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Research article

Comprehensive assessment for hygrothermal comfort with heat and mass fluxes through a clothing layer during cooling seasons

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ABSTRACT

A comprehensive analysis is carried out for achieving hygrothermal comfort by using bidirectional heat and mass fluxes between the human skin and its surroundings during cooling seasons, considering the main characteristics of climate, metabolic rate, and clothing fabrics. As hygrothermal comfort is mainly seen as one-direction heat and mass flux from the close surroundings to the human body, without the emitted heat and mass by the human skin, the purpose of the analysis is to find out proper features of the respective clothing fabric according to the inlet boundary conditions, i.e. heat and mass flux from the human body, and the outlet boundary features, i.e. heat and mass flux due to the climate conditions. Thereby, a novel mathematical modelling is developed for heat and mass transfer, respectively. Then, the software Wolfram Mathematica is applied for the numerical solutions of the model. After the model is validated, a sensitivity analysis is carried out. Thereby, it is found that the sensible heat removal by convection, dependent on both airflow and humidity rates, has a great influence on the hygrothermal comfort. Furthermore, solar reflectivity for shortwave radiation, along with longwave radiation from the skin, have influence on the hygrothermal comfort when both ventilation and sweating are set as minimum. Therefore, if the conditions of temperature and relative humidity are proper, both high conductivity and air permeability clothes are recommended. Nevertheless, regarding the reflectivity, it depends on the presence of shortwave radiation, sweating, ventilation, and longwave radiation to consider light-toned or dark colors.

1. Introduction

Hygrothermal comfort is understood as the proper physical conditions namely temperature and humidity, that the human body can stand without experiencing phases of overcooling or overheating [1]. Moreover, studies have proven that temperature and humidity vary in their suitability according to various dynamic factors such as the heat-radiation rate from the human skin, the thermal resistance of the clothing, the heat-convection exchange between the skin and its surroundings, and the respective psychological and physiological conditions of the people, who naturally try to adapt themselves to the physical features, mainly by clothing [2–4].

As the psychological and physiological conditions depend on the person and are not easy predictable, this document focuses on the transfer of heat and mass that drive the changes of humidity and temperature that end up to the hygrothermal comfort.

In a literature review, only focused on physical assessments, solely mass transfer is considered in analyses when skin transpiration is taken account of within porous media [5,6] and combined with conduction heat transfer when the heat range is on an extreme scenario

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[7–9]. Furthermore, the performance of thermal comfort, in function of clothing, could be classified by the heat transfer regime, i.e. conduction, convection, radiation and their combinations.

When the purpose of the clothing is heating up the human body, the main approach is focused on the conductive insulation [10–14], whereas for cooling purposes, or cooling season, the solutions are given considering both heat and mass transfer. It is worthy to mention that for this document, a cooling season is understood as the period when an action of cooling, upon the space and/or the human body, is necessary to achieve hygrothermal comfort and depends on geographical and social factors.

In this case, the objective is to show the influence of a certain characteristic of the surrounded microclimate and/or the self-body activity. For instance, in some studies, shortwave radiation at the surface of the clothing is surveyed [15,16], considering low doses of high-intensity radiation [17], radiative cooling with longwave radiation [18], and the combination of radiation and conduction, considering the air gap between the skin and the cloths as conductive heat transfer [19]. In addition, mass transfer by diffusion trough clothing layers is assessed considering both longwave and shortwave radiation [20,21].

Moreover, convection is assessed and modelled considering the air gap between the skin and the clothing layer, having better results of cooling by applying forced convection, or pumping effect [22]. Regarding analyses of mass and heat transfer by conduction and convection, these have been carried out for females and males along with a scenario of sweating [23,24]. Finally, analysis models with the three heat transfer regimes have been developed, for both cooling and heating, not considering mass transfer in any case [25–27].

Thereby, the mentioned studies have found out the relationship between the outdoor physical conditions and the human-related conditions, always with the purpose of achieving thermal or hygrothermal comfort. Nonetheless, there is not an assessment, to the best of our knowledge, which integrates the three heat transfer manners (breaking down radiation into infrared and ultraviolet) along with the mass transfer considering a double flux trough the clothing layers; this with the purpose of presenting the proper characteristics of clothing fabric according to both climate conditions and body metabolic activity. Therefore, the purpose of this document is to develop an integrated model that shows the heat and mass exchange trough the clothing layers of a person considering the physical sources of both the skin and its surroundings.

Furthermore, this document has the objective to show the influence of the bidirectional heat and mass fluxes upon the hygrothermal comfort perception, taking account of the already-developed ranges of temperature and relative humidity considered as suitable for achieving hygrothermal comfort. The study firstly shows developed mathematical models of heat transfer by conduction, convection and radiation, and a mathematical model for mass transfer trough the clothing layers.

Thereafter, a numerical solution of the models is shown along with the main parameters of hygrothermal comfort to compare them to already-established ranges. Then, a sensitivity analysis is carried out for to finding out the most influencing inputs of the skin, the surrounding microclimate, and the clothing fabric on the hygrothermal comfort perception.

2. Methodology

The physical interaction between the human skin and its immediate-surrounding microclimate is characterized by various fluxes of energy and mass. Furthermore, there are sources of heat and mass from both sides of origin at different magnitudes and directions. In this sense, the layers of clothing can be considered as barriers that control the fluxes trough them [28], depending on features of the clothing such as the conductivity, air permeability, thermal transmittance, and thermal emissivity, among others [29]. Therefore, the fluxes must consider the sources of heat and mass, originated from both the human skin and the surrounding environment as it can be seen in Fig. 1.

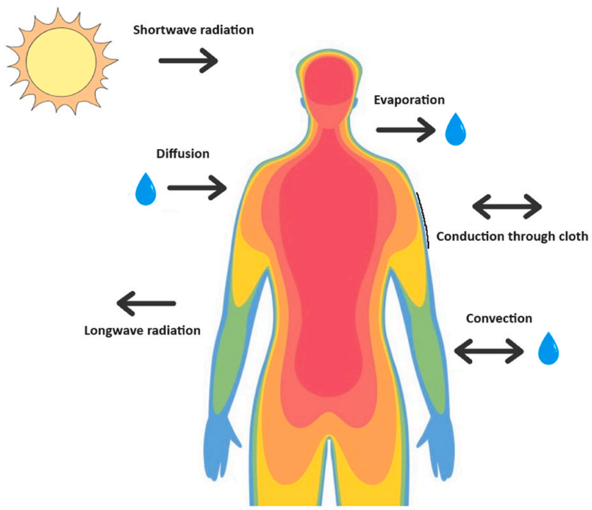

Fig. 1. Heat and mass fluxes between the human skin and its surroundings (image source: own).

From Fig. 1, one can see that the shortwave radiation (wave amplitude 10–400 nm), or ultraviolet radiation, is originated by the sun and aimed towards the human body [16], while the longwave radiation (wave amplitude 700–1000 nm), or infrared radiation, is mainly generated by the human skin to its surroundings [18].

