International Journal of Thermal Sciences 79 (2014) 276–282

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

# Cooling performance of bio-mimic perspiration by temperature-sensitive hydrogel

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ARTICLE INFO

*Article history:*
Received 26 February 2013
Received in revised form
21 January 2014
Accepted 21 January 2014
Available online 23 February 2014

*Keywords:*
Heat dissipation
Evaporation
Temperature sensitive hydrogel
Microelectronics cooling

ABSTRACT

A novel passive cooling solution, Bio-mimic Perspiration Cooling (BP-Cooling), was recently proposed, which mimics the thermoregulation mechanism of living creatures to supply extra passive cooling on demand using an intelligent skin made from temperature sensitive hydrogel (TSHG). In this paper, the heat and mass transfer characteristics of BP-Cooling are investigated. The temperature and humidity fields of BP-Cooling are measured by the Twyman-Green interference technique and modeled by computational fluid dynamics (CFD) simulations. The validated CFD model is further used to study the impacts of different usage conditions, e.g. ambient temperature, ambient humidity, and the starting temperature of BP-Cooling, on the BP-Cooling performance. Results show that BP-Cooling can improve passive cooling performance up to twenty times above natural convection and may be powerful enough to enable next-generation mobile phones perform like personal computers in a wide design envelope.


## 1. Introduction

Recent advances of information technology, including large-capacity flash memories, 4G wireless telecommunication [1,2], and flexible displays [3,4], have increased the potential of mobile phones to replace personal computers (PCs) to become next generation personal central microelectronics devices. However, even the most powerful smart phones nowadays still operate much slower than PCs. One technical bottleneck is heat dissipation, partly due to the fact that mobile phones are not suitable to have cooling fans like PCs. Advanced passive cooling solutions which are quiet and battery saving are of great importance. Bio-mimic Perspiration Cooling (BP-Cooling) proposed by Huang et al. [5] recently can be a promising candidate to meet this demand.

The key component of a BP-Cooling system is a layer of temperature-sensitive hydrogel (TSHG) [6], a smart macromolecular material which is capable of releasing moisture automatically when its temperature exceeds the lower critical solution transition temperature (LCST) [7,8]. This unique thermal response property has drawn many researchers' interests [9–11], and has been successfully used for enzymes immobilization [12–14], solute separation [15], drug delivery control [16–19] and so on. Huang et al. [5] first applied this property to mimic the thermoregulation mechanism of living creatures to control the skin temperature of smart phones. When the skin temperature is high (i.e. above LCST), TSHG can sweat the mobile phones with water and boost the heat dissipation rate through evaporation. TSHG can be replenished by absorbing moisture from surroundings when the skin temperature is low.

In this paper, we focus on the cooling performance of the bio-mimic perspiration from a layer of TSHG. Laser interference technique is used to measure the temperature and humidity fields above the TSHG when BP-Cooling is taking effect. Measured results are used to calibrate a CFD model with the same geometry and under the same environmental conditions. The calibrated CFD model is then extended to study the heat dissipation capability of this novel cooling technology in different application conditions.

## 2. Experiments

### 2.1. Materials preparation

The hydrogel used in the paper is made by Nitrogen-isopropylacrylamide (NIPAM), *N*-methylenebisacrylamide (BIS), Hydroxyethyl methacrylate (HEMA), Sodium dodecyl sulfate (SDS) and Ammonium persulfate (APS) under anoxic conditions. The basic material of the TSHG is NIPAM, which makes the original LCST around 32 °C [20]. We increase the LCST of the TSHG used in the experiments to 37 °C by adjusting the dosage of BIS.

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1290-0729/$ – see front matter 
http://dx.doi.org/10.1016/j.ijthermalsci.2014.01.015

**Nomenclature**

*English symbols*

| | |
|---|---|
| $a$ | thermal diffusivity of air ($m^2/s$) |
| $D$ | mass diffusion coefficient of water vapor in air ($m^2/s$) |
| $g$ | acceleration of gravity ($m/s^2$) |
| Gr | heat transfer Grashof number |
| $Gr_m$ | mass transfer Grashof number |
| $h_{cv}$ | convective heat transfer coefficient ($W/m^2$ K) |
| $h_m$ | mass transfer coefficient (m/s) |
| $h_{pr}$ | perspiration heat transfer coefficient ($W/m^2$ K) |
| $h_{rd}$ | radiative heat transfer coefficient ($W/m^2$ K) |
| $k$ | thermal conductivity ($W/m^2$ K) |
| $L$ | length of the U-groove (cm) |
| $l$ | shape factor of the U-groove (cm) |
| $n$ | the relative refractivity of air |
| Nu | Nusselt number |
| $P$ | pressure (Pa) |
| $P_v$ | water vapor pressure (Pa) |
| Pr | Prandtl number |
| Sc | Schmidt number |
| Sh | Sherwood number |
| $T$ | temperature (K) |
| $x$ | width of the sample cell (cm) |

