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Heat and mass transfer of adult incontinence briefs in computational simulations and objective measurements

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ABSTRACT

This study aims to evaluate the heat and mass transfer of two kinds of multilayer adult incontinence briefs (diapers for short) in the dry condition and dynamic heat and moisture transfer processes in the wet condition in computational simulations and objective measurements. A commercial disposable brief (PROTEC) with polyethylene, superabsorbent polymers (SAP) and polypropylene, and another kind reusable brief (Reusable) with waterproof breathable fabric, full cotton inner pad and moisture management treatment nonwoven were evaluated. A software platform (S-smart system) with user friendly interfaces was employed in computational simulations. Wear trials were conducted by asking young female adults between 20 and 26 years old to wear incontinence briefs. Objective measurements revealed that there was significantly higher liquid moisture management capacity, water vapor permeability, thermal conductance and maximum value of heat flux in the Reusable than in PROTEC briefs. The simulation and wear trial results showed that there were significantly lower temperatures and humidity at the skin in the diaper area and diaper inner surface fabric in the Reusable briefs compared to the PROTEC ones. The good agreement between simulations and wear trials were observed. The 2D and 3D directly visualizes the changes of fabric temperature/humidity gradient and capacity of absorbing moisture etc. in each layer. The results indicate that the superior fabric's heat/moisture transporting properties, when incorporated into diapers, is the main mechanism for reducing heat and wetness of the diaper area. The results provide guidance for the optimal design of Eco-friendly diapers with reusable, breathable, biodegradable materials.

1. Introduction

Disposable diapers and incontinence pads of adults may be mainly worn by people with medical conditions which cause them to suffer from urinary or fecal incontinence. Since these people are unable to control their bladders or bowels, incontinence products are always used in the wet state. While the degree of skin wetness is proportional to incontinence products wetness, this might cause diaper dermatitis [1]. Additionally, the sensation of wetness in the diaper area also showed a strong association with discomfort [2].

In addition to causing skin wetness, like other clothing, the incontinence products, as an interactive barrier, could affect the heat transfer efficiency. They also block the diffusion of fresh air to the skin. The former depresses the rate of heat loss from the body by conduction and convection [3] and the latter is a key factor in clothing comfort [4]. Therefore, it is important for one to know what impact the wearing of incontinence products with different textile materials has on thermal functional performance.

The evaluations on the comfort performance associated with the heat and moisture transfer behaviors of clothing are divided into three phases:

Phase 1: The evaluations were performed by subjective wearer trials. This was also employed in a study in terms of infants' comfort perception of breathable and non-breathable diapers [2]. Since infants could not express themselves verbally, in this study the adult subjects had to wear diapers to participate in the wear trials, although the products used the standard infant diaper component materials. This case demonstrates that the subjective wearer trials might fail to simulate the practical experimental conditions accurately, leading to the inconsistent results.

Phase 2: The objective simulation tests were developed and expressed by the mathematical modeling and numerical simulation [5–12]. There should have been a more acceptable option, however, since the ways of the complex expression uses mathematical models, relevant computational algorithms and numerical solutions, that limit their extensive uses.

Phase 3: More recently, on the basis of the mathematical modeling and numerical simulation, a software platform, called the S-smart system, was designed and developed [13,14]. This is a

