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Experimental and numerical study on a micro jet cooling solution for high power LEDs

LUO XiaoBing[1,2], LIU Sheng[2,3†], JIANG XiaoPing[2,3] & CHENG Ting[1]

[1] School of Energy and Power Engineering, Huazhong University of Science & Technology, Wuhan 430074, China;
[2] Wuhan National Lab of Optoelectronics, Huazhong University of Science & Technology, Wuhan 430074, China;
[3] Institute of Microsytems, Huazhong University of Science & Technology, Wuhan, 430074, China

An active cooling solution based on close-looped micro impinging jet is proposed for high power light emitting diodes (LEDs). In this system, a micro pump is utilized to enable the fluid circulation, impinging jet is used for heat exchange between LED chips and the present system. To check the feasibility of the present cooling system, the preliminary experiments are conducted without the intention of parameter optimization on micro jet device and other system components. The experiment results demonstrate that the present cooling system can achieve good cooling effect. For a 16.4 W input power, the surface temperature of 2 by 2 LED array is just 44.2℃ after 10 min operation, much lower than 112.2℃, which is measured without any active cooling techniques at the same input power. Experimental results also show that increase in the flow rate of micro pump will greatly enhance the heat transfer efficiency, however, it will increase power consumption. Therefore, it should have a trade-off between the flow rate and the power consumption. To find a suitable numerical model for next step parameter optimization, numerical simulation on the above experiment system is also conducted in this paper. The comparison between numerical and experiment results is presented. For two by two chip array, when the input power is 4 W, the surface average temperature achieved by a steady numerical simulation is 34℃, which is close to the value of 32.8℃ obtained by surface experiment test. The simulation results also demonstrate that the micro jet device in the present cooling system needs parameter optimization.

high power LEDs, closed system, micro impinging jets, thermal management

High power light emitting diode (LED) based semiconductor illumination technology, also called

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†Corresponding author (email: shengliu63@yahoo.com)
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solid state lighting (SSL), has become the focus for both research and commercial applications in recent years, because it has a lot of advantages compared with the traditional illumination technologies. Currently, the main general light sources are incandescent lamps, halogen lamps, and fluorescent lamps. Compared with these general light sources, theoretically, LED has several advantages as follows[1]: 1) high luminescence efficiency, good optical monochromaticity, narrow spectrum and being able to emit visible light directly; 2) energy saving and low power consumption, as the power consumption of a LED is only one eighth of an incandescent lamp and one half of a fluorescent lamp under the same illumination efficiency; 3) long lifetime. In theory, LED's average lifetime is as long as 100000 h, which is ten times that of general lamps; and (4) being safe and environment-friendly. LED is a solid state light source and has low calorific value and no thermal radiation, so that LED is generally called cool light source. In addition, LED does not contain any health hazard such as mercury, sodium, etc., and is recyclable and does not cause any pollution. Because of the above mentioned advantages, LEDs begin to play an important role in many applications[2]. Typical applications include back lighting for cell phones and other LCD displays, interior and exterior automotive lighting, large signs and displays, and are soon going to general lighting.

For present LEDs, especially for high-brightness LEDs, both optical extraction and thermal management are critical factors for the high performance of LED packaging. Most of the electrical power in LEDs will be converted into heat for the state of art technology with low internal and external optical extraction efficiency. In general, the produced heat will greatly reduce device luminosity. In addition, the high junction temperature will shift the peak wavelength of LED, thus changing the light color of LED. Narendran et al.[3] have experimentally demonstrated that the life of LEDs decreases with increasing junction temperature in an exponential manner. Therefore, low operation temperature is strongly needed for LEDs, which is a distinguishing feature of SSL versus traditional lighting. Since the market requires that LEDs have high power and packaging density, it poses a contradiction between power density and operation temperature, especially when applications require LEDs to operate at full power to obtain desired brightness. The problem leads to the emerging of major advances in thermal management of LED illumination.

To address the thermal problem of LEDs, numerous researchers both in China and in other countries have conducted the relevant studies. Arik et al.[4] carried out a numerical study to understand the chip temperature profile due to the bump defects. Finite element techniques were utilized to evaluate the effects of localized hot spots at the chip active layer. Sano et al.[5] reported an ultra-bright LED module with excellent heat dissipation characteristics. The module consists of an aluminum substrate having outstanding thermal conductivity, the mount for LED chips being formed into fine cavities with high reflectance to improve light recovery efficiency. Furthermore, the condenser of this LED module is filled with high-refraction index resin on the basis of optical simulation. An improvement in luminance of 25% or more was observed by taking the aforementioned measures in their paper. Petroski et al.[6] developed a LED-based spot module heat sink in a free convective cooling system. Cylindrical tube, longitudinal fin (CTLF) heat sink is used to solve the orientation problem of LED. Chen et al.[7] presented a silicon-based thermoelectric (TE) for cooling of high power LED. The test results show that their TE device can effectively reduce the thermal resistance of the high power LED. Hsu et al.[8] reported a metallic bonding method for LED packaging to provide good thermal dissipation and ohmic contact. Zhang et al.[9] used multi-walled carbon nanotubes and carbon black to improve the thermal performance of thermal interface materials (TIM) in high-brightness LED packaging. Tests show that such a TIM can effectively decrease the thermal resistance. Acikalin et al.[10] used piezoelectric fans to cool LEDs. Their results show that the fans can reduce the heat source temperature by as much as 37.4℃. The piezoelectric fans have been shown to be a viable solution for the thermal management of electronic component and LED.

