Transient performance and intelligent combination control of a novel spray cooling loop system

Wang Jin, Li Yunze *, Wang Jun

School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China

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Sintered porous copper;
Spray cooling;
Thermal control

Abstract Effective thermal control systems are essential for the reliable working of insulated gate bipolar transistors (IGBTs) in many applications. A novel spray cooling loop system with integrated sintered porous copper wick (SCLS-SPC) is proposed to meet the requirements of higher device level heat fluxes and the harsh environments in some applications such as hybrid, fuel cell vehicles and aerospace. Fuzzy logic and proportional-integral-derivative (PID) policies are applied to adjust the electronic temperature within a safe working range. To evaluate the thermal control effect, a mathematical model of a 4-node thermal network and pump are established for predicting the dynamics of the SCLS-SPC. Moreover, the transient response of the 4 nodes and vapor mass flowrate under no control, PID and Fuzzy-PID are numerically investigated and discussed in detail.

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1. Introduction

Insulated gate bipolar transistors (IGBTs) as a power electronic device have been widely used to efficiently deliver electrical power in home electronics, industrial drives, telecommunications, transport, electric grid, and numerous other applications. In general, IGBTs are cooled either by convective air or liquid cooling to manage heat dissipation and junction temperatures to achieve efficiency and reliability. However, as the requirements appear for higher device level heat fluxes and harsh environments (thermal condition like transient heat load change and mechanical conditions like vibration and strike) in some applications such as hybrid, fuel cell vehicles and aerospace, there is a pressing need for better thermal management techniques capable of handling higher heat flux than the traditional cooling ways. Spray cooling (heat flux up to 1200 W/cm²) is a promising candidate to address the thermal concerns of systems which have been studied in power electronic devices like a laterally diffused metal oxide semiconductor field effect transistor (LD-MOSFET) in a 500-MHz radio frequency (RF) power amplifier, direct bonded copper (DBC) board and hybrid vehicle electronics.

As an appealing choice for many cooling systems, spray cooling has been studied by many researchers. In addition to theoretical understanding about heat transfer mechanism, parameters of spray cooling like nozzle type, heat surface structure, volumetric flux and subcooling degree were also studied widely. Pautsch and Shedd proved experimentally that multiple nozzle arrays allowed for higher peak heat fluxes but used fluid inefficiently due to interactions between
neighboring sprays. This result has also been proved by Lin and Ponnappan. Kim et al. conducted spray cooling experiments respectively on plain and microporous coated surfaces and proved that spraying water droplets on a microporous coating surface enhanced heat removal due to the capillary pumping phenomenon through the microporous cavities connecting each other. Different surface enhancements consisting of cubic pin fins, pyramids, and straight fins have also been studied by Silk et al. Visaria and Mudawar studied the effect of volumetric flux on spray cooling heat transfer and found that the volumetric flux had a dominant effect on heat transfer as compared to other hydrodynamic properties of the spray. However, all the experiments so far presented have mainly focused on the impact factors of heat transfer and how to improve heat transfer performance while ignoring the design of configuration and thermal control in the spray cooling loop system to realize the feasibility of spray cooling in the harsh environments mentioned above.

A porous material which has the hydraulic effects of surface tension and capillary forces can capture the liquid droplets and draw the liquid into the porous substrate to reduce droplet splash and realize vapor–liquid separation when the liquid droplets impinge on the porous surface. Besides, it can also achieve the highly effective heat transfer performance and liquid transport which has been verified by many researchers. Sintered porous copper as one of the porous materials has been widely used as wicks in flat plate and cylindrical heat pipes for maintaining a closed circulation and facilitating heat transport. Therefore, this paper presents a well-designed spray cooling loop system with integrated sintered porous copper wick (SCLS-SPC) to enhance the liquid availability and system stability.

Though SCLS-SPC can be used in a complicated mechanical environment, it cannot work properly except for the application of active thermal control strategy due to transient heat load change. Therefore, the control of SCLS-SPC plays an essential role in the reliable working of applications. Fuzzy logics which have several advantages such as ease and robustness for characterizing non-linear thermal systems have been widely used for the control of nonlinear thermal processes and for hybrid fuzzy-PID control of more complex thermal objects. Considering the SCLS-SPC is a typical nonlinear thermal system, this paper presents an intelligent control strategy which adopts the pump as the controlling variable, and which is designed by combining the fuzzy and traditional PID control to realize the thermal control of SCLS-SPC.

