Article
http://justc.ustc.edu.cn
Received: July 29, 2021; Accepted: August 20, 2021

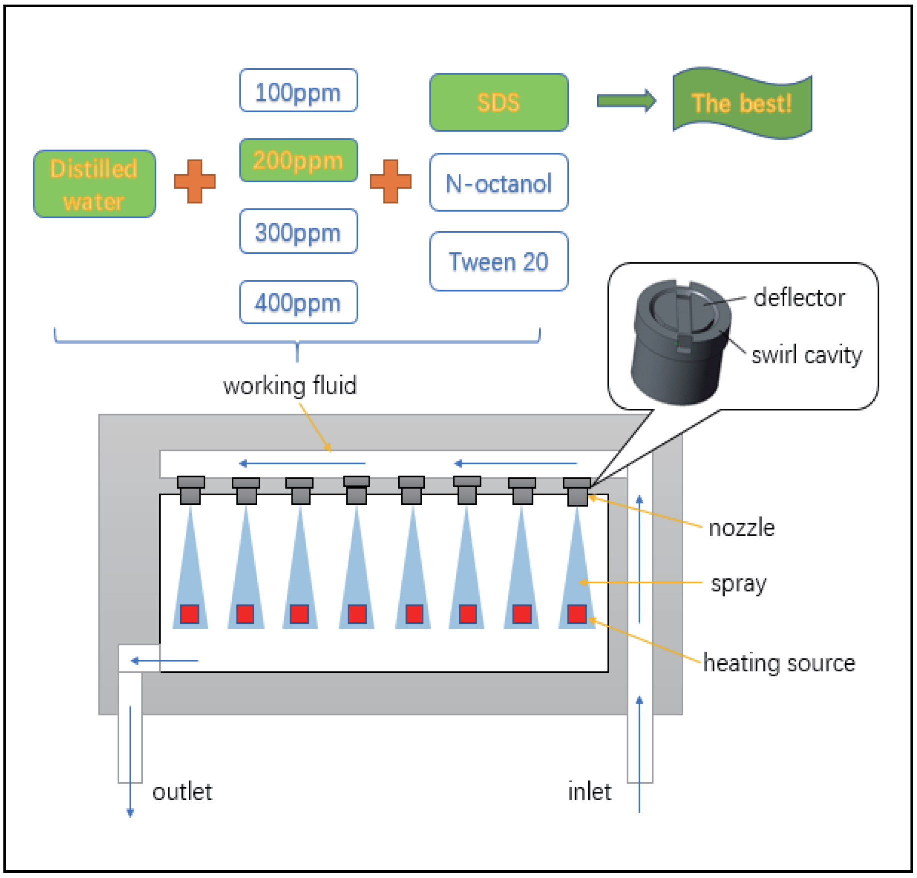
Experimental study on the effect of additives on the heat transfer performance of spray cold plate

Ruoxin Liu, Rui Zhao, Yongle Nian, and Wenglong Cheng ✉

Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei 230027, China

✉Correspondence: Wenglong Cheng, E-mail: wlcheng515@163.com

Graphical abstract



Adding 200 ppm of sodium dodecyl sulfate (SDS) can increase the heat transfer coefficient of the spray cold plate by 19.8%

Public summary

■ The spray cold plate can meet the heat dissipation needs of compact and multiple heat sources.

■ The strengthening effect of additives under the condition of spray cold plate is greatly weakened, but there are still some concentrations of additives that have positive effects. For example, adding 200 ppm of SDS can increase the heat transfer coefficient of the spray cold plate by 19.8%.

■ The mechanism of additive strengthening was studied and the heat transfer correlation formula of additive acting on spray cold plate was obtained. The maximum errors were 2.1%, 2.8% and 5.4% respectively.

Citation: Liu R X, Zhao R, Nian Y L, et al. Experimental study on the effect of additives on the heat transfer performance of spray cold plate. *JUSTC*, **2022**, 52(1): 4. DOI: 10.52396/JUSTC-2021-0152

Article

http://justc.ustc.edu.cn

Received: July 29, 2021; Accepted: August 20, 2021

Experimental study on the effect of additives on the heat transfer performance of spray cold plate

Ruoxin Liu, Rui Zhao, Yongle Nian, and Wenglong Cheng ✉

Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei 230027, China

✉Correspondence: Wenglong Cheng, E-mail: wlcheng515@163.com

Cite This: *JUSTC*, **2022**, 52(1): 4 (7pp) Read Online Supporting Information

Abstract: The spray cold plate has a compact structure and high-efficiency heat exchange, which can meet the requirements of high heat flux dissipation of multiple heat sources, and is a reliable means to solve the heat dissipation of the next generation of chips. This paper proposes to use surfactants to enhance the heat transfer of the spray cold plate, and conduct a systematic experimental study on the heat transfer performance of the spray cold plate under different types and concentrations of additives. It was found that among the three surfactants, sodium dodecyl sulfate (SDS) can improve the heat transfer performance of the spray cold plate, and at the optimal concentration of 200ppm, the heat transfer coefficient of the spray cold plate was increased significantly by 19.8%. Both the n-octanol-distilled water and Tween 20-distilled water can reduce the heat transfer performance of the cold plate using multi nozzles. In addition, based on the experimental data, the dimensionless heat transfers correlations for the spray cold plate using additives were conducted, and the maximum errors of dimensionless correlations for using additives were 2.1%, 2.8%, and 5.4% respectively. This discovery provides a theoretical analysis and basis for the improvement of spray cold plates.

