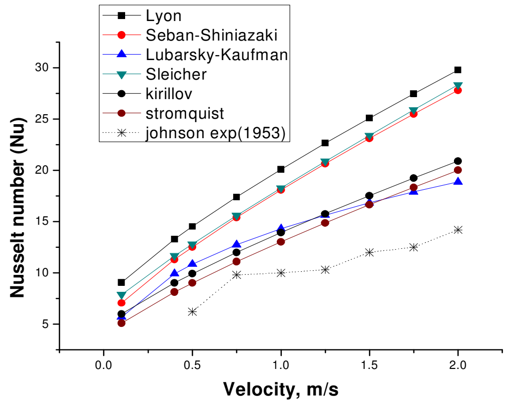

Figure 4- Comparison with the experimental results for LBE, Johnson (1953)

6.2 Effect of turbulent prandtl number (Pr_t) on Nusselt number

Both the experimental and theoretical studies in the open literature suggest prandtl number larger than 1.0 [4]. the Nusselt number decreases with the increase of turbulent number. In COMSOL the default value is 0.9 for turbulence models. In the simulations of the test section, the Nusselt number has been calculated for turbulent prandtl number of 0.9, 2.0 and 3.0 for seeing the effect of nusselt number on Pr_t .

6.3 COMSOL approach

Conjugate heat transfer module has been chosen to carry out this study. Since the flow is at high Reynolds's number it is important to enter the accurate value of Turbulence Kinetic Energy (TKE) as boundary conditions in CFD simulations to predict the flows and avoid convergence problems [11]. In the present analysis, k-ε turbulence model is selected and the values of TKE, initial Turbulent Intensity(I) and eddy length scale (l) is specified at each velocity as given below,

$$TKE = 3/2(UI)^2 \qquad (14)$$

Where U= initial velocity magnitude

I= initial Turbulent Intensity given as

$$I= 0.16Re^{-1/8} \qquad (15)$$

$$\text{Eddy Length Scale, } l=0.038L \qquad (16)$$

Here L= characteristic length

For proper convergence the mesh size of 1/5th of the least dimension of the element present in the model is selected based on trails and experience for this problem.

7.1 Results

Nusselt number is computed by temperature distribution data which is obtained by simulating the test section in COMSOL. The plots are generated for turbulent prandtl numbers of 0.9 , 2.0 and 3.0

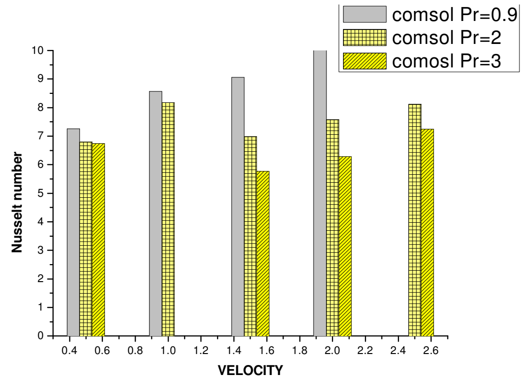

Figure 5. Nusselt number for various Pr_t

In figure 5 as mentioned in section 6.2, there is a decrease in the value of Nusselt number with the increase in turbulent Prandtl number for various velocities

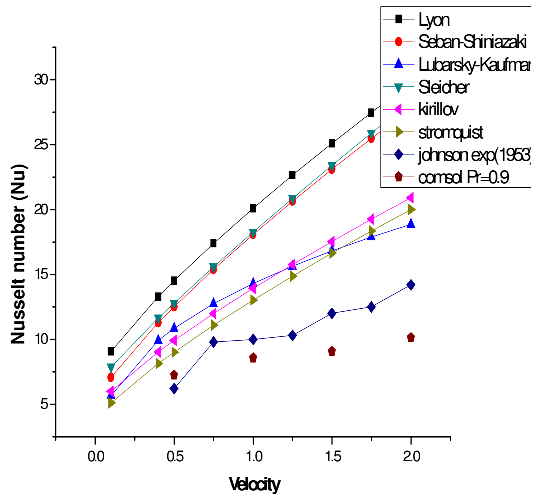

Figure 6. Nusselt number calculated from comsol at Pr_t=0.9 in comparison with other HTC's

In the above figure the default value of Pr_t 0.9 is used. The temperature distribution of the solid wall surface and the free stream temperature at various points in the test section are tabulated to calculate the Nusselt number.

