PREDICTING THE COMFORT OF NONWOVEN BARRIER FABRICS IN EXTREME ENVIRONMENTS

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INTRODUCTION

An important end-use for nonwoven fabrics is in surgical gowns and chemical protective clothing. They are also used as insulation materials in apparel worn for cold weather protection. For these end-uses, nonwovens must possess a diverse and often contradictory set of properties: they must provide a barrier against external environmental agents such as bacteria or body fluids, or they must prevent the penetration or permeation of hazardous chemicals or vapors. Nonwovens used in cold weather apparel must insulate against the loss of body heat that can result in hypothermia. The essential protective properties of nonwoven fabrics frequently conflict with the need to provide a comfortable thermal environment for the wearer. Failure to provide a comfortable thermal environment is a serious deficiency since some materials, including surgeons' gowns and chemical protective suits, are worn in hot and humid environments or where the wearer is engaged in strenuous activity that produces excessive amounts of body heat and sweating. At the other extreme, nonwovens used in cold weather clothing must prevent the loss of body heat while reducing moisture condensation that can lead to a deterioration in cold insulation performance and discomfort associated with sensations of wetness or chilling. This research demonstrates new and highly useful laboratory procedures for measuring the heat and moisture transfer properties of textile materials. An analytical model is described for predicting the thermal comfort of clothing systems from laboratory measurements. These tools were used in a program that analyzed the comfort performance of specially selected groups of nonwoven barrier fabrics exposed in hot and humid or extremely cold conditions. The effects of parameters related to heat and moisture transfer are examined: The effects of fabric type, skin conditions, skin-clothing configuration are reported for single and multilayer clothing ensembles. This research produced a deeper understanding of the role of wicking, absorption and condensation phenomena in the transfer of heat and moisture through single layer fabrics and through multiple layer clothing ensembles. The observed correlations among objective and subjective measurements of thermal comfort phenomena provide verification of the comfort models developed by this program.

METHOD

The thermal analyzing system consists of three parts: an environmental control chamber, a sweating hot plate component that simulates the skin or body, and a computer analyzing system.

Control of environmental conditions. Tabai ESPEC's Platinous Lucifer Model PL-2G, programmable low temperature and humidity chamber was used to produce artificial environmental conditions. A skin simulating guarded hot plate, or sweating hot plate, was placed inside the chamber. The chamber controlled temperature in the range -40~100°C, and humidity in the range 30~98%. Air currents were varied from 0.12 to 0.36 m/sec.

Simulated skin models. Thermal resistance and thermal conductivity were measured, using a specially modified Thermolabo Kawabata thermal analyzing system [1]. Simultaneous heat and moisture transfer was measured using a sweating hot plate featuring simulated sweating glands supplying water to the heated surface at the rate of 0.002-0.2 ml/min. per gland. The water flow was controlled using a peristaltic pump. Three skin models were used to simulate dry, dry/space and wet/space conditions and clothing configurations. A fourth model was used to simulate skin partially wet with sweat.

Distribution of heat and moisture in clothing systems. Micro-thermocouples and thin film microhygrometers were used to measure temperature and vapor pressure levels on the simulated skin surface, between fabric layers and in the ambient air surrounding the test ensemble.

RESULTS

We analyzed the physical and structural properties, as well as the heat and moisture transfer, of various nonwoven fabrics. We used simulated skin models to determine transfer properties at different levels of temperature, humidity, and air velocity. This allows us to examine the relationship between nonwoven structure and heat and moisture transfer properties related to comfort. Laboratory predictions of comfort are correlated with subjective ratings of warm/cool and wet/dry sensations.

CONCLUSIONS

The predicted comfort zone for nonwoven barrier fabrics can be extended to include environmental temperatures several degrees in excess of skin temperature (34°C). The factor of fabric design most influential in extending the range of the comfort zone, as indicated by predicted maximum tolerable environmental temperature, is the ability of the nonwoven to transmit moisture vapor. Our research confirms several previous studies [2] that have shown that structural features, not the component fiber, are the most important controllers of moisture vapor diffusion.

