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A STUDY OF THE INFLUENCE OF FOG ON HEAT LOSS THROUGH CLOTHING

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Table of Contents

Abstract

Fog is often perceived to increase heat loss in already cold environments. The physical process responsible for the increase in heat loss is not completely clear. However, the following explanation serves as a method of defining the process involved, and quantifying heat loss increases due to the presence of fog. In a cold environment, fog particles penetrating clothing or impinging on bare skin will evaporate upon reaching (or nearing) the higher temperature surfaces. Since evaporation is endothermic, the phase change from liquid to vapor removes a calculatable amount of heat from the surface. Thus, the heat of vaporization of the mass of water reaching the higher temperature surfaces should be equal to the increase in heat loss due to fog, if any increases are actually observed. Bare skin was emulated using the surface of a sweating hot plate covered with filter paper. Heat losses were measured with and without the presence of fog. The bare skin tests showed high correlation between increases in fog density and increased heat loss. Next, experiments were performed using an air and vapor permeable aramid fabric (Nomex®III), an air impermeable and vapor permeable fabric (Gore-Tex® Type I), and single faced fleece (a fabric widely used for thermal insulation). The air permeable fabrics, Nomex®III and single faced fleece, did show detectable increases in heat loss with fog density, but to a lesser extent than the response of the bare plate. Whereas, the Gore-Tex®, which is air and liquid water impermeable, showed no significant change in heat loss due to the presence of fog. Further tests were then conducted with Gore-Tex® infiltrated with air. To simulate the effects of air convection due to windy environmental conditions or body motion, air was drawn in under the fabric, as would occur through the garment openings. Under these conditions Gore-Tex® responded with significant heat loss increases, as expected.

Introduction

Background There is a perception of "wet cold" being worse than "dry cold" at the same temperature, but no physical explanation. The term "wet" could only be referring to high water vapor concentrations, but it is known that water vapor in the air has no effect on dry heat loss. Fog, composed of actual water droplets as opposed to water vapor, is an atmospheric phenomenon, physically and psychologically associated with wet cold. Thus, fog becomes a potentially significant physical factor for "wet cold" heat loss through clothing, not yet investigated experimentally.

Heat loss through clothing is due primarily to four main heat transport mechanisms: (1) conduction, (2) radiation, (3) convection, (4) vaporization. Each vary in magnitude depending on physical conditions. Thus, total heat loss is generally of the form:

$$Q_{total}=Q_{conduction}+Q_{radiation}+Q_{convection}+Q_{vaporization} \quad (1)$$

where Q is the heat loss per unit area in (W/m^2). However, a heat loss increase onset by the presence of fog is due to water droplet vaporization. Since this heat loss is due to the phase change of water from liquid to vapor, we have:

$$Q_{vaporization}=\frac{HD(C_{skin}-C_{ambient})}{\delta}=H\frac{dm}{dt} \quad (2)$$

where H is the latent heat of vaporization, D is the diffusion constant, C_{skin} and $C_{ambient}$ are the skin and ambient vapor concentrations respectively, δ is the thickness of the material, and dm/dt is the rate of water vaporization, in units of (kg/m^{2}s).

In a foggy environment, if all the water droplets infiltrating the warm surface of skin or fabric vaporizes, then the rate of water vaporization *(dm/dt)* from Eq.(2) will be equal to the rate of water infiltration upon the surface due to fog. The rate of water infiltration may be measured under average fog conditions, therefore setting this value equal to *(dm/dt)* results in the theoretical value of average heat loss due to water vaporization in the presence of fog. This value is then compared with the actual value obtained from the experimental data. A correlation between the values confirms that the observed increase in heat loss is indeed due to the vaporization mechanism.

Characteristics of Fog For the effects of fog in the laboratory to be meaningful a standard meteorological calibration of fog was required [Pilie,p6]. The quantity of visibility in meters is given by:

$$V = \frac{c\Sigma N_i r_i^3}{\beta \Sigma N_i r_i^2} \approx \frac{2.6 k\bar{r}}{\beta} \tag{3}$$

where V is the visibility in meters, N_i is the concentration of droplets of radius r_i in (m^{-3}), β is the liquid water content in (g/m^3), c is a numerical scattering factor equal to 2.6, and r is the mean droplet radius in μm. The value k is a constant (typically between 1 and 2) varying with the width of the drop size distribution as follows:

$$k = 1 + \frac{\sigma}{\bar{r}} \tag{4}$$

where σ is the standard deviation of the droplet distribution. Hence, the measurement of liquid water content in (g/m^3) and mean particle radius in (μm) may be used to determine visibility. However, when a photocell is used to measure the visibility it was found in an experiment by Aufm Kampe (1950) that a more accurate value of visibility is obtained using Koschmieder's Equation [Mason, p118] which relates visibility to light intensity by:

$$V = \frac{3.91d}{\ln(I_1/I_0)} \tag{5}$$

where d is the distance between the light source and the photocell, and I_0 and I_1 are the light intensities in the absence and presence of fog, respectively. Since light intensity is proportional to the square of the photocell output voltage [Hecht], we have:

$$V = \frac{3.91d}{2\ln(v_1/v_0)} \tag{6}$$

where v_0 and v_1 are the photocell voltages in the absence and presence of fog respectively.

