Research on Simulation of Heat Transfer Characteristics of Intermittent Spray Cooling

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Abstract. Intermittent spray cooling is a new type cooling technology with the energy-saving advantage which can enhance the spray cooling performance and reduce energy was established consumption. In this paper, the three-dimensional simulation model of intermittent spray cooling, and it is the first time using the simulation method to study the heat transfer characteristics of intermittent spray cooling. The simulation results show that intermittent spray cooling effect can be optimized by adjusting spray cycle and duty ratio, and there is the optimal spray cycle and duty ratio at lower flow rate. The simulation results were compared with the experimental results under the same working conditions, and the calculation error was discussed, which is permitted for engineering application.

1. Introduction
Devices in the fields of power electronics $^{[1]}$, steel forging $^{[2]}$, medical health $^{[3]}$ and aerospace $^{[4][5]}$ show a trend of the development higher power density, which causes the problems of energy consumption and heat dissipation. In many fields, these problems restrict the further development and application of those devices.

The traditional cooling methods, such as heat pipe cooling, heat sink and air cooling, cannot meet the cooling requirements of the devices with higher heat flux. Some new cooling technology has appeared in recent years, including microchannel cooling and spray cooling. Spray cooling has a wide application foreground which can be used in the cooling field of high heat flux device $^{[6][7]}$, with the stronger cooling ability, higher critical heat density, lower circulation flow rate and uniform surface temperature.

During spray cooling process, the working medium is sprayed onto the surface of the object, such as chips, devices and electrical equipment, and a cooling liquid film is formed on the surface. Depending on the flowing of the liquid film and the evaporation of cooling medium, the heat can be removed from the surface of the heat source. Through more in-depth studies of heat transfer mechanism, it was found that spray cooling effects can be further optimized by reducing the thickness of liquid film and decreasing the interaction between the spray droplets and the hot vapor. Therefore, in order to further enhance the cooling performance of the spray cooling system, a new spray cooling method $^{[1-3]}$, called intermittent spray cooling, was proposed. In the intermittent spray process, the sum of the time taken by the adjacent injection action and the stop injection action is called the spray cycle. The ratio of the spray action time to the single cycle time called duty ratio.
Intermittent spray cooling technology, involving the subjects of bubble dynamics, two-phase flow, heat transfer theory and other subjects, is extremely difficult to study. And most current researches still rely on the experiments to study the heat exchange mechanism of intermittent spray cooling.

In this paper, the 3D simulation model of intermittent spray cooling was established. Under the different spray cycle and duty ratio, the characteristics of heat transfer were analyzed and the results were compared with the published experimental results.

2. Model and Meshing

2.1. Geometric Model and Meshing
The simulation model is established based on intermittent spray cooling experiment[8]. This simulation involved using a 60° solid conical micro-atomization nozzle with 0.74mm diameter of outlet. Table 1 shows the nozzle parameters given by the manufacturer.

| Nozzle diameter (mm) | Spraying Flow (L/h) |
|----------------------|---------------------|
|                      | 3bar    | 5bar    | 7bar    | 10bar   | 15bar   | 20bar   |
| 0.74                 | 14.2    | 17.5    | 20.6    | 24.6    | 30.1    | 34.6    |

The nozzle parameters are shown in Table 1. The computational domain is a cylinder with the diameter of 40mm and the height of 35mm. The grid in the central region is encrypted, owing to the nozzle is located at the centre of the circle on the upper surface of the cylinder. The selected fluid region mesh is depicted in Figure 1.

2.2. Mathematical Model
The air is set as a continuous phase in this model. The mass conservation equation, momentum equation, energy equation and Realizable k-ε model are activated.

Five nozzles are set with different parameters in start times and stop times in order to achieve the intermittent spray cooling. Figure 2 illustrates the atomization of cooling medium in the 200ms spray cycle.
cycle. The results depicted in Figure 2 show that intermittent spray can be realized by using different start and stop time of spraying. TAB model is selected for droplet breakage and random walk model for droplets track. Dynamic drag model and species transport model need to be used in the spray process. The components in the calculation domain during the spraying process are set as air and water vapor. Eulerian wall film model is used to simulate the change of liquid film on the cooling surface.

