Surface Differential Scanning Calorimeter for Evaluation of Evaporative Cooling Efficiency

Ruslan Burtovyy, Ph.D., Binyamin Rubin, Ph.D., Mahmut O. Kesimci, M.Sc, Igor Luzinov, Ph.D.,
Jeffery Owens, Ph.D., Konstantin G. Kornev, Ph.D.

Clemson University, Clemson, South Carolina UNITED STATES

Correspondence to:
Ruslan Burtovyy email: rburtov@clemson.edu

ABSTRACT

We developed a Surface Differential Scanning Calorimeter for the quantitative analyses of thermodynamic and heat transfer properties of thin fibrous and porous samples. It has been demonstrated that the calorimeter is capable of measuring cooling power as well as temperature decrease in a reliable and reproducible way. Considering its low cost the equipment can be a valuable option for studying cooling/heating systems in laboratory settings.

INTRODUCTION

Materials for protective clothing have a high fiber density that significantly decreases their permeability. A reduction of the material's permeability results in a dramatic decrease of the natural efficiency of evaporative cooling of the human body and, in many cases, it leads to thermal stresses [1, 2]. Design of materials with an efficient heat transport characteristics requires a reliable instrument that would be able to evaluate the materials performance at different environmental conditions. Quantitative analysis of thermodynamic and heat transfer properties of thin fibrous and porous materials is a challenging task. In this paper, we demonstrate an instrument that allows one to evaluate the heat transfer properties of different fabrics.

There are three major approaches to measure the fabric performance. The first method is based on the analysis of physiological data (skin temperature, heart rate, etc.) during various types of physical activities performed by humans. The majority of all available published papers on the subject of cooling utilize this method [3-9]. The second approach is evaluation of the system using a guarded sweating hot plate [10]. It is designed to determine the thermal and evaporative resistance of materials producing numerical values for both temperature and power gains in cooling systems. While this approach delivers reliable results, the high cost of the plate does not allow its widespread utilization in laboratory conditions. The third approach uses a thermal manikin and can be described as an advantageous combination of the former two approaches, with both temperature and heat values accessible [11-14]. However the apparent attractiveness of the last approach is diminished by the high expenses associated with the purchasing of the manikin.

The goal of the presented studies has been to develop an inexpensive, reliable method for testing evaporative cooling systems in laboratory conditions.

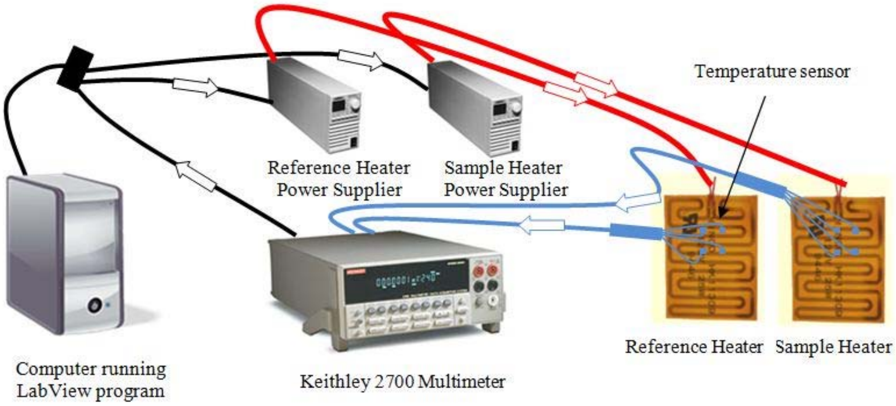

FIGURE 1. Schematic representation of the major components of the SDSC.

APPROACH

The designed and fabricated instrument named Surface Differential Scanning Calorimeter (SDSC) is able to assess cooling efficiency of the materials under development. On its conceptual side, SDSC combines two major techniques for materials' thermal characterization: Differential Scanning Calorimetry (DSC) and Differential Thermal Analysis (DTA). In essence, it measures temperature (ΔT) (DTA) or power (ΔP) (DSC) differences between two heating systems: reference and sample. The reference system simulates the body surface with standard protective clothing on it; the sample system contains the material in question. The measured differences in temperature and power characterize the evaporative cooling efficiency of the material in question.

