Laminar natural convection heat transfer characteristics of molten salt around horizontal cylinder

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Abstract

In order to obtain the laminar natural convection heat transfer mechanism of molten salt, the natural convection heat transfer of multi-component molten salts around a cylinder with different diameters was studied by simulation. The result showed that the natural convective heat transfer of molten salt in the Rayleigh number range of $1.57 \times 10^2 - 2.03 \times 10^6$ could be predicted by Fand's correlation that took the viscous dissipation into consideration, in addition to Prandtl and Rayleigh numbers. With the increasing in Rayleigh number, the effect of viscous dissipation decreased, so the other correlations that neglected the effect of viscous dissipation could also predict the natural convection of molten salt well. Those results could be a foundation for predicting the natural convection heat transfer of molten salt.

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Keywords: Natural convection; Numerical simulation; Boundary layer; Viscous dissipation;

1. Introduction

In recent years, renewable energy utilization, especially solar thermal power generation, has gradually become research hot due to the energy shortage and environmental pollution. Thermal energy storage (TES) is a key process for solar thermal power production, which can mitigate the changes in solar radiation during transient weather cond-

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Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>heat transfer area, $\pi dl$, $m^2$</td>
</tr>
<tr>
<td>$c_p$</td>
<td>specific heat capacity, $J/(kg \cdot K)$</td>
</tr>
<tr>
<td>$d$</td>
<td>cylinder diameter, $mm$</td>
</tr>
<tr>
<td>$d_{0.1}$</td>
<td>cylinder diameter is 0.1 mm</td>
</tr>
<tr>
<td>$d_1$</td>
<td>cylinder diameter is 1 mm</td>
</tr>
<tr>
<td>$d_{10}$</td>
<td>cylinder diameter is 10 mm</td>
</tr>
<tr>
<td>$h$</td>
<td>convective heat transfer coefficient, $W/(m^2 \cdot K)$</td>
</tr>
<tr>
<td>$l$</td>
<td>equivalent diameter, $m$</td>
</tr>
<tr>
<td>$Q_{\text{conv}}$</td>
<td>the amount of heat transfer of natural convection, $W$</td>
</tr>
<tr>
<td>$q$</td>
<td>heat flow density, $W/m^2$</td>
</tr>
<tr>
<td>$ft$</td>
<td>Feet, $1ft=30.48mm$</td>
</tr>
<tr>
<td>$T_m$</td>
<td>qualitative temperature, $K$</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature at a point in space, $K$</td>
</tr>
<tr>
<td>$T_s$</td>
<td>cylindrical surface temperature, $K$</td>
</tr>
<tr>
<td>$T_e$</td>
<td>infinite space temperature, $K$</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>temperature difference in the thermal boundary layer, $K$</td>
</tr>
<tr>
<td>$a$</td>
<td>thermal diffusivity, $m^2/s$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>coefficient of cubical expansion, $(\rho_{\infty}-\rho)/\rho(T_s-T)$, $1/K$</td>
</tr>
<tr>
<td>$\delta$</td>
<td>thermal boundary layer thickness, $mm$</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>thermal conductivity, $W/(m \cdot K)$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>dynamic viscosity, $kg/(m \cdot s)$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density, $kg/m^3$</td>
</tr>
<tr>
<td>$Ge$</td>
<td>Gebhart number, $g\beta/\rho c_p$</td>
</tr>
<tr>
<td>$Gr$</td>
<td>Grashof number, $g\beta(T-T_s)/\nu^2$</td>
</tr>
<tr>
<td>$Nu$</td>
<td>Nusselt number, $h\delta/\lambda$</td>
</tr>
<tr>
<td>$Pr$</td>
<td>Prandtl number, $\nu/\alpha$</td>
</tr>
<tr>
<td>$Ra$</td>
<td>Rayleigh number, $g\beta(T-T_s)/\nu \alpha$</td>
</tr>
</tbody>
</table>

