Research on jet impingement cooling based on serial wedge-shaped wettability patterned surface

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Abstract. Jet impingement cooling technology has been widely used in many engineering fields. However, the flow direction of the water jet on uniform surface at high temperature is uncertain, thus the cooling efficiency using this technology is limited. Here, a serial wedge-shaped wettability patterned surface is fabricated on the aluminum sample to guide the water flow direction. During the water transportation on the patterned surface, the Laplace force is the main driving force. In this study, the cooling characteristics of water jet with different flow rates and initial temperatures are studied by the temperature data obtained according to thermocouples and multiplex temperature meter. Results show that both the center and edge positions of the sample possess excellent cooling efficiency. Additionally, we find that a better cooling effect can be observed when a larger flow rate of water jet was injected on the surface with a higher initial temperature.

1. Introduction

Cooling metal surface at high temperature is of great importance in numerous industrial fields, such as photoelectric devices, atomic energy equipment, avionics and so on [1-3]. As a common cooling technology, jet impingement cooling is a high-efficiency method that injects cooling fluid vertically onto the high temperature surface. After the injection of cooling fluid, a relatively thin boundary layer will be formed near the stagnation point. Theoretically, shortening the boundary layer can effectively enhance the heat exchange efficiency. In addition, utilizing jet impingement cooling to realize the heat transfer can greatly save space compared with other cooling methods that depend on cooling equipment volume. Thus, jet impingement cooling is suitable for local heat transfer. In recent years, extensive attention on the jet impingement cooling has been paid by experts and scholars in the academic and engineering fields, and the jet impingement cooling has been used in the practical industrial projects such as electronic equipment and laser equipment. Generally, jet impingement cooling can be divided into two categories according to the cooling medium including gas jet impingement cooling and liquid jet impingement cooling. Although the cost of gas jet impingement cooling is relatively low, its poor heat transfer ability can hardly meet the heat dissipation requirements of high heat flow density [4]. In contrast, the excellent heat transfer ability of liquid jet impingement cooling engenders its widely used in many cooling devices for various engineering applications. In traditional liquid jet cooling process, the direction of fluid flow cannot be controlled [5], so the stable flow of liquid jet cannot be performed on the high temperature surfaces. As a result, to achieve the cooling effect, more coolant (liquid jet) will be consumed.

In this paper, a serial wedge-shaped wettability patterned surface was fabricated on the aluminum plate by combining laser etching, electrochemical etching, and low surface energy modification. The
prepared serial wedge-shaped wettability patterned surface could realize the directional and pumpless transportation of water, and could be used for the directional jet impingement cooling for high temperature surface. Compared with the traditional single wedge-shaped patterned surfaces for pumpless transportation [4, 6-9], the serial wedge-shaped wettability patterned surface can realize the long-distance transportation of fluid because the superficial area and its width are not affected by the end size of the track, demonstrating the good practicability. 8 K-type sensors embedded in the aluminium plate were used to monitor and record the cooling characteristics of high temperature surface. Moreover, the cooling characteristics of aluminum surface were investigated under different initial temperature and water flow rate.

2. Materials and methods

2.1. Experimental materials
1060 aluminum plate (Al, purity > 99%) was purchased from Suzhou Metal Material Manufacturer (China). Fluoroalkysilane (FAS, C₈F₁₃H₄Si(OCH₂CH₃)₃) was purchased from Degussa Co., (Germany). Absolute ethanol (C₂H₅OH) was purchased from Tianjin Fuyu Fine Chemical Co., Ltd (China). All chemicals were of analytical pure and were used as received.

2.2. Fabrication of the serial wedge-shaped wettability pattern
According to the previous study of Song et al [10], the patterned surface with wedge-shaped track can be fabricated on the surface of Al plate by electrochemical etching and laser etching. Figure 1a shows the preparation process of the wettability pattern. Before electrochemical etching, the oxide layer on the Al surface was polished with 1500 grade abrasive papers. Then, the polished surface was cleaned by ultrasonic in deionized water for 3 min, and the obtained Al plate was electrochemical etched by 800 mA/cm² current in 0.1 mol/L NaCl solution for 10 min to obtain the micro/nanostructures. After electrochemical etching, the obtained surface was superhydrophilic. Subsequently, the superhydrophilic Al surface was immersed in 1 wt% FAS ethanol solution for 30 min, and then dried at 100°C for 10 min. The resulting surface revealed superhydrophobicity. Finally, the superhydrophilic serial wedge-shaped region was obtained by using a fiber laser marking machine (SK-CX30, Shanghai Sanke Laser Technology Co., China) at 12 W power, 20 kHz frequency and 200 mm/s traverse speed to remove FAS on the superhydrophobic Al surface.

