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Topic A7: Thermal comfort

COOLING CLOTHING UTILIZING WATER EVAPORATION

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SUMMARY

We developed cooling clothing that utilizes water evaporation to cool the human body and has a mechanism to control the cooling intensity. Clean water was supplied to the outer surface of the T-shirt of the cooling clothing, and a small fan was used to enhance evaporation on this outer surface. To prevent wet discomfort, the T-shirt was made of a polyester material having a water-repellent silicon coating on the inner surface. The chest, front upper arms, and nape of the neck were adopted as the cooling areas of the human body. We conducted human subject experiments in an office with air temperature ranging from 27.4 to 30.7 °C to establish a suitable water supply control method. A water supply control method that prevents water accumulation in the T-shirt and water dribbling was validated; this method is established based on the concept of the water evaporation capacity under the applied environment.

INTRODUCTION

To mitigate the problems of global warming and energy wastage, it is desirable to reduce the operation of heating, ventilating and air-conditioning systems in the summer. This, however, elevates the indoor temperature and increases the percentage of occupants dissatisfied with the thermal environment. Clothing creates an individual microclimate around an occupant. Removing excess (or wearing additional) clothing provides an effective solution for individual control of thermal sensation. However, clothing without cooling equipment cannot form a cooler microclimate than the climate of the surrounding environment. Phase change materials (PCMs) and chilled water circulation have been used to provide cooler microclimate (e.g., Nishihara et al., 2001, Gao et al., 2010, Flouris and Cheung, 2006). However, PCMs need to be chilled for fixation before use, and the cooling period is limited owing to their melting heat capacity. To obtain a long cooling period with a PCM, replacement of the chilled PCM or installation of a large amount of PCM is required. For chilled water circulation, large equipment is needed to chill the water and circulate it. Therefore, cooling of a microclimate by PCM or by circulation of chilled water has limited applications.

The latent heat of water evaporation is large (2417 J/g at 35 °C). Typical heat generation for an office worker with a skin surface area of 1.7 m^2 is 170 W, which corresponds to the evaporation heat of 250 ml/h of water. For occupants staying indoors, it is easy to obtain this amount of clean water. Some systems that utilize water evaporation to cool the body are now available commercially (e.g., Seft Development Lab and Ichigaya, 2005, Web Japan, 2005,

Daisaku Shoji, 2012). Air conditioned clothing (Seft Development Lab and Ichigaya, 2005, Web Japan, 2005), which is equipped with small fans to promote ventilation in the space between clothing and the body, aids the evaporation of sweat. However, the sweat secretion rate is small when the activity intensity of occupants is low. Therefore, evaporation cooling may be insufficient for achieving thermal comfort. An icy cooling scarf (Daisaku Shoji, 2012), made of high-molecular-weight-polymer material that retains water, chills the neck through water evaporation. However, the cooling intensity of this scarf cannot be controlled. Thus, to the best of our knowledge, no evaporation-cooling-based systems have yet been developed to include a mechanism to control evaporation intensity. Therefore, Sakoi et al. (2011) developed cooling clothing that had a mechanism to control the water supply rate. In their study, a motor pump was used to diffuse water to the outer surface of the T-shirt. Through the use of air conditioned clothing, water evaporation was enhanced on the outer surface of the T-shirt. The motor pump was operated by a direct current (DC) power supply whose output was controllable by a knob. The study results confirmed the effectiveness of their system in reducing heat discomfort. However, the system faced a drawback of causing local cold discomfort and wet discomfort. Specifically, the strong cooling effect induced by water evaporation made it difficult for the user to adjust the cooling intensity and caused local cold discomfort.

In this study, we developed new cooling clothing based on the concept of water evaporation. To avoid wet discomfort of the user, we fabricated the T-shirt using polyester material that is water-repellent on one side and water-absorbent on the other. We adopted a newly developed water supply control method to avoid water accumulation in the T-shirt. Human subject experiments were performed to gather user responses to the developed cooling clothing. This paper presents the developed cooling clothing and the experimental results.

