Study on performance of micro heat dissipation system base on liquid metal

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Abstract. This paper introduces an advanced liquid metal microcirculation system that uses a liquid metal cycle driven by an electromagnetic pump to achieve heat dissipation. The overall thickness of the structure can be as flimsy as 0.9mm, and the heat dissipation capacity is more than twice that of the corresponding ultra-thin heat pipe. This paper analyzes the performance of the complex by experimenting with the sample and comparing it with the software simulation results, and demonstrates the theoretical analysis method of the liquid metal microcirculation system.

1. Introduction
With the rapid development of electronic technology, electronic devices have entered miniaturization and the cooling system requires less space and higher heat. Microchannel heat dissipation is an advanced cooling method that solves the problem of heat dissipation in extremely high heat flux electronic chips. Currently, microchannel research includes theoretical mechanisms, numerical simulations, structural optimization, processing techniques, industrial applications and two-phase flow [1,2]. Typical microchannel driven pumps include impeller pumps, piezoelectric pumps, electromagnetic pumps, electroosmotic pumps, etc. Cooling media mainly include air, freon, water, alcohol and ethylene glycol [3-5], including two-phase flow and nanofluid [6-8]. Liquid metal (gallium-based low melting point metal) has a series of excellent characteristics, such as low melting point, high boiling point, high thermal conductivity, high heat capacity, stable nature and non-toxicity [9]. At present, research on the basic properties and application fields of liquid metals is gradually deepening [10-15]. High-performance microchannel devices for liquid metals were first proposed, and micro-heat dissipation systems based on liquid metal research are becoming an important research direction in the field of heat dissipation.

In this paper, a new micro-heat dissipation structure is studied, which uses a low-melting-point metal as a medium to circulate in a micro-flow channel with an equivalent diameter of less than 1 mm, and then dissipates heat through a heat-dissipating fin and a cooling fan. The overall thickness of the micro system can reach 0.9 mm, the thickness of the miniature electromagnetic pump, the heat dissipating fin and the cooling fan is large, and the size of the micro electromagnetic pump can reach 15 mm*10 mm*3 mm. In this paper, the theoretical and experimental research on the micro-heat dissipation structure is carried out. The structure and parameters of the research object are shown in table 1 and figures 1 and 2. The physical parameters of liquid metal used in the study are shown in
Table 1. Research object.

|                        | System A                      | System B                      |
|------------------------|-------------------------------|-------------------------------|
| Substrate material     | stainless steel               | stainless steel               |
| Flow section           | 0.5 mm*10 mm                  | 1.0mm*15.0 mm                 |
| Runner length          | 388.5 mm                      | 710.2 mm                      |
| Fan parameter          | Size is 45*45*6 m             | Size is 60*60*8 m             |
|                        | Maximum air volume is 3.8 CFM | Maximum air volume is 4.0 CFM |
| Heat sink parameter    | Fin size is 50 mm*11 mm       | Fin size is 60 mm*36 mm       |
|                        | Wing height is 6 mm           | Wing height is 10 mm          |
|                        | Wing thickness is 0.2 mm      | Wing thickness is 0.2 mm      |
|                        | Gap is 0.8 mm                 | Gap is 1.3 mm                 |

Figure 1. System A.

Figure 2. System B.

Table 2. Physical parameters of liquid metal.

| Melting Point /°C | Density /kg/m³ | Viscosity /Pa·s | Thermal Conductivity /W/(m·°C) | Specific Heat Capacity /J/(kg·°C) | Pr Number |
|-------------------|----------------|-----------------|-------------------------------|-----------------------------------|-----------|
| -5                | 6500           | 0.002           | 30                            | 400                               | 0.0208    |

2. Experiment
The sample was tested in this paper. The results obtained are shown in tables 3 and 4. A ceramic heater was used to simulate the heat source and a K-type thermocouple was used to measure the temperature. The flow rate of the fluid is estimated by using the value of the temperature rise after the fluid flows through the superheat source. The experimental errors mainly include sample size error, test equipment error, experimental condition error, and micro electromagnetic pump driving force...
error.