In China, a lot of researchers have also tried to find the solution to the LED thermal management. Wu et al.[11] used finite element method to analyze the temperature distribution in 1 W high power white LEDs. The simulation results show good agreement with the experimental data. Based on the simulation model, they studied the dependence of chip size on junction temperature. The results show that with a certain lighting efficiency and packaging structure, the size and maximum input power of chip should be optimized because of the thermal dissipation limit. Yu et al.[12] analyzed the dependence of bonding material on the thermal characteristics of high power LED. They build a correlation of bonding material thickness with thermal conductivity and thermal resistance for flip-chip type LEDs. Examples with three typical materials are given to prove the function. The results show that bonding material plays an important role for decreasing LED thermal resistance. Chen et al.[13] utilized the thermal resistance model to predict the junction temperature and instruct the thermal design of high power LEDs. By comparing with experiments, the feasibility of the model is proved. Ma et al.[14] introduced a novel electrical measurement method for thermal resistance and junction temperature of high power LED. They also investigated the influence factors and built an experiment setup, and the experimental results show that the method has the advantages of simple structure and good stability. It can be used to measure thermal resistance and junction temperature of high power LEDs. Wang et al.[15] came up with an equation, which builds the relation of LED output power with thermal characteristic parameters under transient condition. Based on the equation, the dependence of LED output power on different current pulse is analyzed. The variation of optical output and heat with pulse width and duty ratio is presented.

In this paper, an active cooling solution is presented for thermal management of high power LEDs. It utilizes micro jet array to cool the LED chips, the total system is a closed loop. A micro pump drives the working media recirculation, gas and some fluids such as water and liquid metal can be used as working media for the system. Experiments are conducted for the above cooling system, and the results show that it has good cooling performance. To improve the existing design, numerical investigation is also conducted. The comparative results between experiments and simulations demonstrate that the numerical model can be used for parameter optimization. The simulation results exhibit that the micro jet device in the experiment needs to be optimized, and its heat transfer coefficient is about 4140.6 $W/m^2 \cdot K$ under a certain experiment condition.

1 Microjet array cooling system

Figure 1 demonstrates the present LED cooling system. It composes of three parts: a microjet array device, a micropump and a mini water container with a heat sink. It is obvious that such a system is a closed loop one. When LEDs need to be cooled, the present system starts to work. Water in the closed loop system is driven into the microjet array device through an inlet by micropump. Many micro jets will form inside the jet device, which are directly impinged onto the bottom plate of LED array. Since impinging jet has very large heat transfer coefficient, the heat generated by LEDs is easily taken out by the recycling water in the system. The water is heated and its temperature increases after flowing out the jet device, then the heated water enters into the mini water container.

The heat sink with a fan on the water container will cool the water and the heat will dissipate into the environment. The cooled water will be delivered into the jet device to cool the LED array again by the force of the micropump in the system. The above processes constitute one operation cycle of the total system. It should be noted here that the real size of present system can be designed as one small package according to application requirements.

Figure 2 shows the structure of micro jet device in Figure 1 in detail. Here the fluid enters into the jet device through the inlet and forms micro jets to impinge on the top wall of the micro jet device. The substrate for the LED chips is directly located on the top wall of the micro jet device. To decrease the thermal resistance, high conductivity bonding material is used to connect chip substrate and the top wall of micro jet device. In some cases, LED chip substrate can be the top wall of micro jet device directly, which will greatly decrease the thermal contact resistance. To satisfy different applications of LEDs, the present microjet array structure shown in Figure 2 can be changed into several types, the impinging jet cavity can be polyhedron or cylinder shape, the microjet arrays can be distributed at several faces or all faces of polyhedron or cylinder, correspondingly, the LED chips can be located at several or all directions for cooling.