METHODOLOGY

Design of Cooling Clothing

Figure 1 shows our developed cooling clothing system, which is based on the cooling clothing of Sakoi et al. (2011). Water is supplied to the outer surface of a T-shirt by a water secretion system. A desk fan dries the T-shirt, thus cooling the body by evaporation. Hence, the cooling clothing system has three components: 1) a T-shirt that prevents users from feeling wet discomfort, 2) a water secretion system that supplies water to the outer surface of the T-shirt, and 3) a desk fan to accelerate evaporation on this outer surface. Even in a high-humidity environment, our cooling clothing induces a cooling effect by evaporation cooling since the
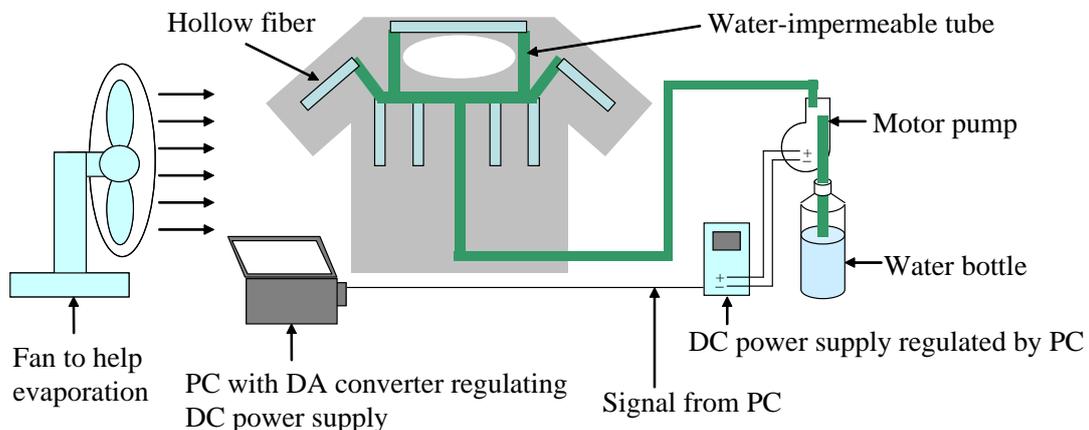

Figure 1. Schematic of our cooling clothing system.

Figure 2. Cooling clothing (red circles indicate cooling locations).

"OFF", "Lv.1", "LV.2"

Figure 3. USB fan used in experiments.

fan promotes convection around the T-shirt.

The water secretion system comprises a small water bottle, a motor pump to supply water, and hollow fibers to diffuse water onto the outer surface of the T-shirt. The output of the DC power supply operating the motor is controlled by an external voltage signal from a digital-analog (DA) converter installed on a personal computer (PC). The output of the DA converter is controlled using an application created in Microsoft Visual Basic Express 2010.

As shown in Fig. 2, the T-shirt is equipped with hollow fibers, which are supported by cotton strips attached to the T-shirt. To avoid wet discomfort owing to the water supply, we used polyester material that is water-repellent on the inner side and water-absorbent on the outer side to fabricate the T-shirt. The chest, front upper arms, and nape of the neck were adopted as the cooled body areas (water-supplied areas).

To increase convection around the cooled body areas, we used a small USB fan (power consumption: 2.5 W), shown in Fig. 3. The intensity of the fan's output is adjustable to three levels: "OFF," "1," and "2."

Water Supply Rate Required for Achieving Thermal Comfort

Assuming that the cooling clothing is used in an environment of 29 °C and 60% RH, we determined the water supply rate required to achieve thermal comfort. Here, we assumed that the metabolic rate of the user was 81.4 W/m^2 (138.4 W for a person with a body surface area of 1.7 m^2) and that the user was wearing a T-shirt, light trousers, undershorts, socks, and shoes (0.43 clo) and used a desk fan generating a 0.8-m/s airflow around the user.

Thermal comfort is achieved when the body's heat production balances its heat loss and the skin temperature and sweat rate respectively coincide with the neutral skin temperature ($T_{sk.comf}$, Eq. (1)) and the neutral sweat secretion rate ($E_{sk.comf}$, Eq. (2)) (Fanger, 1970).

$$T_{sk.comf} = 35.7 - 0.0028\ (M-W) \tag{1}$$
$$E_{sk.comf} = 0.42\ [(M - W) - 58.15] \tag{2}$$

where M is the metabolic rate [W/m^2]; W is external work [W/m^2]; and $T_{sk.comf}$ and $E_{sk.comf}$ are the skin temperature [°C] and sweat secretion rate [W/m^2], respectively, of an average person in a neutral thermal state.

