HEAT TRANSFER ASPECTS OF NATURAL CONVECTION OVER HORIZONTAL CYLINDER IN LIQUID METAL POOL

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1. INTRODUCTION
In advanced nuclear reactors, liquid metal is being proposed to be used as a coolant. When the forced flow of coolant is suddenly lost (due to loss of power to coolant pumps), the natural convection flow may get established. It is important to understand the heat transfer characteristics of the system under natural convection flow conditions. In this paper, the study of heat transfer over a horizontal cylinder submerged in a liquid metal pool is presented.

2. REVIEW OF PREVIOUS WORK
The experimental investigation of natural convection heat transfer from a horizontal cylinder in sodium pool is performed previously by Hata et al. (1999) and others. In all these experiments, wall temperature and bulk temperatures are measured. Several correlations for natural convection heat transfer from a horizontal cylinder were previously proposed. These are analytical or empirical or semi-empirical correlations. These different correlations are found to give different results. Hence in the present work, effort is put to independently study the configuration and obtain the heat transfer characteristics.

3.0 PRESENT WORK
The objective of present work is to (i) generate CFD simulation data for this configuration, (ii) compare the simulation data with previously published experimental data, and (iii) compare the simulation data with existing correlations. The present approach of modeling the geometry in 3D, use of primitive variables (i.e. velocity components, pressure etc), and use of body fitted mesh improves the accuracy of simulation compared to previous approach of 2D simulation used by others. The simulation data is generated over a wide range of cylinder diameter, bulk fluid temperature and heat fluxes.

3.1 System Description
The system consists of a horizontal cylinder of diameter 10.7 mm and length of 550 mm and heated length of 50 mm at its centre. It is submerged in sodium pool contained in a bigger cylindrical container. The heat is generated in heater portion of horizontal cylinder for 40 s. The surrounding sodium absorbs the heat and convection currents due to natural convection starts. The simulation is performed for different heater diameters, heat fluxes and bulk pool temperature. The peripheral variation of wall temperature is computed. The local heat transfer coefficient is computed from the heat flux, wall temperature and bulk pool temperature.

3.2 Simulation
The simulation is performed with the help of PHOENICS CFD software (CHAM, 2005). For discretizing the computational domain, body-fitted grid is used. The variation of wall temperature from bottom to top is obtained for different heat fluxes (fixing bulk temperature and heater diameter) and the result is compared with experimental data of Hata et al. Excellent match is obtained with experimental data.

4. RESULTS
The results are generated from parametric studies (by varying heat flux, diameter and bulk temperature). It is found that the diameter has significant effect on heat transfer. With increase in cylinder diameter, the heat transfer is found to enhance. With rise in bulk temperature, there is not much rise in the heat transfer coefficient. Thus, the heat transfer characteristics are much affected by heater diameter than by bulk temperature. The results are generated for lead-bismuth eutectic as well as sodium. All the simulation data generated was plotted on single graph in the form of variation of Nusselt number against $Gr Pr^2/((1 + Pr))$. Based on the simulation data, following correlation is proposed for estimating heat transfer in this configuration.

$$Nu = 1.246 \times \left( \frac{Gr Pr^2}{1 + Pr} \right)^{0.15732}$$

5. CONCLUSION
The proposed correlation is found to be better than the previously proposed correlations when compared with experimental data of Hata et al.

REFERENCES
3. CHAM Ltd., 2005, “PHOENICS Online Information System”.

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ABSTRACT

The natural convection heat transfer from a horizontal cylinder placed in liquid metal pool is computationally investigated. The heat flux from surface of cylinder to the bulk liquid induces flow due to buoyancy. The effect of cylinder diameter, heat flux and bulk fluid temperature on the heat transfer coefficient is studied. The flow is computed using PHOENICS CFD software. The simulation is transient. The geometry is discretized using a 3D body fitted grid. The temperature variation of the cylinder along its periphery is computed from simulation. The validation of CFD results is performed by comparing the computed wall temperature variation with previously published experimental data. Excellent agreement of computed results with experimental data is observed for various heat fluxes. The heat transfer data is presented in the form of variation of Nusselt number with $Pr^{1/3}/(1 + Pr)$. The heat transfer coefficient is found to rise slightly with bulk temperature. However, the cylinder diameter has a more significant effect on increasing heat transfer coefficient. Simulation data is generated by varying cylinder diameter, heat flux and bulk temperatures. Based on the data, a correlation is proposed. The correlation is shown to predict better compared to other correlations which were previously proposed.

