An Experimental Investigation on the Analogous Transpiration Cooling Utilizing Hydrogels as Coolants

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Abstract. In the applications of transpiration cooling, water acting as a liquid coolant shows excellent cooling performances due to its huge heat capacity and latent enthalpy. However, the fluidity of liquid water could cause extra difficulties on occasions where unexpected interferences to the system balance should be avoided. To overcome the above issue, we propose a new transpiration cooling pattern, in which the liquid water is solidified and stored as hydrogels. In this work, the hydrogel was prepared from the superabsorbent polymer (SAP) and thermogravimetric analysis was conducted to test the water release property and upper critical temperature. Respectively using water and hydrogels as coolant, transpiration cooling experiments on a homemade porous plate were carried out to explore the feasibility and cooling performance of the new transpiration cooling pattern. The results implied that the transpiration cooling with hydrogels and water can both slow down the temperature rising of the structure. The hydrogel can provide considerable cooling effect and is superior for prolonging service time.

1. Introduction

In the development of transpiration cooling, the transition of coolant from gases to liquids improves the cooling effect on high heat flux surface greatly [1]. As a common liquid coolant which has huge heat capacity and latent enthalpy, water plays an important role in researches on transpiration cooling [2,3]. The transpiration cooling based on water has been widely investigated and its high efficiency has been validated in protecting the leading edge of hypersonic vehicles and combustion chamber [4–6]. However, there are still many issues to solve to accelerate its applications. Apart from the complex system for water injection control, the movement of liquid water causes extra problems, such as a higher requirement for sealing and the variation of barycenter position, which may even destroy the balance of the whole system at last. Then, it’s meaningful to make some improvements on the transpiration cooling with liquid water, and the analogous transpiration cooling (ATC) utilizing solidified water could be a new direction.

In the process of ATC, as shown in Figure 1, solidified water acting as a cold source is pre-sealed in the coolant chamber, and its state decides the good sealing performance that it cannot be pushed into the porous matrix at the initial moment. When the chamber temperature is above the phase-change point, the corresponding vapor will flow out through the porous matrix and forms a protection film layer on the surface. It should be noted that phase change may occur anywhere in the traditional transpiration cooling with liquid water while can only happens in the coolant chamber in ATC.
Hydrogels own an integrated ability of water absorption, water retention and water release. And due to the good biocompatibility, hydrogels have been widely studied and applied in the field of agriculture and biomedicine. However, most of the existing researches were focused on the mechanical behaviors, improved synthesis methods and drug sustained release [7–9]. There are little investigations on utilizing hydrogel in the heat dissipation, especially with the application of transpiration cooling. In the work conducted by Huang Z. etc. [10], the bio-inspired nano-skin technique based on the temperature sensitive hydrogels was studied with the aim to enhance the heat dissipation of electron devices.

In this paper, we proposed a new cooling mechanism, i.e. analogous transpiration cooling; then we conducted the experimental investigation on the corresponding cooling performances using hydrogels as coolant, and compared with that of liquid water. The aim is to provide a reference for the designers of heat dissipation.

2. Experimental arrangement

2.1. Experimental system
The experiment was conducted in the open low-speed electrical heated wind tunnel at the University of Science and Technology of China. Compressed air with a controlled flow rate is electrically heated to a given temperature and employed as the mainstream. The measurement instruments include the infrared thermal imaging system (NEC TH504) which captures the temperature distribution on the surface of plate, and several K style thermocouples for the temperature monitor in the coolant chamber at different positions. The accuracy of them is 1% and 0.75%, respectively.

2.2. Test apparatus
The specimen is separated into two main parts, the porous plate and the supporting structure with a chamber inside, as shown in figure 2. The porous plate has an average diameter of 100 µm and a thickness of 4mm, and the size of its upper surface is 42mm*72mm. Three thread holes are drilled in the coolant chamber and the thermocouples are installed to monitor the coolant temperatures at different positions, with a distance of 9mm, 11mm and 6mm to the bottom of the plate, respectively.

Figure 1. Schematics of analogous transpiration cooling and traditional transpiration cooling

Figure 2. Schematic diagram of the experimental system and test apparatus
2.3. **Hydrogels**

In this exploratory experiment, an ordinary superabsorbent polymer (SAP) was used to prepare hydrogels. The SAP is mainly based on the low crosslinked polyacrylic resin and its strong water-absorption could meet our primary requirements on water retention and solidification. By means of natural filtration, it is measured that the SAP has a water absorption ratio up to 167 times of its own weight. In the test, we chose the hydrogels with a ratio of 100:1, and it shows good performance in keeping immobilized.