Furthermore, in regards of mass transfer, the difference between evaporation and diffusion is given by the fact that evaporation is defined as the change of phase of the sweat drops, from liquid to gas, whereas diffusion is the moisture transfer between a zone with high humidity concentration to a zone with lesser concentration [30]. In this sense, relative humidity of the air has a great extent of influence due to the differences of concentration between the air and the skin. If the water concentration in the air is higher, the direction of the mass flux is from the surroundings to the skin, while if the concentration is higher in the skin, this would lose humidity. For both cases the direction of the mass flux could cause a sensation of discomfort, if the levels of relative humidity by the skin are off from a set range of comfort.

Thereby, the magnitude of the respective fluxes establishes a balance (positive or negative) of heat and moisture between the human body and the environment, thus producing an accumulation/discharge of heat and mass. Hence, this storing or releasing of heat and mass achieves hygrothermal comfort according to the humidity and temperature nearby the skin, in comparison with already-stablished ranges.

2.1. Modelling the heat transfer

In order to simplify the calculation of the heat transfer modelling, the following assumptions are considered:

- The materials' properties are not dependent on the temperature and pressure changes, and they are constant.
- There are only two main heat sources namely heat from the human body (infrared) and heat from solar radiation (ultraviolet).
- The heat transfer means are independent of each other.
- All the heat transfer means are simplified as one-dimension along the thickness direction of the clothing layer.
- The airgap thickness between the skin and the clothing layer is constant and it does not present pumping effects.
- The boundary conditions of the model are given by the domain of temperature [288.15 K–318.15 K] and the finite volume $0 < x < 0.1$, $0 < y < 0.1$, $0 < z < 0.0005$, all in meters.

Thereby, if the heat fluxes are analyzed upon a three-dimensional plane, the governing equations of heat flux by conduction can be displayed as follows [30]:

$$q_{cond}(x,y,z) = \frac{k}{\partial x + \partial y + \partial z}\left(\frac{\partial^2 T(x)}{\partial x^2} + \frac{\partial^2 T(y)}{\partial y^2} + \frac{\partial^2 T(z)}{\partial z^2}\right)\bullet \tag{1}$$

where q_{cond} is the local heat flux by conduction in x,y,z direction (W/m^2) and k is the material conductivity (W/m-K). As the heat flux is considered only for the z direction, Eq. (1) could be simplified as:

$$q_{cond} = \frac{k}{dz}\left(\frac{d^2 T(z)}{dz^2}\right) \tag{2}$$

Moreover, the z direction can be considered as the cross-sectional length, L (m) of the contact between the skin and the clothing, i.e. the thickness of the clothing layers. Therefore, Eq. (2) can be displayed as:

$$q_{cond} = \frac{k}{dL}\left(\frac{d^2 T(L)}{dL^2}\right) \tag{3}$$

If various independent layers of clothing are considered in the modelling (cf. Fig. 1), a global coefficient of heat transfer by conduction must be stated. This coefficient can be estimated as the following, considering that the set of layers acts as a homogeneous layer, i.e. uniform heat flux throughout the area of contact [31]:

$$U = \frac{1}{h_e} + \frac{1}{h_i} + \frac{l_1}{k_1} + \frac{l_2}{k_2} + \frac{l_3}{k_3}\cdots \tag{4}$$

where h_e is the thermal exterior surface conductance (13 W/m^{2}K), and h_i is the thermal interior surface conductance (8.1 W/m^{2}K for vertical surfaces). For effects of this document, only one layer of clothing is considered, also with accordance of being used for cooling purposes (low thermal resistance).

Furthermore, as the temperature difference is given by the difference of the temperature of the skin and the outdoor air temperature, the heat transfer by conduction can be summarized from Eqs. (3) and (4) as follows:

$$q_{cond} = A \bullet U \bullet (T_{cloext} - T_{cloint}) \tag{5}$$

Moreover, the heat transfer by convention in a three-dimensional field can be shown as the following:

$$q_{conv}(x,y,z) = h\left(\frac{\partial^2 T(x)}{\partial x^2} + \frac{\partial^2 T(y)}{\partial y^2} + \frac{\partial^2 T(z)}{\partial z^2}\right) \tag{6}$$

where q_{conv} is the local heat flux by convection in x,y,z direction (W/m^2) and h is the dynamic coefficient of convection (W/m^2-K). As the heat transfer through the air between the human skin and the clothing layers is considered as natural convection, i.e. without the presence of a pump or a blower, only propelled by the difference of temperature between the skin and the clothing layer, the Nusselt number is used [30]. Thereby, the coefficient h is calculated as follows:

$$h = \frac{Nu \bullet k_{air}}{L_{zone}} \tag{7}$$

where *Nu* is the Nusselt number (dimensionless), k_{air} is the thermal conductivity of the air (W/m-K) and L_{zone} is the length of the zone where the hygrothermal comfort is assessed, i.e. the space between the skin and the clothing (m). The Nusseslt number is understood as the rate of heat transfer by convection compared to heat transfer if only happens by conduction. This number is calculated as follows, considering that the natural convection happens from a vertical surface:

$$Nu = \left\{ 0.825 + \frac{0387 \bullet Ra^{1/6}}{\left[1 + (0.492/Pr)^{9/16}\right]^{8/27}} \right\}^2 \tag{8}$$

where Ra is the Rayleigh number (dimensionless), and Pr is the Prandtl number (dimensionless). The Rayleigh Number is defined as the proportion of natural convection within the fluid, while the Prandtl number is understood as the velocity of diffusion of the fluid according to its viscosity and thermal diffusivity. Pr is estimated as following:

$$Pr = \frac{\mu \bullet C_P}{k_{air}} \tag{9}$$

where u is the viscosity of the air (N-s/m^2) and C_p is the heat capacity of the air (kJ/kg-K). Ra is calculated as follows:

$$Ra = Gr \bullet Pr \tag{10}$$

where *Gr* is the Grashof number (dimensionless). This number is defined as the proportion between the flotation forces (buoyancy) and viscous forces that act on a fluid. *Gr* is calculated as the following:

$$Gr = \frac{{L_{zone}}^3 \bullet \rho^2 \bullet g \bullet B.\Delta T.\beta}{\mu^2} \tag{11}$$

where ρ_{air} is the density of the air (kg/m^3), g is the acceleration due to gravity (9.81 m/s^2), β is the local air velocity (m/s) and B is the coefficient of volume expansion of the fluid (K). Furthermore, B is also defined as the inverse of the absolute temperature for an ideal gas (1/K).

Then, the heat transfer by convection through the z direction, considering two main heat sources, one from the skin and other directly from the inner surface of the clothing, can be simplified by the following equation:

$$q_{conv} = A \bullet h \bullet (T_{cloint} - T_{zone}) - A \bullet h \bullet (T_{zone} - T_{skin}) \tag{12}$$

Finally, the heat transfer by radiation can be displayed as follows [30]:

$$q_{rad}(x,y,z) = \varepsilon_{SB} \bullet \sigma \bullet \left[(T_{cloext})^4 - (T_{outair})^4\right] \left(\frac{\partial^2 x}{\partial x^2} + \frac{\partial^2 y}{\partial y^2} + \frac{\partial^2 z}{\partial z^2}\right) + met \tag{13}$$

where q_{rad} is the local heat flux by radiation in x,y,z direction (W/m^2), σ is the Stefan-Boltzman constant (W/m^2-K^4), ε_{sb} is the emissivity of the surface and T_{solid} is the temperature at the boundary of the solid body (ultraviolet radiation); and met is the metabolic rate generated by the physical activity of the body (infrared radiation).

