KINETICS OF PHASE TRANSFORMATION AND CAPILLARITY THEORY NEW INSIGHTS INTO HEAT TRANSFER AND MOISTURE HANDLING IN HUMAN CLOTHING AND ANIMAL INSULATION SYSTEMS

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INTRODUCTION

Arctic mammals and birds routinely survive immersion in water and are able to dry themselves in subfreezing weather, yet man in most "high tech" gear is threatened with cold injury and hypothermia by simply sweating. Moisture accumulation in insulation is a major problem. An arctic expedition in 1986 reported a 50 lb. weight gain in sleeping bags used over a four-week period. The authors have been made aware of a clothing system that affords protection from cold injury after water immersion and excessive sweating. It is made of open-cell polyurethane foam surrounded by a thin, vapor permeable, wind resistant shell. Total moisture accumulation of a foam sleeping bag at temperatures of 0 to -20 °F for one week was 3.5 oz. When this gear is saturated with water in sub-freezing temperatures, water disappears from the gear without forming ice, and minimal cold stress and no cold injury occurs. The remarkable performance of this system prompted the authors to reexamine what is known about vapor condensation and ice formation (1). A theoretical analysis of the surface parameters of solids in insulation systems provides a basis for understanding how foam insulation allows its wearers to survive without fire or shelter for weeks in extreme cold with no significant weight gain or frost build-up in their gear and to survive water immersion accidents and periods of excessive sweating without cold injury. The same analysis argues against the use of wool blankets, space blankets, vapor barriers, down, and most synthetic fibers in cold weather gear.

PHASE EQUILIBRIA OF WATER SUBSTANCE AND HEAT-WATER VAPOR TRANSFER

The Clausius-Clapeyron equation describes the relationship among saturation vapor pressure of water and ice, the latent heats of condensation for water and ice respectively, and temperature. According to Fick's law of diffusion, the vapor flux from the body to the environment is proportional to the vapor diffusivity (which varies inversely with atmospheric pressure), the cross-sectional area, and the vapor density gradient. Consequently, water vapor tends to diffuse rapidly away from the body in cold environments. Heat transfer takes place similarly under the influence. of the thermal conductivity of the materials surrounding the body. Ice has a thermal conductivity 92 times and liquid water 23 times that of air. The effect of fiber material for thermal conduction can generally be ignored. The thickness and cross-sectional area of the still-air layer created by a garment are the principal determinants of the insulating properties of a dry clothing system.

THEORIES OF CAPILLARITY

The contact angle of water on a solid surface is determined by the balance of three surface tensions at the edge of the spherical water cap and is described by the Young-Dupre equation. This angle is zero for totally wettable or very hydrophilic surfaces and 180° for totally non-wettable or highly hydrophobic surfaces. Teflon has the highest observed contact angle, 108°, while glass has a wetting angle of 0°. Most"hydrophobic" fibers however have contact angles of roughly 90°. Detergents, salts, and dirt can lower contact angles and may substantially change their moisture handling characteristics. The Young-Laplace equation describes the relationship between the radius of the curved water meniscus in the capillary and the capillary pressure. Capillaries of materials with contact angles greater than 90° tend to push water out of them. The menisci there are curved convex outward or by convention are said to have positive radii of curvature. Capillaries of materials with contact angles less than 90° tend to suck water into them and have concave outward menisci which have negative radii of curvature.

THE KELVIN EQUATION AND NUCLEATION OF CONDENSATION

The saturation ratio, better known as the relative humidity, of capillary condensed water is the ratio between the saturation vapor pressure over the capillary water and that over a flat water surface. The Kelvin equation describes either the elevation or depression of the vapor pressure of capillary water or tiny droplets compared to that over a flat water surface. The radius of curvature of a droplet on a flat solid surface is always positive (convex outward), and under this condition, the Kelvin equation shows that its saturation ratio is greater than 1. Evaporation is favored for such a droplet. In a parallel capillary of a material with a contact angle less than 90°, the water meniscus is concave outward and therefore has a negative radius of curvature. The saturation ratio of water vapor in this configuration is less than 1. Condensation into this capillary is favored since the vapor pressure is low relative to a flat water surface. This effect becomes significant for capillaries of 0.1-0.001 µm. The smaller the capillary the more marked the effect. This is important because virtually all woven fiber systems have capillaries of this sue at every contact point and sometimes within the fibers themselves. with a contact angle of 90°, a parallel capillary would hold water with the meniscus flat, and there would be no tendency for water to move into or out of it under the saturated condition. Therefore, condensation would occur at saturation there. With contact angles greater than 90°, evaporation would be favored out of such capillaries, and the effect would be greatest when capillary size is very small (less than 0.001 µm). In a system with very small capillaries with a contact angle slightly above 90°, as is true for many hydrophobic fiber materials, a slight deterioration in contact angle could cause a huge deterioration in moisture handling since moisture would avidly accumulate in the very small capillaries when the contact angle drops below 90°. For most woven fiber systems, wettable tiny capillaries cause moisture accumulation and thermal insulation deterioration. However, in synthetic open-cell foams, cell radii vary roughly from 0.1 to 1 mm. The vapor condensation on their surfaces requires nucleation (initiation) of tiny droplets. The cells of these foams can be treated as a flat surface for the nucleation of the droplets. This implies that, for contact angles greater than zero, evaparation is favored from such a system--hence the remarkable self-drying characteristics of foam insulations. When the foam is worn in cold weather, supersaturation (saturation ratio greater than 1) develops in the system without condensation, but breakdown of the supersaturation happens only when the ratio exceeds 2.9, as predicted by the nucleation equations described by Hirth and Pound (2). It always leaves, however, a nucleation-free zone near the body, avoiding drastic deterioration of the thermally insulating property. Contact points shift in live animal fiber systems due to active movement of the fibers. Evaporation from the surface of such fibers is favored once contact with another fiber is canceled. Ice formation is inhibited in tiny water droplets on flat surfaces because of the compressive stress of its positively curved surface. Ice formation is favored in tiny wettable capillary-held water because of the decompressive effect of its negatively curved surface. The smaller the capillary or droplet the greater the absolute value of the effect. This explains why ice has never been observed to form in foam gear while it is being worn.

REFERENCES

1. Mason, B.J., The Physics of Clouds, 2nd Edition, 671 pp., London, Oxford University Press, 1971.

2. Hirth, J.P. and Pound, G.M., Condensation and Evaporation, Progress in Materials Science, Vol. II