Two-tank thermal storage of molten salt is a relatively mature TES technology, which has been used in the running solar thermal power station. However, such a thermal storage technology can cause a huge initial investment and high maintenance cost. Single-tank thermocline storage has the properties of the lower initial investment and operation maintenance cost [1], and shows the good application prospect. However, it is difficult to separate the hot and cold fluids by thermocline in the TES of single tank. If a heat exchanger is immersed inside a single-tank, heat energy can be stored in or released from the single-tank through the immersed heat exchanger. During this process the heat transfer around the heat exchanger is the natural convection heat transfer. Therefore, research of natural convection heat transfer of molten salt is very important for designing a single-tank with a heat exchanger immersed in it. So the study of natural convective heat transfer of multi-component molten salts at different range of Rayleigh number ($Ra$) is very important.

At present, a few researchers have studied the natural convective heat transfer of molten salt. Qian et al [2-3] studied the natural convection of fluoride molten salt in cavity using numerical simulation. The result showed that the local Nusselt number ($Nu$) changed depending on the different $Ra$ number, and the natural convection heat transfer was enhanced with the increasing of the $Ra$ number. In addition, Zuo et al [4] studied the thermal storage in single-tank and found that the natural convection heat transfer of molten salt had a certain influence on TES. Zhang et al [5] researched the mixed convection heat transfer of molten salt in the solar collector, and fond the similar result. Lu et al [6] analyzed the natural convection heat transfer of $LiNO_3$ using Joule heating method with fine wire, and found that natural convection heat transfer of $LiNO_3$ fit well with Fand’s correlation that included the influence of viscosity dissipation.

In this paper, the natural convection heat transfer of Hitec salt was studied by simulation at a wide range of $Ra$
number. The simulating results were compared with different correlations that have been published on different journals. The correlations can be explained as follows:

Morgan proposed a simple empirical correlation for Ra number from $10^{10}$ to $10^{12}$ based on a wide literature research [7].

\[ Nu = CRa^n \]  

Churchill and Chu published a semi-empirical correlation for heater transfer in the wide range of Ra number $(Ra<10^{15})$ [8].

\[ Nu = \left( 0.60 + 0.387 \left( Ra / \left[ 1 + \left( 0.599 / Pr \right)^{0.16} \right]^{0.6} \right) \right)^{2} \]  

Fand compared the empirical correlations and experimental data in range of $10^8 < Ra < 10^8$ and created a new correlation [9].

\[ Nu = 0.400Pr^{0.0432}Ra^{0.25} + 0.503Pr^{0.0334}Ra^{0.0816} + 0.958Ge^{0.122} / \left( Pr^{0.0600}Ra^{0.0311} \right) \]  

Tsubouchi published a correlation for laminar natural convection for Ra number from $10^{-6}$ to $10^{2}$ [10].

\[ Nu = 0.36 + 0.048Ra^{0.125} + 0.52Ra^{0.25} \]  

2. Physical model and numerical analysis

The natural convection heat transfer of molten salt around horizontal cylinder in different Ra number range was studied by commercial FLUENT software. Under the effect of buoyancy force, a thermal plume was upward at the top of cylinder surface. So the height of the geometry domain has a great influence on the temperature distribution around cylinder. Therefore, two-dimensional symmetric physical model was used as shown in Fig. 1. The cylinder as heat source was located in the origin of coordinates. In order to analyze the effect of Ra number on the natural convection of molten salt, different cylinder diameters was used. The width of the domain was greater than 100 times of cylinder radius, and aspect ratio of domain was greater than 4. The mesh near the interface of solid-fluid could affect the simulating results, so the mesh near the interface was refined according the method reported by Xin.
et al [11]. The uniform mesh of “C” type was refined on the surface of cylinder and the non-uniform mesh was used far away from the cylinder.

In this study, the boundary conditions could be defined in four different types: left surface was chosen as symmetric boundary condition, bottom and right surface were defined as wall with constant temperature, upper surface of the domain was taken as pressure-outlet type, and constant heat flux was applied on the cylinder.