Again, as the heat flux is considered in only one direction, the heat transfer by radiation could be expressed as follows:

$$q_{rad} = \varepsilon_{SB} \bullet \sigma \bullet A \bullet \left[(T_{cloext})^4 - (T_{outair})^4\right] + met \tag{14}$$

Thereby, taking account of the three heat fluxes trough the clothing layers, the energy balance in the zone determined between the skin and the clothing is displayed as follows:

$$m \bullet C_P \frac{dT_{zone}}{dt} = A \bullet U \bullet (T_{cloext} - T_{cloint}) + A \bullet h_{cloint} \bullet (T_{cloint} - T_{zone}) - A \bullet h_{skin} \bullet (T_{zone} - T_{skin}) + \varepsilon_{SB} \bullet \sigma \bullet A \bullet \left[(T_{cloext})^4 - (T_{outair})^4\right] + met \tag{15}$$

where m is the mass of the air between the skin (kg) and the clothing; C_p is the heat capacity of the air (kJ/kg-K); U is the global coefficient of heat transfer by conduction of the clothing (W/m^2-K); whereas h_{cloint}, h_{cloext} and h_{skin} are the coefficients of heat transfer by convection of the clothing inner surface, clothing outer surface and skin surface, respectively (W/m^2-K). From Eq. (15), the heat storing can be simplified as follows:

$$\rho \bullet V \bullet C_P \frac{dT_{zone}}{dt} = A \bullet \left\{ U \bullet (T_{cloext} - T_{cloint}) + h_{cloint} \bullet (T_{cloint} - T_{zone}) - h_{skin} \bullet (T_{zone} - T_{skin}) + \varepsilon_{SB} \bullet \sigma \bullet \left[(T_{cloext})^4 - (T_{outair})^4 \right] + met \right\} \quad (16)$$

$$\rho \bullet L \bullet C_P \frac{dT_{zone}}{dt} = U \bullet (T_{cloext} - T_{cloint}) + h_{cloint} \bullet (T_{cloint} - T_{zone}) - h_{skin} \bullet (T_{zone} - T_{skin}) + \varepsilon_{SB} \bullet \sigma \bullet \left[(T_{cloext})^4 - (T_{outair})^4 + met \right] \quad (17)$$

Eq. (17) shows that the energy, stored or released, is independent from the area of contact. The heat transfer is only dependent on the length between the human skin and the clothing layers, i.e. z direction. Hence, the temperature of the zone (T_{zone}) between the skin and the clothing, hereby considered as the temperature of comfort, can be solved by using the software Wolfram Mathematica®, and it can be displayed as the following:

$$\Delta T_{zone} = \frac{U \bullet (T_{cloext} - T_{cloint}) + h_{cloint} \bullet (T_{cloint} - T_{zone}) - A \bullet h_{skin} \bullet (T_{zone} - T_{skin}) + \varepsilon_{SB} \bullet \sigma \bullet \left[(T_{cloext})^4 - (T_{outair})^4 \right] + met}{\rho \bullet L \bullet C_P} \bullet \Delta t \quad (18)$$

From Eq. 18 it can be noticed that the comfort temperature difference is a function of the following inputs: skin temperature (related to the human metabolic rate), clothing temperature, clothing thermal resistance, clothing thickness and clothing emissivity coefficient. In this case, the air permeability of the clothing has an influence over the convection heat transfer from the inner clothing to the skin, where the convective coefficient, h_{cloint}, varies because of this factor.

Furthermore, the difference of temperatures within the zone of assessment through a certain period could be displayed as the following:

$$T_{2zone} - T_{1zone} = \frac{U \bullet (T_{cloext} - T_{cloint}) + h_{cloint} \bullet (T_{cloint} - T_{1zone}) - A \bullet h_{skin} \bullet (T_{1zone} - T_{skin}) + \varepsilon_{SB} \bullet \sigma \bullet \left[(T_{cloext})^4 - (T_{outair})^4 \right] + met}{\rho \bullet L \bullet C_P} \bullet \Delta t \quad (19)$$

If it is considered that, there is an initial temperature at second = 0, the consequent temperature of the zone will be T_{2zone} at second = i, as it is shown in Eq. (20):

$$T_{comfort} = \left\{ \left[\frac{U \bullet (T_{cloext} - T_{cloint}) + h_{cloint} \bullet (T_{cloint} - T_{1zone}) - A \bullet h_{skin} \bullet (T_{1zone} - T_{skin}) + \varepsilon_{SB} \bullet \sigma \bullet \left[(T_{cloext})^4 - (T_{outair})^4 \right] + met}{\rho \bullet L \bullet C_P} \right] \bullet \Delta t \right\} + T_{1zone} \quad (20)$$

Thereby, for determining the temperature of comfort, according to the balance of the thermal zone, it is necessary to set an initial temperature considering the initial heat sources at time zero. Therefore, the comfort temperature could be calculated on a determined period.

2.2. Modelling the mass transfer

The presence of a liquid flux trough the clothing in two directions is hereby proposed. It is assumed that from the skin, sweat drops are originated, whereas from the close microclimate, a flux of micro-water drops through the clothing layers occurs. For both cases, it is considered that the physical properties of the liquid is equal to water at normal conditions, as it is shown in Table 1.

Moreover, for simplifying purposes, and in order to propose reasonable initial values on the assessment model, the following assumptions are established:

- Steady state conditions
- Mass transfer in x, y and z directions

Table 1
Physical characteristics of water, considered here for both sweat drops and environmental moisture.

Property	Value
Density at 95 °C (kg/m^3)	961.9
Specific heat (kJ.kg/K)	4.2
Boiling point (K)	373.15
Melting point (K)	273.15
Vapor pressure (kPa)	3.169
Thermal conductivity (W/m.K)	0.6065

- No chemical reactions occur
- Constant pressure (constant concentration and diffusivity)
- The boundary conditions of the model are given by the domain of relative humidity [0 %–100 %] and the finite volume $0 < x < 0.1$, $0 < y < 0.1$, $0 < z < 0.0005$, all in meters.