2. System description and dynamical modeling of SCLS-SPC

2.1. Description of the SCLS-SPC

A novel SCLS-SPC is proposed as shown in Fig. 1. As we know, the traditional cooling system includes the three parts of heat collection, heat transfer and heat dissipation. In this system, the spray unit is the heat collection part, which includes a heater surface, SPC wick and spray chamber. The heat dissipation part consists of a reservoir and a heat sink; the reservoir is filled with SPC wick and the heat sink is tightly attached to the outer surface of the reservoir to realize heat dissipation by forced convection cooling. The heat transfer part is composed of a liquid line, a vapor line, a total liquid line, a valve and a pump; the liquid line is filled with SPC wick. The detailed geometric and material characteristics of SCLS-SPC are provided in Table 1.

The complete cycle of the system is described as follows. Firstly, a high pressure liquid pressurized by the pump is forced through a 2 × 2 nozzle array in the spray chamber and atomized into a dispersion of fine droplets, and then it impacts the SPC wick surface which captures all droplets by the act of capillarity. Meanwhile, some of the droplets spread on the SPC wick surface and evaporate by absorbing the exhaust heat from the heater surface, the rest diffuses to the inner side of the SPC wick forming a special liquid channel. Then, the generated vapor in the spray chamber and the excess liquid in the SPC wick travel along the vapor line and liquid line respectively to the reservoir dissipating heat as heat is rejected to the outer environment by the heat sink. The cooled fluid en-

<table>
<thead>
<tr>
<th>Component and parameter</th>
<th>Value</th>
<th>Component and parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heater surface area (mm × mm)</td>
<td>10 × 10</td>
<td>Vapor line (liquid line)</td>
<td></td>
</tr>
<tr>
<td>Spray height (mm)</td>
<td>8</td>
<td>Outer/inner diameter (mm)</td>
<td>4/2 (2/1)</td>
</tr>
<tr>
<td>Wick height (mm)</td>
<td>4</td>
<td>Length (mm)</td>
<td>50 (50)</td>
</tr>
<tr>
<td>Material</td>
<td>Copper</td>
<td>Total liquid line</td>
<td></td>
</tr>
<tr>
<td>Reservoir Volume (mm × mm × mm)</td>
<td>20 × 20 × 20</td>
<td>Outer/inner diameter (mm)</td>
<td>4/2</td>
</tr>
<tr>
<td>Wick in spray chamber and reservoir</td>
<td></td>
<td>Length (mm)</td>
<td>300</td>
</tr>
<tr>
<td>Wick permeability (m²)</td>
<td>10⁻¹³</td>
<td>Wick in liquid line</td>
<td></td>
</tr>
<tr>
<td>Wick porosity (%)</td>
<td>66</td>
<td>Wick permeability (m²)</td>
<td>10⁻¹¹</td>
</tr>
<tr>
<td>Material</td>
<td>SPC</td>
<td>Wick porosity (%)</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Material</td>
<td>SPC</td>
</tr>
</tbody>
</table>

![Fig. 1 Schematic of SCLS-SPC.](image)
nodel temperatures $T_n$ are adopted as follows: the spray unit, four lumped thermal capacitances ($C_{ob}$, $C_{sp}$, $C_{re}$ and $C_{hs}$) at nodel temperatures $T_{ob}$, $T_{sp}$, $T_{re}$ and $T_{hs}$ respectively. $Q_i$ is the heat load from the heater surface, while $Q_o$ is the heat dissipated to the outer environment. In the figure, $R_{os}$ is the thermal resistance between the heater surface and SPC wick in the spray unit, $R_{th}$ is the thermal resistance between the reservoir and the heat sink.

According to the energy conservation equation, the dynamic model of the heater surface temperature can be calculated by

$$C_{ob} \dot{T}_{ob} = Q_i - (T_{ob} - T_{sp})/R_{os}$$

The differential form energy conservation equation of the spray unit is:

$$C_{sp} \dot{T}_{sp} = (T_{ob} - T_{sp})/R_{os} - m_k h_v + m_l h_l - m h'_l - (T_{re} - T_{hs})/R_{th}$$

where $m_k$, $m_l$ and $m$ are the mass flow rates of the working fluids through the vapor line, the liquid line and the total liquid line respectively; $h_v$ and $h_l$ are the enthalpy values of vapor and liquid in the spray unit; $h'_l$ is the enthalpy value of liquid in the reservoir.

