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Numerical analysis of the flow and heat transfer in cylindrical clothing microclimates – Influence of the microclimate thickness ratio

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ABSTRACT

Clothing microclimates, i.e. the space between the skin and the clothing, can play a central role in the heat and mass exchanges from or to the body. This is especially true for protective clothing, where microclimates are generally thicker and natural convection is more likely to occur. We used a computational fluid dynamics approach to perform numerical studies of fluid flow and heat transfer across cylindrical clothing microclimates for Reynolds number of 3900. Transient simulations were performed for three different values of microclimate thickness to diameter ratio (0.05, 0.10 and 0.25), considering a two-dimensional cross-section of a human limb surrounded by a porous fabric and exposed to cool external air (10 °C). The obtained local heat transfer along the skin shows that increasing the microclimate thickness ratio from 0.05 to 0.25 decreases the convective heat fluxes by up to 100% in the upstream regions of the microclimate, and increases them up to 190% in the downstream regions. This asymmetry, which indicates an increasingly important role of natural convection as the microclimate thickness ratio is increased, is often overlooked in space-averaged approaches due to the opposite changes in the different regions of the microclimate. Local variations in temperature along the outer fabric and in convective fluxes along the skin were significant, reaching up to 14 K and 90%, respectively. The critical thickness ratio above which natural convection should not be ignored was found to be 0.1 (e.g. corresponding to a microclimate thicknesses of 11 mm or 8 mm, around an upper arm or forearm, respectively).

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1. Introduction

Protective clothing safeguards the wearer against hazards in the surrounding environment, including excessive heat or cold, and airborne particles. Examples at different protection levels range from functional sports garments to firefighting and CBRN (Chemical, Biological, Radiological and Nuclear) suits. Requirements for protective clothing frequently conflict with user comfort, in particular thermal comfort. This can affect performance, decreasing productivity and endurance of the worker and increasing the chance of heat stroke [1]. Higher protection is achieved, for example, by adding carbon filter materials underneath a garment of limited permeability, which reduce the penetration of hazardous agents through the garment, but hinder evaporative heat loss (sweat) and forced convection (air ventilation). Loose fits are also preferred in order to minimize contact with the skin of substances accumulated in the fabric. The space between the skin and the clothing, i.e. the clothing microclimate, can be more or less important for heat and mass transfer, depending on its thickness. CBRN clothing often fits very loosely on the wearer, so the microclimates are often large enough for natural convection to take place and change the relative importance of the different transport phenomena around the body [2–5].

Several authors have focused their attention on quantifying flow and/or heat transfer through clothing microclimates. Udayraj et al. [6] provide a review on research in the field of thermal protective clothing. Empirical correlations between Nusselt number (heat transfer) and Rayleigh or Reynolds numbers [7–9] are available, which are widely used throughout literature [4,10]. Experimental studies have also been performed (e.g. Li et al. [11] or Mert et al. [12]), who used 3D scanning and temperature data of thermal manikins in order to establish a relationship between microclimate thickness and heat transfer. These analyses, however, have some shortcomings because of lack of spatial resolution, which may cause significant local variations (e.g. in temperature or concentration of a chemical agent) to be missed [13]. Such information is important when designing complex clothing systems

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Nomenclature

C_p	specific heat capacity
D	diameter
Da	Darcy number
E	total energy
f	vortex shedding frequency
F	external force
g	gravitational acceleration
G	radiative flux
H	thickness
I	turbulence intensity
I_c	ratio between fabric's thickness and outer diameter of the fabric
I_g	ratio between air gap's thickness and outer diameter of the fabric
k	thermal conductivity or Turbulent kinetic energy
K	permeability (reciprocal of viscous resistance)
L_T	turbulence length scale
n	transparent media refractive index
Nu	Nusselt number
p	pressure
q	heat flux
R_CT	thermal resistance of the fabric layer
Re	Reynold's number ($\rho UD/\mu$)
R_t	turbulent Reynold's number
St	Strouhal number (fD/U)
t	time
T	temperature
u, v	fluid velocity components in the x- and y- direction
U	fluid velocity magnitude
x, y	space coordinates