For the mass transfer by diffusion, in rectangular coordinates, the model can be developed as follows [32]:

$$R_A = \frac{\partial C_A}{\partial t} + \left[\frac{\partial N_{A,x}}{\partial_x} + \frac{\partial N_{A,y}}{\partial_y} + \frac{\partial N_{A,z}}{\partial_z}\right] \tag{21}$$

where RA is the rate of the water vapor (kg/m^3-s), C is the mass concentration of the water (kg/m^3), and N is the diffusion (m^2/s). If the water is considered as pure chemical component, the accumulation of mass can be given by the following equation:

$$\frac{d\rho_A}{dt} = \left[\frac{\partial N_{A,x}}{\partial_x} + \frac{\partial N_{A,y}}{\partial_y} + \frac{\partial N_{A,z}}{\partial_z}\right] - R_A \tag{22}$$

where p is the water density (kg/m^3). Since the mass transfer flux can be considered only on the z direction, Eq. (23) can be displayed as follows:

$$\frac{d\rho_A}{dt} = \frac{dN_A}{dl^2} - R_A \tag{23}$$

Therefore, by solving Eq. (23), the accumulation of density of water can be displayed as the following:

$$\rho_{A2} - \rho_{A1} = \left(\frac{N_{A2} - N_{A2}}{l^2} - R_A\right) \bullet \Delta t \tag{24}$$

$$\rho_{confort} = \left(\frac{N_{A2} - N_{A2}}{l^2} - R_A\right) \bullet \Delta t + \rho_{A1} \tag{25}$$

NA can be calculated considering a porous media, in a vertical surface with a length, l (m), by using Darcy's law, as the following:

$$Q = \frac{-k \bullet L^2}{\mu.\beta}(P_b - P_a) \bullet l \tag{26}$$

where Q is the volumetric flow rate of the water (m^3/s), κ is the air permeability of the media (m^3/s/m^2), u is the viscosity of the fluid (Pa.s), Pb–Pa is the pression drop across the porous media (Pa), and l is the length of the vertical surface (m). If the diffusion and the volumetric flow rate are analyzed throughout the length of the vertical surface of the clothing layer, then the diffusion, considered as the moisture distribution within the clothing area, could be displayed as the ratio of the flow through the crossed-section area to the length of the vertical surface, as the following:

$$dN_A = \frac{dQ}{dl} \tag{27}$$

Thus, the density (presence) of water vapor in the zone of assessment, can be finally calculated as follows:

$$\rho_{confort} = \left(\frac{-k \bullet L}{\mu} \bullet \Delta P - R_A\right) \bullet \Delta t + \rho_{A1} \tag{28}$$

For calculating the relative humidity within the assessment zone, Eq. (29) is used:

$$\varphi = \frac{\rho_{comfort}}{\rho As} \bullet 100 \tag{29}$$

where ρAs is the saturation vapor density (kg/m^3), and it can be estimated as follows:

$$\rho As = 6.11 \bullet exp\left[\frac{17.27 \bullet T_d}{T_d + 237.3}\right] \tag{30}$$

where T_d is the temperature of dew point [°C], which is retrieved according to the particular climate conditions of the assessment. Thereby, the relative humidity of the comfort zone is a function of the water viscosity, the air permeability and thickness of the clothing layer, the outside dew temperature, and the sweat production of the human skin. Hence, both temperature and humidity upon the zone between the skin and the clothing layers can stablish the hygrothermal conditions of comfort.

2.3. Experimental setup

To obtain results for being compared to the numerical analysis, a wireless sensor of air temperature and humidity is used, i.e. meter Ymiko, model YS-11®, with an accuracy for temperature of±1 °C and for humidity of±5% (when air temperature is below 25 °C) according to the manufacturer information. The sensor is placed underneath the shirt, at chest level, of a male that does exercise under different metabolic rates, from 1 to 5.2 mets, and under different conditions of air temperature, air speed, global solar radiation, and relative humidity. In this sense, indoor and outdoor scenarios were setup, both for Mexico City during the period of from November 27th to December 1st, 2023. The person who used the wireless meter is the author himself. Therefore, no authorization letter was necessary.

Furthermore, as both the mathematical model and the experimental setup use as much information as possible, and its purpose is to estimate physical values of temperature and humidity, and not subjective votes of hygrothermal comfort, it was considered not including a statical analysis of the results.

The scenarios of measurements are stated as two: indoor conditions, using a treadmill as physical exercise, where ventilation and global solar radiation are set as minimum; and outdoor conditions, also with physical exercise, and with values of radiation and wind speed, which are set on one single day (see Fig. 2).

3. Ranges of hygrothermal comfort

To set the proper values of air temperature and relative humidity, a review of the main ranges is carried on. The study of the hygrothermal comfort has been carried out by several documents [33–36]. In some of them, a range of air temperature and moisture is set as the proper conditions of comfort. The range of these physical properties, estimated from Refs. [33–36] can be seen as averaged values in Table 2.

It must be noticed that the range was built considering only indoor conditions, according to Su et al., Oropeza-Perez et al., Amaripadath et al. and Feng et al. [33–36]. In the case of outdoor conditions, it is stated that the human body can stand somewhat higher levels of temperature and humidity [37]. Nonetheless, for purposes of this study, indoor hygrothermal conditions are taken as a reference of hygrothermal comfort.

It is also worthy to mention that these values are set as the proper of the zone between the skin and the clothing layer, considering that the human body is naturally generating longwave radiation and moisture (sweat), and the external relative humidity and heat sources from the surroundings, thus these are retained by the clothing fabric. Hence, the comfort values of temperature and humidity are slightly different that the regular values considering no clothing [36].

3.1. Assessment model

With the purpose of achieving hygrothermal comfort with the different initial conditions of clothing, metabolic rate, and climate conditions, a flowchart of the hygrothermal comfort achievement is shown in Fig. 3.

Both the data from the wireless meter and the estimated by the numerical model are validated, and then are compared with the ranges of comfort. If some of the output is off the range of comfort, the initial parameters might be changed: type of clothing fabric, level of exercise, solar radiation, ventilation, or even the air temperature and relative humidity, in order to find the proper conditions of hygrothermal comfort.

For the purpose of this assessment, five types of fabrics are selected: white cotton, polyester and nylon, stretch cotton, recycled

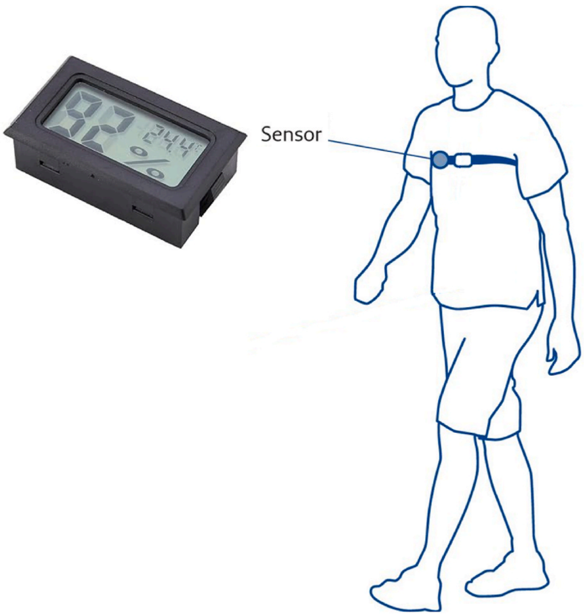

Fig. 2. Temperature and humidity wireless digital meter (image source: own).

Table 2
Average ranges of hygrothermal comfort for air temperature and relative humidity.