Keywords: heat transfer; additives; spray cold plate; dimensionless correlations

CLC number: TK12 **Document code:** A

1 Introduction

With the development of miniaturization and integration of electronic components, the power density of electronic devices increases sharply in recent years. It is reported the power density of a chip made of gallium arsenide (GaAs) was less than 100 W/cm^2, while the power density of a common chip made of gallium nitride (GaN) has reached 200 W/cm^2[1]. However, the existing heat dissipation method can only achieve a heat dissipation capacity of about 120 W/cm^2[1]. Therefore, the heat dissipation of the chip becomes an urgent issue and has caused widespread concern.Spray cooling is a new and efficient cooling technology, which has the advantages of high heat exchange efficiency, fast heat dissipation, small thermal resistance, and good uniformity[2–6]. The spray cold plate adopts the spray cooling mechanism, which arranges multiple micro swirl atomization nozzles side by side and integrates them on the cold plate, which solves the problems of small spray range of a single nozzle, limited spray area and uneven droplet distribution. It can not only meet the needs of compactness and multiple energy sources, but also achieve a heat exchange effect with a high heat flux density of more than 200 W/cm^2[7].

Additives can effectively enhance the heat and mass transfer effect of spray cooling, and its heat transfer enhancement effect on spray cooling has been widely recognized.At present, the research on additives has mostly focused on salt additives and soluble gases or nanofluids. Wang et al.[8] used potassium chloride (KCl) to conduct an open-loop spray cooling experiment and found that there is a certain heat transfer enhancement effect, but the higher the concentration, the worse the heat transfer effect. Das et al.[9] conducted experiments with brine containing dissolved carbon dioxide and found that the heat removal rate showed an upward trend, but it decreased after the concentration exceeded 40%. Pati[10] found that after adding NaCl to the spray, the hindrance of the surface oxide layer to the heat transfer rate is weakened, thereby enhancing the cooling effect. Khoshvaght-Aliabadi et al. used numerical simulation and experimental methods to study the effect of fins on the nanofluid heat dissipation system[11−13]. However, the soluble gas is unstable, and the salt additives are corrosive and easy to block the nozzle. Therefore, our laboratory proposes the use of ionic and high-alcohol surfactants to improve the spray cooling heat exchange effect. Cheng et al.[14, 15] used *n*-octanol and 2-ethylhexanol as additives, and compared them with salt additives, and found that both can significantly enhance the single-nozzle spray cooling heat transfer effect, but the performance of high alcohol additives is better. Chen[16] further explained the dynamic Leidenfrost temperature rise caused by high alcohol surfactants from the perspective of bubble bursting and coalescence. Zhang[17] used high alcohol additives to conduct experiments and found that the heat flux and surface unevenness increased first and then decreased, and the effect in the single-phase region was small, but it was greatly enhanced in the two-phase region, and there is an optimal additive concentration at the same time. Li[18] explained the effect of surfactants on spray characteristics and fluid properties from the perspective of numerical simulation.

DOI: 10.52396/JUSTC-2021-0152

JUSTC, **2022**, 52(1): 4

In summary, some additives can improve the heat transfer performance of spray cooling. However, the previous studies mainly investigated the effect of additives on the heat transfer performance of single-nozzle and open-space spray cooling, the heat transfer performance of multi-nozzle spray cooling by using additives is relatively lacking, and the effect of additives on the spray cooling performance in the case of a closed small spray chamber is still unclear. Therefore, for improving the heat transfer performance of the multi-nozzle cold plate to meet the high-heat flux heat dissipation, this article made an experimental study on the effect of additives on the heat transfer performance of the compact spray cold plate, and different types and concentrations of additives were concerned. In addition, a new dimensionless heat transfer correlation of the three additives was fitted to provide a criterion for the theoretical analysis of the spray cold plate.

2 Experimental system and uncertainty analysis

2.1 Structure of the spray cold plate

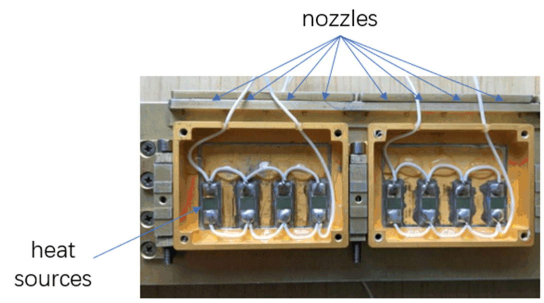
Fig. 1 is the physical picture and the internal flow channel design of the spray cold plate. The micro swirl atomizing nozzles are arranged in parallel and integrated on the cold plate to cool the heat source installed on the back of the cold plate. The front and back sides of the cold plate have 4 slots for installing heat sources. The distance between the front and back sides is 9 mm. The size of the spray cold plate is 380 mm (length) × 64 mm (height) × 9 mm (thickness). The heat source adopts thick film resistors, the substrate is aluminum nitride ceramic, the size of each heat source is 5 mm × 5 mm, the resistance is 160 Ω, the heat sources are connected in parallel, and each 4 heat sources correspond to one spray cavity, and two spray cavities are used for experiment. The installed object is shown in Fig. 1 a.