The SDSC consists of a computer, a data acquisition system (Keithley 2700), two power supplies (TDK-Lambda ZUP) to heat thin, flexible Kapton heaters with low lateral heat loss (Omega Engineering, Inc.), and RTD (Resistance Temperature Detector) sensors (Omega Engineering, Inc.) placed at the center of the heaters. The computer runs a LabView program implementing a proportional integral (PI) control algorithm and data logging *(Figure 1)*.

The design of the system is based on the standard test method for thermal and evaporative resistance of clothing materials using a sweating hot plate (ASTM-F1868). As shown in *Figure 2*, the SDSC has two heating systems. Thin, flexible 10x10 cm^2 Kapton heater films *(Figure 2(a))* are placed onto the Styrofoam insulation *(Figure 2(b))*. Thus, the heat flows only in the upward direction (due to low thermal conductivity of Styrofoam heat flow in the downward direction is negligible). The heaters in both systems are covered entirely by cotton fabrics *(Figure 2(c))*. Cotton fabrics are dipped into water *(Figure 2(d))* to keep them wet, thus simulating a body surface. Materials under testing *(Figure 2(e))* are positioned between the fabric and top insulation.

The first system, which is a reference system, is isolated from the ambient environment by covering the fabric's surface with a plastic film and Styrofoam insulation (simulating impermeable clothing) to prevent evaporation and obtain the temperature and power values for the non-evaporating condition. The second system, which is a sample system, is used to test the evaporative heat transfer of the cooling arrangement of interest and incorporates top Styrofoam insulation ("the clothing").

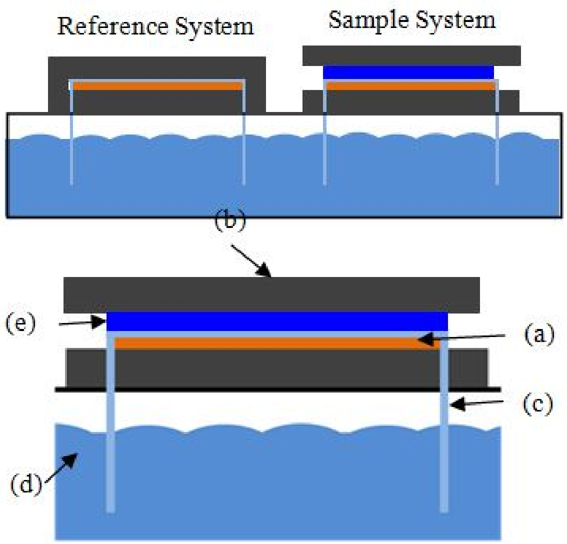

FIGURE 2. Reference and Sample systems arrangement (top) and Sample system close-up (bottom) (see explanation in the text).

The SDSC can be run in two modes: a constant power mode and a constant temperature mode. In constant power mode, the same power is supplied to both systems, while temperatures of the heater plate are monitored. Generated temperature difference is used as a characteristic value of the evaporative efficiency of the arrangement. In constant temperature mode, the systems are maintained at the same constant temperature while the power supplied to each system is monitored. The difference between the power levels required to maintain the heater systems at the same temperature is used as another characteristic of the efficiency of the evaporative cooling.

In order to carry out the actual experiments, the SDSC was placed in a controlled temperature/humidity chamber (Thermal Product Solutions). Fluctuations of temperature and relative humidity inside the chamber were ±0.5 ^oC and ±2 %, respectively. These fluctuations were synchronous, allowing us to state that an absolute concentration of the water vapors in the chamber stayed constant while only temperature underwent some changes. All experiments were run at 35 ^oC temperature inside the chamber and variable relative humidity. The temperature of all heaters was set to 40 ^oC in the temperature-controlled mode. The same power supplied to the heaters in the power-controlled mode was adjusted to maintain the temperature of 40 ^oC for the reference system. The detailed experimental procedure was as follows: desired conditions inside the chamber were reached (duration of about 1hr); temperature control mode was executed (the system reached equilibrium in about 1 hr); and power-control mode was executed (the system reached equilibrium in about 1 hr).