1. INTRODUCTION

The knowledge of natural convection heat transfer in liquid metal is important considering that liquid metal acts as a very effective coolant owing to its high thermal conductivity. In advanced nuclear reactors, liquid metal is being proposed to be used as a coolant. When the forced flow of coolant is suddenly lost (due to loss of power to coolant pumps), the natural convection flow may get established. It is important to understand the heat transfer characteristics of the system under natural convection flow conditions. Study of natural convection heat transfer in various geometries is being performed at author’s institute. In this paper, the study of heat transfer over a horizontal cylinder is presented.

2. REVIEW OF PREVIOUS WORK

2.1 Experimental Investigation

The experimental investigation of natural convection heat transfer from a horizontal cylinder in sodium pool is performed previously by Hata et al. (1999), Fedynskii and Kovalev and Zhukov. The summary of their experimental conditions is given in Table 1. In all these experiments, wall temperature and bulk temperatures are measured. The heat transfer data derived from these two parameters is reported.
2.2 Correlations for Natural Convection Heat Transfer from a Horizontal Cylinder Submerged in Liquid Metal Pool

Several correlations for natural convection heat transfer from a horizontal cylinder were previously proposed. These correlations are classified as listed below:

1. Correlations based on analytical solution of fundamental conservation equations (simplified using boundary layer approximations).
2. Correlations based on experimental data and
3. Correlations based on simulation data (These simulations are multi-dimensional simulation which obviate the need of boundary layer approximations) and hence are more accurate than those in category (1) above.

<table>
<thead>
<tr>
<th>Table 1 Summary of previous experimental studies</th>
</tr>
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<tbody>
<tr>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>Cylinder diameter, mm</td>
</tr>
<tr>
<td>Heat flux, W/m²</td>
</tr>
<tr>
<td>Liquid temperature, °C</td>
</tr>
<tr>
<td>( \frac{Gr Pr^2}{(1 + Pr)} )</td>
</tr>
</tbody>
</table>

Churchill and Chu (1975) presented following semi-empirical correlation for a cylinder with uniform surface temperature for a very wide range of Rayleigh numbers in non-metallic liquids and gases and in metallic liquids.

\[
Nu^{1/2} = 0.6 + 0.387 \frac{Ra}{\left[ 1 + (0.559/Pr)^{0.167} \right]^{0.37}}
\]

(Eq. 1)

Hyman et al. (1953) presented following empirical correlation based on several experimental data including those for liquid metals\(^1\).

\[
Nu = 0.53 (Gr Pr^2)^{0.25}
\]

(Eq. 2)

Kutateladze et al. (1958) presented following correlation for a cylinder with a uniform surface temperature in liquid metals. It was based on the boundary layer approximations.

\[
Nu = 0.67 \left[ \left( \frac{Pr^2}{1 + Pr} \right)^{0.25} \right]
\]

(Eq. 3)

Sugiyama et al. (1991) reported following correlation based on the numerical solution of natural convection heat transfer from a horizontal cylinder with a uniform surface temperature to liquid sodium by finite difference method without using a boundary layer approximation.

\[
Nu = 1.11 \left( Gr Pr^2 \right)^{0.196}
\]

(Eq. 4)

Above correlation is supposed to be applied for \( Gr \leq 1.5 \times 10^4 \). This means for Prandtl number of 0.005, the applicability of this correlation is for \( Gr Pr^2/(1 + Pr) \leq 3.850 \). These different correlations are found to give different results (as will be explained in Section 4.5). Hence in the present work, effort is put to independently study the configuration and obtain the heat transfer characteristics.

3.0 PRESENT WORK

The objective of this study is to perform computational investigation of heat transfer from a heated horizontal cylinder immersed in a liquid metal pool. The heat transfer from surface of the cylinder induces natural convection in the surrounding pool. This configuration is experimentally investigated by Hata et al. (1999). In their experiments, measurement of cylinder surface temperatures (along the periphery from bottom to top) is performed. Based on measured surface and bulk liquid temperatures, average heat transfer coefficient over heater surface is also calculated. The objective of present work is to (i) generate CFD simulation data for this configuration, (ii) compare the simulation data with previously published experimental data, and (iii) compare the simulation data with existing correlations. In previous simulation studies, the geometry is represented by a 2D cylindrical-polar grid and stream function-vorticity method is used for obtaining the flow and temperature fields (Sugiyama, 1991 and Hata, 1999). The drawback of this method is that proper representation of geometry and boundary conditions is not possible. The present approach of modeling the geometry in 3D, use of primitive variables (i.e. velocity components, pressure etc), and use of body fitted mesh improves the accuracy of simulation over previous approach. The main contribution of present work is the generation of simulation data over a much wider range of cylinder diameter, bulk fluid temperature and heat fluxes compared to previously reported works.

