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Numerical Prediction of Thermal Insulation of High-Bulk Nonwoven Fabrics for Extreme Cold Weather Clothing: Radiative Heat Transfer Considerations

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Extended Abstract

High-porosity microfiber-based nonwoven fabrics are widely used in extreme cold weather clothing (ECWC) due to their low density, lightweight nature, and excellent thermal insulation. Accurate prediction of their thermal resistance (R_{ct}) is essential for ensuring safety, performance, and material optimization. While most models attribute heat transfer primarily to conduction, this assumption overlooks the growing significance of radiative transfer in ultra-high porosity structures (porosity >99%), where enlarged photon mean free paths and low solid fractions amplify radiative effects.

Conversely, both natural and forced convection are negligible in such fibrous insulations due to extremely small pore sizes, low Rayleigh numbers, and stagnant air within the structure. This is supported by the ASHRAE Handbook [1] and studies by Zhang et al. [2], which report convection suppression below ~1 mm pore size. Similarly, Zhou et al. [3] model cold-weather nonwovens, considering only conduction, further confirming the minimal role of convection.

In this study, a steady-state 1D numerical model was developed in COMSOL Multiphysics to simulate thermal transport in single-layer microfiber-based high-bulk nonwoven insulation. The model includes conduction and radiation, while convective heat transfer is excluded, consistent with the literature and physical characteristics of the fabric. The radiative component is modelled using the Rosseland diffusion approximation, suitable for optically thick media, and the extinction coefficient is computed based on fiber diameter, porosity, and refractive index using established radiation models [4], [5].

Simulations were performed for samples with constant areal density (100 g/m^2) and porosities ranging from 99.1% to 99.5%. Predicted effective thermal conductivities were validated against R_{ct} measurements obtained via a sweating guarded hotplate (ISO 11092:2014) [6].

Results show that radiative heat transfer contributes up to 29-42% of total heat loss and that neglecting it—especially at 99.4% and 99.5% porosity—can overestimate thermal insulation by over 70%-80%. These findings confirm that in ultra-high porosity nonwovens, radiation plays a critical role in insulation performance, while convection remains negligible. The validated COMSOL model offers a reliable tool for assessing and optimizing ECWC materials.

References

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