Our results also indicate that the properties having the greatest impact on combined heat and moisture transfer are fabric thickness, fiber volume fraction, optical porosity, air permeability, and moisture diffusion. Key structural properties are controlled by the type of nonwoven, post treatment and the presence of impermeable coatings or films.

ENVIRONMENTAL EFFECTS

Environmental variables including air velocity, ambient temperature, and humidity significant affect heat and moisture transfer through nonwoven materials. The rate of heat and moisture transfer through most nonwoven barrier fabrics is proportional to the square root of air velocity. In highly porous materials, heat and moisture transfer is proportional to the square of the wind velocity, due to the effect of wind penetration through low density samples. Thermal resistance increases with decreasing ambient temperature. If the skin is dry, environmental humidity has only a slight effect on heat transfer through hygroscopic materials: the higher the relative humidity the greater the heat transfer rate due to the increase in the moisture regain of the fabric. If sweating is involved, heat transfer decreases with increasing ambient humidity, due to the lower potential for evaporative heat loss to the environment. The degree to which humidity affects heat transfer depends more on the structural properties of the fabrics than the hydrophilicity of component fibers.

EFFECTS OF SWEATING

Our experiments show the effect of sweating on the evaporative heat transfer through nonwoven materials. They show that evaporative heat loss increases in proportion to the area of the skin that is wet with liquid moisture. They show that the temperature and vapor pressure measured in the air layer between the skin and fabric surface are lower over the dry portion of the skin than over the wet fraction, when the skin is partially wet with sweat. The difference between readings of temperature and vapor pressure made over dry and wet regions of a simulated skin surface decreases as the moisture permeation resistance of the nonwoven fabric increases. The buildup of temperature and vapor pressure in the microclimate over the dry fraction of the skin surface is undoubtedly one explanation of why impermeable materials generate a sensation of wetness in clothing wear. Wicking occurs readily in hydroscopic nonwovens in contact with a wet simulated skin surface. Liquid water transport by wicking of moisture condensed in fabric layers is far less likely to occur, simply because sufficient water is not accumulated through condensation to initiate capillary transport. The wicking of water from the skin surface accelerates heat transfer, primarily because it increases the effective evaporating area.

EFFECTS OF CONDENSATION IN COLD WEATHER SYSTEMS

We performed experiments to determine the effects of moisture condensation in a multiple fabric system in a cold weather environment. One system examined consisted of a semipermeable outer layer nonwoven fabric, three thermal insulating layers, a highly permeable nonwettable nonwoven and a highly absorbent next to the skin layer. Thermal transfer was measured for an extended period before, during and after the simulation of sweating. Data show that the vapor pressure beneath the semipermeable outer fabric reaches a saturation level within a few minutes after onset of sweating. The rate of heat dissipation reaches a maximum in about 10 minutes and steady-state conditions exist for several hours after sweating has stopped, due to the accumulation of excess sweat. The temperature and energy loss through the cold weather system drops sharply after the skin surface dries. This temperature drop lowers the saturation vapor pressure and causes moisture to condense with the insulating layers. In a cold environment, water condensed beneath the outer fabric layer freezes to form a thin layer of ice. This phenomenon lowers the effective insulation of cold weather clothing systems.

SUBJECTIVE TESTS

The comfort index predicted by analytical models from laboratory measurements of fabric heat and moisture transfer properties correlates with subjective comfort rating given in a simple test devised by this research. These experiments show that the sensation of warmth or coolness is associated with skin temperature and the thermal energy dissipation rate. The importance of the next-to-skin layer in clothing comfort was confirmed. A wet or strongly hydroscopic next-to-skin fabric layer produced sensations of coolness in a warm/cool subjective rating. Wet/dry subjective comfort correlates with the water vapor pressure measured on the skin surface. The higher the perspiration, sweating or ambient humidity, the less the feeling of comfort associated with wetness.

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