Two-Phase Spray Impingement Density Determination in Microchannel Cooling: Measurement and Optimization Results

Sasmita Bal, Purna Chandra Mishra and Ashok Kumar Satapathy

Abstract Within the past few years, electronic industry has developed vastly. Emerging technologies tend to increase demand for higher power densities in small dimensions. Hence, performance of the equipments used for military or electronic industry needs high heat removal from small areas which directly increase its performance. Hybrid cooling which takes advantage of both microchannel and spray impingement cooling is considered as one of the best technologies for critical heat removal so far. Among all controlling parameters of spray, mass impingement density (MID) is considered as the most influencing parameter for high heat removal. This paper describes an experimental study to evaluate and optimize MID for different values of air and water pressure and nozzle-to-surface height during spray-on microchannel. A mechanical patternator was used for collecting water during spray of base dimension 27 mm × 25 mm which was like the microchannel for which MID was calculated. The air and water pressures were varied from 1 bar to 3 bar for nozzle-to-surface height 10–20 mm. Optimal solution was found through response surface methodology (RSM) which concludes at air pressure 1 bar, water pressure 2.87 bar and nozzle tip to surface distance 17.52 mm maximum MID is achieved.

Keywords Microchannel cooling · Optimization · MID · Spray impingement · Two phase

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1 Introduction

Due to rapid growth in electronic industry, mini- and micro-chips are in high demand. Small size and high-power requirement lead to high heat generation in micro-level for which performance and efficiency both are matter of concern. Critical issues related to high heat flux removal in microelectronics beyond 100 W/cm^2 was mostly addressed [1]. To deal with this problem an exhaustive comparison of all possible cooling processes for micro-level cooling was made [2, 3]. Spray is one of the most promising among all direct cooling techniques applied in laser technique, steel quenching, casting cooling, microprocessor, and chip cooling. Spray cooling has been successfully implemented in thermal management of microelectronics [4]. Though single jet and multi-jet cooling was proposed by many researchers [5, 6], parametric investigation was done by very few researchers where they reported that pressure of the coolant, nozzle-to-surface height and mass flux impingement has a vital role to play [7, 8]. Current investigation reveals a method to find mass impingement density during spray on microchannel and optimize it for different level of parameters.

2 Air–Water Spray Impingement Setup

The following experiment was conducted with the assist of proper experimental setup fabricated and arranged at KIIT University, Bhubaneswar, Odisha, India. The various components that were used in the setup were spray setup, air–water supply, test stand, and patternator. The whole setup was designed to obtain optimized results for every run and to investigate the optimized mass flux impingement for air–water spray cooling. Figure 1 depicts the schematic arrangement of the air–water spray arrangement.

2.1 Spray Generator

The spray nozzles used in this experiment are made by the spraying system co. industrial spray nozzles (1/4 J pressure spray setup internal mix). These are air atomizing nozzles. This setup of spray cooling was specially designed for measurement of heat transfer coefficient (HTC). The spray generator again consists of three different parts, namely (a) pumping system (b) control panel (c) spray cooling test stand.