The governing equations for the two dimensions, symmetric and incompressible laminar fluid (conservation of continuity, momentum and energy conservation equations) could be written as follows:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0
\]

\[
u \frac{\partial u}{\partial x} + \nu \frac{\partial u}{\partial y} = \frac{\partial}{\partial y} \left( \frac{\partial u}{\partial y} \right) + g \beta \left( T - T_e \right) + \frac{u}{\partial y} \frac{\partial u}{\partial y} \]

\[
u \frac{\partial T}{\partial x} + \nu \frac{\partial T}{\partial y} = \frac{\partial}{\partial y} \left( \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial y} \left( \frac{\partial u}{\partial y} \right)^2
\]

The second part in the right side of Eq. (7) is the viscous dissipation term, which is so small and is always ignored in the calculation. When the viscous dissipation is ignored in the energy conservation equation, the non-dimensional function \( Nu=f(Gr,Pr) \) can be got from the above governing equation[12]. Gebhart et al [13] considered the effect of viscous dissipation on the natural convection heat transfer and proposed that the \( Nu \) number was a function of Gebhart number (\( Ge \) \( (Nu=f(Gr,Pr,Ge)) \)), where the viscous dissipation coefficient \( Ge \) could be written as \( g\beta/c_p \). \( Ge \) number is usually very small for most ordinary engineering devices with common fluids for the gravitational field strength of the earth. The quantity \( g\beta/c_p \) usually remains in the range from \( 10^{-6} \) to \( 10^{-4} \) \( ft^{-1} \) (namely \( 3.05\times10^{-8}-3.05\times10^{-5}m^{-1} \)) for most fluids, and the effect of viscous dissipation can be ignored, except the medium of liquid sodium, mercury, normal temperature gas, water and silicone oil [14]. The \( g\beta/c_p \) of molten salt was larger than \( 10^{-4} \) \( ft^{-1} \), so the viscous dissipation should be taken into account. However, Morgan’s, Churchill and Chu’s and Tsubouchi’s correlations except Fand’s correlation all ignored the effect of viscous dissipation.

The standard laminar viscous flow model and the pressure-velocity coupling discretization SIMPLE algorithm were used. The residual values of the continuity and momentum equations were set as \( 10^{-6} \) and that of energy was set as \( 10^{-8} \).

The radiant energy can be absorbed completely at a short distance when the radiant energy entered into the surface of solid or liquid. For metal conductor, the distance is on the order of \( 1\mu m \), for most non-conductive materials, the distance is less than \( 1 \) mm. The engineering material thickness is generally greater than this value, so we think that the solid and liquid do not allow the thermal radiation to penetrate [15]. Therefore, the heat flux of cylinder was only transferred into the surrounding fluid by natural convection heat transfer. The convection heat transfer around cylinder could be represented by:

\[
Q_{con} = hA \left( T_s - T_e \right)
\]

\[
Nu \text{ number could be defined as below,} \]

\[
Nu = hA / \lambda
\]

The thermal physical properties of molten salt were evaluated at the mean film temperature \( [T_m=(T_s+T_e)/2] \).

3. Physical properties of Hitec salt

Hitec salt is an inorganic salt of potassium nitrate, sodium nitrate, sodium nitrite and the mass ratio is 7:40:53. Its melting point is 415K and boiling point is 953K. So it is a good heat transfer medium in the temperature range of 422-811K. The physical properties of Hitec salt come from references [16-18]. The density \( \rho \), thermal conductivity
\( \lambda \) and dynamic viscosity \( \mu \) of Hitec salt could be determined by the Eqs. (10-12) with Kelvin temperature, while the specific heat capacity of 1424 J/(kg·K) was used in this paper.

\[
\rho = 2287.8 - 0.7484T \\
\lambda = 0.76087 - 0.00064T \\
\mu = 0.2149e^{(273-T)/37.54} + 0.00169
\]

(10) (11) (12)

4. Results and discussion

Based on the independence of meshes, natural convection heat transfer of Hitec salt around horizontal cylinder with different diameters (0.1, 0.4, 1, 4, 10mm) was studied. The ambient temperature of molten salt was 573K in the calculation.

Fig. 2 shows the comparison of simulating results with the prediction of other correlations. The ambient temperature of molten salt was 573K in the calculation.