The temperature variation of the reservoir can be expressed by

$$C_{re} \dot{T}_{re} = m_k h_v + m_l h_l - m h'_l - (T_{re} - T_{hs})/R_{th}$$

The heat sink temperature is governed by the conservation energy in

$$C_{hs} \dot{T}_{hs} = (T_{re} - T_{hs})/R_{th} - Q_o$$

The heat dissipation to the outer environment can be calculated by

$$Q_o = k A_{hs} (T_{hs} - T_{en})$$

where $A_{hs}$ is the area of heat sink base attached to the reservoir, $T_{en}$ the temperature of the outer environment, $k$ the heat transfer coefficient of the heat sink.

The enthalpy values of the vapor and liquid are provided by Eqs. (6)–(8), respectively,

$$h_v = c_{pl} T_{sp} + h_{lg}$$

$$h_l = c_{pl} T_{sp}$$

$$h'_l = c_{pl} T_{re}$$

where $c_{pl}$ is the specific heat capacity of the liquid.

The relationships of $m_k$, $m_l$ and $m$ play an important role in the solution of equations from Eqs. (1)–(4). According to the spray cooling heat transfer principle in the spray chamber, numerous micron droplets atomized by a nozzle impinge on the heater surface. By complex synthetic boiling, evaporating and convective heat transfer mechanisms, parts of the droplet evaporate and the rest is heated to saturation. Thus, the heat dissipation by spray cooling can be computed by

$$Q_{sp} = \lambda A_{sp} (m_k h_v + m_l h_l - m h'_l)$$

where $A_{sp}$ is the area of SPC surface in the spray unit, $\lambda$ is spray cooling heat transfer correlation in the plate surface, $\lambda$ is the correction factor of spray cooling heat transfer due to porous wick surface, which is determined by experiment. We design the initial value of $\lambda$ at 1.3 according to Ref. 11.

Because spray cooling is such a complex heat transfer process, there is not an accurate correlation to calculate the value of heat transfer. We adopt the correlation which is established by Ref. 13 through deriving a curve-fit polynomial with experimental data. The correlation is expressed as follows:

$$\frac{q d_{s2}}{\mu h_{lg}} = 4.79 \times 10^{-1} \left( \frac{\rho_e}{\rho_l} \right)^{2.5} \times \left( \frac{\rho_e V^2 d_{s2}}{\sigma} \right)^{0.35} \times \left( \frac{c_{ma} (T_{sp} - T_{re})}{h_{lg}} \right)^{5.75}$$

where $\rho_e$, $\mu_l$, and $\sigma$ are the density, viscosity and surface tension of the liquid respectively, $\rho_e$ and $h_{lg}$ are the density and latent heat of the vapor, $d_{s2}$ is the Sauter diameter of the spray droplet, which is expressed in Eq. (11), $V$ is the average volumetric flux, which can be computed by relationship Eq. (12).

$$\frac{d_{s2}}{d_0} = 3.07 \left( \frac{\rho_e^{0.5} \Delta \rho d_{s2}^{0.5}}{\sigma^{0.5} \rho_l} \right)^{-0.259}$$

where $d_0$ is the inlet diameter of the spray, $\Delta \rho$ is the pressure difference between spray nozzle inlet and spray chamber.
\[ V = \frac{m}{A_{sp}} \]  
(12)

where \( A_{sp} \) is the spray coverage area in SPC surface.

So the mass flowrate of the vapor can be calculated from Eqs. (9)–(12) respectively.

\[ m_v = \frac{Q_{sp}}{C_0} \frac{m_l h_{fg}}{} \]  
(13)

According to the formulation of the hydraulic model, the total mass flowrate of SCLS-SPC \( m \) through the pump can be calculated by

\[ m = \sqrt{\frac{P_s}{Z_s}} \]  
(14)

where \( Z_s \) is the pressure resistance through the total liquid line.

The output pressure \( P_s \) of the pump is always adjusted by a motor-pump load model. Eq. (15) is adopted to express the relationship of pump pressure \( P_s \) and motor voltage \( u \), which is established through deriving a curve-fit polynomial with experimental data in Ref.34

\[ P_s = a + bMu + cMu^2 \]  
(15)

where \( M \) is the driving voltage amplitude under pulse width modulation (PWM), \( a, b \) and \( c \) are the fitting coefficients from experimental data, their values being -0.72, 14.725 and 1.694 respectively.