In this experiment, a miniature swirling atomizing nozzle is used. The spray angle is 35°, the outer diameter is 6.5 mm, the thickness is 5 mm, the outer flange diameter is 7.9 mm, and the outlet aperture is 0.3 mm.The micro nozzles are fixed on the top of the cold plate by thread, and every 4 nozzles are a group, corresponding to a spray chamber, which realizes the compact design.When working, the working medium flowing into the water inlet flows over the cold plate, atomizes into liquid droplets through the nozzle, jets to the surface of the cold plate, and then flows out of the water outlet through the bottom of the cold plate, as shown in Fig. 1 b, the flow distribution of each nozzle is relatively uniform.

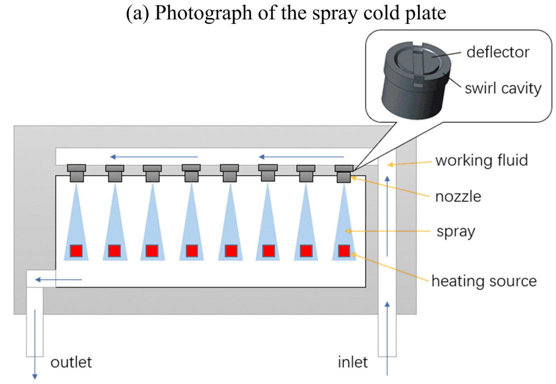
2.2 Experimental system and working conditions

On this basis, an experimental platform for the spray cold plate was designed and built, as shown in Fig. 2. The experimental system includes liquid storage tanks, micro pumps, filters, buffers, cold plates, pressure swirl nozzles, thick film resistors, plate heat exchangers, cryogenic thermostats, flow meters, shock-resistant pressure gauges, data acquisition instruments, etc.

A flow meter and a shock-resistant pressure gauge are installed in front of the cold plate entrance. The range of the



(a) Photograph of the spray cold plate



(b) Design of internal flow channel in spray cold plate

Fig. 1. Physical picture and the internal flow channel design of the spray cold plate.

flowmeter is 0~60 L/h, and the range of the shock-resistant pressure gauge is 0~150 Mpa. The T-type thermocouple is used to measure the temperature of the heating surface. The temperature measurement range is −200 ℃~350 ℃, and the temperature measurement error is ± 0.5 ℃. The experimental conditions are shown in Table 1. The inlet pressure in the table is the relative pressure.

The types and concentrations of additives used in the experiment are shown in Table 1. The concentrations are mass concentrations, and all working fluids are prepared and used on site.The specific experimental operations are as follows: ① Clean the entire experimental system with distilled water, and drain the distilled water after cleaning. ② Prepare different concentrations of SDS, n-octanol and Tween 20 solutions, and store them in stainless steel containers. ③ Turn on the power of the low temperature thermostat, set the water temperature in the thermostat to 15 ℃, and control the temperature of the working fluid at the entrance of the cold plate by adjusting the water flow through the heat exchanger in the low temperature thermostat. ④ Turn on the DC power switch to supply power to the inlet and outlet micropumps, adjust the pump power so that the flow and pressure at the inlet of the cold plate reach the preset value, and it is observed that the spray effect is good and the discharge is smooth. ⑤ Connect the AC transformer to supply power to the heat source resistance, and turn the knob to make the voltage at both ends of the heat source reach the preset value. ⑥ Turn on the power of the data acquisition instrument, and at the same time the supporting software on the computer starts to collect the temperature signal of the thermocouple. ⑦ When the temperature value of the thermocouple changes less than 1 ℃ within 10 minutes, it is considered that the entire experimental sys-

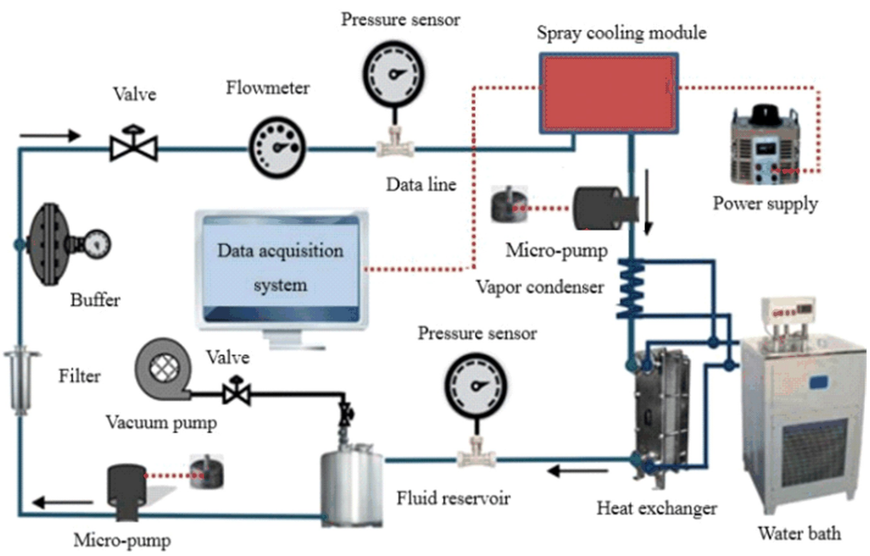


Fig. 2. Spray cold plate experimental system.

