THERMAL ANALYSIS ON HEAT PIPE RECEIVER IN ADVANCED SOLAR DYNAMIC SYSTEM

Xiaohong Gui* and Xiugan Yuan*

Abstract

In this paper, unit heat pipe receiver in advanced solar dynamic system was numerically simulated. Accordingly, mathematical model was set up, numerical calculation method was offered, numerical results were compared with the experimental results concerned. The temperature field of PCM (Phase Change material) was shown, the thermal performance of heat pipe receiver was analyzed. Analysis results show the axial and radial temperature difference of heat pipe are small; the thermal performance of heat pipe receiver is stable and reliable. The existence of void cavity influences the process of phase change; the temperature gradient of PCM zone is very significant because of the effect of void cavity.

Keywords: heat pipe receiver, thermal performance, numerical simulation

Nomenclature

\begin{align*}
  u & = \text{the velocity of axial direction (m/s)} \\
  v & = \text{the velocity of radial direction (m/s)} \\
  p & = \text{pressure (Pa)} \\
  g & = \text{gravitational acceleration (m/s}^2\text{)} \\
  \beta & = \text{liquid volume expansion coefficient of PCM} \\
  \nu & = \text{kinematics viscosity (m/s}^2\text{)} \\
  e & = \text{specific enthalpy (J/kg)} \\
  \rho & = \text{density (kg/m}^3\text{)} \\
  k & = \text{coefficient of heat conductivity (W/(m.K))} \\
  T & = \text{temperature (K)} \\
  t & = \text{time (s)} \\
  c & = \text{specific heat capacity (J/kg.K)} \\
  T_m & = \text{temperature of phase change (K)} \\
  \Delta H_m & = \text{latent heat of phase change (J/kg)}
\end{align*}

Subscripts

\begin{align*}
  0 & = \text{outer wall of PCM canister} \\
  v & = \text{void}
\end{align*}

Introduction

Heat pipe receiver is an important component in advanced solar energy system in space station [1-7]. It can integrate heat absorption, heat transfer and thermal storage as a whole. During sunlight periods in orbit, heat receiver absorbs solar energy, some energy transmit circulating working gas directly, others store in phase change materials. During eclipse periods in orbit, thermal storage materials release heat to circulating working gas, so the whole system can operate normally during the period of eclipse. Because of its importance and technique complexity, heat receiver has been studied since 1960s. Lightening the system and improving efficiency of the system are the focus of the research in the field of space station. Heat pipe receiver not only improves uniformity of temperature, but also makes full use of phase change materials, so the mass and volume of heat receiver can be become less, and perfect thermal performance of heat pipe receiver is verified.

Structure Designing and Working Principle of Heat Pipe Receiver

Heat pipes, using a liquid metal such as sodium, can be utilized to uniformly transfer the solar flux to the PCM and the receiver circulating fluid. A Garrett AiResearch [8] configuration is shown in Fig.1. The heat pipes comprise three function zones: the receiver portion, the Thermal Storage Device (TSD) portion, and Heat Source Heat Exchanger (HSHEX) portion. By removing the PCM from the direct solar flux, a reduction in receiver diameter is available. This is due to the allowable increase in PCM layer thickness, since the problem of high heat fluxes and
the accompanying temperature for circumferential spacing between the canisters to provide for flux distribution. In addition, the evaporation of the heat pipe fluid allows for high fluxes in the receiver portion. The annular canisters containment approach of the baseline design is retained in the heat pipe TSD portion. The HSHX comprises individually sheathed heat pipes for heat exchange with the engine working fluid.

Heat pipe receiver operates in the following manner. During sunlight periods, the isolation in receiver evaporates the heat pipe fluid. Condensation of the heat pipe fluid occurs in the TSD portion, melting the PCM, as well as in the HSHX portion.

During eclipse periods, the receiver portion of the heat pipe is essentially in adiabatic region, although some condensation may occur due to heat losses. The TSD region acts as the heat pipe evaporator, with condensation occurring in the HSHX. For any operating condition, the heat pipe fluid attains a temperature appropriate to the various external temperatures and thermal conductions. Since the heat pipe is basically an isothermal device, the same heat pipe fluid temperature exists throughout an orbit. Orbit height is 500 KM. Orbit period is 90 minutes. Time of sunlight is 54 minutes. Time of eclipse is 36 minutes.

Numerical Calculation of Unit Heat Pipe Receiver

Some hypotheses are as follows:

- All physical parameters do not change with temperature.
- The void volume of PCM canister is fixed, its percentage is 15%.
- Void cavity distributes along the outer wall of PCM canister.