Physical property	Lower limit	Upper limit
Air temperature (°C)	22	27
Relative humidity (%)	40	70

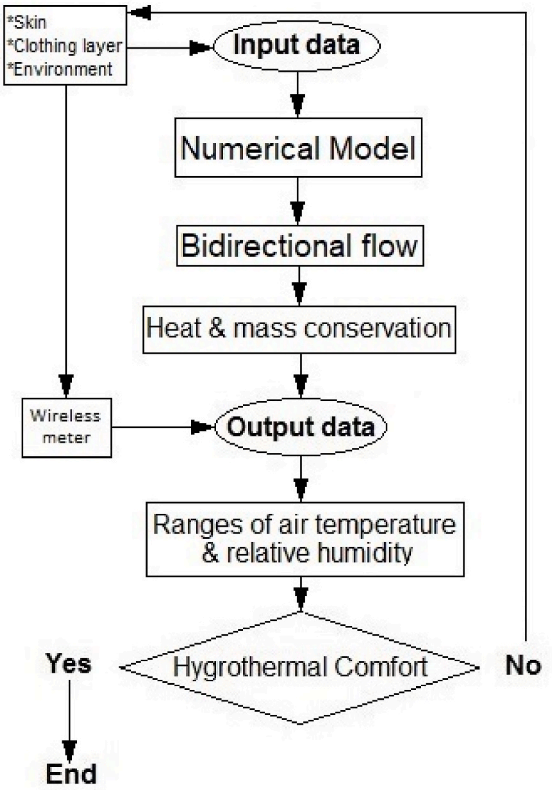

Fig. 3. Hygrothermal comfort assessment according to initial conditions of the human skin, clothing, and surrounding environment.

polyester, and black cotton, which are very common materials for commercial clothing. The main values of conductivity, air permeability, and solar reflectivity of these selected fabrics are displayed in Table 3. The value of solar reflectivity was taken according to the particular color of the fabric.

For simplicity purposes, the thickness of the fabrics is considered in an average of 5 mm, in accordance with the most commonly used values of commercial fabrics [19,41].

Having all the input data, the assessment model is carried out for both numerical model () and measurements to find values of temperature and relative humidity.

4. Results

The measures and the estimated values by the numerical model, using NDSolve of Mathematica [42] were carried out during five straight days, from November 27th to December 1st, 2023, under climate conditions of Mexico City, without a value of global solar

Table 3
Physical values of selective fabrics [38–40].

Type of fabric	Conductivity (W/m-K)	Air permeability ($cm^3/s/cm^2$)	Solar reflectivity (dimensionless)	Density (g/cm^3)
White cotton	0.035	13.14	0.94	1.50
Polyester and nylon	0.025	11.95	0.83	1.08
Stretch cotton	0.030	12.95	0.73	1.56
Recycled polyester	0.050	12.77	0.94	1.38
Black cotton	0.035	13.14	0.05	1.50

radiation and ventilation, i,e. indoor environment. During the measurements, the relative humidity presented a range of 58–71 %, and an indoor air temperature within a range of 23.4–25.3 °C. Regarding metabolic rate, it is set within the range of 1–5.2 mets, i.e. from stand still condition to moderately strenuous activity.

Regarding the assessment under outdoor conditions, the outputs were recorded on just one day, December 2nd, 2023, in Mexico City, from 11:00 to 12:00 h, with a global solar radiation of 590–602 W, with a 53 % of relative humidity, 24.6 °C of outdoor air temperature, and 6 km/h (1.67 m/s) of wind speed. All the values set as average. Furthermore, as in the experimental setup of indoor conditions, the metabolic rate is set within the range of 1–5.2 mets.

Figs. 4–7 show the behavior of the comfort temperature and relative humidity at given conditions with the five proposed fabrics of the assessment. It can be noticed that in Fig. 4, for 1.5 mets, results of show a discrepancy between the measured and estimated results, this can be explained by the fact that during the measurements of the comfort temperature (experimental measurements), a variation of the indoor air temperature could occur, therefore it affected the output results.

Nevertheless, as these fabrics have various characteristics of conductivity, air permeability and solar reflectivity, mainly, the results are in accordance with these features. For instance, when there is no ventilation nor solar radiation, the heat transfer trough the clothing layer can be considered mainly by conduction. Thereby, polyester and nylon present the highest temperature, due to its low conductivity. Nonetheless, when sweating increases, heat transfer by convection starts to be predominant therefore the conductivity of the fabric loses influence and the air permeability becomes in the most influencing feature, as it can be seen in Fig. 4 with white and black cotton, that have the highest values of air permeability and present the highest heat transfer (lowest temperature).

Moreover, when both solar radiation and ventilation are present, solar reflectivity has a extend of influence on the temperature of comfort. Nevertheless, when swearing is present, air permeability is again the most influencing feature to achieve hygrothermal comfort, as it can be seen in Figs. 6 and 7, where black cotton (solar reflectivity 0.05 and air permeability 13.14 $m^3/s/m^2$) has the highest temperature without exercise and one of the lowest with it. This means that the heat removal by convection is higher than the heat flow of longwave radiation from the skin and the shortwave radiation from the sun, all together.

Thus, one can notice that the conductivity of the fabric only has influence when there is no physical activity on the body, i.e. when there is no additional moisture in the skin. Once sweating is present, heat transfer by conductions loses importance letting convection be the must important heat meaning, with air permeability as the most important characteristic of the clothing layer.

4.1. Model validation and limitation

The results shown in Figs. 4–7 are compared with other results from already-published documents, in order to find out the accuracy of the experimental setup. The comparison is carried out taking selected results under similar scenarios of air temperature and metabolism. Thereby, three documents are compared with the findings, as it is shown as follows:

According to Table 4, under specific conditions of type of fabric, air temperature, wind speed, metabolism and/or solar radiation, three selected data show that the results calculated in this document have the same order of magnitude than the results from the referenced documents, hence the model can be considered as validated.

Nevertheless, it is important to mention that under other some conditions, not mentioned in the document, the results might differ, thus the scope of the model is limited only for the initial boundary conditions stated on the Methodology section.

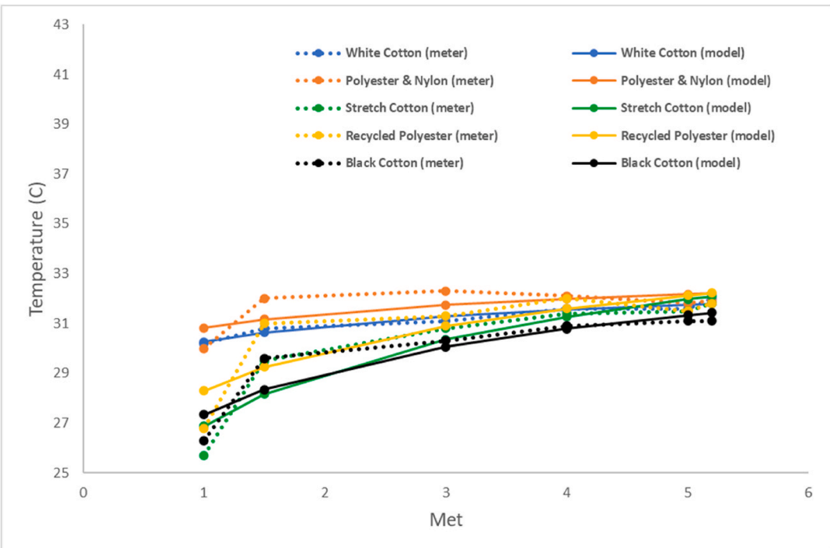

Fig. 4. Air temperature between skin and clothing at different metabolic rates under indoor conditions.