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Nomenclature

C^*	saturated water vapor concentration, kg m^{-3}
C_a	water vapor concentration in the air filling the inter-fiber void space, kg m^{-3}
C_f	water vapor concentration in the fibers of the fabric, kg m^{-3}
C_{res}	dry respiration heat loss, W m^{-2}
C_{skA}	convective heat loss from the skin in the area covered by clothing, W m^{-2}
C_{skU}	convective heat loss from the skin in the area uncovered by clothing, W m^{-2}
c_v	volumetric heat capacity of the fabric, kJ m^{-3} K^{-1}
D_a	diffusion coefficient of water vapor in the air of the fabric, m^2 s^{-1}
D_f	diffusion coefficient of water vapor in the fibers of the fabric, m^2 s^{-1}
DRY	dry heat loss from human body, W m^{-2}
E_{rsw}	evaporative heat loss by regulatory sweating from skin, W m^{-2}
E_{dif}	diffusive heat loss from skin surface, W m^{-2}
E_{res}	latent respiration heat loss, W m^{-2}
E_{skA}	evaporative heat loss from the skin in the area covered by clothing, W m^{-2}
E_{skU}	evaporative heat loss from the skin in the area uncovered by clothing, W m^{-2}
$FL_{(R)}$	elementary total thermal radiation incident inside the clothing traveling to the left (right), W m^{-2}
Γ_f	effective sorption rate of the moisture
Γ_{lg}	Evaporation/condensation rate of the liquid/vapor
M	metabolic rate of human body, W m^{-2}
Gs	Incidence of the external thermal radiation, W m^{-2}
l	distance between skin surface and inner surface of clothing or the neighboring clothing layers, m
h_{lg}	mass transfer coefficient for evaporation and condensation, m s^{-1}
Kl	thermal conductivity of the liquid water, W m^{-1} K^{-1}
K_{min}	minimum thermal conductance of body tissue, W m^{-2} - K^{-1}
K_{mix}	effective thermal conductivity of the fabric, W m^{-1} K^{-1}
K_l	Thermal conductivity of the liquid water, W m^{-1} K^{-1}
m_{rsw}	regulatory sweating in g s^{-1} m^{-2}
m_s	sweat accumulation on the skin surface in g s^{-1} m^{-2}
p_A	proportion of clothing-covered area
p_h	proportion of dry heat loss at the clothing-covered area
p_m	proportion of moisture vapor from the skin at the clothing-covered area
S_v	surface volume ratio of the fiber, m^{-1}
S_c	the heat storage of the core, W m^{-2}
S_s	the heat storage of the skin, W m^{-2}
r	fiber radius
R_{ea}	evaporation heat resistance on the skin surface, m^2 - Pa W^{-1}
R_{esk}	evaporation resistance of the skin, m^2 Pa W^{-1}
R_{skA}	radioactive heat loss from the skin in the area covered by clothing, W m^{-2}
R_{skU}	radioactive heat loss from the skin in the area uncovered by clothing, W m^{-2}
$T(T_{fi})$	temperature of the fabric, K
T_{sk}	temperature of skin surface, K
T_{cr}	temperature of core, K
T_r	temperature of the air, K
W	Moisture transfer resistance, s m^{-1}
V_{bl}	skin blood flow rate, l h^{-1} m^{-1}
ε_a	volume fraction of water vapor
ε_f	volume fraction of fibers
ε_l	volume fraction of liquid phase
ε	porosity of the fabric
ρ_l	density of the liquid water, kg m^{-3}
τ_a	effective tortuosity of the fabric for water vapor diffusion
ξ_1	proportions of moisture sorption at fiber surface covered by air
γ	surface tension of fiber, J m^{-1}
θ	contact angle of the liquid water on the fiber surface
α	effective angle of capillaries in the fabric
β	radiation absorption constant of the fiber, m^{-1}
η	dynamic viscosity of liquid, kg m^{-1} s^{-1}
λ	heat of sorption or desorption of vapor by fibers, kJ kg^{-1}
λ	heat of sorption or desorption of liquid by fibers, kJ kg^{-1}
σ	Stefan–Boltzmann constant, W m^{-2} K^{-1}

computer aided design tool with user-friendly interfaces which can be operated easily by the common designers, engineers and researchers without professional background knowledge of mathematics and computational techniques. In the earlier work, the thermal functional performances, wearing the hydrophilic and hydrophobic sportswear (single-layer) [13], and personal protective clothing (PPC, two-layer clothing assemblies), were simulated [15]. There was good correspondence between the predicted results and the experimental measurements, on the temperature at the skin, core and inner surface of the clothing, and the humidity in the clothing microclimate, suggesting that the S-smart system is satisfactory. 2D and 3D visualizations of this system further demonstrates the dynamic observations of heat and moisture transfer in clothing. However, the above mentioned simulation tests were limited to single-layer clothing or two-layer clothing assemblies made of common thickness of the fabric. To date, the simulation tests of a multilayer clothing assembly with unusual thickness such as diapers, has not yet been investigated.

Modern incontinence products of adults have a layered construction, which is illustrated in Fig. 1. From outside to inside, the commercial products (Fig. 1(A)) consisted of an outer shell of polyethylene film as a moisture barrier (outer layer), an absorbing layer of a mixture of cotton and superabsorbent polymers (SAP) for wetness (middle layer), and a wicking layer nearest the skin of polypropylene nonwoven material with a distribution layer directly beneath, which transfers wetness to the absorbent layer (inner layer). According to the literature, good water transport properties of incontinence products, such as high absorption capacity, low rewet, and fast strike-through time, are related to wet comfort [16–18]. Our previous study [19] found that the PPC cotton underwear with moisture management treatment (MMT) had significantly higher cumulative one-way moisture transport capacity and liquid moisture management capacity, which made clothing microclimate humidity significantly lower. Meanwhile, PPC outerwear made of waterproof breathable fabric had significantly higher water vapor permeability and thermal conductance, which helped clothing to speed up the evaporation process and heat dissipation. Based on the previous study, we extend our investigation to the newly designed incontinence products, which are hybrids of reusable briefs made of waterproof breathable fabric and disposable inner pads. The pads consisted of a replaced inner layer of full cotton nonwoven with MMT and an outer layer made of very thin breathable paper for the construction of the holding pads, and the same SAP/cotton absorbent middle layer, due to