Table 1. Experimental conditions.

Category	Value
Ambient temperature (℃)	18.0
Environmental pressure (MPa)	0.1
Inlet pressure (MPa)	0.1
Working fluid flow (L·h^{-1})	53.0
Inlet temperature (℃)	15.0
Nozzle diameter (mm)	0.3
Types of additives	SDS, *N*-octanol, Tween20
Additive concentration (ppm)	100 / 200 / 300 / 400

Table 2. Measurement error of each measurement parameter.

Parameters	Measurement error
Temperature (℃)	± 0.5
Pressure (MPa)	± 0.002
Voltage (V)	± 0.5
Flow (L·h^{-1})	± 0.1
Current (mA)	± 1
Length (mm)	± 0.1

tem has reached thermal equilibrium, record the data, and adjust the transformer for the next round of experiments. ⑧ After a whole set of experiments, stop supplying power to the heat source, and when the surface temperature of the cold plate drops below 20 ℃, turn off the inlet and outlet micropumps and the cryogenic thermostat. ⑨ Clean the entire experimental system with distilled water. After cleaning, drain the distilled water and proceed to the next set of experiments.

2.3 Uncertainty analysis

In this experiment, a thick film resistor with aluminum nitride substrate is used as the heat source, which is connected to the shell by welding. Its thermal conductivity is high (170 W/(m·k)), the area of the heat source is small, and the backside is covered with thermal insulation material, so the heat is mainly dissipated by the spray cooling of the cold plate, and its power is calculated by

$$P = UI \tag{1}$$

where U and I are heating voltage and current respectively.

The heat flux density is calculated by

$$q'' = P/A_w = UI/A_w \tag{2}$$

where A_w is the area of the heating surface.

The heat transfer coefficient is calculated by

$$h = \frac{q''}{T_w - T_{in}} \tag{3}$$

where T_w is the surface temperature of the heating surface, and $T_{\rm in}$ is the inlet temperature of the working fluid.

The measurement error of each measurement parameter is shown in Table 2. According to the uncertainty transfer formula:

$$\sigma_y = \sqrt{\sum_{i=1}^{n}\left(\frac{\partial f}{\partial x_i}\right)^2 \sigma_{x_i}^2} \tag{4}$$

The uncertainty of main parameters discussed in the heat exchange correlation section can be calculated, which is shown in Table 3.

3 Experimental results and discussion

Using different concentrations of SDS-distilled water, *n*-octanol-distilled water, and Tween 20-distilled water as cooling fluids, experiments were carried out using the spray cold plate experimental system introduced above to explore the effect of additives on the heat transfer performance of the spray cold plates.

3.1 Influence of the concentration of additives on the heat transfer performance of spray cold plate

The cooling curve and heat transfer coefficient curve under different additive concentrations are shown in Figs. 3～5. It

DOI: 10.52396/JUSTC-2021-0152
JUSTC, **2022**, 52(1): 4

Table 3. The uncertainty of main parameters.

Parameters	Uncertainty
q'' (W·cm^{-2})	± 1.4%
h (W·cm^{-2}·K^{-1})	± 1.5%
Nu	± 2.5%
Re	± 0.7%
Pr	± 2.5%
W_e	± 0.2%
ε	± 0.8%

can be seen from the figure that the heat flux density and the surface temperature of the cold plate are generally linear, indicating that within the temperature range of the experiment, each working medium has not reached its saturation temperature, and the spray cooling is in the single-phase zone. In addition, it can be seen that the adding of part of the concentration of SDS significantly improves the heat transfer effect of the spray cold plate, among which 200 ppm SDS has the best heat exchange effect, followed by 100 ppm. The heat exchange effect of 400 ppm is only slightly better than that of distilled water. The addition of 300 ppm SDS makes the heat exchange effect of the spray cold plate worse, that is, with the concentration of additives increase, the heat exchange performance shows a phenomenon of first getting better and then getting worse. Considering the optimal concentration of 200 ppm, when the surface temperature of the cold plate is 30 ℃, 55 ℃, and 80 ℃, the heat transfer coefficient is increased by 27.10%, 13.71%, and 18.55%, respectively.

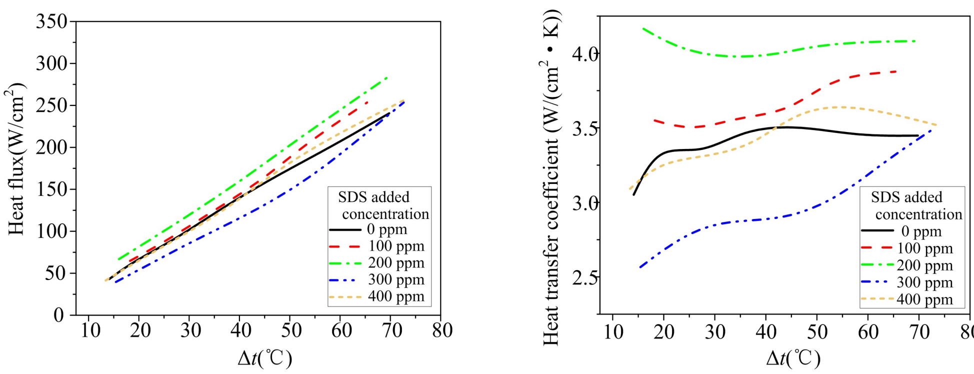


Fig. 3. Cooling curve and heat transfer coefficient curve under different SDS concentration.