Table 3. Experimental result of system A.

| Heat source power/W | Electromagnetic pump head/kPa | Heat source temperature °C | Heat source inlet temperature °C | Ambient temperature °C | Flow /ml/min | Reynolds number |
|---------------------|-------------------------------|----------------------------|---------------------------------|------------------------|--------------|----------------|
| 4.55                | 0.57                          | 47.7                       | 28.4                            | 22                     | 5.44         | 57.5           |
| 9.5                 | 0.95                          | 54.4                       | 29.2                            | 22                     | 8.70         | 92.0           |
| 11                  | 0.95                          | 60.3                       | 30.0                            | 22                     | 8.37         | 88.5           |
| 13.2                | 1.14                          | 62.9                       | 31.5                            | 22                     | 9.70         | 102.6          |

Table 4. Experimental result of System B.

| Electromagnetic pump lift/kPa | Temperature of heat source 1/°C (30 W) | Temperature of heat source 2/°C (15 W) | Temperature of heat source 3/°C (15 W) | Ambient temperature °C | Flow /ml/min | Reynolds number |
|-------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|------------------------|--------------|----------------|
| 0.9                           | 52.5                                   | 50.5                                   | 43.5                                   | 18.0                   | 47.35        | 328.8          |
| 1.8                           | 48.7                                   | 46.6                                   | 41.5                                   | 18.0                   | 86.08        | 597.8          |

3. Simulation calculation

The flow and heat transfer simulation analysis of the system was carried out using the finite element software ANSYS. Assuming that the fluid motion state is laminar flow, according to experimental data and simulation analysis results, the structure Reynolds number is less than 2300. Since the temperature of the system is not high and the forced air cooling is used, the influence of radiation heat transfer is finite, so the radiation heat transfer of the structure is neglected in the simulation.

3.1. System A

The results of the system simulation analysis are shown in table 5 and figure 3. The error between the simulation results and the experiment is no more than 5%, the experimental results are reliable and the simulation results are credible.

Table 5. Simulation results at an ambient temperature of 22°C.

| Heat source/W | Electromagnetic pump lift/kPa | Heat source temperature °C | Heat source temperature comparison | Flow /ml/min | Flow comparison | Reynolds number |
|---------------|-------------------------------|----------------------------|-----------------------------------|--------------|----------------|----------------|
| 4.55          | 0.57                          | 46.5                       | 2.6%                              | 5.19         | 4.8%           | 54.9           |
| 9.5           | 0.95                          | 56.2                       | -3.2%                             | 8.46         | 2.8%           | 89.5           |
| 11            | 0.95                          | 61.7                       | -2.3%                             | 8.46         | 1%             | 89.5           |
| 13.2          | 1.14                          | 64.3                       | -2.2%                             | 10.1         | -4.0%          | 106.8          |

As can be seen from the above results, when the thickness of the microcirculation channel is 0.5 mm and the overall thickness is 0.9mm, the flow rate of the low melting point metal of system A can reach 9.7 ml/min. According to formula \( Q = c \rho V \cdot \Delta T \), the heat carrying capacity of the liquid metal in the structure is \( Q = 0.42 \Delta T \). In the above formula, \( Q \) is heat W; \( c \) is specific heat capacity, \( \rho \) is density, \( V \) is volume flow and \( \Delta T \) is— fluid temperature difference.

Heat source temperature comparison and flow comparison means the difference between the experimental value and the theoretical value.
3.2. System B

The results of the system simulation analysis are shown in Table 6 and Figure 4. The error between the simulation results and the experiment is no more than 5%, the experimental results are reliable and the simulation results are credible.

Table 6. Results at an ambient temperature of 18°C.

| Electromagnetic pump lift/ kPa | Temperature of heat source 1/°C (30 W) | Temperature of heat source 2/°C (15 W) | Temperature of heat source 3/°C (15 W) | Flow/ml/min | Reynolds number |
|-------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|-------------|----------------|
| Theoretical value             | 0.9                                    | 50.2                                   | 50.6                                   | 43.0        | 45.2           | 313.9 |
| Experimental error            | 0.9                                    | 4.6%                                   | -0.2%                                  | 1.2%        | 4.8%           |
| Theoretical value             | 1.8                                    | 47.3                                   | 46.9                                   | 42.8        | 84.6           | 587.5 |
| Error                         | 1.8                                    | 3.0%                                   | -0.6%                                  | -3.0%       | 1.7%           |