The characteristics of fog produced in the environment vary from region to region depending on geographic and atmospheric conditions. Fog produced in inland (radiation fog), coastal (advection fog), or high altitude (orographic fog) regions all vary in liquid water content and droplet size distribution. Physical fog models have been developed that describe the various fog types in terms of average drop diameters, dispersion, and liquid water content [Binua p235-6, Pilie p5]. Thus, measurements of visibility along with the mean droplet radius, and mean liquid water content were made during the course of the experiment for purposes of classifying the fog produced in the lab (see Table I).

Table I: *Summary of Laboratory Fog Characteristics*

Average Droplet Radius[1]	r	7.69×10^{-6} m
Standard Deviation of Droplet Distribution	σ_r	5.59×10^{-6} m
Dispersion Coefficient	σ_r / r	0.727
Average Liquid Water Content[2]	ß	11.79 g/m^3
Standard Deviation of Liquid Water Content	$\sigma_ß$	5.57 g/m^3
Average Visibility[3]	V	2.93 m

[1] see p6 for details [2] see p7 for details [3] see p8 for details

Experiment

Fog Generation The mixing of warm, wet and cool, dry air masses was the chosen method of fog generation [Amelin, p67]. The warm air was produced using an enclosed, high temperature chamber which was filled with water and kept at boiling point. Air streamed through the water, was heated, and reached vapor saturation. The cool dry air was obtained by: first, having air stream through a chamber of Drierite® (anhydrous calcium sulfate, an active desiccant which absorbs 10% to 14% of its weight, when absorbing water from air); then the dry air is streamed through copper tubing placed inside a low temperature reservoir of solid CO_2 (an insulated chamber of dry ice at approximately -58 C). The air streams, upon mixing, produced fog varying in density depending on temperatures and flow rates.

Measuring Methods The output of the fog generator was directed into a Thermatron® environmental chamber (the temperature in the chamber was lowered, then the air flow was stopped, so that fog could collect), where a sweating hot plate assembly had been placed. This enabled the fog to reach equilibrium within a controlled temperature environment, while thermocouples within the chamber, and heat lost from the plate surface were monitored by computer. An *RTD* (*R*esistance *T*emperature *D*etector) within the sweating hot plate, and thermistors just above the plate measured the temperature difference between the plate surface T_{skin} , and the ambient air $T_{ambient}$. Since heat loss from the plate increased with this temperature difference, all heat loss data were analyzed in the form of $Q/(T_{skin} - T_{ambient})$. In this form the heat loss response was roughly independent of any small temperature variations.

