Experimental study on heat transfer characteristics of flow on an inclined hot metal plate

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Abstract. In order to deeply understand the heat transfer characteristics of water and foam at high temperature with different inclination angles and initial surface temperature, pure water and foam were selected to conduct experimental research on high temperature surface liquid flow with inclination angles of 45 ° and 70 ° and initial surface temperature of 110 ° C, 210 ° C, and 310 ° C. It is found that the difference between the flow pattern and heat transfer of pure water and foam on the surface of high temperature metal plates is more obvious when the surface initial temperature is higher. The water flow form horseshoe-shaped low temperature region with the lateral width increasing and the longitudinal length decreasing on the higher temperature surface. The foam on the high-temperature surface is mainly cooled by the strip shaped area flowing in the mainstream direction; the length of the cooling area covered by the foam of the high-temperature surface is significantly longer than pure water.

1. Introduction

The method of passing a liquid film on the surface of a high-temperature wall is the main method for cooling in many fields such as industry, aerospace, nuclear energy, etc. When a fire occurs, for the metal equipment or fuel tank near the fire source, covering the outer surface of the high-temperature wall surface by spraying or other methods can significantly slow the wall temperature rise and avoid loss of metal mechanical strength [1], this kind of effective heat insulation protection measures can prevent the fire from spreading and the explosion of fuel in the container after being heated to a great extent. Because the liquid film flow on the high-temperature wall can involve many complex processes such as liquid film fluctuation, heat and mass transfer, and film rupture and drying, many scholars have carried out related research. Kabov [2-3] studied the liquid film flow on the vertical surface through experiments and theory, and analyzed the influence of Reynolds number and other parameters. Zhang [4-6] studied the special flow pattern and temperature distribution of the aqueous liquid film flowing on the vertical hot / cold wall surface, and analyzed the influence of the Marangoni effect. Yu [7] studied the fluctuation characteristics of the liquid water film flow formed by the wall inclination at normal temperature and the Reynolds number through experimental methods. Liu Mei [8] conducted an experimental study on the thickness change of the liquid film formed by the gravity-driven water film flow on the surface of the vertical flat plate at room temperature. Wang Buxuan [9] proposed a revised predictive formula for
the critical heat flow rate of liquid film fracture based on the research on the effect of capillary-induced interface evaporation in liquid film heat and mass transfer. Wang Yanhong [10] used the molecular dynamics simulation software LAMMPS to study the phase transition behavior of liquid argon films with different liquid film thicknesses on the hydrophilic platinum wall and hydrophobic platinum wall, and analyzed the liquid film thickness and wettability on the horizontal wall. However, most of the current research focuses on the room temperature wall surface or the wall surface temperature is less than 100 °C, less concerned about the large temperature difference between the high temperature wall and the fluid liquid film, which reflects the obvious influence of the liquid film boiling phase transition characteristics. In addition, it is also very important to consider foaming fires for oil fires in petrochemical tank farms and converter substations, etc. It is also important to understand the flow and heat transfer characteristics of foams on different inclined high-temperature surfaces and the differences between them and water films. Due to the complex nature of the foam's multi-phase flow, it determines the complexity and particularity of its flow on high-temperature walls in fires. Except Gao Yang [11] studied the vertical surface of compressed air foam under the action of flame radiation through theoretical and experimental methods In addition to thermal insulation performance, there are few related research reports.

In this paper, the experimental methods were used to study the flow and heat transfer properties of pure water and foam at the same flow rate on the surface of high temperature metal plates with different inclination angles, the characteristics of heat transfer mechanism and fire thermal protection engineering design have certain guiding significance.

2. Experimental system structure and equipment
The entire liquid flow experiment system is shown in Figure 1.

![Figure 1. Experimental system diagram](image1.png)

The high-temperature surface size of the metal plate used in the experiment is 1.0 m × 1.0 m. As shown in Figure 2 show, the metal plate is heated by its built-in and evenly distributed 20 electric heating tubes of the same type, with a total power of 30kW, heating the entire metal plate surface after setting the experimental temperature, the maximum temperature deviation in the experimental area is ≤2 °C.