2.3. Characterization
The contact angle of water droplet on the surfaces were measured by an optical contact angle meter (Krüss, DSA100, Germany), the volume of water droplet in the measurement was 4 µL. The transportation processes of the water droplet on the high temperature Al surface was recorded by high-speed camera (Sony DSC-RX10 III, Japan). All the tests were implemented at ambient temperature.

Figure 1. The schematic of the preparation process, digital image of the patterned surface, contact angle of the wedge-shaped wettability patterned surface. (a) The schematic of the preparation process. (b) Digital image of the wedge-shaped wettability surface with superhydrophilic region I and superhydrophobic region II. (c) Digital image of the contact angle of water droplet in superhydrophilic region. (d) Digital image of the contact angle of water droplet in superhydrophobic region.
2.4. Experimental setup

The structural parameters of Al plate sample and the schematic of the experimental setups are shown in Figure 2a and Figure 2b, respectively. As shown in Figure 2b, the sample was placed on a heater (HP-1515, Shanghai Hanbang Industrial Co., Ltd, China) that was set at a constant temperature. Water was injected to the starting position of the serial wedge-shaped wettability pattern by a syringe pump (Longer Pump, LSP01-1A, China). Owing to the directional transportation of water on the sample surface, the high temperature of sample surface can be reduced by the directional flow of water. As shown in Figure 2a and Figure 2b, 8 holes were drilled at the bottom of the sample. Then, 8 K-type thermocouples (Sensor 1-Sensor 8) which were connected with the multiplex temperature meter (DC5508U, DCUU, China) to measure the temperature were placed in different positions (S1–S8) of the sample. The thermocouples placed in positions S1–S4, and S5–S8 were used to measure the temperature of the center and edge positions of the sample, respectively. By connecting PC with the multiplex temperature meter, the temperature curves of the sensors at each position during the test were monitored. Moreover, the obtained temperature data were recorded at a sampling frequency of 1 Hz.

![Figure 2. Structural parameters and the experimental setups. (a) Al patterned plate with superhydrophilic wedge-shaped pattern and the superhydrophobic background. The installation positions of the 8 thermocouples are denoted as the red circles. (b) The schematic of the experimental setups.](image)

3. Results and discussion

3.1. Analysis of structural parameters and wettability of serial wedge-shaped patterned surface

As shown in Figure 1b and Figure 2a, the Al plate surface with a wedge angle of 5° was processed by electrochemical etching, laser etching and FAS modification. Every wedge of the serial wedge-shaped patterned surface has the wide end width of 3 mm and the narrow end width of 1.8 mm. Compared with the single wedge-shaped patterned surface, the long-distance transportation of water can be realized through the serial wedge-shaped patterned surface [10]. As shown in Figure 1b, there was a reservoir III at the end of the track, which can collect water transported through the serial wedge-shaped track. When the water collected in reservoir III reaches a certain volume, the water will fall from the Al sample due to gravity. Moreover, a small notch was made at the edge of reservoir III by a file to facilitate the flow of water. The water contact angles of region I and region II were shown in Figure 1c and Figure 1d, respectively. In region II, micron-sized rough structures were produced after electrochemical etching [9,10]. On this basis, through the low surface energy modification by FAS, superhydrophobicity was obtained and the contact angle of the surface reached about 160°. In region I, the FAS layer was removed by laser etching, and new micron-sized rough structures were regenerated [10]. Thus, the surface of region I revealed superhydrophilic, and the contact angle was about 0°.
3.2. Analysis of the transportation mechanism of water on serial wedge-shaped wettability patterned surface.

As shown in Figure 3, the pumpless and directional transportation test of the water droplet was performed on a horizontal serial wedge-shaped wettability patterned surface. The droplet with a volume of ≈ 70 μL was released from the needle at the starting position of the serial wedge-shaped pattern. Then, the droplet was immediately captured by the superhydrophilic pattern. Thereafter, the water droplet was transported from the narrow end of the track to the wide end with an average velocity of ≈ 0.14 mm/ms.