*Greek symbols*

| | |
|---|---|
| $\beta$ | the volumetric thermal expansion coefficient |
| $\delta$ | optical path difference (nm) |
| $\varepsilon$ | emissivity of U-groove surface |
| $\gamma$ | latent heat of water vaporization (J/kg) |
| $\lambda$ | laser wavelength (μm) |
| $\nu$ | kinetic viscosity ($m^2/s$) |
| $\rho$ | density ($kg/m^3$) |
| $\sigma$ | Stefan–Boltzmann constant ($W/m^2$ $K^4$) |
| $\tau$ | time (s) |

*Subscripts*

| | |
|---|---|
| $a$ | ambient |
| $s$ | surface |
| $v$ | vapor |

### 2.2. Experimental method

To simulate the heat dissipation of smart phones, a simple cuboid sample cell is fabricated, which is 13 cm long, 3 cm wide and 4 cm thick. The sample cell is longer than a regular smart phone to have enough optical path length for better measurement accuracy. The temperature and moisture distributions resulted from the heat dissipation of the sample cell are obtained by measuring the interference fringe patterns above the sample cell using a Twyman-Green interferometer [21], as shown in Fig. 1. A rectangular U-groove filled with TSHG is located on the top of the sample cell. The sample cell is heated by a planted heater rod, whose diameter is 0.8 cm and length is 4 cm, wrapped with an aluminum foil, right under the U-groove. A pair of thermocouples with a measurement certainty no more than ±0.2 K is placed on the U-groove surface to monitor and regulate the surface temperature. The rest surfaces of the sample cell are thermally insulated.

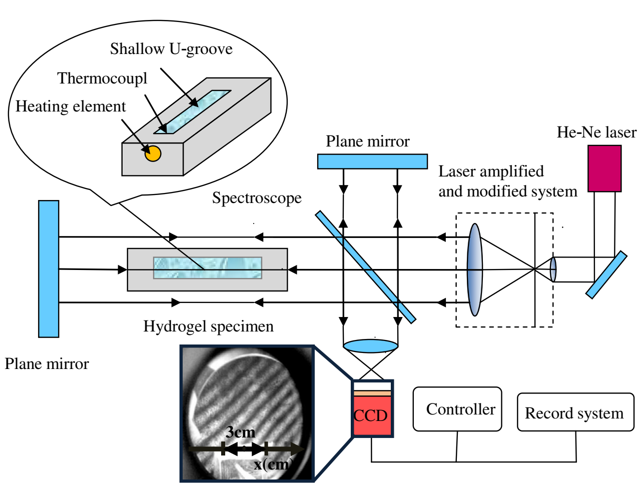


**Fig. 1.** Schematic of the experimental system. The picture from the CCD camera shows the initial interference fringe pattern at homogeneous ambient temperature and humidity.

The laser beam from the interferometer's He–Ne laser, after expanding, filtering and collimating, is divided into two using a beam splitter. One of the beams is directly reflected as the reference beam and the other is reflected after going through the air above the sample cell. The variations of the air refractivity, caused by the temperature gradients and the water evaporation from the TSHG, make the changes of interference fringe patterns. The inference fringe patterns are collected using a CCD camera, and the data are processed and analyzed using a computer.

### 2.3. Experimental data reduction

According to the theory of interference, the refractive index change of air ($\Delta n$) can be determined by

$$\Delta n = \delta / 2L, \quad (1)$$

where $\delta$ is the optical path difference, $L$ is the length of the U-groove that filled with TSHG on the sample cell. Under normal conditions (air pressure $P \approx 101{,}325$ Pa and temperature $T \approx 273.15$ K), the relative refractivity of air ($n$) is a function of air temperature and pressure, and also affected by the partial pressure of water vapor ($P_v$) according to [22–24],

$$n = \left(77.5348 + \frac{0.439108}{\lambda^2} + \frac{0.003666}{\lambda^4}\right)\frac{P}{T} - 11.27\frac{P_v}{T}, \quad (2)$$

where $\lambda$ is the laser wavelength, which is 0.6328 μm in the experiments. If the ambient pressure is constant, i.e. $P \equiv 101{,}325$ Pa, the derivation of Equation (2) gives

$$\mathrm{d}n = \frac{11.27P_v - 273.15 \times 291.768}{T^2}\mathrm{d}T - \frac{11.27}{T}\mathrm{d}P_v. \quad (3)$$

Therefore, the relationship between the refractive index change and the temperature field satisfies

$$\Delta n = \frac{11.27P_v - 273.15 \times 291.768}{(T + \Delta T)^2}\Delta T; \quad (4)$$