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Exploring Thermal Resistance of Nonwoven Fabric Structures in Cold-Protective Clothing Using Computational Fluid Dynamics

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ABSTRACT

Canadian winters bring extreme cold, posing significant risks to outdoor workers, such as discomfort, numbness, and severe health issues. Cold-protective clothing mitigates these risks, but current designs, often made from synthetic fibers in nonwoven structures, face optimization challenges due to the complex heat transfer processes within textiles. Experimental evaluations, while informative, are time-consuming, prone to variability, and unable to isolate the contributions of conduction, convection, and radiation. This limits the assessment of key parameters like single fiber thermal conductivity, porosity, fiber emissivity, wind velocity and orientation. Computational fluid dynamics (CFD) simulations provide a robust alternative, enabling detailed heat transfer analysis and facilitating textile thermal optimization. In this project, CFD simulations will be performed for a textile structure exposed to varying conditions of wind velocity, temperature, and orientation to examine the combined effects of heat transfer mechanisms.

Heat transfer in the computational domain is modeled as a combination of conduction, convection, and radiation. Air is treated as a Newtonian, incompressible fluid with temperature-independent properties, while textiles are modeled as porous media, with pressure drop and permeability related using Darcy's law. This approach assumes laminar flow within the textile region due to the low air velocity. Using the finite volume method, 3D steady state incompressible Navier-Stokes equations of continuity, momentum, and energy are solved. The momentum equation incorporates a sink term to account for pressure drops caused by fibers, with permeability values obtained experimentally and theoretically. The equilibrium energy equation assumes thermal equilibrium between fluid and solid zones, resulting in implicitly capturing convection. Radiation effects are evaluated using the Rosseland model. Also, the unique structure of natural hollow fibers is examined for its impact on thermal resistance.

Preliminary expectations suggest that increased wind velocity amplifies convection's role in overall thermal resistance, with textile permeability playing a crucial role in determining this effect. More permeable textiles are anticipated to exhibit greater contributions from convection, though the extent remains to be quantified. Validation against experimental results from a developed skin model bench test will ensure simulation accuracy.

This approach quantifies the contributions of conduction, convection, and radiation, optimizing textile structures under varying conditions of wind velocity, orientation, and temperature. These findings aim to advance the development of cold-protective clothing using sustainable natural fibers, enhancing outdoor workers' comfort while fostering eco-friendly, innovative thermal insulation solutions for industry partners.