During the pumpless and directional transportation of water, there are two main forces acting on the droplet: the Laplace force ($F_L$) and the hysteresis resistance ($F_H$). The Laplace force provides a driving force for the transportation of water, while the hysteresis resistance of the superhydrophilic pattern to the water droplets hinders the transportation process [9,10]. Therefore, the resultant force ($F_R$) acting on the water can be estimated as follows:

$$F_R = F_L - F_H$$

![Figure 3. Sequential images of the water droplet transportation processes on a horizontal serial wedge-shaped patterned surface with the wedge angle of 5°.](image)

3.3. Analysis of cooling characteristics of water jet impingement.

After the injection of water jet on the serial wedge-shaped patterned surface, the water was captured owing to its superhydrophilicity, and then pumplessly and directionally transported from the narrow end to the wide end. In this section, we found that the transportation of water on the serial wedge-shaped pattern can effectively reduce the surface temperature of the heated sample. By keeping the water jet flow rate at 2700 μL/min, the cooling characteristics of the sample surface at different temperatures are shown in Figure 4. As shown in Figure 4a~Figure 4h, the initial temperatures of the surfaces in 8 groups of tests were 70°C, 80°C, 90°C, 100°C, 110°C, 120°C, 130°C, 140°C, respectively, and the injection of jet for cooling started at about 10 s. The initial temperature was based on the temperature measured by the four sensors placed on the center of the patterned surface (S1~S4 shown in Figure 2a). It is found that the temperature measured by the four sensors placed on the edge of the sample (S5~S8 shown in Figure 2a) was a little lower than those placed on the center.

When the water jet was injected on the sample surface with high temperature, the temperature first decreased rapidly. Then, with the continuous jet injection, the decreasing trend of temperature gradually slowed down. We found that the cooling law on the center of the track was consistent with that on the edge of the sample. The rapid cooling rate at the beginning of the cooling process was due to the high initial temperature of the surface causing the quick water evaporation. Meanwhile, the evaporation took away a large amount of heat, and this phenomenon was obvious on the surface at a higher temperature, as shown in Figure 4f~Figure 4h.

Under 2700 μL/min jet flow rate of water injection and 1 min jet cooling time, the temperature difference before and after sample cooling with different initial temperature was shown in Figure 5a. The temperature data of sensors 1~8 revealed that the cooling range of the sample gradually increased
with the increase of the initial temperature, indicating that the cooling effect of the water jet was obvious at high temperature. We speculated that the water evaporation at a higher initial temperature could take away more heat, and resulted in a larger temperature difference. Furthermore, the temperature difference at the center of the pattern was higher than that at the edge of the pattern. Water flew through the center of the pattern, thus the positions that enabled the transportation could carry away more heat owing to water flow and water evaporation.

Figure 4. Transient temperature response of thermocouples embedded in the sample. (The initial temperatures of the sample surfaces were 70°C, 80°C, 90°C, 100°C, 110°C, 120°C, 130°C, and 140°C, respectively.)

Figure 5b shows the temperature difference between the center position and the edge position of the sample after cooling under the same flow rate and cooling time parameters. The temperature difference between the center and the edge of the sample was larger at a higher initial temperature. When the initial temperature was 90°C and cooled for 1 min, the temperature difference before and after sample cooling with different jet flow rate was shown in Figure 5c. On both the center positions and the edge positions of the sample, the temperature difference before and after cooling gradually increased with the increase of jet flow rate, which means the cooling effect is better at a higher jet flow rate. We found that a larger jet flow rate could take away more heat and demonstrate a better cooling effect on the sample surface.
Figure 5. Temperature response of thermocouples embedded in Al plate after jet cooling for 1 min. (a) The temperature difference before and after sample cooling with different initial temperature. The jet flow rate was 2700 μL/min. (b) The temperature difference between the center positions and the edge positions of the sample after cooling. (c) The temperature difference before and after sample cooling with different jet flow rate under the initial temperature of 90°C.

Through the analysis of Figure 4 and Figure 5, it can be concluded that the serial wedge-shaped wettability patterned surface can produce the high-efficiency cooling effect during jet impingement cooling on the surface with high temperature. This patterned surface has a wide range of applications in electronics, biomedicine, aerospace and other fields due to its outstanding advantages such as simple structure and high jet cooling efficiency.

4. Conclusion

In this paper, the water jet impingement cooling characteristics on the serial wedge-shaped patterned surface of high temperature Al plate were studied. Superhydrophobic surface with a superhydrophilic serial wedge-shaped pattern was prepared on Al plate by laser etching, electrochemical etching and FAS modification. Owing to the driven of Laplace force, the pumpless and directional transportation of water jet flow could be achieved on the serial wedge-shaped pattern. Since the water jet of directional transportation could save a lot of coolant compared with the traditional jet, it could greatly improve the cooling efficiency of the surface with high temperature. Results show that both the center and edge positions of the sample achieved high cooling efficiency, and the cooling effect was more obvious when the surface has a higher initial temperature and injected with a larger jet flow rate. In addition, we found that the temperature decreased greatly on the sample with a high initial temperature during the initial stage of jet cooling due to the rapid evaporation of water taking away a lot of heat. We envision that our study may open up new avenues for jet impingement cooling for surfaces with high temperature.

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