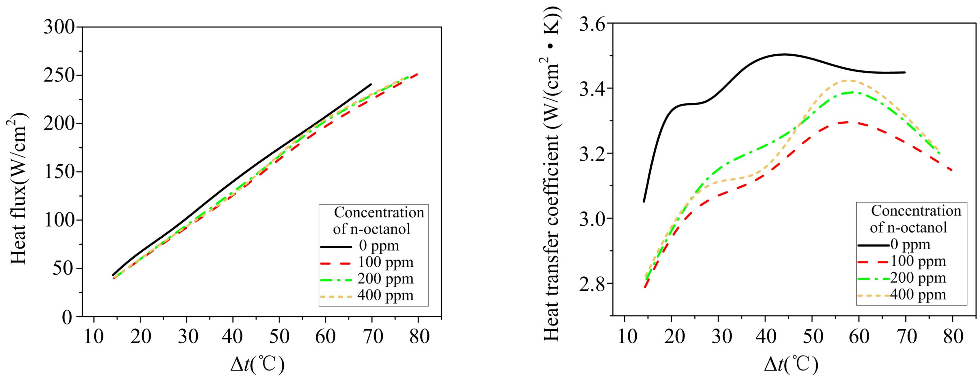


Fig. 4. Cooling curve and heat transfer coefficient curve under different n-octanol concentration.

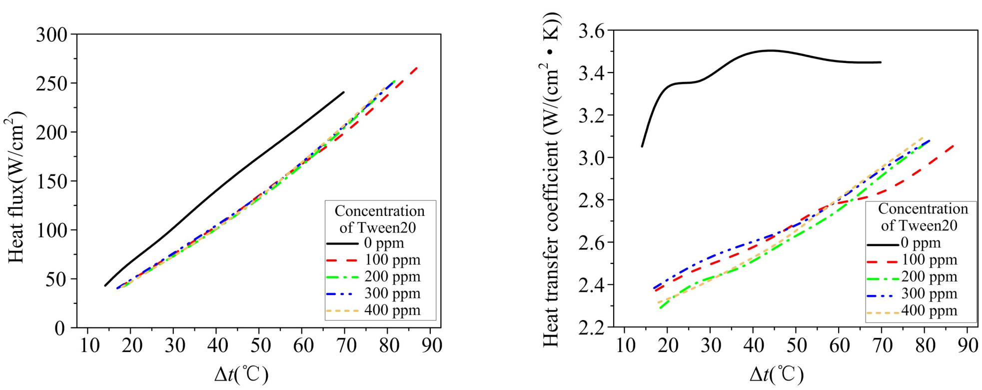


Fig. 5. Cooling curve and heat transfer coefficient curve under different Tween 20 concentration.

DOI: 10.52396/JUSTC-2021-0152
JUSTC, **2022**, 52(1): 4

Different from the effect of SDS, the addition of *n*-octanol increases the surface temperature of the cold plate and thus reduces the heat transfer coefficient of the cold plate, shown in Fig. 4. Among the three concentrations, 200 ppm *n*-octanol has the best heat exchange effect, and 100 ppm has the worst heat exchange effect, but all have worse heat exchange effects than distilled water. For the concentration of 200 ppm, when the surface temperature of the cold plate is 30 ℃, 55 ℃, and 80 ℃, the heat transfer coefficient is reduced by 9.66%, 7.43%, and 3.48%, respectively. The addition of Tween 20 also significantly weakens the heat exchange of the spray cold plate, although the 300 ppm Tween 20 showed the best performance, the heat transfer coefficient is reduced by 29.37%, 28.51%, and 17.94% respectively with the cold plate surface temperature at 30 ℃, 55 ℃, and 80 ℃, respectively.

3.2 The effect of spray cold plate on the strengthening effect of additives

To specify the difference in the effect between the cold plate using multi nozzles and single nozzle, the experimental comparison was made, shown in Fig. 6. The optimal concentration of SDS, *n*-octanol and Tween 20 were selected as 200 ppm, 200 ppm and 300 ppm for the cold plate and it were 800 ppm, 200 ppm and 45 ppm for a single nozzle[14, 15]. It can be clearly seen from the figure that compared to the single nozzle, the effect of additives on spray cooling has been greatly weakened by using the cold plate.It could be mainly because that the drainage problem could generate in the small closed spray cavity of the compact micro-nozzle array cold plate with high foaming additives. The three additives used in the experiment have a lower density than water and they are partially miscible, so it is easy for them to float on the surface of the working fluid, increasing the flow resistance and viscosity, and the foaming property is extremely enhanced. In the single-nozzle experiment[17, 18], the heating surface is an open platform, the liquid film stays on the heating surface for a short time and the spray flow rate is small. In the environment of the spray cold plate enclosed small spray cavity, foaming makes the drainage effect sharply worse, and the liquid film continues to accumulate, causing the droplets hitting the heating surface to dissipate heat and the convective heat exchange between the liquid film and the heating surface is greatly weakened, so the heat exchange effect becomes poor.