To learn more about its property of water loss at high temperature, a Thermogravimetric Analysis (TGA) test was conducted and the result is shown in figure 3. From figure 3, we can find that there is an obvious weight drop once the heating begins. When the temperature increases to 173.61°C, the ratio of weight loss reaches 98.85%, which means that the water absorbed almost completely releases. Besides as the temperature keeps rising, no more water releases and the SAP decomposes at a temperature about 400.86°C.

![Figure 3. TGA curve of the hydrogel](image)

3. **Analysis of experimental phenomena**

Under the same mainstream conditions, $T_\infty = 500^\circ\text{C}$ and $V_\infty = 1000\text{L/min}$, three groups of comparative experiments were conducted at different chamber conditions, i.e. empty, filled with SAP hydrogel and pure water.

3.1. **Temperature distribution on the whole surface**

Figure 4 shows the temperature distributions on the surface with an empty chamber at different time intervals, in which the mainstream flows from top to bottom. It should be noted that when the mainstream achieves to a relatively stable state, the moment as the plate is exposed to the hot temperature mainstream is chosen as the initial state, and is marked as $\Delta t=0$. As shown in figure 4, the surface temperature of the porous plate increased with time, and the high-temperature region moved towards the outlet of wind tunnel. The highest temperature on the surface monitored is about 322°C.

![Figure 4. Temperature distributions of the porous plate with an empty chamber](image)
To study the cooling performance of analogous transpiration, the temperature drops of the porous plate using SAP hydrogels and water as coolants from that with the empty chamber are calculated at the same time intervals and exhibited in figure 5 and figure 6.

![Figure 5](image-url)

**Figure 5.** Temperature drop on the surface of porous plate with SAP hydrogels and empty chamber

From the figures, we can find that the existence of coolant slows down the temperature rising rate in both cases, and the temperature drop varies with time. For SAP hydrogels, the temperature drop is 100°C at Δt=1min, and decreases to 30°C at Δt=5min. This phenomenon is mainly caused by the variation of coolant height in the chamber, as the time exposed to high heat flux increases, the coolant filled has no contact with the plate anymore and the heat dissipation is weakened. In addition, through the comparison of figure 5 and 6, it can be found that at the same time intervals, the liquid water always exhibits a better cooling effect than hydrogels, because the effective mass of water is smaller for hydrogels at the same coolant volume.

![Figure 6](image-url)

**Figure 6.** Temperature drop on the surface of porous plate with water and empty chamber

3.2. Local temperature on the surface and in the chamber
As the surface temperature and coolant temperature varies in different positions, the local rectangle area A is chosen (as shown in figure 2), and the corresponding average temperature is calculated.
Figure 7. Variations of temperature averaged over area A and monitored by thermocouple 2 in the chamber

Figure 7 presents the transient variations of temperature within area A (curves) and the chamber temperature measured by thermocouple 2 under different chamber conditions. From figure 7, one can observe the following phenomena: 1) compared to the empty chamber, the temperatures on the surface and in the chamber are obviously lower when using hydrogels and water as coolant, especially at the initial stage. 2) In the case of hydrogels and water, there is a delay in temperature rising, and this delay period is longer when using hydrogels as coolant. Especially, during the intervals from 200s to 1000s, the hydrogels even has a better cooling effect than water. During this period, the hydrogels have a longer contact time with the porous plate due to the interstitial structure of stacked gels granule. 3) The chamber temperatures of gels and water change synchronously and increase gradually to 85°C. It indicates that under such experimental conditions, the monitor point is still be filled with coolant.

4. Conclusions
A series of exploratory experiments were conducted based on the newly proposed analogous transpiration cooling. From the analysis, the following conclusions can be drawn:
1) In comparison with the empty chamber, the filling of coolant, i.e. hydrogels and water, shows an excellent performance in slowing down the rising of surface temperature.
2) The delay period and the changing trend of surface temperature are different in analogous transpiration cooling with hydrogels and water. In general, water performs better within the first 200s, while the cooling effect of hydrogels lasts longer and is superior when the exposure time is more than 200s.
3) Hydrogels can provide considerable cooling performance with water and maintain a stable state without any coolant fluctuation and fluidity. Therefore the ATC using hydrogels as coolant holds great potential in the heat dissipation applications.

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