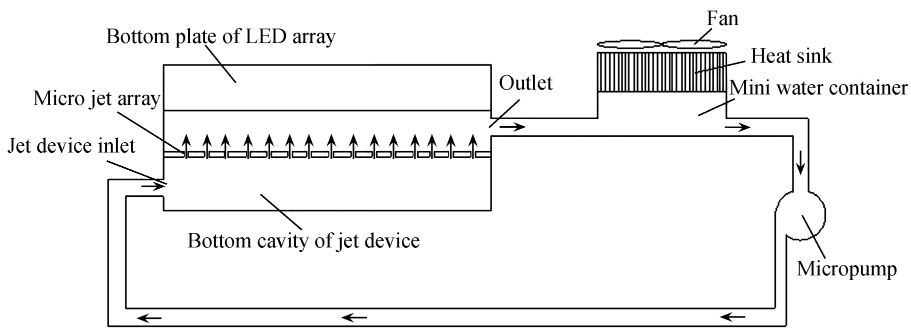

Figure 1 Present closed microjet array cooling system.

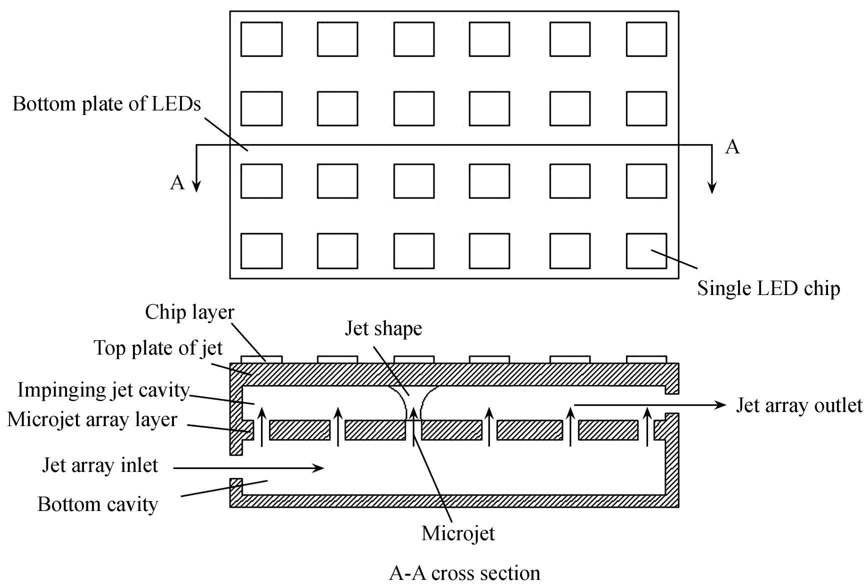

Figure 2 Microjet array cooling device.

The present system is based on the impinging jet to transfer heat, which has been demonstrated as an efficacious cooling solution in many applications[16,17]. Therefore, the most distinguishing advantage of the present concept is its high heat transfer efficiency. In addition, since many micro jets are used to impinge on the top wall, theoretically, the temperature distribution in LED chip substrate can be uniform.

2 Experiment system

Experiment system is constructed as shown in Figure 3, which is nearly the same as the one shown in Figure 1. In Figure 3, the heat sink with a fan is located below the mini fluid container, which is different from the description in Figure 1. However, this will not result in any difference for function and effect. It should be noted that Figure 3 just demonstrates the experiment system. In real applications, the sizes of both micro pump and heat sink should be reduced. Figure 4 shows the temperature measurement on 2 by 2 LED chips packaged with the micro jet device. The surface temperature of the chips is measured by Raytek non-contact infrared thermometer. Such a measured temperature is different from the LED chip junction temperature. However, it can reflect the magnitude of chip junction temperature. Since this paper does not concentrate on the junction temperature measurement, and it focuses more on evaluating the cooling performance of the present cooling system. Therefore, such a treatment is enough. The details about the experiment system are as follows. The micropump is based on electromagnetic principle, which is custom designed and made locally in China. Its input voltage can be adjusted to obtain different flow rate. In default, the input voltage is AC 220 V, and the flow rate is 10 mL/s. The diameter of micro jet is 0.5 mm. The working media of the system is water. The heat sink with a fan is purchased from the commercial electronics market; the mini water container is designed according to the surface area of the heat sink. The size of each LED chip is 1 mm by 1 mm. The substrate size is 15 mm by 15 mm, and the distance between each chip is about 3 mm. Figure 5 gives the detailed sizes of the LED chip layout on the substrate.

The detailed sizes of the micro jet device in experiment are shown in Figure 6. Since the top cavity of the micro jet device is exactly the same as that of the bottom cavity, Figure 6 just exhibits the sizes of the top cavity. In Figure 6, both the length and width of the top cavity are 8 mm, and the