Geometric Model

The geometric model of unit heat pipe receiver is shown in Fig.2. The outer diameter of heat pipe is 25 mm. The length of heat pipe receiver portion is 200 mm. The length of Thermal Storage Device is 700 mm. The length of HSHX portion is 100 mm. The TSD portion contains covers twenty seven PCM canisters. The Physical dimension of PCM canister is shown in Fig.3. The physical parameters of phase change material are shown in Table-1.

Mathematical Model

Zone of PCM

The flow is consistent incompressible. Two-dimensional axisymmetric continuity equation, momentum equation of z-orientation and r-orientation, energy equation expressed by enthalpy method of PCM canisters are as follows:

![Figure 2: The geometric model of unit heat pipe receiver](image2)

**Figure 2:** The geometric model of unit heat pipe receiver

![Figure 3: Physical dimension of PCM canister](image3)

**Figure 3:** Physical dimension of PCM canister
1. Continuity Equation :
\[
\frac{\partial u}{\partial z} + \frac{1}{r} \frac{\partial (r v)}{\partial r} = 0
\] (1)

2. Momentum Equation :
\[
\frac{\partial u}{\partial t} + \frac{\partial u}{\partial z} \left( \frac{u}{r} \right) + \frac{1}{r} \frac{\partial (r v)}{\partial r} = -\frac{1}{\rho} \frac{\partial P}{\partial z} + g \beta (T - T_m) + \nu \nabla^2 u ,
\] (2)

\[
\frac{\partial v}{\partial t} + \frac{\partial (u v)}{\partial z} + \frac{1}{r} \frac{\partial (r v^2)}{\partial r} = -\frac{1}{\rho} \frac{\partial P}{\partial r} + \nu \left( \nabla^2 v - \frac{v}{r^2} \right),
\] (3)

3. Energy Equation :
\[
\frac{\partial (\rho e)}{\partial t} + \frac{\partial (\rho u e)}{\partial z} + \frac{1}{r} \frac{\partial (r \rho v e)}{\partial r} = k \nabla^2 T ,
\] (4)

The relationship between enthalpy and temperature is given as :
\[
T = \begin{cases} 
T_m + e/c , & e \leq 0 \\
T_m , & 0 < e < \Delta H_m \\
T_m + (e - \Delta H_m)/c , & e \geq \Delta H_m
\end{cases}
\] (5)

PCM is solid \((e \leq 0)\). PCM is liquid \((e \geq \Delta H_m)\). PCM is in phase change \((0 < e < \Delta H_m)\), that is, PCM is in the concurrent zone of solid and liquid, PCM is mushy.

**Zone of Void Cavity**

Since the axial temperature gradient is very small, the temperature of void cavity is defined by radial steady heat transfer equation.

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) = 0
\] (6)

**Method of Solution**

The CFD Software (Fluent 6.1) is used to simulate the heat transfer of unit heat pipe receiver. Software (gambit 2.1) is used as fore-treatment [9]. In Fluent 6.1, the separate solver is used to solve the equations. Finite control volume method is used to discrete the above equations, thus the above complex partial differential equations are converted to alphabetic equation group, and then SIMPLE and Line-line iteration are used for solving numerically.

**Meshes Plotted**

The meshes of unit heat pipe receiver are shown in Fig.4. Rectangular meshes are used in zone of PCM, zone of void cavity, heat pipe wall. Triangle meshes are used in zone of canister wall.

**Initial and Boundary Conditions**

**Boundary Conditions**

- Inlet of gas tube in Heat Source Heat Exchanger (HSHX) portion is defined as velocity inlet.

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**Table-1 : Physical parameters of phase change material**

<table>
<thead>
<tr>
<th>Phase change material</th>
<th>80.5LiF-19.5CaF$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point (K)</td>
<td>1040</td>
</tr>
<tr>
<td>Latent heat (kJ/kg)</td>
<td>790</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>2.21 x 10$^{-5}$</td>
</tr>
<tr>
<td>Density in solid (kg/m$^3$)</td>
<td>2670</td>
</tr>
<tr>
<td>Density in liquid (kg/m$^3$)</td>
<td>2100</td>
</tr>
<tr>
<td>Coefficient of heat conductivity in solid (W/m.K)</td>
<td>5.9</td>
</tr>
<tr>
<td>Coefficient of heat conductivity in liquid (W/m.K)</td>
<td>1.7</td>
</tr>
<tr>
<td>Specific heat capacity in solid (kJ/kg.K)</td>
<td>1.841</td>
</tr>
<tr>
<td>Specific heat capacity in liquid (kJ/kg.K)</td>
<td>1.97</td>
</tr>
</tbody>
</table>

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**Fig.4 The partial meshes of unit heat pipe receiver**
Outlet of gas tube in Heat Source Heat Exchanger (HSHX) portion is defined as outflow.