During the experiment, pure water and foam were used as experimental liquids respectively. The foam was a 3% aqueous film-forming foam stock solution, which was foamed by a compressed air foam system to form a multiphase flow liquid foam with a gas-liquid mixing ratio of 6: 1. Before starting the experiment, adjust and fix the metal plate to the set angle, then heat the surface of the metal plate to the set temperature and keep it at a constant temperature, and then fill the storage tank with quantitative water or use the compressed air foam system to generate quantitative. The foam is injected into the liquid storage tank, and the liquid outlet is quickly opened. At the same time, data acquisition and video recording equipment such as temperature are turned on, so that the entire process of the experimental liquid flowing through the high temperature surface and the temperature change of the high temperature
hot surface are effectively recorded. The amount of pure water and foam liquid used in the experiment were 500ml, and they all flowed out vertically from the liquid outlet at a flow rate of 50ml/s and came into contact with the surface of the high-temperature metal plate and flowed down the surface. The experiment included metal plate inclination angles θ of 45° and 70°. The initial temperature Tw0 of the surface of the metal plate before the test liquid flowed out through the liquid outlet was 110 °C, 210 °C and 310 °C respectively, the ambient temperature was 18 °C to 19 °C.

3. Results and analysis

When the inclination angle of the metal plate surface is 45 and 70° respectively, under different initial high-temperature surface conditions, the three typical positions of Point 1-3 on the ideal flow path of the heated metal plate surface are directly below the injection port of the experimental liquid (the specific location is shown in Figure 1 (b)). The minimum temperature Tmin that can be reached after flowing the same amount of pure water (indicated by "W") and foam (indicated by "F") is shown in Figure 3. It can be seen from the figure. For pure water, although the minimum temperature at Point 1 closest to the liquid outlet increases with the increase of the initial temperature of the high-temperature metal plate, the minimum temperature at a tilt angle of 45 and 70° of the high-temperature metal plate is below 50 °C. While the minimum temperature at Point 2 and Point 3 is below 100 °C when the initial temperature of the high-temperature metal plate is 110 °C, the minimum temperature of the other two initial surface temperature scenarios is above 175 °C, which shows at this point, the temperature at Point 2 and Point 3 is not effectively cooled. At the same time, compared with pure water, the cooling effect of foam at each position is significantly better, and the difference in cooling effect of foam and pure water at each point is more obvious when the initial temperature of the surface of the high-temperature metal plate is higher. In addition, when the inclination angle of the high-temperature metal plate is 70°, the cooling effect of the foam at Point 2 is better than that when the inclination angle of the high-temperature metal plate is 45°.

![Fig. 3 The lowest temperature at typical locations on the surface of the metal plate](image-url)

Figure 4 is a photo of the flow patterns formed on the high temperature surface of the metal plate using pure water and foam under different initial high temperature surface conditions when the surface inclination angle of the high temperature metal plate is 45° and 70°. It can be seen from the figure that the difference between the two becomes more obvious as the initial temperature of the high-temperature surface increases. When the initial temperature of the high-temperature surface is 110 °C, pure water can be covered and wetted on the high-temperature surface according to the ideal flow path vertically downward from the liquid outlet. No obvious drops are seen on the surface of the high-temperature metal plate liquid. When the inclination of the high-temperature metal plate is 45°, the shape of the liquid film covered by the surface of the metal plate is approximately horseshoe-shaped when the initial temperature of the pure water is 210 °C and 310 °C, and a large amount of liquid is in the form of discontinuous drops from the lower edge of the liquid film. Rolling off, this is because when the liquid film on the surface of the high temperature metal plate is heated, due to the uneven temperature distribution of the liquid film, a special surface tension is, the Marangoni effect, which causes the flow...
to form a horizontal standing wave and two A side standing wave. At the same time, due to the relatively high temperature of the surface of the metal plate, the liquid film on the surface of the metal plate cannot maintain its original shape, and obvious dry spots appear, and the strong heat flux density on the surface of the metal plate makes it easy to make The liquid on the surface evaporates to form a film-like boiling, so that the liquid on the surface quickly rolls off in the form of droplets, which does not wet the wall well and cool it. When the inclination of the high-temperature metal plate is 70 °, the liquid on the surface flows faster under the action of gravity due to the increase of the inclination angle, so that it has a relatively greater downward flow momentum. Therefore, when the initial temperature of the high-temperature metal plate is 210 ° C it exhibits a horseshoe-shaped distribution shape caused by the Maragoni effect, and when the initial temperature of the high-temperature metal plate reaches 310 ° C, the wall surface temperature is high, even though the flow has a large momentum at this time, it still shows obvious The Maragoni effect. For the foam, regardless of the inclination of the surface of the high-temperature metal plate and the initial temperature, the white foam is mainly concentrated on the edge and lower part of the main wetted area. Moreover, although the coverage and wetting area of the foam on the high-temperature surface decreases with the increase of the initial surface temperature, under the conditions of the inclination of the metal plate surface and the initial temperature studied, it does not appear to be affected by the Maragoni effect. Obviously. This shows that although the main component in the foam is also water, compared to pure water, the difference in surface tension and other properties causes the two to have larger coverage, wetting, and flow patterns on the same high-temperature wall surface.