Therefore, the mechanical pump voltage can be applied as a controlling variable to realize the continuous adjustment of spray pressure drop and mass flowrate.

3. Intelligent combination control strategies

The purpose of thermal control is to maintain the working temperature of electronics in a safe range. In the SCLS-SPC system, the heater surface is adopted as the controlled object, while the pump is applied as the controlling variables to control the temperature of the heater surface. Focusing on the adjustable controlling variables of the pump, we choose the control strategy which combines the fuzzy control and traditional PID control to realize the temperature control of SCLS-SPC. Fig. 3 shows the Fuzzy-PID control system structure diagram which can realize parallel fuzzy and traditional PID control. In the figure, \( T_{ref} \) is the reference setting value of heater surface temperature, \( e_k \) and \( \Delta e_k \) are the error and error change rate of heater surface temperature with the reference value, \( u_{k1} \) and \( u_{k2} \) are the output of the PID controller and fuzzy controller respectively, \( E \), \( EC \) and \( U \) are the fuzzy sets reflecting the linguistic values of \( e_k \), \( \Delta e_k \) and \( u_{k2} \) respectively.

3.1. PID controller

The control law for the traditional discrete PID controller is shown in:

\[ u_{k1} = K_p e_k + T_s \sum_{j=0}^{k} e_j + T_d (e_k - e_{k-1}) \]  
(16)

where \( K_p, T_i \) and \( T_d \) are respectively the proportional gain and the integral and differential constants of the PID controller, and \( T_s \) is the sampling period, the subscripts “\( k \)” and “\( k-1 \)” represent values at the current and previous sampling instants, respectively. The values of \( K_p, T_i \) and \( T_d \) are acquired by Ziegler–Nichols tuning method. They are 6.7, 0.005 and 0.00043 respectively.

3.2. Fuzzy decision unit

The fuzzy decision unit control system comprises a fuzzifier transforming \( e_k \) and \( \Delta e_k \) into fuzzy values \( E_i \) and \( EC_j \), a fuzzy inference engine upon linguistic rules in a database to acquire the fuzzy control value \( U_{(i)} \), and a defuzzifier that transforms \( U_{(i)} \) into a real output number \( u_{k2} \). The linguistic rule in the rule database takes the general form:

If \( e_k \) is \( E_i \) and \( \Delta e_k \) is \( EC_j \), then \( u_{k2} \) is \( U_{(i)} \). where \( E_i \), \( EC_j \) and \( U_{(i)} \) are the fuzzy sets reflecting the linguistic values of \( e_k \), \( \Delta e_k \) and \( u_{k2} \) respectively; the subscript variables \( i, j(i) \) denote the

![Fig. 3 Fuzzy-PID control system structure diagram.](image)
analytical ranks associated with these linguistic values in Table 2. \( \Delta e_k \) is the difference between \( e_k \) and \( e_{k-1} \).

In the designed fuzzy controller, the inputs and outputs are the error \( e_k \), error change rate \( \Delta e_k \) of heater surface temperature with the reference value and the motor voltage \( u_{k2} \) of the pump respectively. Their fuzzy unit and domain are so defined that the fuzzy unit of \( e_k \), \( \Delta e_k \) and \( u_{k2} \) are the same which are \{NB, NM, NS, O, PS, PM, PB\} and \{\(-6,6\)\} respectively. Gaussian membership functions are used to define the linguistic values in the fuzzifier; the membership functions of \( e_k \), \( \Delta e_k \) and \( u_{k2} \) are shown in Fig. 4. Mamdani-type fuzzy inference algorithm is applied to acquire the output fuzzy unit by fuzzy aggregating of the fuzzy unit of each rule and result rule. The linguistic rules are shown in Table 3, which is based on design experience. The centroid method, which overlaps with each other to provide a smooth output between regions, can realize the defuzzification in the defuzzifier. The real value of the fuzzy controller output is determined by:

\[
u_{k2} = \frac{\sum_{i=1}^{7} \sum_{j=1}^{7} U_{i,j}(e_k, \Delta e_k) \mu_{R_{j0}}}{\sum_{i=1}^{7} \sum_{j=1}^{7} \mu_{R_{j0}}} \tag{17}\]

where \( U_{i,j} \) is the output value in the fuzzy domain, \( \mu_{R_{j0}} \) the membership degree of the output fuzzy unit \( U_{j0} \).