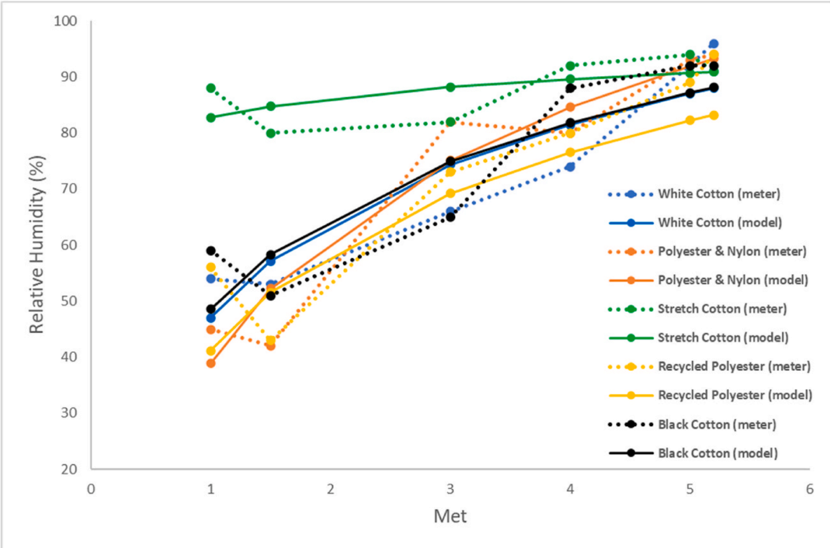

Fig. 5. Relative humidity between skin and clothing at different metabolic rates under indoor conditions.

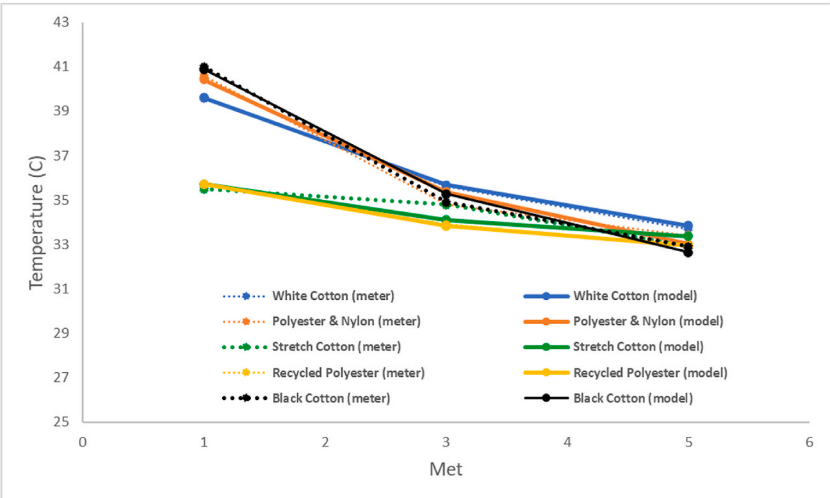

Fig. 6. Air temperature between skin and clothing at different metabolic rates under outdoor conditions.

4.2. Error analysis

Once the results are estimated, a geometrical difference between each other, i.e. discrepancy, is calculated. The absolute values of the discrepancies are shown in Figs. 8 and 9 for temperature and relative humidity, respectively.

In Fig. 8 one can notice that the differences between the results measured and the estimated by the model are not higher than 1.8 °C. Hence, one can consider that there is a good agreement with the results.

From Fig. 9 it is seen that from the whole universe of outputs, only 3 discrepancies are higher than 12 % of relative humidity. In this case, higher values of discrepancy, in general, between measured and estimated results, are found. This can be explained by the characteristics of air permeability of the clothing, which might allow in an easier manner the fluctuation of airflow between the skin and the clothing layer driving to forced flow (pumping effect). Nevertheless, although this phenomenon is difficult to control, the results can be considered in agreement with the developed model.

4.3. Analysis of results

According to Figs. 4 and 6, the temperature between the skin and the clothing layer shows opposite behaviors with and without airflow: under minimum airflow rates, the temperature presents an increase with higher metabolic rate namely the increase of

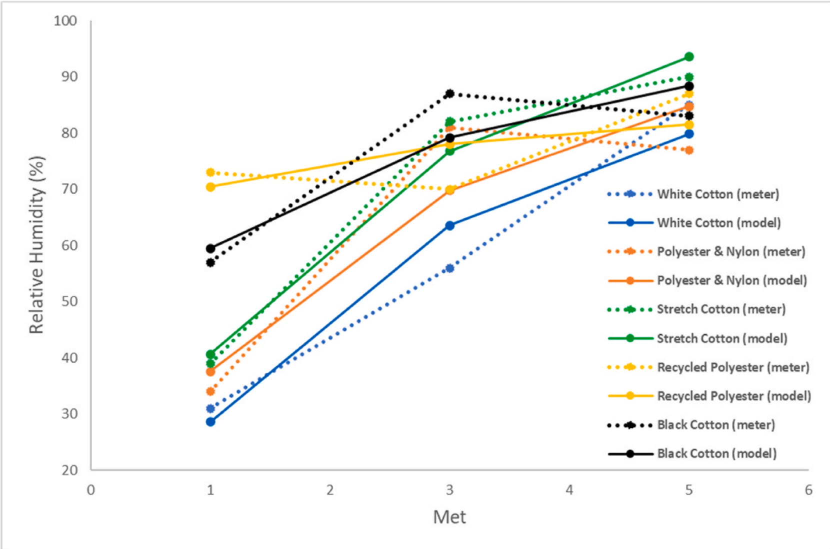

Fig. 7. Relative humidity between skin and clothing at different metabolic rates under outdoor conditions.

Table 4
Comparison of selected results between this document and references [18,19,21].

Common specific conditions	Reference	Result of reference – Results of this document
White cotton fabric Air thickness: 5 mm Air temperature (reference): 10–32°C Air temperature (document): 23.4–25.3°C Metabolism (reference and document): 1 met	[18]	28.3 °C–30.2 °C
White cotton fabric Air thickness: 5 mm Air temperature (reference): 22.85°C Air temperature (document): 24.6°C Metabolism (reference and document): 3 met	[19]	35.85 °C–35.7 °C
White cotton fabric Wind speed (reference): 0.5 m/s Wind speed (document): 1.67 m/s Solar radiation (reference): 380 W/m^2 Solar radiation (document): 590–602 W/m^2 Metabolism (reference and document): 5 met	[21]	30.4 °C–33.7 °C

longwave radiation from the skin. On the other hand, when ventilation is presented, the high levels of moisture, mainly by sweating, allow sensible heat removal by convection, thus decreasing the temperature.