3.1 System Description

The geometry adopted for simulation is similar to that taken by Hata et al. (1999) for their experiments. Schematic diagram of the system is shown in Fig. 1. The system consists of a horizontal cylinder with central heated portion (of 50
mm length) and unheated portions (250 mm each) at both the ends. The heat is rejected to the sodium which surrounds the cylinder. The bulk temperature of the pool is maintained at different levels (e.g. 400°C to 800°C). The investigation is performed for different bulk liquid temperatures as well as for different cylinder diameters (e.g. 7.6 mm, 10.7 mm and 25 mm). In each case, surface heat flux is varied over a wide range (50 kW/m² to 2660 kW/m²). In the experiments of Hata et al., heating is performed for 40 seconds and outer surface temperature of heated portion of the horizontal cylinder is measured. Hence in the present CFD simulation, transient study is performed for 40 seconds. At the final time step, values of surface temperature obtained from CFD are compared with experimental data.

3.2 Computational Model

The simulation is performed using PHOENICS (Version 3.6.1) CFD software (CHAM, 2005). The model is shown in Fig. 2. Owing to symmetry, half of the physical domain is modeled. Thus the computational model shown in Fig. 2 represents half of the total domain shown in Fig. 1. The domain is discretized using body fitted grid. Total 312000 cells were generated for simulation. The grid size is 40X50X156. Heat flux boundary condition is given on the surface of the cylinder. The LVEL (i.e. the Length scale and VELOCITY) model, which is a zero equation turbulence model, is used. The results are also generated with k-ε turbulence model but it is found to give same results as LVEL model. The transient simulation for 40 seconds is performed with the time step of 4 seconds. The results of 1 s time step and 4 s time step are found to be same. Thus, presented results are time step independent and also turbulence model independent (Vaidya, 2010). For each time step, 100-150 iterations are performed for convergence. Boussinesq approximation for density is invoked for modeling the buoyancy driven flow. Initial condition for transient simulation is uniform bulk fluid temperature and stagnant flow field.

![Figure 1 Schematic diagram of the system](image-url)
3.3 Properties of Sodium

Conductivity, viscosity and specific heat of sodium is represented by Eq. (5), Eq.(6) and Eq. (7) respectively (Incropera and DeWitt, 2001).

\[ k = 101.34 - 4.319 \times 10^{-2} T \] (Eq. 5)

\[ \nu = 1.0117 \times 10^{-3} \times T^{-1.2276} \] (Eq. 6)

\[ c_p = 2.7439 \times 10^{0.04} T^2 - 0.5649 T + 155 \] (Eq. 7)

For Boussinesq approximation, reference temperature is 371°C, reference density is 860.2 kg/m³ and thermal expansion coefficient is 2.866 x 10⁻⁴ K⁻¹.

3.4 Validation

For cylinder diameter of 10.7 mm, and bulk liquid temperature of 400°C, Hata et al. (1999) have given the surface temperature variation for various heat fluxes. This data is used for validating PHOENICS results. Figure 3 shows the comparison of experimental and computed temperature difference (surface temp – bulk temp) for heat flux of 1x10⁵ W/m² and 5x10⁵ W/m². Figure 4 shows the comparison for heat flux of 1x10⁶ W/m² and 2.66x10⁶ W/m². It can be seen that PHOENICS results match well with the experimental results at various heat fluxes.
Figure 4 Comparison of experimental and computed temperature difference (surface temp – bulk temp) for heat flux of $2.66 \times 10^6$ and $1 \times 10^6$ W/m².

**4.0 COMPUTATIONAL RESULTS**

In present work, the heat and fluid flow is computed for following conditions. (i) Cylinder diameter – 7.6 mm, 10.7 mm and 25 mm. (ii) Bulk temperature – 400°C, 500°C, 600°C and 800°C. (iii) Heat flux – 1 kW/m² to 2600 kW/m². For each case, average wall temperature is computed. Based on averaged wall temperature and bulk fluid temperature, average heat transfer coefficient is computed. Heat transfer characteristics are expressed in the form of variation of Nu with $Gr Pr^2/(1+Pr)$. Detailed explanation of results is given in forthcoming sections. All these results are generated for sodium as well as lead-bismuth eutectic. The results for lead-bismuth eutectic are qualitatively same as sodium and hence are not reproduced for brevity. For obtaining a correlation, however, entire data of sodium as well as lead-bismuth is included, as is explained later.

**4.1 Effect of Bulk Fluid Temperature on Heat Transfer Characteristics**

Figure 5 shows the variation of Nusselt number against $Gr Pr^2/(1+Pr)$ for different bulk fluid temperatures. The heater diameter is 7.6 in all these cases. It can be seen that with rise in bulk fluid temperature, the Nusselt number at a given $Gr Pr^2/(1+Pr)$ very slightly rises. Same study is conducted for heater diameter of 10.7 mm also. The result is shown in Figure 6. In this case, the Nusselt number is found to increase by 5% for a rise in bulk temperature by 200°C. Thus, the heat transfer characteristics are not significantly affected by bulk temperature.