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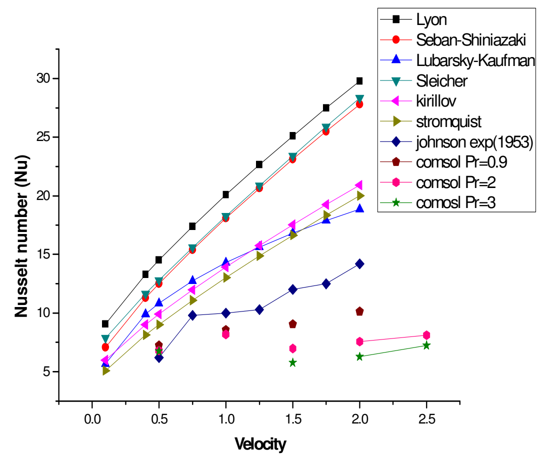

Figure 7. Nusselt number calculated from comsol at Pr_t=0.9, 2.0, 3.0 in comparison with other HTC's

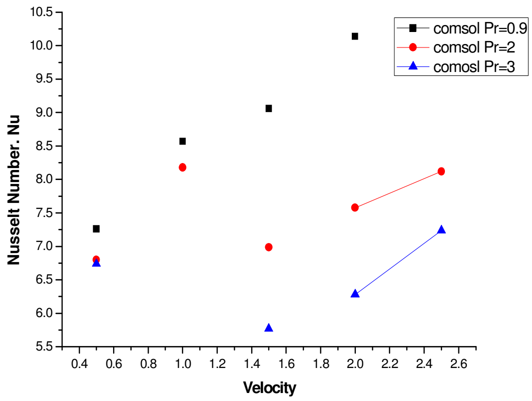

Figure 8. Nusselt number points from comsol at Pr_t=0.9, 2.0, 3.0 at different velocities

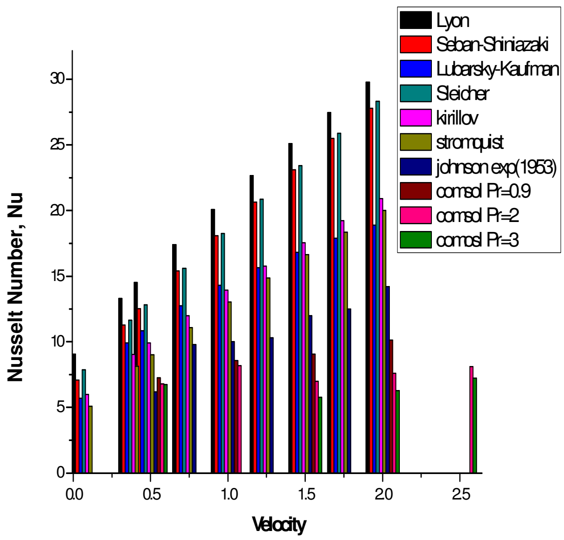

Figure 9. Shows the range of data points for various correlations and obtained Nu from comsol simulations

From the above plots it is observed that the Nusselt numbers estimated from this study are slightly lower than the HTC's available for liquid metals, the possible reason for the discrepancy may be due to the source of LBE properties by different authors. From figure 9 we can observe that the data calculated lies in the lower range of Stromquist relation (equation 9) at $Pr_t = 0.9$. Further scope of the study would be carrying out a detail analysis with finer mesh sizes to check the mesh sensitivity.

7.2 Conclusions

It is observed that the Nusselt number decreases with the increase in turbulent prandtl number. The Nusselt number values of the test section simulated in comsol lies closer to the range of HTC's proposed by Kirillov and Stromquist (equations 8 & 9 respectively). Hence these two HTC's can be used in designing the experiments and can be given as the input to thermal hydraulics codes involving LBE. Finally similar process can be applied to check the applicability of HTC involving LLE in fusion applications and determine the heat transfer.

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