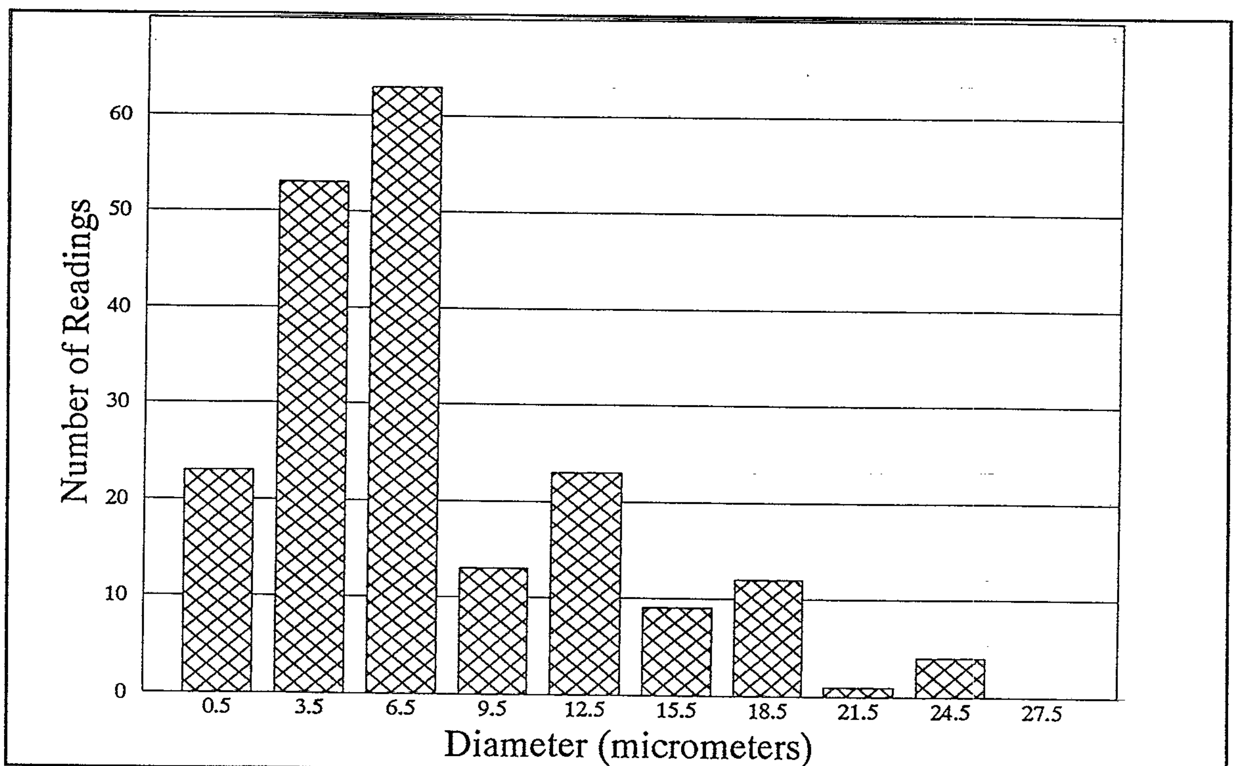

Figure 1 *The diameter distribution of the fog particles measured in the lab.*

The droplet radius distribution was calculated by observing fog particles under a stereoscopic microscope. Since fog droplets coalesce and vaporize within a few seconds, it was neccesary to immerse the the particles into a thin layer of oil before viewing them under the microscope. After over two-hundred measurements were made, a reasonable distribution of the droplet sizes was obtained, shown in Fig.1. The mean and standard deviation of the particle radii were calculated as $(7.69 \pm 5.59) \times 10^{-6}$ m, resulting in a dispersion coefficient σ/r of 0.727.

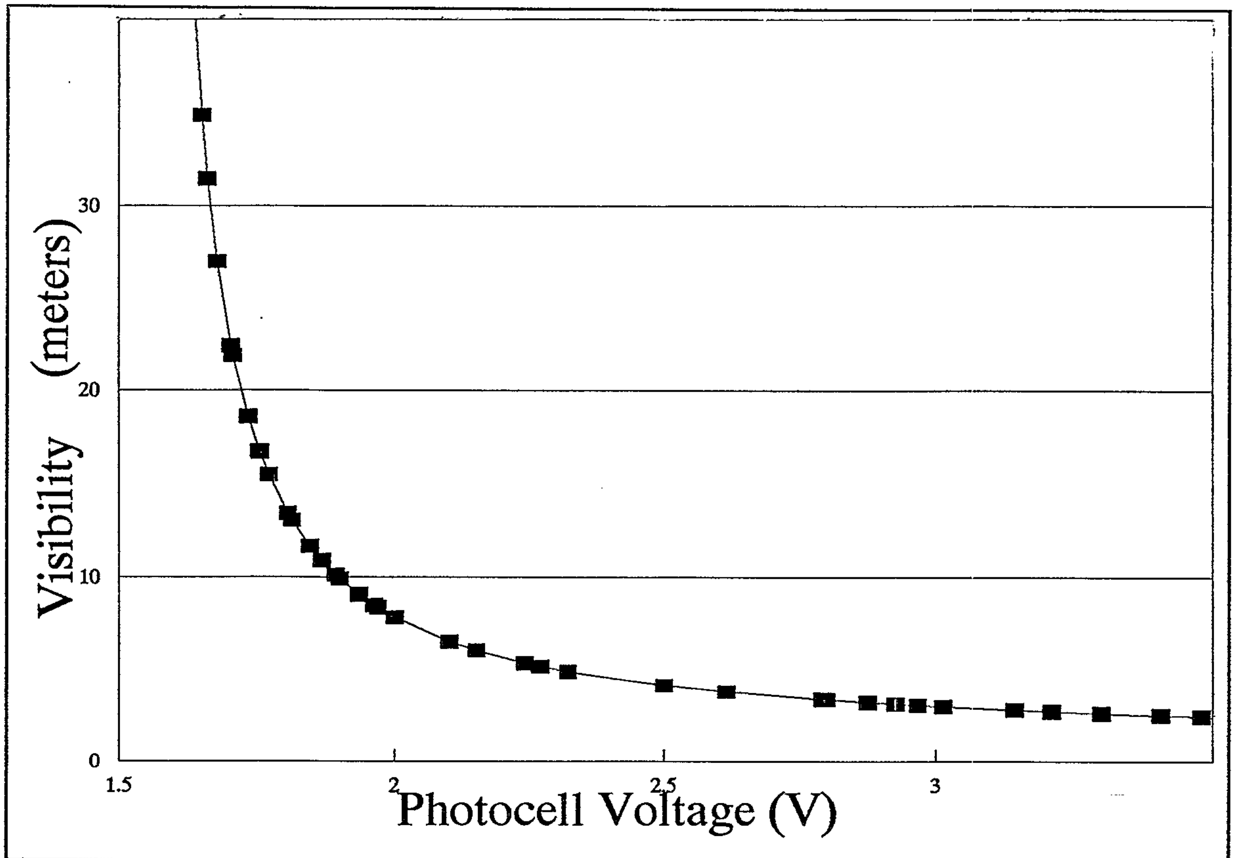

Figure 2 *Calibration plot for the fog within the chamber measuring visibility as a function of photocell voltage.*

To determine the amount of fog within the chamber at any given time during the experiment, the following procedure was required. First, a low power, 632.8 nm helium-neon gas laser (Uniphase® model# 1507-0) was directed though the environmental chamber (a length of 1m) to a cadmium sulfide photocell. A small lens was used to disperse the beam evenly over the surface of the photocell to increase the sensitivity of the detector to variations in light intensity. Data aquisition was obtained using a computer to average photocell voltages in intervals of a few seconds, and store the voltages as a function of time. The photocell output voltage was a measure of the amount of fog within the chamber, and from using Eq.(6), the corresponding value of visibility is obtained. The resulting plot of visibility in the standard meteorological units of meters, against photocell voltage is shown in Fig.2.