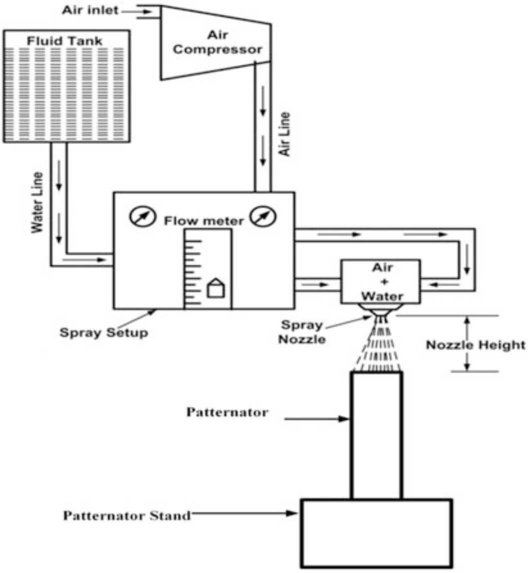

Fig. 1 Experimental setup for spray impingement

The spray nozzle consists of two steam chambers, namely

(a) Pressurized fluid water chamber
(b) Pressurized air chamber

The pressurized air influences the water or the fluid coming out of the hole and along these lines it also atomizes the fluid film. In this current experiment, the air atomizing nozzle (1/4 J pressure spray setup internal mix) is used. The increase in pressure difference between the fluid and air results in an increase in the relative speed between them.

2.2 Test Stand

The test bed was designed and fabricated to conduct the test for average and local value of mass flux impingement for spray cooling system. The test bed was designed in such a way that the height of the nozzle, the distance of the patternator from the nozzle and its positioning can be adjusted according to the needs. The test is kept gently on a stand that consists of an area of 250 mm × 200 mm.

2.3 Patternator

The mass flux in a given period is measured by collecting the water sprayed in a patternator. It is a device that is used to measure the amount of spray emitted and visualize its pattern at the same time. The distribution of fluid particles from the spray nozzle is called patternation. A nozzle spray which shows good patternation concludes that the spray has a preferable degree of symmetry and spray distribution.

2.4 Methodology and Procedure

The pumping system through which the compressed air and water shall flow was turned on and set according to the required adjustments. The pipes were checked for any kind of leakages. The control panel was turned on. Using the rotameter, the pressure of air and water were set. The experiment was conducted at three various pressures for air, i.e., 1, 2, and 3 bars. The water was also set at three different pressures during the various runs at 1, 2, and 3 bars. The spray nozzle was moved with the help of the pulley and fixed at the required height. The test bed was then measured from the nozzle tip and kept at distance of 10, 15, and 20 mm. The test was conducted at three different heights to find out the height where the optimized value for mass flux impingement will be achieved. The test bed was fixed at its position by the help of rubber stoppers. Then the experiment was conducted at various pressures and heights. To find more optimized value of the mass flux impingement, five test runs were made. The water collected in the patternator was measured after each run and the experiment proceeds.

3 Result and Analysis

3.1 Measurement of Average Mass Impingement Density

A graduated square glass compartment having measurements (25 mm × 27 mm 20 mm) was utilized to gather and measure the amount of water at various pressures of water and air. The different air and water pressures taken into consideration were 1, 2, and 3 bars. The length of splash is 4 s for accumulation of water in the rectangular patternator for count of normal impingement density at a specific mix of air–water. In the wake of setting the spray, the patternator was put under the spray and the distance between the nozzle tip and the patternator was maintained as 10, 12, and 15 mm for various test runs. The gathered water (m_{w}) was utilized to find mass impingement density using Eq. 1.

$$\dot{m} = \frac{m_{\mathrm{w}}}{A \times \Delta\tau \times 3600} \tag{1}$$

where $\dot{m}$ = mass impingement density, L/m^2-h, A = cross-sectional area of the patternator = (0.025 × 0.027) m^2, $\Delta\tau$ = duration of spray = 4 s, m_{w} = mass of water collected in liter.

3.2 *Response Surface Optimization of Spray Parameters*

The response surface methodology (RSM) was applied to develop optimization models for the influencing spray parameters. Before performing the cooling experiments, the optimal values of the MID were determined with the help of design of experiments and test data.

Design of Experiments (MID)

Water pressure, air pressure, and nozzle-to-target distance are the three levels of input variables are used. Twenty runs were produced by this procedure to perform the MID determination experiments. Table 1 shows the input variables with their levels and the coded model matrix along with the experimental outcome.