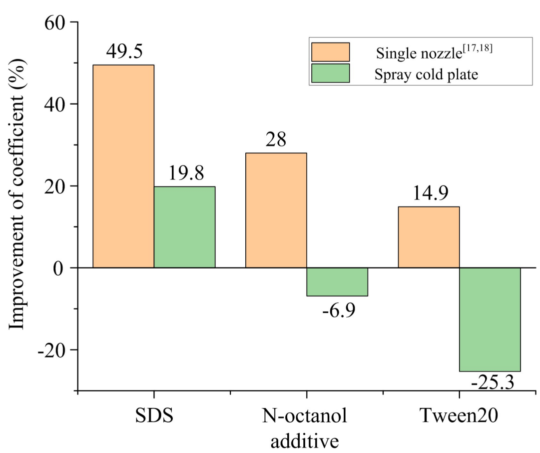


Fig. 6. Comparison of results between spray cold plate and single nozzle.

3.3 Physical properties of additives and their effects on spray characteristics

The additives used in the experiment are at the level of ppm, so the density, latent heat, boiling point and other physical properties of the working medium have no obvious changes. Fig. 7 shows the viscosity changes and the surface tension curves of each additive at different concentrations. It can be seen that the viscosity increases with the increase of the concentration at low concentrations, and no obvious change after reaching a certain concentration, which increases by 9.7% at most compared with water. It can also be seen that the surface tension decreases significantly with the increase of the concentration, and tends to be stable after reaching the critical micelle concentration (CMC). CMC of SDS and Tween 20 was 150 ppm and 400 ppm respectively, while *n*-octanol did not reach the CMC point. The physical properties were measured at 25 ℃.

Additives are substances that are slightly soluble in water, act on the water surface and form agglomerates in the water body. It mainly affects heat transfer by changing the surface tension of water. According to the mechanism of droplet breaking, the condition of droplet breaking is that W_e is greater than W_{eb} (critical Weber number), and the Weber number is inversely proportional to the surface tension σ, so the smaller the surface tension, the larger the Weber number, the easier the droplets are broken and atomized into small liquid drops. In addition, the reduction of surface tension can reduce the

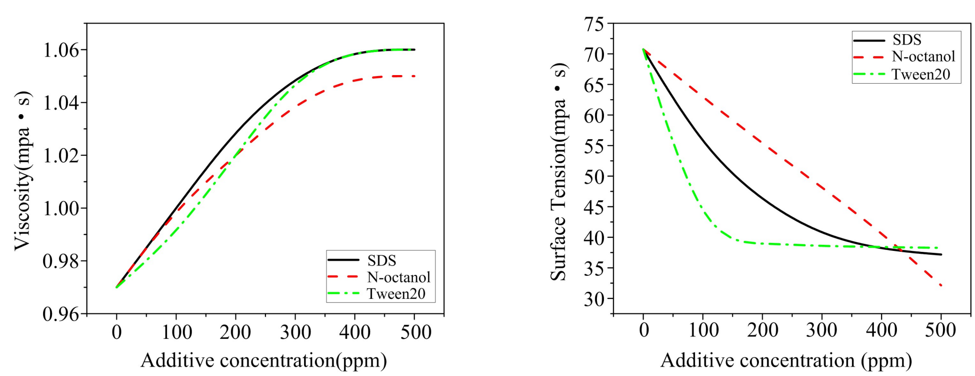


Fig. 7. The change curve of additive viscosity and surface tension with concentration at 25 ℃.

DOI: 10.52396/JUSTC-2021-0152
JUSTC, **2022**, 52(1): 4

solid-liquid contact angle, improve the spreadability and wettability of liquid droplets on the heating surface, and is conducive to boiling heat transfer. When the promotion effect is greater than the above-mentioned weakening effect, the overall heat exchange performance of the spray cold plate appears to be enhanced, so there is still a partial concentration of SDS that has a positive effect on the heat exchange performance of the spray cold plate.

4 Dimensionless correlations for spray cold plate using additives

The spray cooling in this experiment is in a single-phase zone, and the heat transfer characteristics are mainly affected by the spray characteristics, the physical properties of the working fluid, and the temperature. It can be represented by

$$f\left(h, D, k, \rho, \bar{u}, \bar{d}, \mu, \sigma, C_p, T_{\text{in}}, T_{\text{surf}}, T_{\text{sat}}\right) = 0 \tag{5}$$

Among them, h is the convective heat transfer coefficient(W/(m^2·K)), D is the width of the heating surface (m), k is the thermal conductivity (W/(m·K)), ρ is the fluid density (kg/m^3), $\bar{u}$ is the average droplet velocity (m/s), $\bar{d}$ is the average sauter diameter of the droplet (m), μ is the viscosity coefficient (Pa·s), σ is the surface Tension(N/m), C_p is the specific heat capacity of the working fluid(J/(kg·m^3)), T_{in} is the inlet temperature of the working fluid(℃), T_{surf} is the surface temperature of the cold plate (℃), T_{sat} is the saturation temperature of the working fluid(℃).