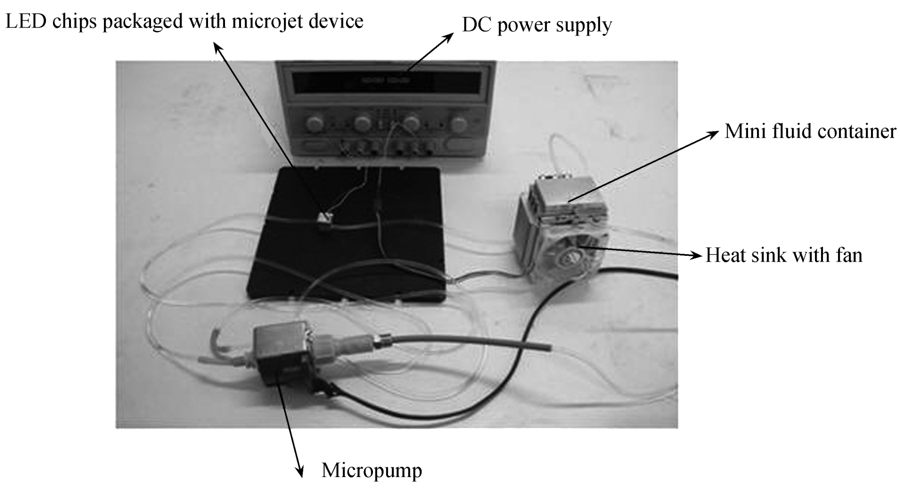

Figure 3 Experiment system.

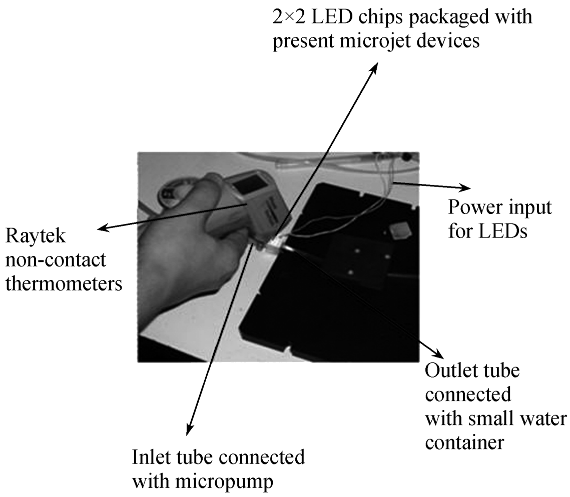

Figure 4 Surface temperature measurement of LED chips.

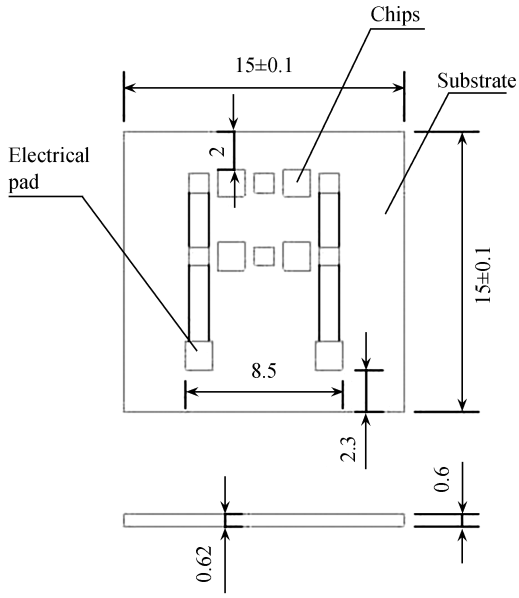

Figure 5 Detailed size of LED chip layout on substrate.

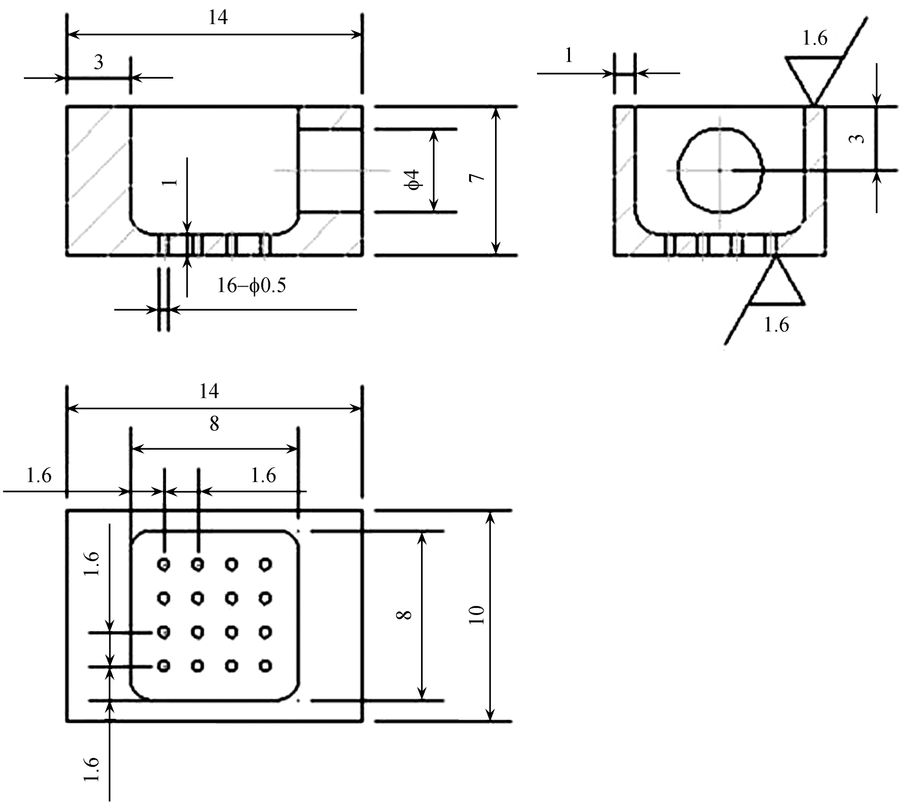

Figure 6 Detailed size of top cavity of micro jet device used in present experiments.