When \( Ra < 1 \) (d=0.1mm), the natural convection heat transfer of Hitec salt fit well with Fand’s correlation that took the influence of viscous dissipation into account. The biggest deviation between numerical simulation data and Fand’s correlation was 7.00% when \( Ra < 1 \). However, the deviation from Churchill and Chu’s, Tsubouchi’s and Morgan’s correlations was 14.8%, 23.1% and 27.8%, respectively. So the effect of viscous dissipation couldn’t be ignored in natural convection when \( Ra < 1 \). Lu et al. got the same results using molten LiNO\(_3\) as heat transfer medium [6]. At this condition, the viscous dissipation coefficient \( g\beta/\rho_c \) was about \( 2.80 \times 10^{-3} \text{ m}^1 \), so the influence of viscous dissipation on natural convection of molten salt couldn’t be ignored [14]. Therefore, Fand’s correlation could give a good prediction. Along with the increase in \( Ra \) number (1 < \( Ra < 2.03 \times 10^6 \)), the other correlations could also predict the \( Nu \) number well as well as Fand’s correlation. It indicated that the effect of viscous dissipation on natural convection heat transfer decreased with the rise in \( Ra \) number. Therefore, the correlations that ignored viscous dissipation could also give a better prediction when \( Ra \) number changed from 1 to 2.03 \( \times 10^6 \).

Fig. 3 shows the natural convection heat transfer coefficient of Hitec salt around different cylinder diameters. The natural convection heat transfer coefficient of molten salt decreased with the increase in cylinder diameter at the same heat flux. The reason was that the thermal boundary layer thickness and the thermal resistance increased with the increasing of cylinder diameter, which results in the natural convection heat transfer coefficient deceased.

Fig. 4 shows the temperature boundary distribution around different diameters cylinder with heat flux of \( 1.0 \times 10^4 \) W/m\(^2\). The constant temperature (\( T \)) line in Fig.4 was calculated by \((T-T_s)/(T_c-T_s)=0.99\). It obviously shows that the
thermal boundary layer thickness increase from 0.995 to 1.34mm at the bottom of cylinder when the cylinder diameter increase from 0.1 to 10mm, which results in the decrease in heat transfer coefficient for the conductive coefficient of molten salt is very lower. The heat transfer inside the thermal boundary layer was mainly conduction, so the thermal resistance increased around a bigger cylinder. However, the Nu number increased with the rise in cylinder diameter. It can be explored from two inspects. The first is the relative thermal boundary layer thickness to the cylinder diameter [19]. The ratio of the thermal boundary layer thickness $\delta_t$ to the cylinder radius $d/2$ is decreased with rise in cylinder diameter, which is about 19.9 (for diameter of 0.1mm), 2.08 (for diameter of 1mm) and 0.268 (for diameter of 10mm), respectively. The relative thickness of thermal boundary indicated that the thermal conductive resistance around the smaller diameter cylinder is higher than that around the larger diameter cylinder, which results in reduce in convective heat transfer intensity. So the Nu number around the smaller diameter cylinder is smaller than that around the bigger diameter cylinder. The second is the thermal-convective resistance, which can be calculated by $1/hA=(T_w-T_{\infty})/Q_{conv}$ and find that the convective-thermal resistance decreased from 5.22 to 0.162K/W with the increase in cylinder diameter (0.1, 1, 10mm). So the Nu number increased with the rise in cylinder diameter.
5. Conclusions

- The natural convection heat transfer of multi-component molten salts can be predicted by Fand’s correlation when $Ra$ number is range from $1.57 \times 10^2$ to $2.03 \times 10^6$. However, when $Ra > 1$ the numerical simulation data can also be predicted by classical correlations that ignored the effect of viscous dissipation.
- With the increase in cylinder diameter, the thermal boundary layer thickness of cylinder is increased and thermal resistance inside the boundary layer is elevated, which results in the decrease in natural convection heat transfer coefficient.
- The convective-thermal resistance is decreased with the rise in cylinder diameter, which results in the augment in convective heat transfer intensity, so the $Nu$ number is increased.

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References


