A THERMAL MANIKIN TEST METHOD FOR EVALUATING THE PERFORMANCE OF LIQUID CIRCULATING COOLING GARMENTS

Walter B. Teal, Jr., P.E.

Navy Clothing & Textile Research Facility, PO Box 59, Natick, MA, USA

INTRODUCTION

Microclimate cooling systems (MCS) utilizing a circulating liquid to transfer heat from the skin surface to some type of heat sink have been and are being developed to alleviate heat stress. The common component in such systems is a liquid cooling garment (LCG). Fundamental heat transfer theory dictates that the performance of LCGs will be dependent on a variety of factors including (but not limited to), both the flow rate and temperature of the circulating fluid. Thermal manikins (TM) have been used to evaluate the performance of LCGs, but these tests have failed to look at the effect of flow rate (except over a fairly narrow range), and have generally not attempted to derive descriptive equations for predicting LCG performance (1-4). In this study, a TM test method has been developed for evaluating the performance of LCGs which accounts for both fluid temperature and flow rate, and results in a descriptive model for predicting LCG performance.

MATERIALS and METHODS

The method uses a fully wetted thermal manikin maintained at the same temperature as the environment (35°C, 50% rh). Fluid flow rate, the temperature of the fluid entering and exiting the LCG, and the power required by the TM are monitored continuously. The TM is allowed to come to equilibrium with the LCG in place, but without fluid flow. Fluid flow is then initiated at a predetermined rate and inlet temperature, and the TM again comes to equilibrium. The difference between the TM power without fluid flow and with fluid flow is calculated, and this becomes the net cooling power of the LCG at that particular flow rate and inlet temperature. This test is conducted in duplicate at six different combinations of flow rate and inlet temperature.

The results of these tests are used to derive a prediction model of the form:

$$Q=a+bF+cF^2+dT+eFT+fF^2T$$

Where Q is the cooling rate, F is flow rate, T is the inlet temperature, and lower case a through f are constants specific to the ensemble (combination of LCG and the overgarment). The matrix of six TM tests is used to generate six simultaneous equations which are solved to determine a through f. Once a through f are determined, the cooling rate, Q, can be predicted for any combination of flow rate, F, and inlet temperature, T.

To test this approach, a typical LCG was evaluated on the TM. The LCG was a whole body (torso, arms, and legs) garment manufactured by Exotemp Systems, Inc. of Ontario, Canada. The LCG was worn under the Toxicological Agent Protective (TAP) suit worn by US military Explosive Ordnance Disposal personnel. The TAP suit is an impermeable, butyl rubber, completely encapsulating garment. The LCG flow rates used were nominally 4.5, 7.0, and 9.7 gallons per hour (gph). The inlet temperatures used were nominally 50 and 70 degrees Fahrenheit. Combining the flow rates and temperatures results in a matrix of six test conditions, which were run in duplicate. A prediction model was developed as described above, and the predicted cooling rates were compared to the actual cooling rates obtained from the test.

RESULTS

The actual flow rates and inlet temperatures used during the tests, and the resulting cooling rates achieved are shown in Table 1. Note that the flow rates and temperatures in Table 1 do not exactly match the nominal set points described above. This is due to the lack of automated feedback control on the cool water supply system. The actual flow rates and inlet temperatures measured during the test, and not the nominal set points, were used when deriving the prediction model.

The equation for predicting the performance of the Exotemp whole body LCG, when worn under the TAP suit in a 95 degree F environment is:

$$Q=608.3-1.872(F)+3.477(F^2)-4.874(T)-0.477(F)(T)+0.001(F^2)(T)$$

Where the predicted cooling rate (Q) is in watts, flow (F) is in gph, and inlet temperature (T) is in degrees Fahrenheit. The predicted rates are shown in Table 1 for comparison with the actual cooling rates.

From Table 1 it is clear that the model provides very accurate predictions of cooling rate as measured on the Thermal Manikin. The predicted cooling rate never differs from the actual cooling rate by more than 2%.

It is now possible to use this model for estimating LCG performance. For example, if a cooling system using the Exotemp LCG under the TAP suit is used with an ice based cooling system that typically provides 40 degree F water at 5 gph, then the approximate cooling rate in a 95 degree F environment would be 397 watts.

Table 1. Thermal Manikin Test Results
Actual and Predicted Cooling Rates
Exotemp Shirt and Pants Under the TAP Garment

Flow rate (gph)	Temperature (degrees F)	Actual Cooling (watts)	Predicted Cooling (watts)
4.56	69.98	184	181
4.46	70.08	179	181
4.52	47.90	330	336
4.51	48.01	340	335
7.00	70.13	196	195
7.01	69.87	197	197
7.03	48.75	371	370
6.97	47.26	378	380
9.69	69.68	261	265
9.71	69.86	267	264
9.69	53.31	411	418
9.63	53.62	419	413

The equation may also be used to determine the flow rate required to achieve a particular cooling rate with a known cooling system. For example, if a portable vapor compression type system that typically provides 65 degree F water is to be used for cooling, and a cooling rate of 250 watts is desired, the necessary flow rate would be 7.76 gph. (This is calculated by substituting 65 for T and 250 for Q in the prediction equation, and solving for F.)

It is important to note that there are some limitations in the use of this test method and the prediction model. The prediction model demonstrated here only applies to the Exotemp whole body LCG when worn under the TAP suit in a 95 degree F environment. The test matrix must be repeated for every LCG/overgarment combination. If performance at environmental temperatures significantly different than 95 degrees F are to be predicted, then a more complex model incorporating environmental temperature as a variable must be developed, and a larger test matrix must be executed.

CONCLUSIONS

A test method has been developed for evaluating the performance of LCGs on a Thermal Manikin. A matrix of three flow rates and two inlet temperatures are tested, and the results used to develop a prediction model. The prediction model shows excellent agreement with experimental results, but is limited to the ensemble and environment in which the test was conducted.

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