### Table 2 Fuzzy sets and their linguistic values.

<table>
<thead>
<tr>
<th>Fuzzy set</th>
<th>Rank</th>
<th>Linguistic value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>-6</td>
<td>Negative big</td>
</tr>
<tr>
<td>NM</td>
<td>-4</td>
<td>Negative middle</td>
</tr>
<tr>
<td>NS</td>
<td>-2</td>
<td>Negative small</td>
</tr>
<tr>
<td>ZO</td>
<td>0</td>
<td>Zero</td>
</tr>
<tr>
<td>PB</td>
<td>6</td>
<td>Positive big</td>
</tr>
<tr>
<td>PM</td>
<td>4</td>
<td>Positive middle</td>
</tr>
<tr>
<td>PS</td>
<td>2</td>
<td>Positive small</td>
</tr>
</tbody>
</table>

### Table 4 Parameters and their values for the simulation of SCLS-SPC.

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design working parameter</td>
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<td></td>
</tr>
<tr>
<td>Heat load (W)</td>
<td>( Q_i )</td>
<td>400</td>
</tr>
<tr>
<td>Heat sink temperature (K)</td>
<td>( T_{hs} )</td>
<td>293.5</td>
</tr>
<tr>
<td>Heat sink temperature (K)</td>
<td>( T_{ws} )</td>
<td>327.25</td>
</tr>
<tr>
<td>Spray unit temperature (K)</td>
<td>( T_{sp} )</td>
<td>386.58</td>
</tr>
<tr>
<td>Reservoir temperature (K)</td>
<td>( T_{re} )</td>
<td>327.25</td>
</tr>
<tr>
<td>Thermal capacity of heater surface (J/K)</td>
<td>( C_{ob} )</td>
<td>7.13</td>
</tr>
<tr>
<td>Thermal capacity of spray unit (J/K)</td>
<td>( C_{sp} )</td>
<td>15.52</td>
</tr>
<tr>
<td>Thermal capacity of reservoir (J/K)</td>
<td>( C_{re} )</td>
<td>31.05</td>
</tr>
<tr>
<td>Thermal capacity of heat sink (J/K)</td>
<td>( C_{hs} )</td>
<td>98.05</td>
</tr>
<tr>
<td>Thermal resistance between the heater surface and SPC wick in spray unit (K/W)</td>
<td>( R_{os} )</td>
<td>0.1</td>
</tr>
<tr>
<td>Thermal resistance between reservoir and heat sink (K/W)</td>
<td>( R_{rh} )</td>
<td>0.12</td>
</tr>
</tbody>
</table>

### Table 3 Fuzzy linguistic rules.

<table>
<thead>
<tr>
<th>( E_i ), ( E_{C_j} )</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>ZO</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
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<td>NB</td>
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<tr>
<td>PB</td>
<td>ZO</td>
<td>ZO</td>
<td>NM</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
</tr>
</tbody>
</table>

### 3.3 Fuzzy-PID switch

The final output \( u_0 \) of the Fuzzy-PID controller is acquired by comparing \( e_k \) with controller switch value \( e_0 \), expressed as:

\[
\begin{align*}
|e_k| & > e_0, u_0 = u_{k2} \\
|e_k| & \leq e_0, u_0 = u_{k1}
\end{align*}
\]  

where \( e_0 \) is the setting switch value, which is 1.5 in this system.

### 4. Numerical simulation and discussion

To evaluate the intelligent combination control action, three different control schemes are numerically considered, which are no control, PID control, and Fuzzy-PID control respectively. The initial operating parameters of SCLS-SPC are listed in Table 4. The system dynamics and control effects are simulated under two disturbance cases, which can be seen in Fig. 5 and Table 5.

#### Case I

The heat load \( Q_i \) is given a \(-10\%\) step disturbance.

#### Case II

The heat load \( Q_i \) is given a \(+20\%\) periodical step disturbance.

### 4.1 Heat load \(-10\%\) step disturbance

Firstly, comparing the temperature responses of \( T_{ob}, T_{hs}, T_{sp} \) and \( T_{re} \) under no control, we can acquire the transient dynamic...
From Fig. 6 we can see that both $T_{ob}$ and $T_{hs}$ decrease directly to their new steady states when the heat load takes a $-10\%$ step disturbance. However, $T_{ob}$ settles in 1520 s with a final change of $-6.7$ K while the settling time and final change of $T_{hs}$ is 1852 s and $-2.2$ K, which is longer and smaller than $T_{ob}$. These suggest that $T_{ob}$ is more sensitive to the step disturbance.