The average liquid water content within the chamber was measured using the following procedure. A container of desiccant (Drierite®) was placed upon an accurate digital scale, then foggy air from the chamber was drawn through the desiccant using a vacuum pump with a known (*measured*) flow rate. Mass increases of the desiccant were then measured over time, giving a value of mass of water absorbed for a given time interval *(dm/dt)*. Since a known volume of air is drawn by the pump in a given time interval, the value *(dm/dt)* is easily converted to a value of *(dm/dv)* in units of g/m^3, which is the total water content (including water vapor) of the foggy air. The liquid water content is then determined by calculating the saturation water vapor content in the chamber (from the chamber temperature), and subtracting this from the total water content. Measurements were taken for the entire range of fog densities obtainable in the chamber, and from this data the value of average liquid water content obtained was (11.79 ± 5.57)g/m^3.

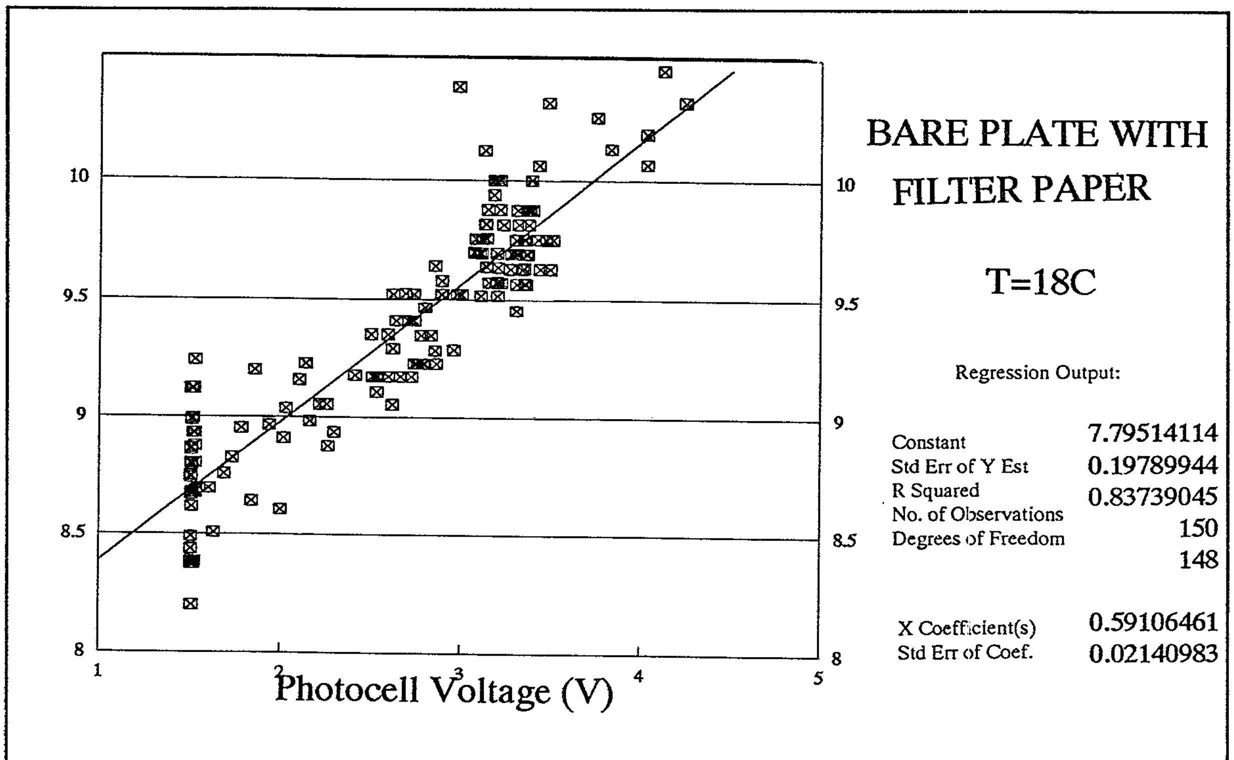

Figure 3 *The heat loss response of the sweating hot plate covered with filter paper in the presence of fog.*