2.3. Boundary Conditions
The pressure at the outlet of nozzle is set as 0.4Mpa, the ambient temperature is set as 20℃ and the gravitational acceleration is 9.81m/s. It is supposed that the computational domain is filled with still air at the initial moment.

The upper surface of the computational domain is set as pressure inlet with the initial velocity of 0m/s. The lateral surface of the computational domain is set as pressure outlet. Both upper boundary and lateral boundary are set as escape mode in DPM model.

The bottom boundary is set as wall-jet mode in DPM model with no wall-slip condition. Heat flux density is 100W/cm² and material is set as copper. Eulerian wall film model is selected to simulate the liquid film formed by atomized droplets on the bottom surface.

3. Results discussion
3.1. Heat transfer performance with different spray cycle
In the intermittent spray cooling process, the surface temperature of the heat source is always fluctuating due to the alternating action of spraying and stopping spraying, as shown in Figure 3. Figures 4 and 5 are the surface temperature distribution of the heat source under different cycle conditions. When the spray cycle is 200ms, the temperature distribution on the surface of the heat source is more uniform, and the temperature rise during the spray stop process is smaller. Under the condition that the spray cycle is 600ms, the higher temperature at the center of the heat source surface leads to poor temperature distribution uniformity, and the increase of the spray cycle results in a larger range of temperature changes during the spray process and the spray stop process. To compare with the experimental results, this paper defines that surface temperature of the heat source is stable when the peak temperature fluctuation is no more than 5℃ within 5 spray cycles in simulation.

![Figure 3. The change of bottom average temperature with time when spray cycle is 200ms and duty ratio is 0.5](image)

The reliability of the simulation model plays a decisive role in the result of numerical calculation, the following is the reliability demonstration of the model. The results of the simulation and the experiment are compared to testify the reliability. Figure 6 shows the average temperature of the heat source surface in different spray cycles obtained by simulating calculation. In the case of different spray
cycles, the error between the experimental data and the simulated data is less than 15% which is permitted for engineering application.

Figure 4. The surface temperature distribution of the heat source at different times when the spraying cycle is 200ms and duty ratio is 0.5

Figure 5. The surface temperature distribution of the heat source at different times when the spraying cycle is 600ms and duty ratio is 0.5

Figure 6. The average surface temperature of the heat source under different spray cycles when duty ratio is 0.5
3.2. Heat transfer performance with different duty ratio

Different cooling performance can be achieved by changing the spray cycle and duty ratio of intermittent spray cooling. The effect of duty cycle on intermittent spray cooling has not been discussed in the aforementioned experimental studies. While in this paper, it is studied by changing the duty ratio of the atomization model with a spray cycle of 200ms.

Figure 7 depicts the variation of the average temperature and maximum temperature on the surface of the heat source with the duty cycle. As can be seen from Figure 7, when the duty ratio is less than 0.75, the average temperature and the maximum temperature of the heat source surface are reduced with the increasing of duty ratio, and the effect of spray cooling is improved. However, when the duty ratio exceeds 0.75, the effect of spray cooling becomes decreasing. As the duty ratio increases, the cooling medium distributed in the whole spray cycle will increase and the time for the liquid film on the surface of the heat source to be disturbed by the droplets in a single spray cycle increases, therefore the heat exchange effect of spray cooling is enhanced. However, when the duty ratio is greater than 0.75, the liquid film formed by the spray on the surface of the heat source becomes thicker, resulting in an increase in thermal resistance and a longer escape time for bubbles, which affects the heat transfer effect.

![Figure 7. The bottom average temperature and the maximum temperature when change the duty ratio with a spray cycle of 200ms](image1)

![Figure 8. Comparison of intermittent spray cooling effect at different flow rates](image2)

4. Conclusions

According to the above simulation calculation results, the following conclusions are drawn:

- In intermittent spray cooling system, the reduction of the spray cycle causes a greater interaction between consecutive injections, leading to a higher heat transfer rate.
- Under the simulation conditions, the cooling effect of intermittent spray at a duty cycle of 0.75 can approach or even exceed the cooling effect of continuous spray. Therefore, intermittent
spray cooling system can save the cooling medium to a certain extent, enhance the heat transfer effect and reduce energy consumption.

- With the increase of flow rate, the cooling effect of intermittent spray is obviously enhanced.
- The simulation results were compared with the experimental results under the same working conditions. The simulation calculation error is less than 15%, which is permitted for engineering application.

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