As can be seen from the above results, when the thickness of the microcirculation channel is 1.0 mm and the overall thickness is 1.2 mm, the flow rate of the liquid metal of system A can reach 87.0 ml/min. According to formula \( Q = c \rho V \cdot \Delta T \) the heat carrying capacity of the liquid metal in the structure is \( Q = 3.77 \Delta T \). In the above formula, \( Q \) is heat W; \( c \) is specific heat capacity, \( \rho \) is density, \( V \) is volume flow and \( \Delta T \) is—fluid temperature difference.
4. Theory and result analysis

The system resistance analysis in this paper is shown in table 7 and figure 5. According to the data in the research, the following conclusions can be drawn.

Table 7. System flow resistance analysis.

| Flow section | Hydraulic diameter/ mm | Total length of the runner/mm | System resistance/ kPa | Flow/ ml/min | Reynolds number |
|--------------|------------------------|-------------------------------|------------------------|-------------|----------------|
| System A    | 0.5mm*10mm             | 0.952                         | 388.5                  | 0.57        | 5.19           | 54.9           |
|             |                        |                               |                        | 0.95        | 8.46           | 89.5           |
|             |                        |                               |                        | 1.14        | 10.1           | 106.8          |
| System B    | 1mm*15mm               | 1.875                         | 710.2                  | 0.9         | 45.2           | 313.9          |
|             |                        |                               |                        | 1.8         | 84.6           | 587.5          |

Figure 5. Volume flow and pressure test results.

4.1. Theoretical analysis of system flow

The simulation of the system uses the conventional scale fluid flow theory. The paper compares the simulation and experimental results of the liquid metal flow. The results are in good agreement, indicating that the hydraulic diameter is 0.952 mm and the flow section thickness is 0.5 mm. The flow law conforms to the conventional scale flow heat transfer theory. As can be seen from the data in the table, the smaller the flow path size, the greater the structure resistance, the slower the flow rate, the smaller the size and flow rate reduction, and the smaller the size, the more the flow rate is reduced. On the basis of this paper, the runner size is further reduced, the structure resistance will be greatly increased, the flow rate will be greatly reduced, and the heat dissipation capacity will be greatly reduced. The system will lose its obvious advantages compared with the traditional heat dissipation method, and the processing difficulty will increase. The precision is high and the system performance is poor.

4.2. System size reduction effect

The formula of heat transfer capacity of liquid cooling system has been shown as follows. 

\[ Q = c \rho V \cdot \Delta T \]

In the above formula, \( Q \) is heat W; \( c \) is specific heat capacity, \( \rho \) is density, \( V \) is volume flow and \( \Delta T \) is— fluid temperature difference.

The heat capacity of the microcirculation system with an overall thickness of 0.9 mm in System A is \( Q = 0.42\Delta T \). If a high thermal conductivity material is used, the one-dimensional cylindrical wall
thermal conductivity formula is as follows \( Q = \frac{2\pi \lambda (t_1 - t_2)}{\ln(r_2 / r_1)} \). Considering the position of the heat source and the uncertainty of the shape of the heat conducting plate in actual use, taking half of the heat transfer capacity of the one-dimensional cylindrical wall, when the ratio of the heat source of the 0.9 mm copper plate to the heat exchanger plate is 100, the thermal conductivity of the copper plate is \( Q = 0.49\Delta T \), which This is equivalent to a liquid metal microcirculation structure. When the overall thickness of the system is further reduced, the heat transfer amount of the high thermal conductive material plate is proportionally reduced, while the flow rate of the liquid metal microcirculation system is accelerated, the heat transfer amount is accelerated, and the liquid metal microcirculation structure loses the performance advantage.

5. Conclusion
In the microchannel flow system, when the flow path size is limited to a certain extent, the fluid cannot be regarded as a continuous medium, and the conventional scale flow and heat transfer theory will not be applicable. The flow path scale is further reduced, and the fluid motion will be dominated by the effects of quantum motion, and the reaction will be free molecular flow motion. This limit is different for gases, liquids, and liquid metals. The critical dimension of liquid is smaller than that of gas, and the critical dimension of liquid metal is smaller than that of water.

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