height is 6 mm. The diameter of the outlet in the top cavity is 4 mm. There are 16 micro jets in the micro jet device, and they are uniformly distributed in the plate, which separates the micro jet device as top cavity and bottom cavity. Since LED chip substrate is directly positioned on the top surface of the micro jet device, the distance between micro jets and LED chip substrate should be the same as the height of the top cavity, which is about 6 mm. The diameter of the inlet is 4 mm.

It should be noted that for the components in this experiment system, no intention has been made to optimize the dimensions, materials and structures. The numerical optimization, especially for micro jet device should be conducted in next step.

3 Accuracy analysis

Temperature is the target parameter for the present experiment analysis. It is measured directly by Raytek non-contact thermometer. Since there are no other indirect measurement parameters, and the experiment uncertainty in the present experiments is only the measurement error of the thermometer. The Raytek non-contact thermometer can achieve 98 percent accuracy for the measurement of 90 percent common objects. Since LED chips are common electrical devices, the error range of temperature measurement for the present experiments is about 2%.

4 Experiment results and analysis

Figure 7 reveals the surface temperature dependence of LED chip on time at different input power levels with and without the cooling of present microjet system. In these experiments, the flow rate of the micro pump is 10 mL/s. Because the diameter of the inlet is 4 mm, correspondingly, the flow velocity at the inlet is about 0.8 m/s. In Figure 7, the ordinate denotes the surface temperature of LED chips, the abscissa indicates the operation time. In the experiment series, the input electric current are 0.3, 0.6, 1, 1.5, 2 A, corresponding voltages are 6.3, 7.1, 7.4, 7.9, 8.2 V respectively. To compare the cooling effect, when the input current is 0.3 A, the present cooling system does not work. It is obvious from Figure 7 that without the present cooling system, the surface temperature of LEDs increases very quickly, in the case, the heat produced by LED chips is just dissipated out by natural convection at the micro jet device shell and the top surface of LED chips, therefore, the temperature of LED surface increases very quickly. For 0.3 A and 1.89 W power, the temperature increases from 27℃ to 112.2℃ in ten min. However, with 0.6 A and 4.26 W, after operation with

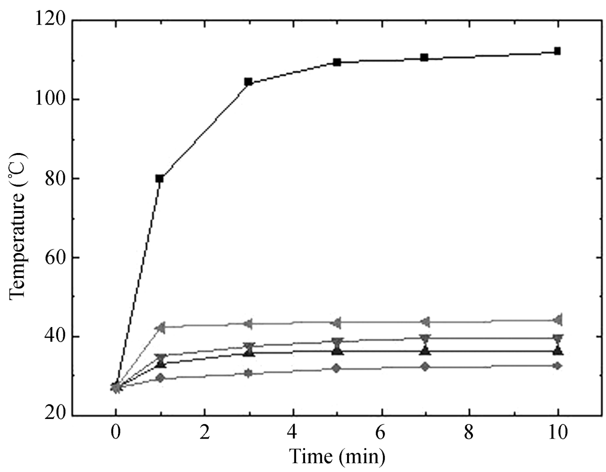

Figure 7 LED surface temperature with time at different input power and cooling conditions. ■, 0.3 A, 6.3 V, no cooling; ◆, 0.6 A, 7.1 V, with cooling; ▲, 1 A, 7.4 V, with cooling; ▼, 1.5 A, 7.9 V, with cooling; ◀, 2.0 A, 8.2 V, with cooling.

present cooling system, the temperature just changes from 27℃ to 32.4℃. The comparison clearly demonstrates the cooling performance of the present system. Figure 7 also shows that by using the present cooling system, even the electric current increases to 2 A, voltage is 8.2 V, the surface temperature of LED chips only varies from 27℃ to 44.2℃. These results demonstrate that with the present cooling system, it is promising that LED chips can work at large electric current and low operation temperature, which provides the potential for LED chips to achieve high light-output efficiency, good optical efficiency, and longer life.