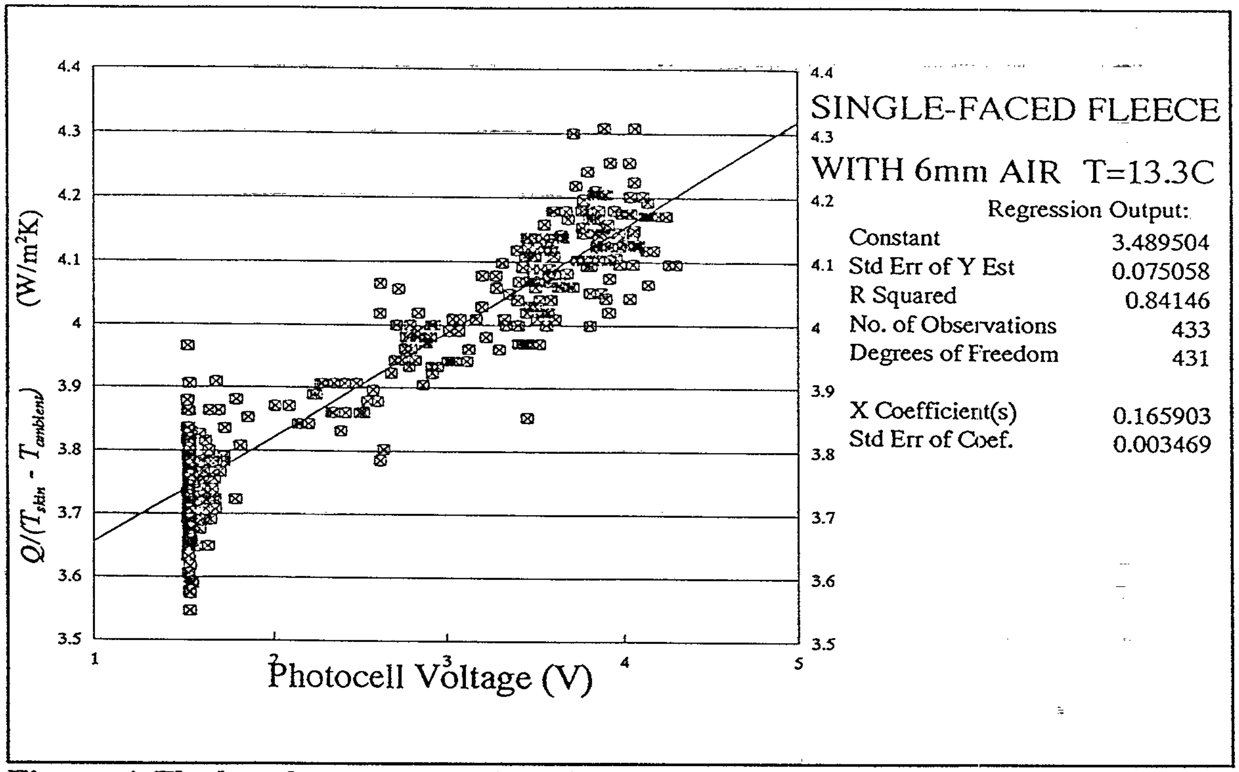

Figure 4 *The heat loss response of single-faced fleece pocket liner with a 6mm air layer, in the presence of fog.*

Data Analysis The data from the tests were originally obtained in the form of $Q/(T_s - T_a)$, and photocell voltage V against time. The data was then converted to graphs of $Q/(T_s - T_a)$ against *Voltage*, since the time variable was common to both of these quantities. A regressional analysis was taken for each plot, since linearity was observed. The bare sweating hot plate was tested first, and the results are shown in Fig.(3). The results of the tests conducted on the fabrics are shown in Figs.(4-9), along with the graphs. Using the calibration plot (Fig.2), the heat losses may be analyzed in terms of *Visibility* against $Q/(T_s - T_a)$, if required. The values of best x-coefficient obtained from the regression is a measure of the material's response to fog. The regression equation is used to find the best value of heat loss for each material without the presence of fog (V = 1.56V), and under *average fog conditions*. The average fog condition was quantified by averaging the photocell voltages observed during experiments; the value obtained was $V_{average} = (2.214 \pm 0.604)V$. This value was also used in Eq.(6) to determine the average visibility quoted in TableI.

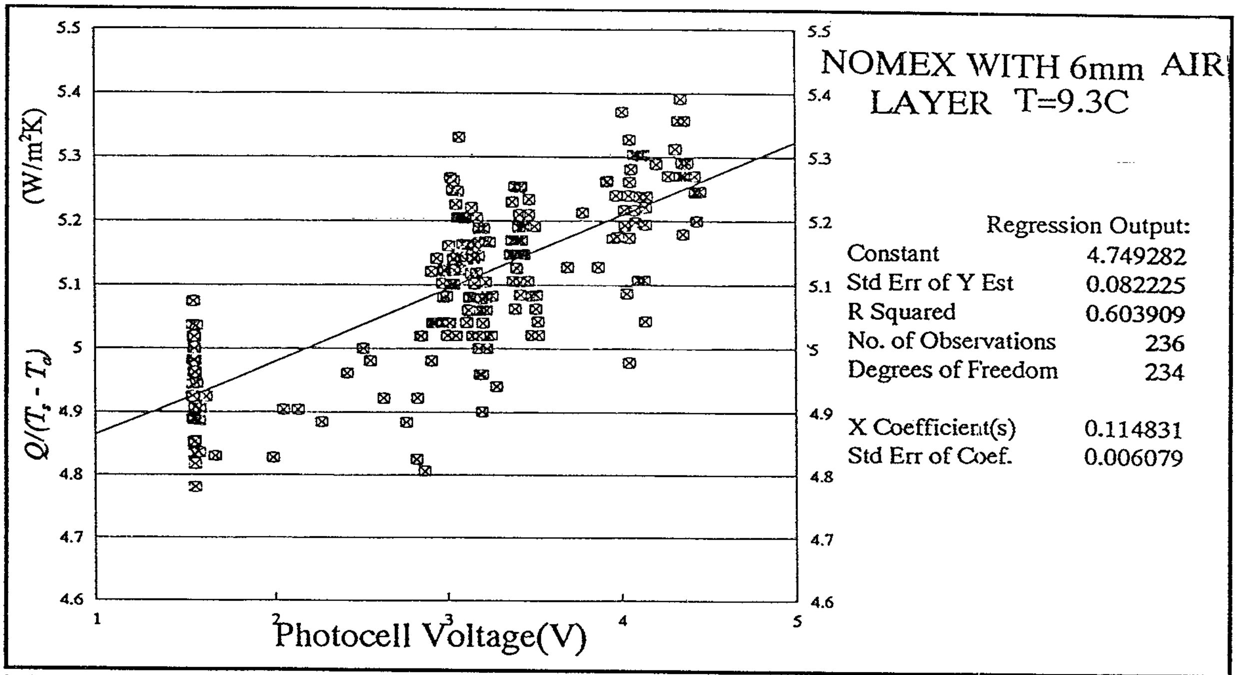

Figure 5 *The heat loss response of Nomex®III, with a 6mm air layer, to increases in fog density.*