The effect of W is usually negligible. Further, according to Eq. (2), the evaporation heat loss by sweating ($E_{sk.comf}$) is 16.6 W for a body area of 1.7 m^2 and M of 81.4 W/m^2. Thus, the remaining 121.8 W has to be removed in other ways (i.e., convection, radiation, insensible perspiration, and respiration) for achieving thermal comfort. Convection and radiation both depend on the temperature difference between the skin and the surrounding environment. A rise in environmental temperature reduces this difference and thus decreases the heat loss caused by convection and radiation from the human body having a given $T_{sk.comf}$. The shortage of heat loss, called the thermal load, is estimated to be around 60 W. To compensate for the thermal load, we supplied water to cool the body by evaporation. The latent heat of water is 2417 J/g, so the water supply rate required to achieve thermal comfort is 1.4 g/min.

When the motor pump is operated at a DC power at 6 V, the motor pump outputs 0.57 g/s. We adopted ON/OFF control for the DC power supply. Table 1 presents the output regulation of our cooling clothing. At the start of water supply, the hollow fibers, which are meant to release water to the T-shirt, are not filled with water. Therefore, we establish two regulation levels: a warm-up period and an output period. During the warm-up period, the motor pump operates continuously to fill the inner space of the hollow fibers with water. During the output period, water is released from the hollow fiber at the user's preferable rate. The rate of 2.5 s/min (obtained by dividing 1.4 g/min by 0.57 ml/s) in the "medium" mode is the water supply rate required to achieve thermal comfort. In the "strong" mode, the system supplies water for a duration 1.5 times that in the medium mode, and in the "weak" mode, the system supplies water for half as long.

Table 1. Output regulation for compensating for thermal load.

Regulation level	Warm-up period (0~16 s)	Output period (after 16 s)
Weak	Continuous	1.25 s/min
Medium	Continuous	2.5 s/min
Strong	Continuous	3.7 s/min

Human subject experiments

To validate the performance of the developed cooling clothing, we conducted human subject experiments in a student office where air temperature was maintained at 28 °C (see Fig. 4) and humidity was not controlled. Experiments were conducted from July 30 to August 2, 2012. Four students participated in the experiments every day. They remained in the office from 10:00 to 17:00 and performed their usual tasks (the break time was set between 12:00 and 13:00). The subjects wore the developed cooling clothing (T-shirt), light trousers, undershorts, socks, and shoes (0.43 clo). They adjusted the water supply rate of the cooling clothing and the intensity and location of the USB fans according to their preferences. By

Table 2. Scales of perception.

Thermal sensation	Comfort sensation	Wet sensation
+3: hot	+3: very uncomfortable	+3: very wet
+2: warm	+2: uncomfortable	+2: wet
+1: slightly warm	+1: slightly uncomfortable	+1: slightly wet
0: neutral	0: comfortable	0: dry
−1: slightly cool		
−2: cool		
−3: cold		

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Figure 4. Scene of experiment.

administering an in-house developed PC-based questionnaire to the subjects, we collected their perceptions of the whole body, head, chest, and back every 30 min in accordance with the scales presented in Table 2. The subjects were permitted to step away from their desks temporarily. However, they were requested to respond to more than 80% of the questionnaires during the experiments. The presence of the subjects on their seats was detected by recording temperatures measured using thermocouples attached to the seats.

RESULTS AND DISCUSSION

Experimental Results

During the experiments, air temperature and relative humidity (RH) in the office were within 27.4–30.7 °C and 38.3–63.7%, respectively. The output regulation mode, as described in the previous section and Table 1, was applied to compensate for the thermal load. Figures 5–7 show the thermal sensation and comfort sensation for the whole body and the wet sensation for the chest as reported by the subjects from 10:30 to 16:30. These figures show both the average values of the subjects' responses as well as the standard deviation. In the figures, "control compensating for thermal load" refers to data collected during this experiment. The responses at 10:00 (start of experiment), 12:30 (break time), and 13:00 (after break time) were not included in the figures, because the subjects were not acclimatized to the office conditions at these times, and consequently, data for this period showed wide dispersion. The number of responses varied with time because the subjects were permitted to temporarily step away from their desks. With regard to the thermal sensation, the subjects reported feeling colder, i.e., below the scale of neutral. The cooling clothing and USB fan produced a sufficient cooling effect to achieve a thermally neutral sensation. However, the subjects felt "slightly uncomfortable" and "slightly wet" during the experiments. A post-experiment interview of the subjects revealed that the subjects felt dribbling of water from the cooling clothing and some of them therefore stopped the operation of the cooling clothing.