### Table 5  Settling times, overshoot and steady state values of PID and Fuzzy-PID.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No control</th>
<th>PID</th>
<th>Fuzzy-PID</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^*$</td>
<td>$\sigma^*$</td>
<td>$\varepsilon^*$</td>
<td></td>
</tr>
<tr>
<td>Motor voltage</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Vapor mass flowrate</td>
<td>1230</td>
<td>$-1.41$</td>
<td>$-1.41$</td>
</tr>
<tr>
<td>Heater surface temperature</td>
<td>1520</td>
<td>$-6.7$</td>
<td>$-6.7$</td>
</tr>
<tr>
<td>Spray unit temperature</td>
<td>1543</td>
<td>$-4.7$</td>
<td>$-4.7$</td>
</tr>
<tr>
<td>Reservoir temperature</td>
<td>1783</td>
<td>$-4.2$</td>
<td>$-4.2$</td>
</tr>
<tr>
<td>Heat sink temperature</td>
<td>1852</td>
<td>$-2.2$</td>
<td>$-2.2$</td>
</tr>
</tbody>
</table>

Note: (1) error band of $\tau^*$ is 0.05 K for temperatures and 2% final value for others; (2) the units for overshoot value $\sigma^*$ and steady state value $\varepsilon^*$ are “K” for temperatures respectively, $\tau^*$ is “s” for steady state time, “%” for others.

Fig. 6  Transient responses of temperature and mass flowrate under step disturbance.
sensitive to the heat load change than $T_{hs}$ is. The temperature response of spray unit $T_{sp}$ and reservoir $T_{re}$ have the same trends as heat surface $T_{ob}$ and heat sink $T_{hs}$, whereas the causes are different. Spray unit temperature $T_{sp}$ drops directly with the decrease of $T_{ob}$. $T_{re}$ decreases simultaneously since less water is vaporized and flows into the reservoir. $T_{sp}$ is observed to settle down at 1543 s later with a final drop of $-4.7$ K. The settling time and final change of $T_{re}$ is 1783 s and $-4.2$ K, which is longer and smaller than $T_{ob}$. The vapor mass flowrate decreases directly with a settling time of 1230 s and a final change of $-1.41 \times 10^{-5}$ kg/s because spray unit $T_{sp}$ decreases when the heat load takes a step reduction.

Secondly, when the thermal control strategy of PID and Fuzzy-PID are adopted in the SCLS-SPC to realize temperature control, the controlled heater surface temperature $T_{ob}$ under PID and Fuzzy-PID controller achieves the thermal control as expected with zero error, while the settling time and overshoot of PID is 57.1% and 31.3% as compared with the open loop response, which is smaller and quicker than the case with a PID controller. Spray unit temperature $T_{sp}$ in PID and Fuzzy-PID all increases to new steady states, yet the overshoot and settling time of Fuzzy-PID controller are smaller, which are $-27\%$ and $40.6\%$ of the base reference open loop response. The temperature responses of the reservoir and heat sink $T_{re}$ and $T_{hs}$ are the same under PID and Fuzzy-PID controller, which all drop to new steady state values. The smaller final change of $T_{re}$ in Fuzzy-PID controller is 32% below the base reference open loop response, and the overshoot and settling time are also smaller compared with the values in PID and Fuzzy-PID controller, which are 96.4%, 57.4%, 43.5%, and 48.1% respectively. Similar change is found in heat sink temperature $T_{hs}$.

Finally, from Fig. 6, it can also be concluded that the temperature responses of $T_{ob}$, $T_{hs}$, $T_{sp}$ and $T_{re}$ under Fuzzy-PID

![Fig. 7](image_url)  
Fig. 7  Transient responses of temperature and mass flowrate under periodical disturbance.
are different. The transient response of spray unit temperature $T_{sp}$ under Fuzzy-PID control first increases and then decreases to a new steady state which is opposite to the heater surface temperature $T_{ob}$. This means that the adjusting of mass flowrate and pump pressure in the spray unit is more sensitive than heat load change is, which leads to a shorter settling time $T_{sp}$ than $T_{ob}$. The temperature responses of $T_{re}$ and $T_{hs}$ both first temporarily decrease and then gradually increase to their steady states while the settling time of $T_{re}$ is shorter than $T_{hs}$. As compared with $T_{ob}$ transient, the dynamic process of $T_{re}$ is a little slower and less sensitive, which suggests that $T_{ob}$ is more sensitive than $T_{re}$ to the Fuzzy-PID control strategy which chooses the pump as the controlling variable to adjust the mass flowrate and pressure drop. The response of vapor mass flowrate $m_v$ relies on spray unit temperature $T_{sp}$, which is similar to the response of $T_{sp}$.