Introduce five dimensionless parameters: Nusselt number $\text{Nu} = \dfrac{hD}{K}$, Reynolds number $\text{Re} = \dfrac{\rho \bar{u} \bar{d}}{\mu}$, Weber number $W_e = \dfrac{\rho \bar{u}^2 \bar{d}}{\sigma}$, Prandtl number $\text{Pr} = \dfrac{C_P \mu}{k}$, dimensionless temperature $\varepsilon = \dfrac{T_{\text{surf}} - T_{\text{in}}}{T_{\text{sat}}}$. Get the new correlation as

$$\text{Nu} = f(\text{Re}, W_e, \text{Pr}, \varepsilon) \tag{6}$$

The heat transfer correlation equations of the three additives are obtained by fitting, and the form is as

$$\text{Nu} = A \cdot \text{Re}^B \cdot W_e^C \cdot \text{Pr}^D \cdot (E + \varepsilon^F) \tag{7}$$

The heat transfer correlation coefficients of the three additives are shown in Table 4, and the fitting curves are shown in Figs. 8～10. It can be seen from the figure that the calculated value of the heat transfer correlation equation fits well with the experimental value, and the maximum error is 2.1%, 2.8%, and 5.4%, respectively.

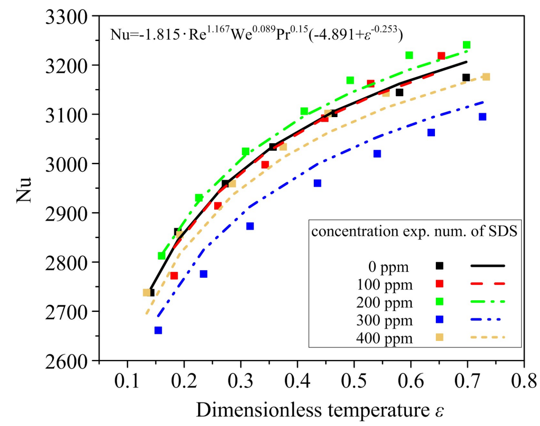


Fig. 8. Fitting curve and experimental value of SDS.

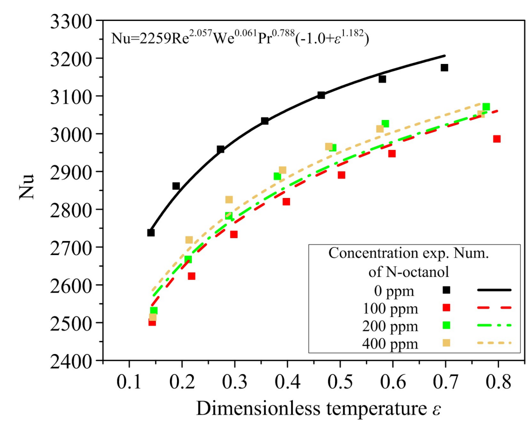


Fig. 9. Fitting curve and experimental value of n-octanol.

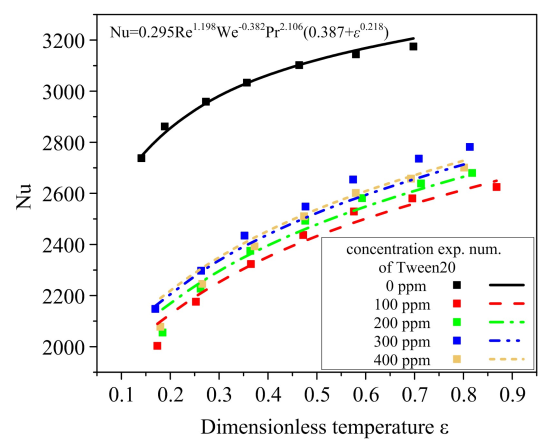


Fig. 10. Fitting curve and experimental value of Tween 20.

5 Conclusions

For improving the heat transfer performance of multi-nozzle cold plate to meet the high-heat flux heat dissipation, this article made an experimental study on the effect of additives on the heat transfer performance of the compact spray cold plate, and different types and concentrations of additives were concerned. In addition, a new dimensionless heat transfer correlation equation of the three additives was fitted to provide a criterion for the theoretical analysis of the spray cold plate. The main conclusions are as follows:

The addition of a partial concentration of SDS has a certain effect on improving the heat transfer performance of the spray cold plate. In this experiment, the optimal concentration of SDS is 200 ppm, which increases the heat transfer capacity of the spray cold plate by 19.8%. Both the addition of n-octanol and Tween 20 weaken the heat transfer performance of the spray cold plate. The optimal concentration of n-octanol is 200 ppm, which reduces the heat transfer capacity of the spray cold plate by 6.9%; the optimal concentration of Tween 20 is 300 ppm, which weakens the heat exchange capacity of the spray cold plate by 25.3%. This result is completely different from the single-nozzle additive experiment. In this experiment, the reason that the additives will greatly

DOI: 10.52396/JUSTC-2021-0152
JUSTC, **2022**, 52(1): 4

Table 4. The coefficient of heat exchange correlation of each additive.

Additives	coefficient					
	A	B	C	D	E	F
SDS	−1.815	1.167	0.089	0.150	−4.891	−0.253
N-octanol	2259	2.057	0.061	0.788	−1.000	1.182
Tween20	0.295	1.198	−0.382	2.106	0.387	0.218

weaken the effect of spray cooling performance is due to the foaming property of the additives and the drainage caused by the closed small spray cavity of the spray cold plate. In addition, based on the experimental data, the dimensionless heat transfer correlations of the spray cold plate under the action of additives is conducted, and the maximum error is 2.1%, 2.8%, and 5.4%.