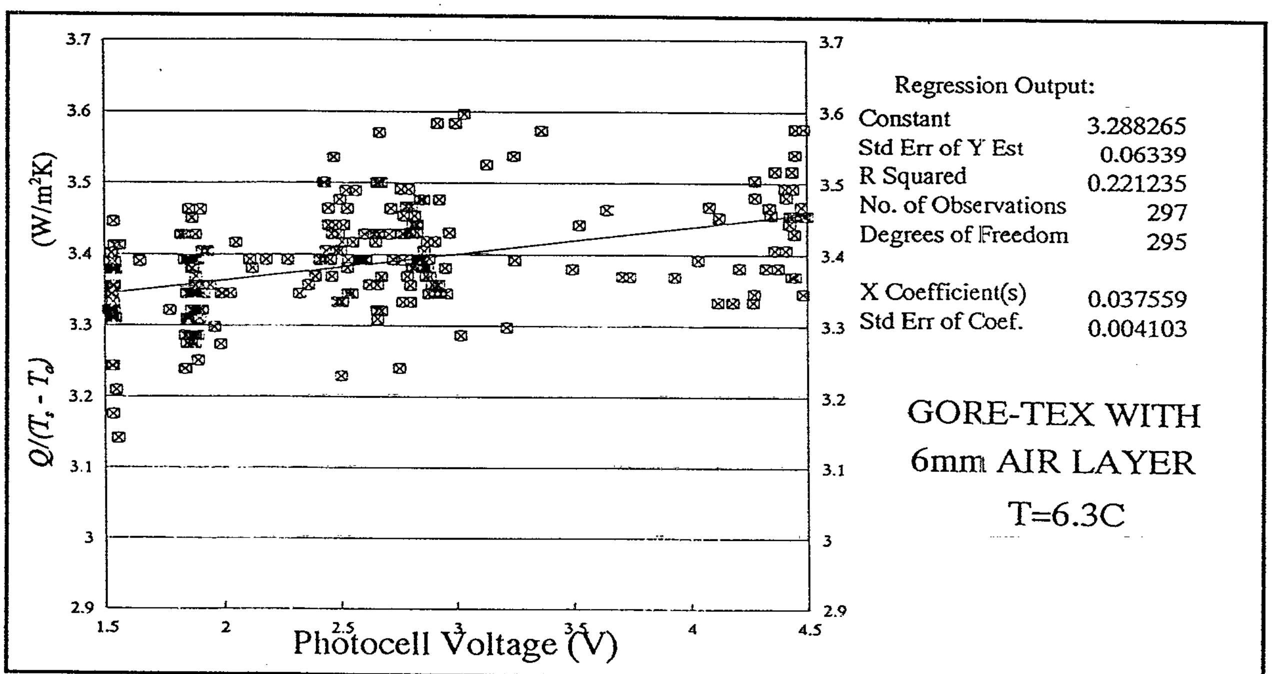

Figure 6 *The heat loss response of Gore-Tex® Type I, with a 6mm air layer, to increases in fog density*