Table 1 CCF RSM formed coded experimental model matrix (MID)

Std	Run	Factor 1	Factor 2	Factor 3	Response 1
		A: water pressure (p_{w})	*B*: air pressure (p_{a})	*C*: nozzle height (*H*)	MID
		bar	bar	mm	L/h m^2
1	1	1	1	10	113,927
2	2	3	1	10	260,103
3	3	1	3	10	98,477
4	4	3	3	10	239,037
5	5	1	1	20	201,515
6	6	3	1	20	299,691
7	7	1	3	20	178,148
8	8	3	3	20	282,747
9	9	1	2	15	201,515
10	10	3	2	15	310,155
11	11	2	1	15	266,827
12	12	2	3	15	257,387
13	13	2	2	10	173,672
14	14	2	2	20	242,293
15	15	2	2	15	259,259
16	16	2	2	15	257,159
17	17	2	2	15	259,259
18	18	2	2	15	259,556
19	19	2	2	15	258,963
20	20	2	2	15	259,325

Experimental Model Obtained Using RSM (MID)

The regression analysis was accomplished, and a quadratic model was obtained for determining the MID from experimental values, which is represented in Eq. 2:

$$\begin{aligned}\mathrm{MID} = & -12.392 + 2.767 \times p_{\mathrm{w}} - 21783.87045 \times p_{\mathrm{a}} \\ & + 71407.196H + 100.875 \times p_{\mathrm{a}} \times p_{\mathrm{w}} - 2099.025 \times p_{\mathrm{a}} \\ & \times H - 94.875 \times p_{\mathrm{a}} \times H - 2677.36364 \times p_{\mathrm{w}}^{2} + 3594.63 \\ & \times p_{\mathrm{a}}^{2} - 2021.194 \times H^{2}\end{aligned} \tag{2}$$

Response Surface Analysis

The response surface investigation of the experimental values was conducted by design expert 8 software. The variation of MID is shown in Fig. 2 corresponding to air and water pressures. The peak value of MID was obtained at high value of water pressure and low value of air pressure. This is because the atomization of the water particle is more potent at greater values of air pressure, which allows maximum blownup of the water droplets and thus MID decreases. Figures 3 and 4 show variation of MID with water pressure and nozzle height and with air pressure and nozzle height, respectively. As water pressure increases MID increases, and as nozzle height increases, MID increases for a certain height and after that it decreases. Figure 4 shows significant effect of air pressure and nozzle height on MID.

Adequacy Test for Model

In this case, *A*, *B*, *C*, along with *AC* and C^2 are significant model terms. Values greater than 0.1 indicate the model terms are not significant. Table 2 shows adequacy test for the model.