Greek letters

β	thermal expansion coefficient
γ	porosity, ratio between volume of fluid and volume of solid
ε	emissivity or Turbulent energy dissipation rate
μ	dynamic viscosity
ρ	density
σ	Stefan-Boltzmann constant
θ	angular coordinate, $\theta = 0^\circ$ corresponding to the upstream side of the clothed limb and $\theta = 90^\circ$ to the point at the surface of the clothing with maximum y-coordinate

Subscripts

∞	far field (free stream)
air	air
avg	average
conv	convective
f	fluid
fab	fabric
gap	air gap
in	inlet
K	permeability-based
max	maximum
out	outlet
r	radial
rad	radiative
skin	skin
τ	tangential

such as protective clothing, where local peaks in temperature or concentration can be problematic, for example resulting in a burn or posing a health risk [2]. Numerical simulation approaches, particularly those based on Computational Fluid Dynamics (CFD), provide the necessary spatial resolution by solving the multiple transfer phenomena model equations, but need to be validated through comparison with published experimental results or benchmark numerical studies [14,15].

Natural convection has motivated ample numerical and experimental research due to its relevance in engineering applications such as nuclear energy systems and cooling of electronics [16]. Natural convection in rectangular enclosures has been studied for different aspect ratios and Rayleigh numbers by Corcione [17], and for different enclosure inclinations by Soong et al. [18] and Khezzar et al. [19]. Davis [20] and Ampofo and Karayiannis [16] provide benchmark numerical and experimental data for natural convection in rectangular enclosures for Rayleigh numbers between 10^3 and 10^6 and for 1.58×10^9, respectively. The coupling of natural convection and radiation for flat geometries has been studied by Akiyama and Chong [21] and, for different inclinations, by Vivek et al. [22] and Mayor et al. [23], who concluded that radiant exchange has a significant effect on heat transfer patterns in enclosures. Cylindrical geometries have also received some attention, namely by Stringer et al. [24], who computed flow around 2D circular cylinders for a range of diameters and flow conditions, Molla et al. [25] who accounted for radiation and natural convection, and Schäfer and Turek [26] who provided benchmark computations of laminar flow around 2D and 3D cylinders. The influence on the flow of a porous outer layer around an inner impermeable cylinder has been studied numerically by Bhattacharyya and Singh [27] and experimentally by Ozkan et al. [28], Gozmen et al. [29], Ozkan et al. [30] and Gozmen and Akilli [31] who concluded that the permeable outer layer is efficient in reducing the turbulent kinetic energy and the frequency of vortex shedding at the wake of the inner cylinder.

Transport phenomena in microclimates between the skin and clothing have been numerically studied, mainly considering a flat microclimate [23,32]. Flow and heat transfer in microclimates created by a cylindrical limb surrounded by a porous layer have also been studied using transient simulations [33–37]. Barry et al. [33] provides a concise analysis of CFD modelling strategies on different scales (microscale – fabric material; mesoscale – fabric-covered cylinder/limb; macroscale – full body), arguing that modelling in a cylindrical geometry is useful for understanding the interaction between material properties and transport processes. Sobera et al. [34] proposed a 2D steady Reynolds Averaged Navier Stokes (RANS) approach to modelling of flow, heat and mass transfer around a cylinder covered by an air-permeable fabric layer. Later [35], the authors further explored the subject by performing Direct Numerical Simulation (DNS) and comparing the results to those obtained using RANS, showing that the steady RANS approach had some shortcomings in the prediction of local heat and mass transfer. Sobera et al. [37] performed 3D transient RANS (T-RANS) simulations of the subcritical flow around a fabric-covered cylinder and tested their performance and accuracy by comparing results against DNS at an external *Re* of 3900 [36]. They concluded that T-RANS results are in better agreement with DNS and experimental data than earlier RANS results, while still much less computationally expensive than DNS. These papers [33–37] focus on situations where natural convection in the microclimate can be neglected. However, when ambient air velocities are low, or for example when a subject is indoors, natural convection can

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