PERSONAL COOLING GARMENT PERFORMANCE: A PARAMETRIC STUDY

John Frim, Robert D. Michas, Brad Cain
Defence and Civil Institute of Environmental Medicine
North York, Ontario, CANADA M3M 3B9

INTRODUCTION

Personal cooling systems (PCSs) are finally becoming an operational reality in military operations. This is especially so following the successful use of the Exotemp CD-2 system by Canadian Forces Sea King helicopter pilots during the 1990 Persian Gulf War (1). Although PCSs have been widely used in many non-military settings and situations (2—5), this was, to the best of our knowledge, the first time ever that personal cooling was used in aircraft during actual combat. This first-use clearly demonstrated that PCSs can reduce thermal physiological strain, enhance comfort and performance of air crew, and extend mission duration.

Soldier systems designers are now looking to the future when possibly even foot soldiers will be wearing portable PCSs to alleviate the thermal stress of advanced protective clothing systems. However, such systems will not become a reality unless the efficiency can be improved to reduce the weight and bulk of the system.

Heat transfer considerations suggest that the efficiency of a refrigeration unit can be greatly improved by raising the temperature of the cooling fluid closer to ambient temperature. Since this would reduce the thermal gradient between the skin and the cooling fluid, body heat removal would be compromised. However, it was postulated, based on simple mass flow and heat capacity principles, that a compensatory increase in the fluid circulation rate might restore the heat removal to the desired level.

To test if this would indeed be the case, we conducted a parametric study of the Exotemp garment using the CORD thermal manikin in Dartmouth, Nova Scotia. The aim of the study was to establish the relationships between fluid inlet temperature, flow rate, and heat removal. The effect of tubing length was also examined.

MATERIALS and METHODS

Three cooling vests with approximately 20, 37 and 50 m of tubing were constructed by Exotemp specifically for this study. The vests were identical in size and general pattern of the tubing layout. The different tubing lengths were accommodated by varying the number of vertical traverses in each flow loop, which essentially altered the spacing between tubes. The cooling vests were placed directly onto the aluminum skin of the manikin and were covered by an exterior garment representative of a helicopter flight ensemble.

Three flow rates (nominally 200, 500 and 1000 mL/min) and three fluid inlet temperatures (nominally 5, 15 and 25°C) were used with each vest while the ambient temperature and surface temperature of the manikin were held constant (21 and 34°C, respectively). Cooling fluid (water) for the vest was provided from a refrigerated bath via a variable speed pump. Tests were conducted by holding the coolant supply temperature constant while the flow rate was adjusted to the desired level. After the three flow rate tests were complete, the coolant supply temperature was readjusted and the three flow rates were run again. For each new test setting, the system was run for at least 1 h to permit a steady state heat exchange to be attained. All tests with a single vest were completed in one day.

Ambient and fluid inlet/outlet temperatures were scanned continuously and averaged over 1-min intervals by a Hewlett-Packard data acquisition system, while manikin temperatures and heat exchanges were measured by the manikin control system. To simplify analyses, the data from the final 10 min of each flow rate setting test for each variable were averaged to represent the value under that test condition. Vest heat exchange was calculated from the manikin data as well as from the mass flow rate of the cooling fluid, its heat capacity and its temperature rise.

To better visualize the relationships of the variables, two models of heat transfer were developed from first principles. For simplicity, the garment was treated as a single tube heat exchanger, with heat exchange occurring between the garment and the manikin on one side, and the garment and helicopter flight ensemble/ambient air on the other. Heat transfer at any point along the tube was a function of the temperature gradient between the fluid and the effective environment. Manikin power was modeled as heat transfer to the cooling fluid and to the ambient environment.

RESULTS

The original plan was to plot the manikin and vest heat removals against either fluid flow rate or inlet temperature as families of curves in which the other variable was constant. However, technical difficulties precluded obtaining exactly the same settings of fluid flow rate and garment inlet temperature between tests. Conditions were, however, adequately stable at any setting to yield nine data points for each garment.