Figure 8 shows the LED surface temperature variation with time at different input power levels and pump flow rates. The ordinate ΔT denotes the difference between the measured LED surface temperature and the environment temperature. In every experiment case, the environment temperature is slightly different. To effectively reflect the cooling effect resulting from the micro pump flow rate, here the relative temperature is used in ordinate. It is observed from Figure 8 that the LED surface temperature is relatively higher than those with large flow rate when the micro pump flow rate is low and at the same input power for LED chips. For an input current of 2 A, and 8.2 V voltage, an increase of 28℃ between the LED surface temperature and environment temperature is observed at a pump flow rate of 2.5 mL/s. However, with the same input power, when the pump flow rate increases to 10 mL/s, the LED surface temperature is 17.2℃ higher than environment temperature. This means that large pump flow rate can result in better cooling performance. The above phenomena can be explained as follows. When pump flow rate increases, the heat transfer coefficient of impinging jets in the microjet device will increase, thus the heat from LED chips will be taken out more efficaciously. However, it should be noted that with the increase of the pump flow rate, the micropump will consume more power, which will increase the operation cost. In real applications, there should be some trade-off in design between the heat transfer efficiency and power consumption.

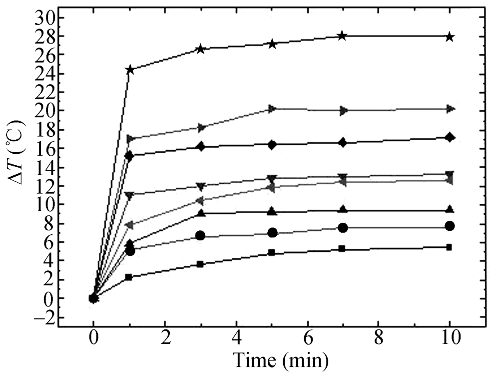

Figure 8 LED surface temperature with time at different input power and micro pump flow rate. ■, 0.6 A, 7.1 V, 10 mL/S; ●, 0.6 A, 7.1 V, 2.5 mL/S; ▲1 A, 7.4 V, 10 mL/S; ▼, 1 A, 7.4 V, 2.5 mL/S; ◄, 1.5 A, 7.9 V, 10 mL/S; ►, 1.5 A, 7.9 V, 2.5 mL/S; ◆, 2 A, 8.2 V, 10 mL/S; ★, 2 A, 8.2 V, 2.5 mL/S.

Figure 9 shows the LED surface temperature variation with time at different fan operation conditions. In the experiment series, the fan input power is 1.6 W. It can be observed from Figure 9 that when the input current is 1 A and the voltage is 7.4 V, the LED surface temperature with fan operation is 4.8℃ lower than that without fan operation after 10 min. It is obvious that the cooling performance of the present system will be much better when the fan on the heat sink works. The above phenomena attributes to the following reasons. The water in system takes out heat from LED chips, its temperature will increase, if it cannot be cooled down before next cycle, the water temperature will increase continuously, which will greatly deteriorate the heat transfer between LED chips and micro jet device. Therefore, the LED chips cannot be maintained at suitable operation temperature. In the present system, the heat exchange between the recirculation water and environment mainly depends on the fins and fan. When the fan does not work, the heat exchange will mainly rely on the natural convection at the fins and the connection tube in the system. However,

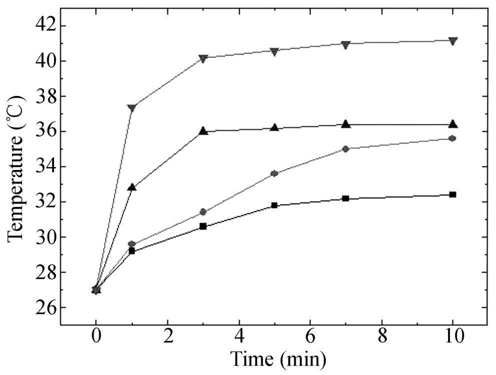

Figure 9 LED surface temperature variation with time at different fan operation conditions. ■, 0.6 A, 7.1 V, fan operation; ●, 0.6 A, 7.1 V, no fan operation; ▲, 1 A, 7.4 V, fan operation; ▼, 1 A, 7.4 V, no fan operation.

when the fan works, the heat exchange between the system and environment is mainly through the forced convection, the heat transfer efficiency will greatly increase.

The above experiments demonstrate that the proposed closed-loop micro jet cooling system can be an effective way for high power LED cooling: it has good cooling performance, and the thermal resistance between LED chips and environment will sharply decrease. Another advantage for the present system is that it can take the heat in the confined space into a wide space, which will facilitate the design and applications.

However, the present cooling system is an active cooling solution with a micro pump in system, which will increase the system cost to some extent. Therefore, it should have trade off between the cost and performance in real applications. For many large scale high power LED devices where the total cost for chips is high, passive cooling cannot satisfy the thermal management requirement, the present cooling system will be a good choice.