**4.2 Effect of Cylinder Diameter**

The variation of average Nusselt number with $Gr Pr^2/(1+Pr)$ is plotted for different diameters. Figure 7 shows the change in Nusselt number due to change in diameter from 7.6 mm to 10.7 mm. It is seen that, with rise in diameter from 7.6 mm to 10.7 mm, Nusselt number rises by about 5%. Similarly, the change in Nusselt number due to change in diameter from 10.7 mm to 25 mm is also studied as shown in Figure 8. It is found that with rise in diameter from 10.7 mm to 25 mm, Nusselt number rises by about 15%. Thus, the cylinder diameter is found to have significant impact on Nusselt number.

While proposing a correlation for heat transfer coefficient for this configuration, it is important that the correlation should be based on the data which is generated for various diameters covering a wide range.
Figure 5 Variation of Nu with GrPr$^2/(1+Pr)$ for different bulk temperatures for heater diameter of 7.6 mm

Figure 6 Variation of Nu with GrPr$^2/(1+Pr)$ for various bulk temperatures for heater diameter of 10.7 mm
4.3 Results for Lead-Bismuth

All the above mentioned studies given for sodium are also repeated for lead-bismuth eutectic. Thus, heater diameter is varied from 7.6 mm to 25 mm, bulk temperature is varied from 400°C to 800°C and heat flux is varied to achieve a range of GrPr^2/(1+Pr). Even for lead-bismuth eutectic, it is found that the heat transfer is in-significantly affected by bulk temperature and the effect of cylinder diameter is more pronounced.
4.4 Correlation based on CFD Simulation Data

The data from all above cases, which include data obtained by varying heat flux, cylinder diameter, bulk fluid temperature and working fluid, is compiled to give a single plot of Nu against $Gr Pr^2/(1 + Pr)$. The resulting plot is shown in Figure 9. A linear fit to the entire data is also shown in the figure. The following correlation is proposed based on simulation data.

$$Nu = 1.246 \times \left( \frac{Gr Pr^2}{1 + Pr} \right)^{0.15732}$$  \hspace{1cm} (8)

4.5 Comparison of Present Simulation Data with Previous Correlations and Experimental Data

The simulation data generated is compared with the previously proposed correlations (viz. Hyman, Kutateladxe, Churchill, Sugiyama correlations). It is also compared with experimental data of Hata et al. and Fedynskii.

Figure 10 shows the comparison of proposed correlation and other previously proposed correlations with experimental data of Hata et al. Figure 11 shows the comparison of proposed correlation and other previously proposed correlations with experimental data of Fedynskii. In both the figures, it can be seen that the proposed correlation agrees well with both the experimental data sets. The previously proposed correlations except Sugiyama’s correlation under predict especially at lower range.
Figure 10 Comparison of proposed correlation and previously proposed correlations with experimental data of Hata et al.

Figure 11 Comparison of proposed correlation and previous correlations with experimental data of Fedynskii
5.0 SUMMARY AND CONCLUSIONS

Three-dimensional transient CFD simulation is performed to investigate the natural convection heat transfer from horizontal cylinder submerged in liquid metal pool. The objective of the work is (i) to understand the effect of various parameters on heat transfer, (ii) generate data from parametric studies and (iii) propose a correlation and validate it.

The simulation data is generated for bulk temperature of 400°C, 500°C, 600°C and 800°C for cylinder diameters of 7.6 mm, 10.7 mm and 25 mm and heat flux ranging from 1 kW/m² to 2660 kW/m² (ensuring that the maximum temperature in the pool is well below the boiling limit). The data is generated for Sodium as well as lead-bismuth eutectic.

The simulation is performed with the help of PHOENICS CFD software. For modeling the submerged horizontal cylinder, body fitted grid is used. Boussinesq approximation is used for computing the buoyancy induced flows. The simulation data is validated by comparing the wall temperature predicted by CFD simulations with experimental wall temperature data reported by Hata et al. (1999).

The effect of bulk temperature on heat transfer is studied. It is found that with rise in bulk temperature, there is slight increase in overall heat transfer. The effect of cylinder diameter on heat transfer is studied. It is found that the diameter has significant effect on heat transfer. With increase in cylinder diameter from 7.6 mm to 25 mm, 20% increase in Nusselt number is observed.

Based on simulation data generated in present simulation, a correlation is proposed. The proposed correlation matches well with previously published experimental data. It is found to perform better than the various other correlations. It can be concluded that the correlation obtained by solving full form of conservation equations numerically are much better than empirical correlations or those obtained theoretically using boundary layer approximations.

REFERENCES

8. CHAM Ltd., 2005, “PHOENICS Online Information System”.