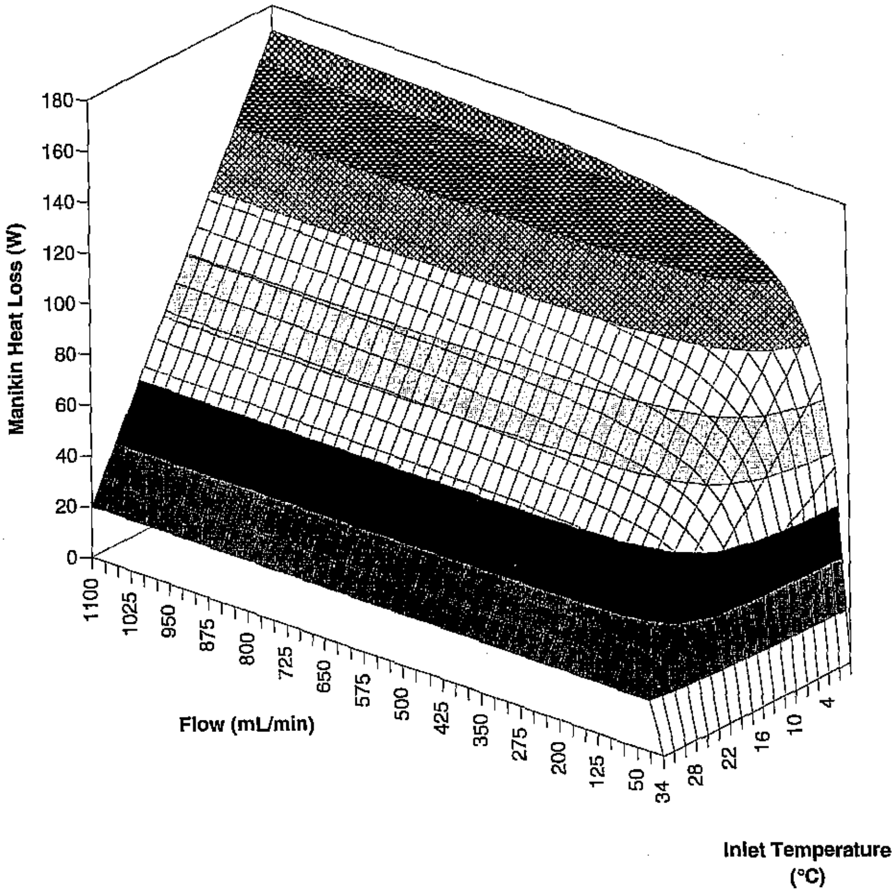
The final equation derived for heat loss from the manikin was

$$\dot{H} = \dot{H}_0 + k_1 F(T_m - T_{in})\left[1 - e^{-k_2 \frac{L}{F}}\right]$$

where k_1 and k_2 are constants incorporating various heat transfer coefficients, F is fluid flow rate, L is tube length, T_m is manikin surface temperature, T_{in} is coolant inlet temperature, and $\dot{H}_0$ is manikin heat loss at zero flow (measured to be 20 W).

Rather than deriving the values of the various heat transfer coefficients from first principles, the models were fitted to the data obtained in this study using the nine data points for a given vest. Due to problems with the quality of the calorimetric data, the model fit with the manikin measurements was better, and the figure below shows the manikin model results as a wire frame surface plot. The values of r^2 for the 20, 37 and 50 m vests were 0.98, 0.97 and 0.99, respectively.

The most striking feature of the model is that heat removal is steeply dependent upon fluid flow rate only at lower flow rates, and it quickly becomes essentially independent of flow rate at higher flows. Closer inspection of the graph also shows that the dependence of heat removal on fluid flow rate extends to fairly high flow rates only when the inlet temperature is low. For the 20 m vest shown in the figure, flow rates greater than 300 mL/min have only a marginal effect on heat removal. The model results are qualitatively similar for the 37 and 50 m vests, the main difference being that heat removal remains sensitive to higher values of flow as the tubing length increases.



CONCLUSIONS

This study shows that proportional compensatory increases in fluid flow rate to overcome reduced temperature gradients between the garment and the body may not restore body heat removals to desired levels. Information of this type is essential in the design and optimization of future personal cooling systems where bulk and weight must be reduced. This study demonstrates that effective PCSs must be designed as a system rather than as two independent units coupled by a tubing umbilical.

REFERENCES

1. Bossi, L.L.M., Glass, K.C., Frim, J. and Ballantyne M.J. 1993, Operation Friction: Development and introduction of personal cooling for CH124 Sea King aircrew. *DCIEM No.* **93-06.**

2. Nunneley, S.A. 1970, Water cooled garments: a review. *Space Life Sciences* **2,** 335-360.

3. Shvartz, E. 1972, Efficiency and effectiveness of different water cooled suits — a review. *Aerospace Medicine* **43,** 488-491.

4. Webb, P., Troutman, S.J. Jr. and Annis, J.F. 1970, Automatic cooling in water cooled space suits. *Aerospace Medicine* **41,** 269-277.

5. Frim, J. and Morris, A. 1992, Evaluation of personal cooling systems in conjunction with explosive ordnance disposal suits. *DCIEM No.* **92-31.**