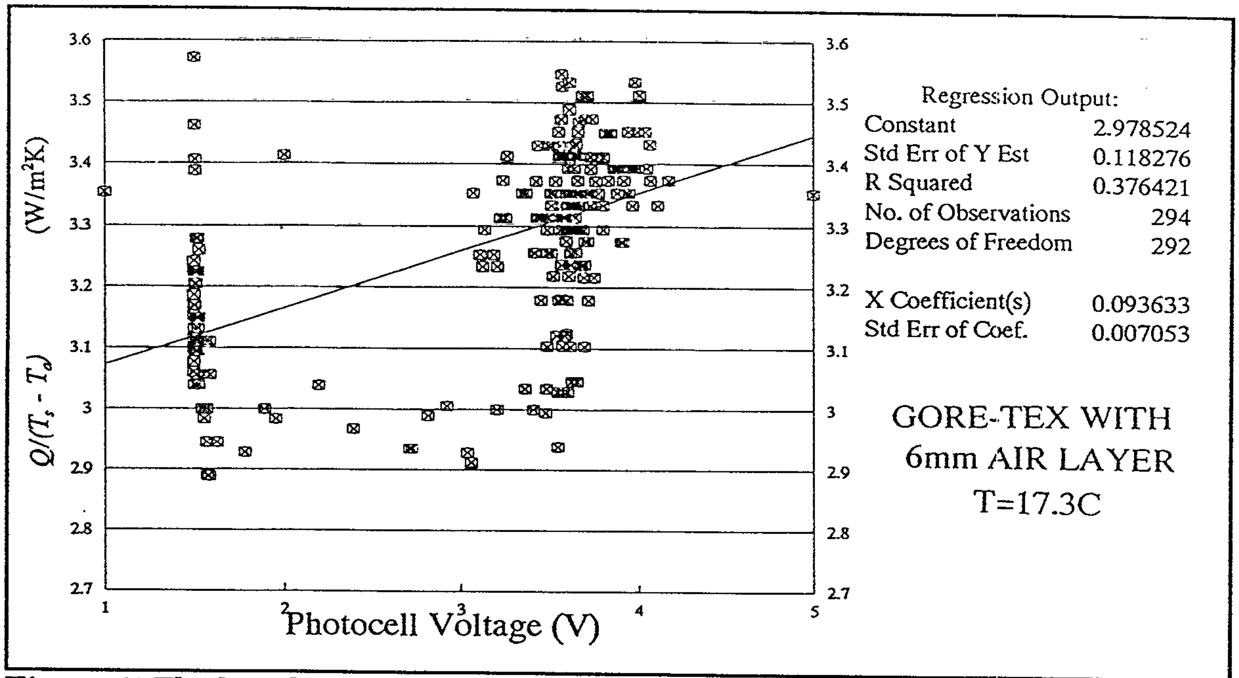

Figure 7 *The heat loss response of Gore-Tex® with a 6mm air layer, to increases in fog density.*

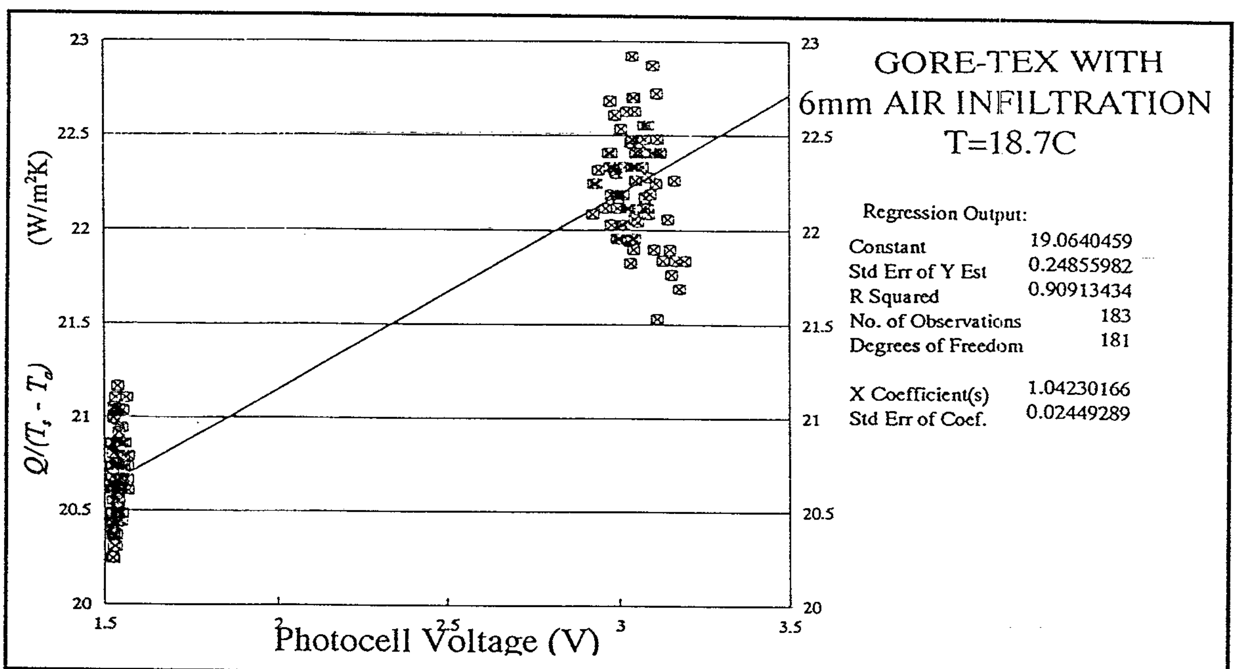

Figure 8 *The heat loss response of Gore-Tex® with a 6mm air infiltrated layer, to increases in fog density.*