For both cases, the thermal resistance of the clothing, typically expressed by clos (0.1.55 m2-K/W), which is closely related to the conductivity, shows a low extent of influence on cooling purposes. This is because the fabrics selected in the assessment were set for being used as only one layer, therefore the value of resistance is set as lowest as possible.

Regarding relative humidity, Figs. 5 and 7 show that the behavior is similar with and without ventilation: the increase in sweating raises the relative humidity in both cases. This reaffirms that the removal heat by convection is sensible, due to there is no phase change of the sweat drops within the zone of skin-clothing fabric.

Thereby, for figuring out which initial conditions of exercise and clothing are the optimal for achieving hygrothermal comfort on both scenarios of indoor and outdoor conditions, a sensitivity analysis is carried out.

4.4. *Sensitivity analysis*

For the indoor scenario, and at a metabolic rate of 1 met (stand still), stretch cotton and black cotton present the lowest values of temperature, being within the range of comfort (22–27 °C), followed by recycled polyester, white cotton, and polyester and nylon, which are not on the comfort range.

Furthermore, for the same scenario, with higher metabolic rates (1.5–5.2 mets), all the fabrics are off the range of comfort. Nevertheless, black cotton presents results somewhat better. This can be explained by the emissivity value of black color, which once the longwave radiation is absorbed by the fabric, this is immediately emitted to its exteriors, decreasing in a slightly manner the

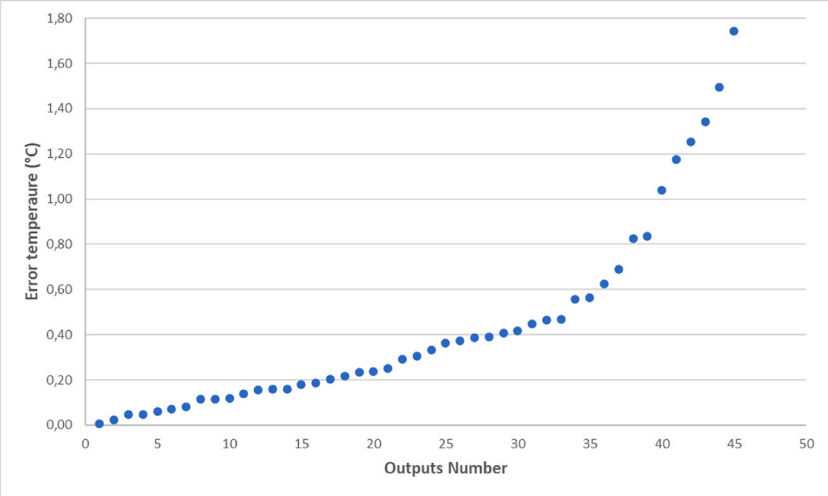

Fig. 8. Absolute discrepancy between measured and estimated values of temperature.

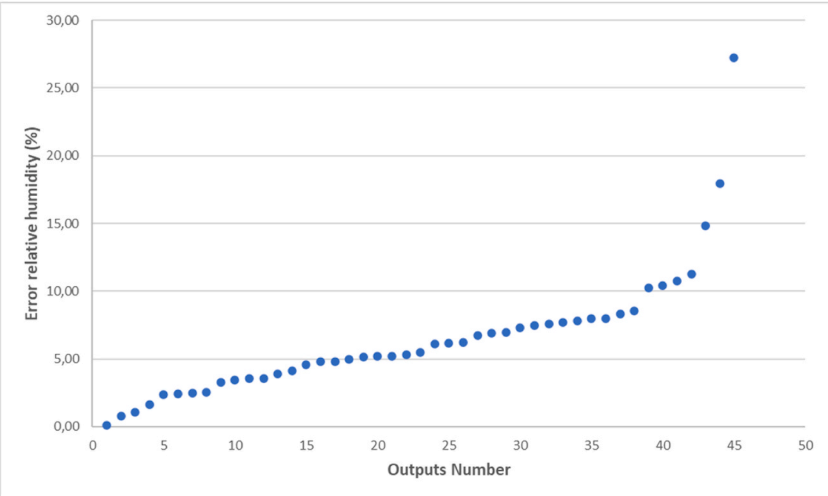

Fig. 9. Absolute discrepancy between measured and estimated values of relative humidity.

temperature between the skin and the clothing layer.

Regarding relative humidity, for the same indoor scenario at 1 met, only stretch cotton presents humidity off the comfort range (40–70 %), whereas for metabolic rates from 4 mets all the fabrics show values above the range of comfort. This is explained by the high rates of sweating (0.22–0.38 ml/s) which are difficult to remove, even though the high air permeability of the assessed fabrics, as it is graphically shown in Figs. 10 and 11. These figures show image footages of different clothing fabrics made by the digital microscope Mustool G1000®.

From Figs. 10 and 11 one can observe the air permeability of different fabrics, represented, by proxy, by the number of irregular holes in the surface. Notice that synthetic fabrics such as nylon and polyester do not present a clear permeability.

Stepping on the outdoor scenario, at a metabolic rate of 1 met, stretch cotton and recycled polyester show the lowest temperature, in accordance with their value of solar reflectivity. Nonetheless, while the sweating rate increases, and with the presence of ventilation, the temperatures of all the fabrics tend to converge to a narrow range of 32.7–33.9 °C. In either case, none of the results are within the zone of comfort.

Nevertheless, ventilation helps to achieve hygrothermal comfort, regardless the presence of solar radiation. This drives to the conclusion that air permeability has more influence on the comfort than the reflectivity of the fabric, which only is important when sensible heat removal by convection is not presented or is minimum.

This is reinforced with the analysis of relative humidity upon an outdoor scenario, showing that the fabrics with higher values of air permeability present the lowest values of moisture. The only exception is stretch cotton, which, likewise on the indoor scenario, presents high levels of humidity. This can be explained by its thickness and density, which are slightly higher than the other fabrics (cf.