In the above experiments, there are some points to be noted. First, in experiments, the micro-pump will produce heat; part of the heat will be transferred into the recirculation water, which will increase the heat load of the present cooling system to some extents. In real applications, the heat generated by pump will be specially controlled; the micro pump design and selection will be important for the system optimization and application. Secondly, the temperature measured by non-contact infrared thermometer is an averaging surface temperature, it can indicate the LED chip junction temperature to a great extent, also, it meets the precision requirement for evaluating the cooling performance of the present cooling system. However, the measured temperature is not sufficient to reflect the temperature information in LED chips array. Even on LED chips surface, the temperature gradient still exists, the precise measurement needs help from high-quality infrared camera or other means. Thirdly, the time duration in experiments is determined by temperature variation. If the measured temperature does not have obvious change, it is supposed that the steady situation of heat transfer is achieved. Since the temperature in the system comes to be stable quickly, the measurement time is also short. From the viewpoint of system reliability evaluation, it is not enough; the measurement time should be extended greatly. The further work is on going and will be drafted in a separate publication.

5 Numerical simulation on the micro jet device

Microjet device is the key part of the present cooling system shown in Figure 1. Its cooling performance determines the cooling effect of the total system. As shown in Figure 2, the device is small and the impinging jets are in a closed space, the sensor distribution and measurement is difficult to implement without sophisticated micro sensors, numerical simulation is an effective way to understand and optimize the flow and temperature distribution in the microjet device. In order to come up with a suitable numerical model to realize the numerical optimization, it is necessary to compare numerical results with experimental results.

There are several heat transfer means in the microjet device: LED chips produce heat, nearly all the heat will be transferred to impinging jet flow and jet device shell by forced convection and conduction respectively. For the latter, the heat in the jet device shell will exchange with the environment by natural convection. It is obvious that such a model reflects a coupled heat transfer process including natural convection, liquid forced convection and conduction. Here, commercial CFD code Fluent 6.2 is used for simulation.

Figure 10 demonstrates the simulation model of micro jet device, to compare the calculation results with experimental ones, all the parameters in simulation are exactly the same as those in experiments. Here the flow rate at the fluid inlet keeps constant at 10 mL/s, since the inlet diameter is 4 mm, the flow velocity at entry will be about 0.79 m/s. The micro jet shell material is stainless steel. The inlet water temperature is about 27℃. Other sizes are the same as those shown in Figure 6. Because the Reynolds number is about 3876, the turbulence model must be used for simulation. Here the turbulence model used in simulation is standard $k-\varepsilon$ model. Convergence study on grids is conducted before the calculation. They are refined until the flow field changes by 1%.

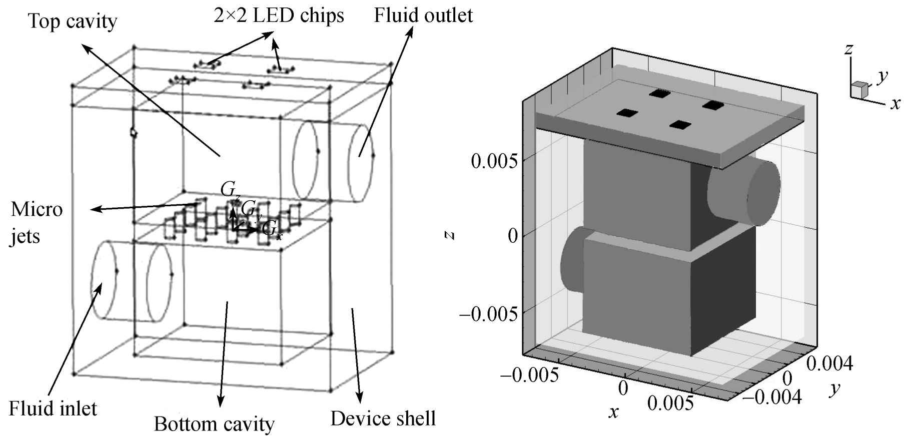

Figure 10 Simulation model at a certain view angle.

Figure 11 shows a temperature comparison between experiments and simulations. In 30 min, the temperature achieved by experiments is nearly steady, it is near 32.8℃, which is close to the steady simulation result of 34℃. The comparison shows that simulation model can be used for simulation and further optimization. In addition, the measured temperature in the present experiment can reveal the junction temperature magnitude to a great extent.