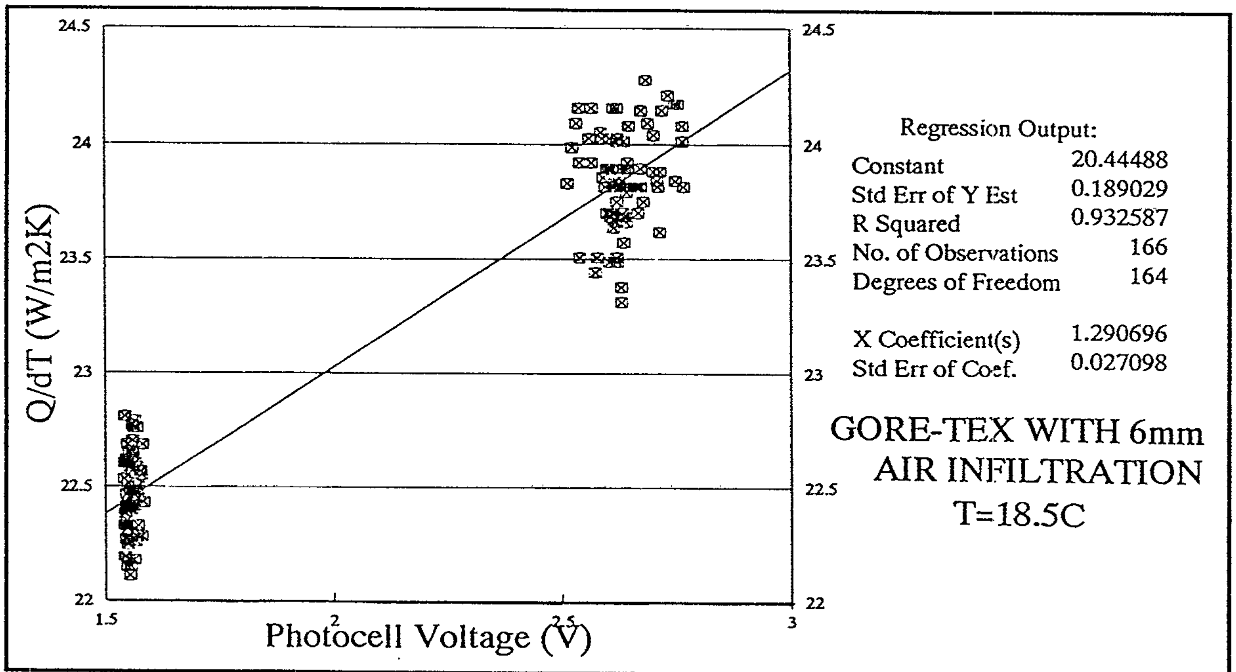

Figure 9 The heat loss response of Gore-Tex® , with 6mm air infiltration, to increases in fog density.

Results A summary of the results of the heat loss tests is shown in Table II, which lists the experimental values of the average heat loss increases due to the presence of fog. It can be seen that all the the materials did respond, to some extent, although the response of Gore-Tex® was negligible. The theoretical values may be obtained by using the relation given in Eq.2, from the rate of water infiltration, the heat of vaporization of water, and the average temperature gradient between the plate and the ambient air. The rate of mass infiltration was measured by placing a weighed test material into the foggy chamber and measuring the increase in mass of the material after a measured duration of time had passed. The observed increase in mass is due to the mass of liquid water absorbed from the fog. The results of the mass infiltration tests give an average value of $(6.4590 \pm 3.2327)\ W/m^2$. This value is then divided by the average temperature gradient across the plate for each fabric. The theoretical values in heat loss are then compared with the experimental values, as quoted in Table II.

Table II: *Summary of Results*

Materials	Heatloss without Fog[1] (W/m^2K)	Heatloss with Average Fog[2] (W/m^2K)	Heatloss Increase (W/m^2K)	Theoretical Increase[3] (W/m^2K)
Bare Plate	8.7172	9.1036 ± 0.3569	0.3864 ± 0.3568	0.3986 ± 0.1995
Single Faced Fleece	3.7483	3.8157 ± 0.1002	0.0674 ± 0.1002	0.3034 ± 0.1518
Nomex®III	4.9284	5.0039 ± 0.0693	0.0751 ± 0.0693	0.2586 ± 0.1294
Gore-Tex® TypeI	3.3469 3.1246	3.3714 ± 0.0227 3.1858 ± 0.0565	0.0245 ± 0.0226 0.0612 ± 0.0565	0.2292 ± 0.1147 0.3712 ± 0.1858
Gore-Tex® TypeI with Air Infiltration	20.6900 22.4584	21.3714 ± 0.629 23.3021 ± 0.779	0.6814 ± 0.629 0.8437 ± 0.779	0.4185 ± 0.2069 0.4134 ± 0.2069

[1] values were obtained using the regression equations for each material, with a photocell voltage $V = 1.56V$
[2] values were obtained using the regression equations, with a photocell voltage of $V = (2.214 \pm 0.604)\ V$
[3] values were calculated from the measured average rate of water infiltration, multiplied by the latent heat of vaporization over the area of the plate, giving: $H(dm/dt)_{average}/Area = (6.459 \pm 3.2)\ W/m^2$. This value was then divided by the measured average of temperature difference across the plate $(T_{skin}-T_{ambient})$ for each material.

Conclusion

Measurable increases in heat loss were evident in all fabric systems, although the magnitude is probably significant only for the bare plate and air infiltration conditions. In a very dense fog, the size of the changes was comparable to those expected on the basis of the vaporization of water mass collected per unit time, by the fabrics. However, the experimental errors were too large to permit a detailed comparison to theory.

References

1. Amelin, A.G., "Theory of Fog Condensation", 2nd ed., S. Monson Wiener Bindery Ltd., Jerusalem, 1967.

2. Binua, W., "Sea Fog", China Ocean Press, Beijing, and Springer-Verlag, Heidelberg, 1985.

3. Hecht, E., "Optics", 2nd ed., Addison-Wesley, Reading, Mass., 1987. p.44

4. Mason, B.J., "The Physics of Clouds", 2nd ed., Oxford University Press, London, 1971.

5. Pilie, P.J., *A Review of Project Fog Drops,* in "Progress of NASA Research on Warm Fog Properties & Modification Concepts", Office of Technology Utilization, NASA, Wash. D.C., 1969, pp.(1-6)

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