Acknowledgments

This work is supported by the National Natural Science Foundation of China for the financial support (51876198).

Conflict of interest

The authors declare that they have no conflict of interest.

Biographies

Ruoxin Liu is currently a Master student in the Energy and Heat Transfer Laboratory of the Department of Thermal Science and Energy Engineering under the supervision of Prof. Wenlong Cheng at University of Science and Technology of China. His research mainly focuses on high heat flux heat dissipation and related research on surfactants.

Wenglong Cheng received his PhD degree in engineering thermophysics from University of Science and Technology of China in 2002 and is currently a professor of University of Science and Technology of China. His research interests include high heat flux heat dissipation and heat and mass transfer enhancement, thermal control and thermal management, thermal analysis of complex systems, and energy conversion and advanced power systems.

References

[1] Sharratt S A. Optimized structures for low-profile phase change thermal spreaders. UCLA, 2012. https://www.proquest.com/openview/458543586e3fc0902691c769a42a91e7/1?pq-origsite=gscholar&cbl18750.

[2] Xu X, Wang Y, Bang Y, et al. Recent advances in closed loop spray cooling and its application in airborne systems. *Journal of Thermal Science,* **2021**, *30* (1): 32–50.

[3] Fucheng H, Haihong D, Fan M. Research on simulation of heat transfer characteristics of intermittent spray cooling. *IOP Conference Series: Earth and Environmental Science,* **2021**, *647*: 012060.

[4] Zhou Z F, Chen B, Wang R, et al. Comparative investigation on the spray characteristics and heat transfer dynamics of pulsed spray cooling with volatile cryogens. *Experimental Thermal and Fluid Science,* **2017**, *82*: 189–197.

[5] Yata V V R, Bostanci H. Investigation of spray cooling schemes for dynamic thermal management. Proceedings of the 16th Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems Itherm. Orlando, USA: IEEE, 2017: 744-751. https://ieeexploreieee.53yu.com/abstract/document/7992560/.

[6] Alkhedhair A, Jahn I, Gurgenci H, et al. Parametric study on spray cooling system for optimising nozzle design with pre-cooling application in natural draft dry cooling towers. *International Journal of Thermal Sciences,* **2016**, *104*: 448–460.

[7] Jiang L J, Jiang S L, Cheng W L, et al. Experimental study on heat transfer performance of a novel compact spray cooling module. *Applied Thermal Engineering,* **2019**, *154*: 150–156.

[8] Wang Y, Zhou N, Yang Z, et al. Experimental investigation of aircraft spray cooling system with different heating surfaces and different additives. *Applied Thermal Engineering,* **2016**, *103*: 510–521.

[9] Das L, Munshi B, Mohapatra S S. The enhancement of spray cooling performance in nucleate and transition boiling regimes by using saline water containing dissolved carbon dioxide. *Journal of Thermal Science and Engineering Applications,* **2019**, *12* (2): 4044170.

[10] Pati A R, Mohapatra S S. The effect of oxide layer in case of novel coolant spray at very high initial surface temperature. *Experimental Heat Transfer,* **2019**, *32* (2): 116–132.

[11] Khoshvaght-Aliabadi M, Deldar S, Hassani S M. Effects of pin-fins geometry and nanofluid on the performance of a pin-fin miniature heat sink (PFMHS). *International Journal of Mechanical Sciences,* **2018**, *148*: 442–458.

[12] Hassani S M, Khoshvaght-Aliabadi M, Mazloumi S H. Influence of chevron fin interruption on thermo-fluidic transport characteristics of nanofluid-cooled electronic heat sink. *Chemical Engineering Science,* **2018**, *191*: 436–447.

[13] Khoshvaght-Aliabadi M, Hassani S M, Mazloumi S H, et al. Effects of nooks configuration on hydrothermal performance of zigzag channels for nanofluid-cooled microelectronic heat sink. *Microelectronics Reliability,* **2017**, *79*: 153–165.

[14] Cheng W L, Zhang W W, Jiang L J, et al. Experimental investigation of large area spray cooling with compact chamber in the non-boiling regime. *Applied Thermal Engineering,* **2015**, *80*: 160–167.

[15] Cheng W, Xie B, Han F, et al. An experimental investigation of heat transfer enhancement by addition of high-alcohol surfactant (HAS) and dissolving salt additive (DSA) in spray cooling. *Experimental Thermal and Fluid Science,* **2013**, *45*: 198–202.

[16] Chen H, Cheng W L, Peng Y H, et al. Dynamic Leidenfrost temperature increase of impacting droplets containing high-alcohol surfactant. *International Journal of Heat and Mass Transfer,* **2018**, *118*: 1160–1168.

[17] Zhang W W, Li Y Y, Long W J, et al. Enhancement mechanism of high alcohol surfactant on spray cooling: Experimental study. *International Journal of Heat and Mass Transfer,* **2018**, *126*: 363–376.

[18] Li Y Y, Zhao R, Long W J, et al. Theoretical study of heat transfer enhancement mechanism of high alcohol surfactant in spray cooling. *International Journal of Thermal Sciences,* **2021**, *163*: 106816.

DOI: 10.52396/JUSTC-2021-0152
JUSTC, **2022**, 52(1): 4