In the present experiments, we adopted a water supply control method that provides thermal comfort. However, because of the water supply rate being larger than the water evaporation rate during the experiments, water accumulated in the T-shirt and dribbled away. For practical use of the developed cooling clothing, we need to develop a water supply control method wherein the water supplied is less than the water evaporation capacity under applied conditions.
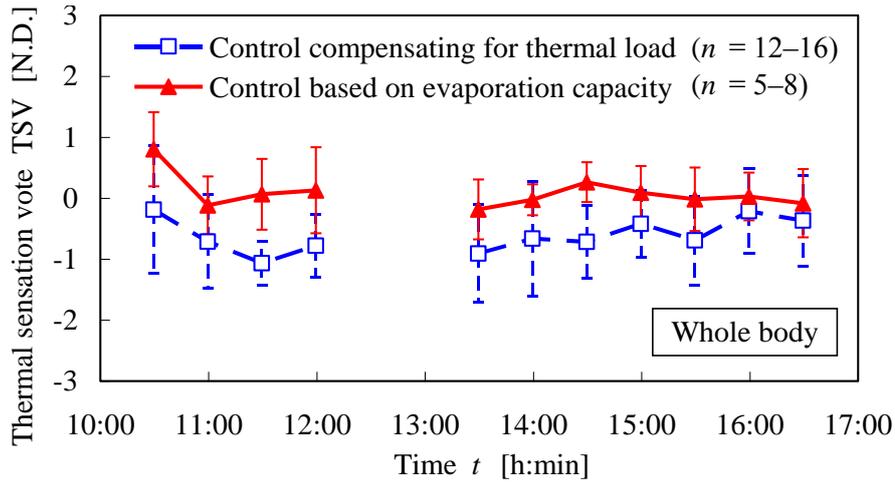
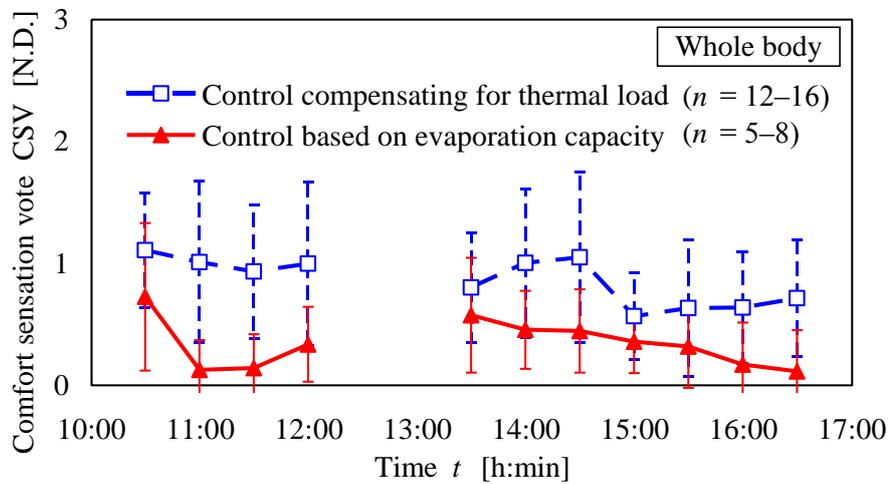Figure 5. Thermal sensation for the whole body during experiments.

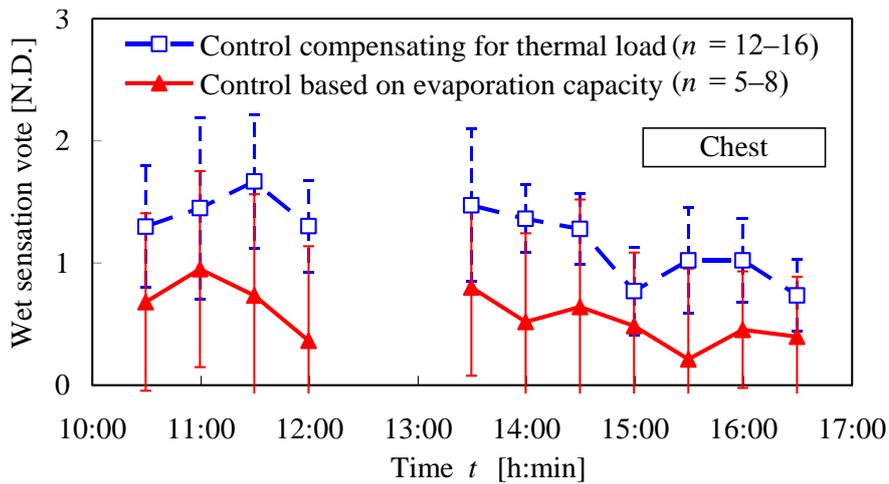Figure 6. Comfort sensation for the whole body during experiments.