![Fig. 4 Photographs of water and foam flow patterns on the surface of the metal plate ((i): water; (ii): foam).](image)

When the inclination of the surface of the high-temperature metal plate is 70 ° and the initial temperature is 310 ° C, the temperature distribution of the surface of the metal plate in which pure water and foam cover the flowing area on the metal surface is shown in Figure. 5. When pure water is used as
the experimental liquid, the horseshoe flow pattern formed by the Maragoni effect also corresponds to its temperature field distribution shape. When the foam is the experimental liquid, its temperature distribution on the surface takes the form of a band-shaped low-temperature region and the center temperature is the lowest, and the temperature is higher the closer to the two sides of the boundary. It can be seen that the surface within a certain flow range when pure water is used the cooling zone has obvious lateral expansion in its mainstream direction, while the foam cooling zone is mainly along the mainstream direction, and the lateral cooling zone is significantly smaller than that in pure water.

![Fig. 5 Surface temperature change of metal plate](image)

Figure 5 shows the maximum effective cooling width $\delta_{\text{max}}$ that can be achieved under each experimental condition value. It can be seen from the figure that under the same liquid flow conditions, the width of the effective cooling of the surface of the high-temperature metal plate by the foam is significantly lower than that of pure water. When the surface inclination angle is 45°, the effective cooling area width of the foam is more than that of pure water. 50%, when the surface inclination is 70°, the faster liquid flow rate on the surface strengthens the heat transfer process between the liquid and the high-temperature surface to a certain extent, and the lateral width of the effective cooling area is increased. The width of the effective cooling zone in pure water is reduced by about 43%, which is slightly less than when the surface inclination is 45°.

![Fig. 6 The maximum width of the effective cooling area on the surface of the hot metal plate](image)

When the inclination of the high-temperature metal plate is 70° and the initial temperature is 310 °C, along the ideal flow path down the high-temperature metal surface below the liquid outlet, pure water and foam make the plate at a typical moment after the liquid begins to flow out of the liquid outlet The temperature drop at each point on the surface ($\Delta T$ is the difference between the initial temperature and the temperature of the high-temperature metal surface, which indicates that the liquid makes the temperature of the metal plate surface change in temperature). It can be seen from the figure that when pure water acts, the larger temperature drop mainly occurs within the length of 0.15m on the flow path, while the effect of foam The larger temperature drop mainly occurs within the 0.4m length of the flow path. Although the $\Delta T$ after the 0.5m length of the flow path is also significantly reduced, it still has a more obvious cooling effect than pure water. According to the flow pattern of the foam on the surface
of the high-temperature metal plate (Figure 4 (f)), it can be seen that although the lower half of the high-
temperature surface exceeds 0.5m in length along the flow path, the white foam is still covered, but at
this time The cooling effect of the high temperature surface has been significantly lower than the
temperature drop on the half of the flow path on the metal plate. It is inferred that the reason for this
result is that a large amount of liquid in the foam liquid has evaporated in the upper half of the high
temperature surface. In the lower half of the high-temperature surface, the bubbles that flow on the high-
temperature surface are mainly air bubbles containing a large amount of air. This kind of dry foam with
a low water content has a significant reduction in the cooling effect on the high-temperature surface.

![Graph](image)

**Fig. 7 Temperature at a typical moment in the direction of liquid flow on a tilted hot metal plate**

4. **Conclusion**

1) Under the conditions of the same surface inclination and initial temperature, there is a clear difference
in the flow state of pure water and foam on the surface of the high temperature metal plate, which in
turn affects the heat transfer and cooling law between the liquid and the high temperature metal plate,
and the difference between the two As the initial temperature of the high-temperature surface increases,
it becomes more obvious.

2) When the inclination angle of the high-temperature surface is small and the temperature is high,
the shape of the liquid film and the effective cooling area covered by the pure water on the surface of
the metal plate is similar to the shape of a horseshoe. The horseshoe-shaped wetting area decreased
significantly. However, within the range of experimental conditions, the foam liquid is mainly cooled
by strips along the mainstream direction.

3) Under the same liquid flow rate, the width of the effective cooling of the surface of the high-
temperature metal plate by the foam is significantly lower than that of pure water. When the surface
inclination is 45 °, the effective cooling area of the foam is reduced by more than 50% compared with
pure water. When the surface inclination angle is 70 °, the width of the effective cooling area of pure
water and foam is increased due to the increase of the liquid flow rate on the surface, but the width of
the effective cooling area of the foam is reduced to about 43 %.

4) The effective cooling area coverage of the foam in the flow direction is significantly longer than
that of pure water.

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