4.2. Heat load + 20% periodical step disturbance

In actual environments, the applications like hybrid, fuel cell vehicles and aerospace will confront periodical working conditions. Therefore it is necessary to study the Fuzzy-PID control effect in SCLS-SPC under periodical disturbance. To examine the effectiveness of Fuzzy-PID control, we calculated the system’s transient responses subject to the disturbance of $Q_i$.

From Fig. 7 we can see that the temperature responses of $T_{ob}$, $T_{hs}$, $T_{sp}$ and $T_{re}$ under no control have the same trends with the periodical heat load disturbance, and $T_{ob}$ is more sensitive to heat load change than other temperature nodes. Spray unit temperature $T_{sp}$ changes directly with $T_{ob}$, $T_{re}$ changes simultaneously with the change of vapor flowrate flowing into the reservoir, which can be seen in Fig. 7(f). With the employment of PID and Fuzzy-PID, heater surface temperature $T_{ob}$ is restrained well with zero steady state error, while the other three temperatures $T_{hs}$, $T_{sp}$ and $T_{re}$ and vapor mass flowrate $m_v$ all quickly reach a steady state with little overshoot thanks to the quick response of the controlled variable $u$, which can be seen in Fig. 7(e). Moreover, comparing the control effects under PID and Fuzzy-PID, it can be seen that Fuzzy-PID can realize quicker settling time and smaller overshoot than PID; The temperature responses of $T_{ob}$, $T_{hs}$ and $T_{re}$ under Fuzzy-PID control have the same trends with the periodical heat load disturbance while $T_{re}$ is opposite to them. This implies that the adjustment of mass flowrate and pump pressure in the spray unit is more sensitive than heat load changes. $T_{ob}$, which is directly impacted by heat load $Q_i$ and $T_{sp}$, responses subsequently with the control steady state error zero. The transient performance of vapor mass flowrate $m_v$ is directly impacted by $T_{sp}$.

(2) Fuzzy-PID control strategy which adopts the pump in SCLS-SPC as the controlling object is applied to maintain the working temperature of applications in a safe range. Numerical simulations are performed to analyze the transient characteristics and control effect under no control, PID and Fuzzy-PID conditions when the heat loads are subjected to two disturbances: step reduction and periodical step disturbances.

(3) The simulation results validate that Fuzzy-PID can achieve faster response and smaller overshoot than PID which realizes the thermal control of the heater surface as expected compared with the no control condition; The temperature trends of the spray unit and reservoir are determined by the heat transfer status between the heater surface, spray unit, reservoir and heat sink, as well as the mass flowrate changes of the working fluid. External heat load disturbance $Q_i$ can only result in the responses of $T_{ob}$ directly. These analyses can prove that it is feasible to apply Fuzzy-PID to control the voltage of the pump to realize the thermal control of SCLS-SPC.

5. Conclusions

This paper offers a detailed mathematical model and a method to control the thermal and hydraulic parameters of SCLS-SPC comprising of a spray cooling loop system with sintered porous copper wick.

(1) A novel spray cooling loop system with integrated sintered porous copper wick is presented in this paper, and the mathematical model of a 4-node thermal network and pump are established for predicting the dynamics of SCLS-SPC.

References

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Wang Jin is a Ph.D. candidate at the School of Aeronautic Science and Engineering, Beihang University. She received her B.S. degree from Shanxi University in 2009. Her major research interest is the thermal control of advanced spacecraft.

Li Yunze received the Ph.D. degree in engineering thermal physics from Tsinghua University in 2002. Currently, he is a professor with the School of Aeronautics Science and Engineering, Beihang University. His current major research interests include thermal control and energy management of aerospace systems.

Wang Jun is an academician of China National Engineering Research Institute, a professor with the School of Aeronautics Science and Engineering, Beihang University. His area of research includes environment simulation technology, environment control, air conditioning and refrigeration.