Figure 7. Wet sensation for the chest during experiments.

New Water Supply Control Method for Suppressing Water Accumulation in T-shirt

The water evaporation capacity under applied conditions, E_{max}, is given as

$$E_{max} = 16.5 h_{c.i} (P_{cl.i}{}^* - P_a) f_{cl.i} \tag{3}$$

where E_{max} is the water evaporation capacity under applied conditions [W/m²], $h_{c.i}$ is the convective heat transfer coefficient of the cooled body area [W/m²°C], $P_{cl.i}{}^*$ is the saturated vapor pressure at the surface temperature of the clothing in a cooled area [kPa], P_a is the environmental vapor pressure [kPa], and $f_{cl.i}$ is the clothing area factor, i.e., the ratio of the clothing surface area to the skin surface area, in a cooled area [-].

We calculated E_{max} by assuming an environment with an air temperature of 29 °C, RH of 60%, and airflow rate of 0.84 m/s (USB fan is used), with a clothing surface temperature of 29 °C in the cooled area, $f_{cl.i}$ of 1.0, and the chest (with area of 0.1047 m²) as the cooled body part. The convective heat transfer coefficient of the chest, $h_{c.i}$, was set as 7.01 W/m²°C in accordance with Oguro et al. (2002). The calculated E_{max} was 185.4 W/m², and the maximum evaporation capacity on the chest was 19.4 W. Thus, the maximum water supply rate that can prevent water accumulation in the clothing was determined to be 28.9 g/h. If the water supply rate exceeds 28.9 g/h, the excess water will accumulate in the T-shirt and dribble away. We developed a new water supply control method (Table 3), wherein the "strong" mode corresponds to a water supply rate of 28.9 g/h and the "weak" and "medium" modes correspond to water supply rates that are 1/3 and 2/3, respectively, of that in the "strong" mode.

Table 3. New output regulation (water supply control method) based on evaporation capacity.

Regulation level	Warm-up period (0~12 s)	Output period (after 12 s)
Weak	Continuous	0.28 s/min
Medium	Continuous	0.56 s/min
Strong	Continuous	0.84 s/min

Validation of New Water Supply Control Method

To confirm the effectiveness of the new water supply control method, we conducted additional human subject experiments on August 3 and 6, 2012, in a student office maintained at around 28 °C. The experimental procedure was the same as that for the first experiment.

Figures 5–7 also show the thermal sensation and comfort sensation for the whole body and wet sensation for the chest as reported for the new water supply method (referred to as "control based on evaporation capacity" in the figure). The thermal sensation reported for the new method was around the neutral scale. The new method improved the comfort sensation and wet sensation compared with those in the previous experiment performed using the control method that compensates for thermal load.

The experimental results confirmed that our cooling clothing provided a cooling effect to the subjects' body. However, in order to ensure thermal comfort, we need to consider both the thermal load under applied conditions and the water evaporation capacity in the applied environment. Water in excess of the water evaporation capacity will accumulate in the T-shirt and subsequently dribble; this excess water does not contribute to evaporation cooling but rather causes wet discomfort. Therefore, the water supply rate should be restricted to be smaller than the water evaporation capacity. Ensuring thermal comfort by use of the cooling clothing is difficult when the thermal load is much larger than the water evaporation capacity.

In such a case, we can increase the water evaporation capacity by increasing the cooling area of the body.

CONCLUSIONS

We developed new cooling clothing that is based on the principle of evaporation of water supplied to the outer surface of a T-shirt made of polyester material that is water-repellent on the inner side and water-absorbent on the outer side. Its cooling intensity, i.e., water supply rate, is controllable. The performance of two water supply control methods was tested via human subject experiments in a warm environment. The first method, based on compensation of the thermal load, failed to prevent wet discomfort of the subjects and resulted in excessive water supply. However, the second method, which is established based on the water evaporation capacity under applied conditions, improved the subjects' thermal sensation and thermal comfort and did not cause wet discomfort. Ensuring thermal comfort by use of the cooling clothing is difficult when the thermal load is much larger than the water evaporation capacity. Both the thermal load and the water evaporation capacity are important parameters for our evaporation-based cooling clothing. The water evaporation capacity may be controlled by changing the cooling area of the body.

ACKNOWLEDGEMENT

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