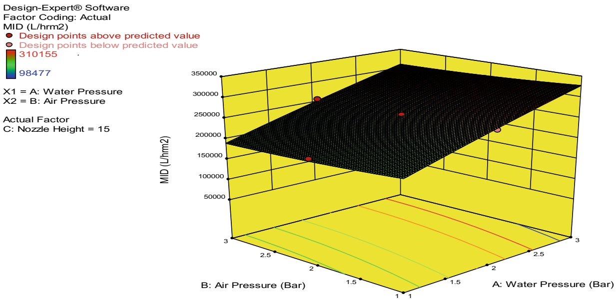

Fig. 2 Variation of MID with respect to p_{w} and p_{a} at H = 15 mm

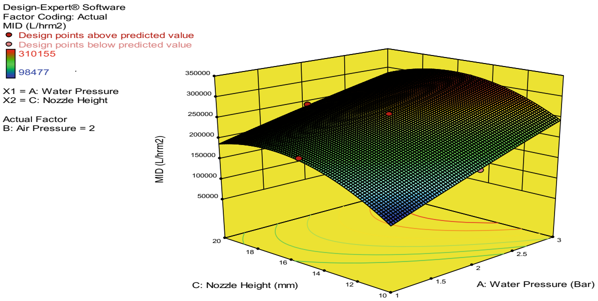

Fig. 3 Variation of MID with respect to p_w and H at $p_a = 2$ bar

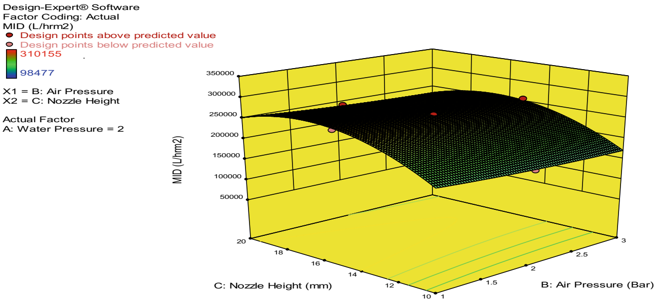

Fig. 4 Variation of MID with respect p_a and H at $p_w = 2$ bar

Response Surface Optimization

The response surface optimization was conducted to find the favorable condition in which the optimal MID was achieved. The condition is mentioned in Table 3.

Experimental Validation

Test was performed at the predicted maximum parametric conditions, i.e., for $p_w = 2.87$(bar) and $p_a = 1$(bar), nozzle height = 17.52 mm. The same procedure was followed to find MID in those conditions [9]. In the trial of experiment at the optimal conditions, the MID was obtained to be 318,448.14 (L/m^2-h). Comparing this value of MID with the key data, the experimental validity was verified with a minimum deviation. This may be due to the reason that due to experimental set up limitations.

Table 2 Adequacy test for the model

Source	Sum of squares	Mean square	F value	p-value Prob > F	
Model	6.012E+010	6.680E+009	443.81	<0.0001	Significant
A-water pressure	3.578E+010	3.578E+010	2376.90	<0.0001	
B-air pressure	7.442E+008	7.442E+008	49.44	<0.0001	
C-nozzle height	1.019E+010	1.019E+010	676.79	<0.0001	
AB	81406.13	81406.13	5.408E-003	0.9428	
AC	8.812E+008	8.812E+008	58.54	<0.0001	
BC	1.800E+006	1.800E+006	0.12	0.7366	
A^2	1.971E+007	1.971E+007	1.31	0.2791	
B^2	3.553E+007	3.553E+007	2.36	0.1554	
C^2	7.021E+009	7.021E+009	466.46	<0.0001	
Residual	1.505E+008	1.505E+007			
Lack of fit	1.466E+008	2.932E+007	37.58	0.0623	Insignificant
Pure error	3.901E+006	7.803E+005			
Cor total	6.027E+010				
Std. dev.	3879.77	R-squared	0.9975	AICc	417.88
Mean	2.340E+005				

Table 3 Optimized predicted MID value

p_w (bar)	p_a (bar)	Nozzle height (mm)	MID (L/h m^2)	Desirability
2.87	1	17.52	318456.82	1

4 Conclusion

Mass impingement density during spray plays an important role as it is directly associated with heat transfer rate. Increase in water pressure results in increase in spray density. On the other hand, at fixed water pressure, decrease in air pressure tends to increase mass flux. The reason may be because of increment of air pressure, intensity of atomization increases. The effect of nozzle-to-surface distance on mass impingement density (MID) was experimentally investigated. It was observed that, as the impingement height is increased from 10 to 15 mm, the nozzle cone angle increases and MID also increases. However, further increase of height from 15 to 20 mm causes lesser number of liquid droplets impinged on the target area.

The current research includes the optimization of controlling parameters like air–water pressure, nozzle-to-target distance on MID, etc., using RSM. Test was carried out at the estimated maximum parametric conditions, i.e., for $p_w = 2.87$ bar, $p_a = 1$ bar and nozzle height = 17.52 mm. The same method was followed to find the maximum MID in those conditions. In the trial of experiment at the maximum conditions, the MID was obtained to be 318,448.14 L/m^2-h. Comparisons of this data of MID with the key data confirmed the experimental validity with a minimum deviation.

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