The receiver portion of heat pipe is defined as periodic heat flux.

Wick is defined as porous.

Heat transfer between heat pipe wall and liquid sodium in the receiver portion is boiling heat exchange.

Heat transfer between PCM canisters and heat pipe wall in Thermal Storage Device (TSD) portion is heat conduction.

Heat transfer between gas and heat pipe wall in Heat Source Heat Exchanger (HSHX) portion is convection.

**Initial Condition**

- The initial temperature is defined as 900 K.
- Time of one period is 90 minutes. Time of sunlight is 54 minutes. Time of eclipse is 36 minutes.

**The Analysis of the Thermal Performance of Heat Pipe Receiver**

The temperature field of the first PCM canister (close to receiver portion of heat pipe) at the end of sunlight is shown in Fig.5. The temperature field of the 14th PCM canister (in the middle of TSD of heat pipe) at the end of sunlight is shown in Fig.6. The temperature field of the 27th PCM canister (close of HSHX of heat pipe) at the end of sunlight is shown in Fig.7.

From these figures, it can be observed that:

- At the end of sunlight, the temperature of all PCM canisters is more than the melting point of PCM. All PCM canisters melt. Heat transfer of heat pipe is very effective. The utilization of PCM is greatly improved. Stability and reliability of heat pipe receiver are greatly improved.

- The existence of void cavity influences the process of phase change. The temperature gradient of OCM zone is very significant because of the effect of void cavity. Since the thermal resistance of void cavity is much bigger than that of OCM side wall, the heat transfer of PCM side wall is very important.

The temperature field of the first PCM canister (close to receiver portion of heat pipe) at the end of shadow is shown in Fig.8. The temperature field of the 14th PCM canister (in the middle of TSD of heat pipe) at the end of
shadow is shown in Fig.9. The temperature field of the 27th PCM canister (close to HSHX of heat pipe) at the end of shadow is shown in Fig.10.

From these figures, it can be observed that:

- At the end of eclipse, the temperature of all PCM canisters is less than the melting point of PCM. All PCM canisters freeze. Heat transfer of heat pipe is very effective. The utilization ratio of PCM is greatly improved. Thus heat pipe receiver owns good stability and reliability.

- The existence of void cavity reduces the thermal storage ability of PCM canister. The temperature is rather low when void cavity exists. The temperature gradient of PCM zone is very significant because of the effect of void cavity. So the thermal stress increases.

The comparison between our simulation results and the results of NAL experiment in Japan is shown in Fig.11 [10]. The temperature change trend of our numerical results is consistent with the results of NAL experiment in Japan. Hence, the numerical results are reliable. And the mathematical and physical model built in this paper are correct. Heat transfer performance of heat pipe receiver including heat pipe is good, and the axial temperature difference of heat pipe is small. Therefore, the thermal performance of heat pipe receiver is stable and reliable.

**Conclusions**

- At the end of sunlight, the temperature of all PCM canisters is more than the melting point of PCM. All PCM canisters melt. Heat transfer of heat pipe is very significant. The utilization of PCM is greatly improved. Stability and reliability of heat pipe receiver are greatly improved.

- During sunlight, the existence of void cavity influences the process of phase change. The temperature gradient of PCM zone is very significant because of the effect of void cavity. Since the thermal resistance of void cavity is much bigger than that of PCM side wall, the heat transfer of PCM side wall is very important.

- At the end of eclipse, the temperature of all PCM canisters is less than the melting point of PCM. The temperature difference between one and another canister situated at different places of heat pipe is not large. All PCM canisters freeze. Heat transfer of heat pipe is very effective. The utilization ratio of OCM is greatly improved. Thus heat pipe receiver owns good stability and reliability.

- During eclipse, the existence of void cavity reduces the thermal storage ability of PCM canister. The temperature is rather low when void cavity exists. The temperature gradient of PCM zone is very significant because of the effect of void cavity. So the thermal stress increases.

- Heat transfer performance of heat pipe receiver including heat pipe is good. The radial temperature difference
of heat pipe is small. Therefore, the thermal performance of heat pipe receiver is stable and reliable.

References