For reliable and reproducible operation of SDSC it is crucial that two systems produce equivalent results when tested under identical conditions. . Several experiments were performed to ensure such performance. In general, two systems show about 0.01 W and 0.2 °C difference when operated in constant temperature and constant power mode, respectively. Furthermore, the systems demonstrated identical performance in constant temperature mode when set at several temperature values *(Figure 3)*. The results demonstrate very good reliability of the SDSC. The reproducibility of the experimental results was checked by performing a few experiments under identical environmental conditions and set-up arrangements. The obtained results were found to be in the error range for the difference between two systems. Thus, it indicates very good reputability and reproducibility of the SDSC.

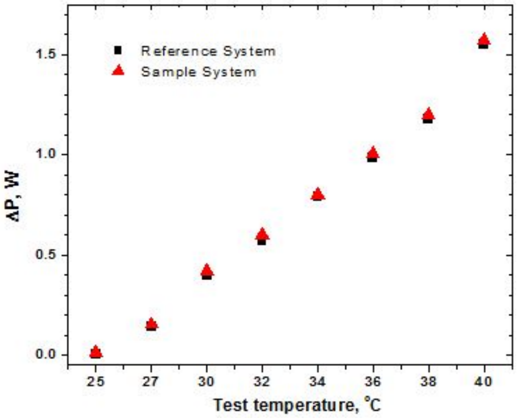

FIGURE 3. Power supplied to identical Reference and Sample systems at different set temperature.

Following extensive testing of the SDSC, several measurements were carried out to demonstrate capabilities of the equipment.

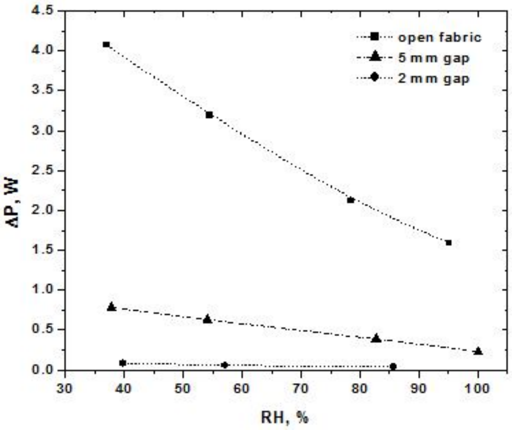

FIGURE 4. Cooling power generated in different "gap" arrangements.

The efficiency of evaporative cooling of a simple "air gap" system was measured. The air gap of 2 mm and 5 mm between wet fabric and top insulation was set by appropriate spacers. The results are presented in *Figure 4* and *Figure 5*.

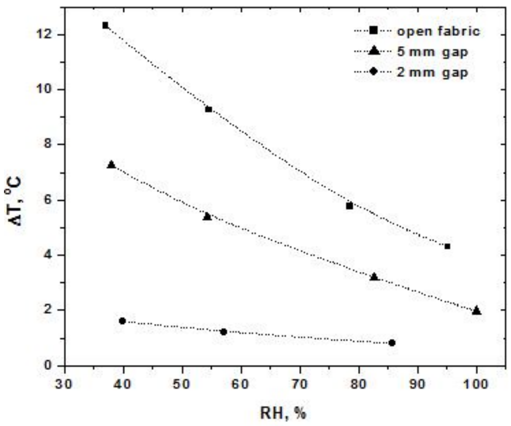

FIGURE 5. Temperature difference generated in different "gap" arrangements.

It is evident that both cooling power as well as temperature difference due to evaporation depends on the water vapor concentration of the outside environment. "Open fabric" configuration lacks any top insulation, simulating the situation without protective clothing. In our experiments it can generate about 400 Wm^{-2} of cooling power, compensating entirely for the power during moderate work rate [15] as it is intended to be done naturally through evaporation of water on the skin's surface. This result confirms that the SDSC can measure power values reliably. As can be expected, the maximum cooling effects gets smaller with decreasing gap size. Whereas it is still sizable (about

75 Wm^{-2}) at 5 mm, it goes down to about 8 Wm^{-2} for a 2 mm gap.

A similar trend is observed for surface temperature difference. For the open surface, the resulting average "skin" temperature at moderate humidity is in the vicinity of 31–32 ^{o}C, which is close to average normal temperature for the human skin [16]. The above mentioned result evidences that the SDSC is capable of producing values in very good agreement with those observed in real life. Again, a 5 mm gap reveals a still-promising temperature drop of about 5 ^{o}C for moderate relative humidity values.