Figure 12(a) and (b) shows the simulated temperature distribution and velocity distribution in the micro jet device described in Figure 11. In Figure 12(a), the maximal surface temperature appears at the locations of 4 LED chips, which is about 34℃. Figure 12(b) demonstrates the velocity distribution inside the micro jet device. It can be observed from Figure 12(b) that the impinging jets do not arrive at the top wall. There are some vortexes inside the top cavity. By the simulation results, it is found that the flow resistance in the micro jet device is about 23551 Pa. The heat carried out by water is about 3.18 W, the temperature difference between the top wall and water is about 3 K. The real heat transfer area between water and the micro jet device is about 256e-6 m^2. Therefore, based on the equation $Q=\alpha F\Delta t$, it is easy to obtain the heat transfer coefficient of the micro jet device: $\alpha=\frac{Q}{F\Delta t}=\frac{3.18\mathrm{W}}{(256e-6*3)\mathrm{m}^2\cdot\mathrm{K}}=4140.6\ \mathrm{W/m^2}\cdot\mathrm{K}$. It should be

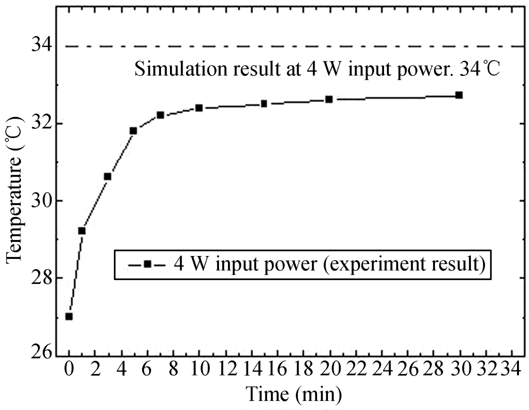

Figure 11 Temperature comparison between simulation result and experimental result.

noted that there is 4 W electrical power to be inputted into the four pieces of chips. Twenty percent of the electrical power is converted into 0.8 W optical energy and is emitted out, the other 80 percent of the electrical power will generate 3.2 W heat. From the simulation results, there is 3.18 W heat to be taken out by water cooling. Therefore, based on the energy conservation, 0.02 W heat will be dissipated out by natural convection at the shell of the micro jet device and the top surface of the LED chips. It is also found from Figure 12(b) that the design of the top cavity of the micro jet device is not ideal, the top cavity height is too large. Therefore the impinging jets cannot efficaciously reach the top wall because of large flow resistance in the top cavity. Nevertheless, the micro jets still have large impact on disturbing the fluid flow in the top cavity, even the micro jets do not reach the top wall and form impinging jets, the heat transfer coefficient of the present micro jet device is still large compared with conventional heat transfer means. In conclusion, the present device design needs parameter optimization to assure that the micro jets can impinge on the LED substrate directly, which will gain the best heat transfer efficiency.

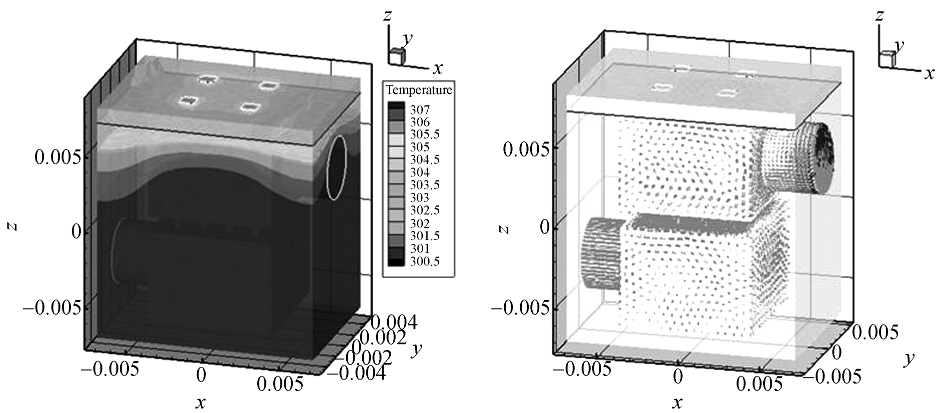

Figure 12 (a) Temperature distribution in micro jet device; (b) velocity distribution in micro jet device.

6 Summary

A closed-loop micro jet cooling system is proposed for the thermal management and packaging of high power LEDs in this paper. System-level experiments and preliminary numerical simulations are conducted, and the main conclusions are as follows:

(1) Comparative experiments demonstrate that the present cooling system has good cooling performance. It can efficaciously cool the LED chips. Without the present cooling system and just by natural convection to dissipate heat, at 16.4 W input power, the measured temperature of 2 by 2 LED chip array surface is about 112.2℃ after 10 min operation; however, when cooled by the present cooling system, its temperature is just 44.2℃.

(2) The larger micro pump flow rate will result in better cooling performance, however, it also increases the operation cost; the reliability and performance of the micro pump have important impact on the present cooling system.

(3) The simulation on the experimental device shows that at 4 W input power, the steady temperature of 2 by 2 LED chips array is about 34℃, which is close to the experimental temperature of 32.8℃. The comparative results demonstrate that the present simulation model can be used for next step parameter optimization and analysis.

(4) The simulation results demonstrate that the flow resistance in the micro jet device is 23551 Pa at 10 mL/s flow rate. The heat transfer coefficient is about 4140.6 $W/m^2 \cdot K$.

(5) The parameter optimization on system and micro jet device and the long time reliability test should be conducted in next step research.

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