THE NEXT GENERATION SWEATING THERMAL MANIKIN SYSTEM

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INTRODUCTION

When operating under non-uniform heat loss conditions, traditional conductive metal manikiins can incur a measurable temperature differential across the skin surface, affecting total system accuracy. This effect is compounded when using a sweating skin layer, which adds additional thermal resistance to the measuring instrument. In a joint project funded by the U.S. Navy Clothing & Textile Research Facility (NCTRF) and the U.S. Army Natick Research, Development and Engineering Center, a unique thermal manikin was developed using heat pipe technology for manikin skin heating. This manikin also incorporates a permanent, high-conductivity porous metal sweating skin layer to evaluate latent heat loss.

In standard thermal manikin technology, electric heating elements are applied across the inside surface of a thermally conductive shell at uniform spacing. Uniform heat addition, coupled with a spatially varying heat loss, results in a measurement error arising from the non-uniform surface temperature of the shell. The uncertainty of the surface temperature distribution degrades the accuracy of the calculation of the thermal insulation (clo) of the garment system in the following equation,

$$clo = k * (T\ ambient - T\ surface)/\ (\text{Power to Section}/\ \text{Section Surface Area}).$$

where **k** is a units conversion constant to convert to units clo.

To make this calculation as accurate as possible, measurement errors in each of the three process variables must be reduced. Errors associated with ambient temperature and power measurements can be minimized using standard engineering principles. The errors associated with surface temperature distribution require adaptive heating to maintain skin temperature uniformity.

The addition of a sweating skin layer compounds this error. Typical skin systems include a wicking fabric layer, a supply tube network and small fluid pumps. Installing and removing this skin layer adds another source of random error due to garment fit. The wicking fabric adds a layer of insulation that prevents the manikin shell temperature sensors from measuring the true film layer temperature and causes additional variability in actual surface temperature. Non-uniform evaporative cooling further degrades the temperature uniformity of the manikin's skin.

The Heat Pipe Manikin (named "Bo") was designed and built to address these issues and to improve the state of the art in thermal manikin technology.

Heat Pipe Application Fundamentals (1)

Heat pipes operate using an evaporation cycle of a working fluid to transfer energy at high flux densities (Fig. 1). This effective, high thermal conductivity also allows them to produce isothermal surfaces at metabolic heating levels. The basis of operation is a sealed container filled with a working fluid at saturation pressure. A small (0.05°C) temperature differential in the chamber wall causes fluid evaporation at the higher temperature regions and condensation, thus heat transfer, at the low temperature areas. This inherent adaptive heating behavior is what makes the heat pipe ideal for an isothermal skin manikin system.

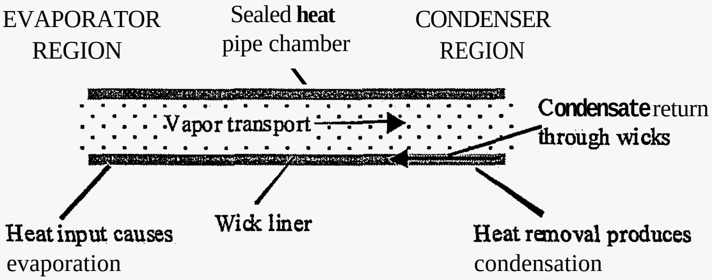

Figure 1. Basic Heat Pipe Operation

MATERIALS AND METHODS

Manikin System Design

The 16-zone manikin system was composed of 10 heat pipe regions with aluminum hands, feet, head and shoulders. Each of the 10 regions was an independent, hermetically sealed copper heat pipe. Central passageways in the heat pipes allowed electrical and fluid lines to pass between sections internal to the manikin. Rotary articulation was provided in the shoulders to allow dressing.

The control system used a Hewlett-Packard, high-accuracy scanner to measure sensor inputs and heater power. Precision thermistors were potted onto the surface of the manikin, and low-temperature coefficient resistance wire was used for zone heating. Heater drivers used analog command voltages with linear amplifiers for stability and low electrical noise.

A Pentium PC with a dedicated manikin control program, ThermDACTM, provided the operator interface. ThermDACTM included digital and graphical displays, temperature control, data logging and real-time data analysis capabilities. Automatic test modes allowed the operator to measure garment clo, water vapor permeability index (I_m) or to evaluate microclimate-cooling garments. During test execution, a data windowing function allowed the user to view statistical data during any time period during the run.

Sweating Skin Design.

The sweating skin used a permanent porous metal layer bonded to the outside of all 16 manikin sections. The metallic skin was designed for application to any metal surface, specifically to conform to the anatomical shapes of a manikin. Positive-displacement metering pumps supplied fluid to sweating manikin zones, where a capillary network within the metal skin further dispersed it. Fluid would then wick from the capillary network to the surface of the porous **skin.**

System Testing.

Prior to manikin assembly, each heat pipe region was bench tested by operating vertically (standing manikin operation) and horizontally (prone manikin operation) over a range of heat fluxes from 10 to 500 $W \cdot m^{-2}$. *An* array of thermocouples was mounted to selected points on the **skin** surfaces to measure temperature uniformity during all tests.

Following assembly and calibration of the system, basic performance and repeatability tests were performed. These included replicate nude manikin clo tests, wetting coverage tests of the sweating skin and dispensed volume repeatability measurements on the perspiration supply pumps.

RESULTS

The system has met or exceeded all of the design goals as follows:

Heat Pipe Manikin Design and Performance.

The anatomically shaped heat pipe manikin regions can maintain single zone temperature uniformity within 0.1°C at 40 $W \cdot m^{-2}$ in both vertical and horizontal orientations. The manikin design provides internal routing for all cabling and irrigation tubes.

Sweating Operation.

The porous metal skin system provides continuous and uniform wetting with a nominal flow rate range of 50 to 500 $ml \cdot h^{-1} \cdot m^{-2}$ without compromising the thermal accuracy of the heat pipes. Operation of the system is simple and repeatable and requires little surface maintenance.

Measurement and Control System.

The completed system has temperature resolution of 0.01°C with measurement accuracy of 0.05°C at 35°C. Power calculation is accurate to 0.1% for better than 1% total accuracy in clo measurement. The system has a maximum nominal heat flux of 500 $W \cdot m^{-2}$ for short heat up time and quick setpoint stability. The fluid control system allows independent volumetric flow dispensing to the individual zones and is variable over the course of a test.

CONCLUSIONS

o The adaptive heating provided by heat pipe technology can produce near isothermal shell temperatures and is a significant improvement over standard distributed heating methods.

- The porous metal skin design is robust, easy to use and doesn't compromise thermal accuracy of the surface film temperature measurement.
- Evaluation and performance testing **of** the system is currently in progress at the Navy Clothing and Textile Research Facility in Natick, MA. Testing will be performed to correlate with NCTRF's aluminum manikin (A1) and prior studies (2).

REFERENCES

1. Faghri, **A. 1995,** ***Heat pipe science and technology*** (Washington, **D.C.** **:** Taylor & Francis Publishing).
2. Teal, **W. B.** Jr. **1998,** Report **on** the heat stress testing **of** standard and prototype garments in support **of** the **JSLIST** program, In-House Report **5** Feb **98,** Navy Clothing & Textile Research Facility, Natick, MA.