CONCLUSIONS

The Surface Differential Scanning Calorimeter designed to quantify the evaporative cooling effect was developed. The equipment is characterized by good reliability and reproducibility of the results. Measured values for "open fabric" configuration directly correspond to cooling power and skin temperature observed in real-life situations. Given its low cost and compact design, the SDSC can be used as inexpensive substitute for a sweating guarded hot plate in assessing performance of various cooling systems in a laboratory environment.

ACKNOWLEDGEMENT

The project was supported by the U.S. Air Force contract FA8650-09-D-5900.

REFERENCES

[1] Gibson, P. W.; Factors influencing steady-state heat and water vapor transfer measurements for clothing materials; *Textile Research Journal* 1993, *63*, 749-764.

[2] Nunneley, S. A.; Heat stress in protective clothing: Interactions among physical and physiological factors; S*candinavian Journal Of Work, Environment And Health* 1989, *15*, 52-57.

[3] Cadarette, B. S., DeCristofano, B. S., Speckman, K. L., et al.; Evaluation of three commercial microclimate cooling systems; *Aviat Space Environ Med* 1990, *61*, 71-76.

[4] Reffeltrath, P. A.; Heat stress reduction of helicopter crew wearing a ventilated vest; *Aviation Space and Environmental Medicine* 2006, *77*, 545-550.

[5] Lehmacher, E. J., Jansing, P., and Küpper, T.; Thermophysiological responses caused by ballistic bullet-proof vests.; *The Annals of occupational hygiene* 2007, *51*, 91-96.

[6] Cheuvront, S. N., Goodman, D. A., Kenefick, R. W., et al.; Impact of a protective vest and spacer garment on exercise-heat strain; *Eur J Appl Physiol* 2008, *102*, 577-583.

[7] Hadid, A., Yanovich, R., Erlich, T., et al.; Effect of a personal ambient ventilation system on physiological strain during heat stress wearing a ballistic vest; *Eur J Appl Physiol* 2008, *104*, 311-319.

[8] Lee, K. C., Tai, H. C., and Chen, H. C.; Comfortability of the bulletproof vest: Quantitative analysis by heart rate variability; *Fibres Text. East. Eur.* 2008, *16*, 39-43.

[9] Barwood, M. J., Newton, P. S., and Tipton, M. J.; Ventilated vest and tolerance for intermittent exercise in hot, dry conditions with military clothing; *Aviat Space Environ Med* 2009, *80*, 353-359.

[10] Cao, H., Branson, D. H., Peksoz, S., et al.; Fabric selection for a liquid cooling garment; *Textile Research Journal* 2006, *76*, 587-595.

[11] Bogerd, N., Psikuta, A., Daanen, H. A. M., et al.; How to measure thermal effects of personal cooling systems: Human, thermal manikin and human simulator study; *Physiol Meas 31*, 1161-1168.

[12] Bendkowska, W., Klonowska, M., Kopias, K., et al.; Thermal manikin evaluation of pcm cooling vests; *Fibres Text. East. Eur. 18*, 70-74.

[13] O'Brien, C., Blanchard, L. a., Cadarette, B. S., et al.; Methods of evaluating protective clothing relative to heat and cold stress: Thermal manikin, biomedical modeling, and human testing; *Journal of occupational and environmental hygiene 8*, 588-599.

[14] Xu, X., Endrusick, T., Laprise, B., et al.; Efficiency of liquid cooling garments: Prediction and manikin measurement; *Aviat Space Environ Med* 2006, *77*, 644-648.

[15] Holmes, D. A.; Waterproof breathable fabrics; *Handbook of technical textiles* 2004, 282-316.

[16] Israelski, E. W.; Basic human abilities; *Handbook of Human Factors in Medical Device Design* 2011, 23-63.

AUTHORS' ADDRESSES

Ruslan Burtovyy, Ph.D.
Binyamin Rubin, Ph.D.
Mahmut O. Kesimci, M.Sc
Igor Luzinov, Ph.D.
Jeffery Owens, Ph.D.
Konstantin G. Kornev, Ph.D.
Clemson University
161 Sirrine Hall
Clemson, SC 29634
UNITED STATES