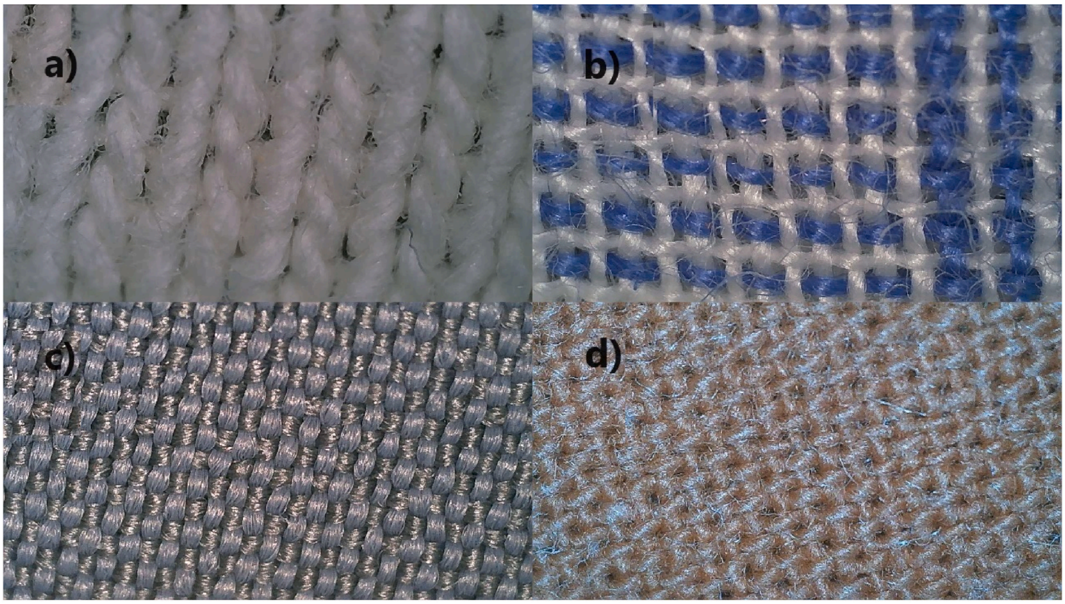

Fig. 10. Microscopic image footages of four different clothing fabrics: a) natural cotton, b) linen, c) polyester, and d) raw cotton (image source: own).

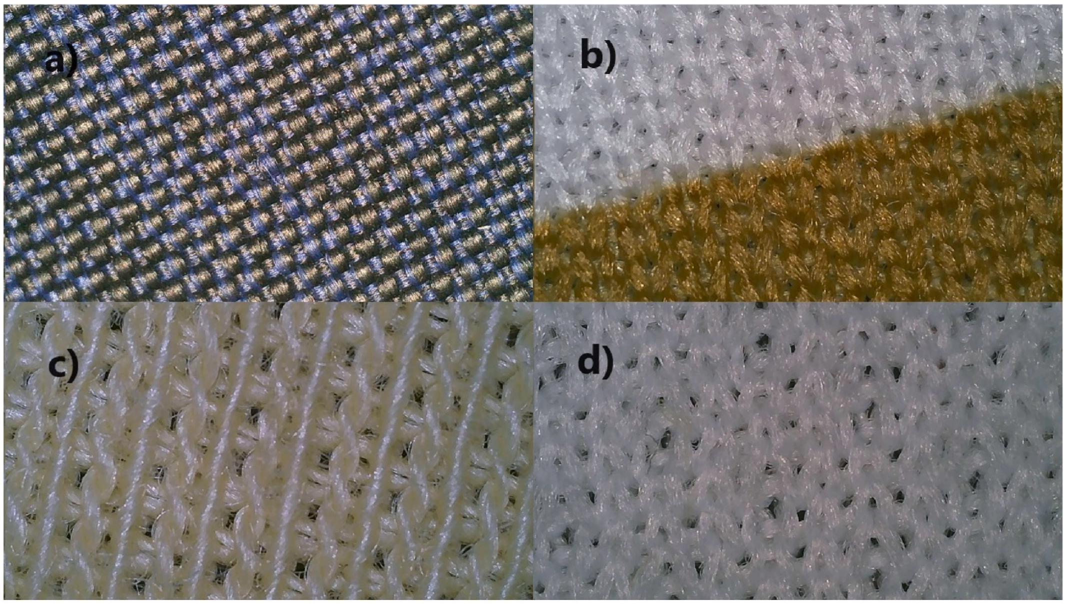

Fig. 11. Microscopic image footages of four different clothing fabrics: a) nylon, b) polyester and nylon, c) stretch cotton, and d) recycled polyester (image source: own).

Table 3).

Carrying out a comparison between the influence of both air permeability and reflectivity on the hygrothermal comfort achievement, it is found that, according to the temperature of comfort of the different types of fabric, reflectivity can decrease it by a maximum of 5.3 °C, considering the difference between the highest and lowest values of solar reflectivity (recycled polyester, 0.94, and black cotton, 0.05) at the same conditions, i.e. 1 met, radiation of 600 W.

On the other hand, considering the highest and lowest values of air permeability (white cotton, 13.14 $m^3/s/m^2$, and polyester and nylon, 11.95 $m^3/s/m^2$) the temperature decrease is 8.1 °C and 7.2 °C, respectively, if it is considered that the activity is increased from 1 to 5 mets, at conditions of wind speed of 1.67 m/s. In other words, is more likely to achieve thermal comfort by using ventilation and a breathable fabric than changing the reflectivity of the clothing, even when solar radiation is presented.

As a final comment of the sensitivity analysis, the usage of permeable fabrics for cooling has its advantage by the fact that natural ventilation could be used, even for national-wide scenarios of energy saving, considering that more hours of hygrothermal comfort might be reflected on less hours of air-conditioning consumption, which has been assessed in previous documents for warm-conditions countries [43,44].

5. Conclusions

A novel assessment model for calculating air temperature and relative humidity between the human skin and a clothing layer for cooling purposes is developed, considering bidirectional fluxes of heat and mass. After the model is validated with experimental results, two scenarios of analysis are set: indoor and outdoor conditions. In outdoor conditions, the presence of solar radiation and ventilation is the main feature. For both scenarios, five types of clothing fabrics are used at different levels of metabolic rate (measured in mets). Results show that on the indoor scenario, the longwave radiation from the human body increases both the temperature and the relative humidity, where stretch cotton and black cotton present the best results.

For the outdoor scenario, the increase of the sweating rate, along with an airflow raising, decreases the air temperature between the skin and the clothing, also showing that the best results of humidity and temperature are achieved with fabrics with high air permeability, and regardless of the value of reflectivity, which has influence only without both sweating and ventilation.

Moreover, making an analysis of the results and the bidirectional model, it is found that for heat transfer, longwave radiation from the skin and shortwave radiation from the sun are only significant when there is not convective heat transfer, mainly occasioned by sweating drops, the air permeability of the clothing layer, and the presence of ventilation. Regarding mass transfer, the outdoor humidity is important to enhance the convective heat transfer. Nevertheless, the moisture from the skin is higher when physical exercise is done, therefore the heat transfer is also higher regardless of the environmental humidity.

Therefore, making a priority pyramid of the heat transfer meanings upon the model of assessment to reach hygrothermal comfort, it is concluded that heat transfer by convection has the greatest extent of influence, followed by the heat transfer by radiation. Finally, heat transfer by conduction has the least extent of influence, opposite to the bias that conductive thermal resistance of the clothing is the most important parameter, at least for thermal comfort.

With this, it is concluded that the use of air-permeable fabrics and high thermal-conducting layers are essential to achieve hygrothermal comfort. Furthermore, the use of high solar reflective fabrics is also recommendable, but only when sweating is not presented, due to sweat rates help to decrease the temperature with the help of airflow, and the color of the fabric starts to lose influence on achieving hygrothermal comfort.

As a final comment, the limitations of the study are given by the fact that the model only calculates the temperature and relative humidity between the skin and the clothing layer, but not other outputs such as sensitive or latent heat in order to estimate the heat loss/gain, with and without phase change. Furthermore, a potential source of error might be the sudden changes of wind speed, due to the model is considered only for steady-state conditions. Therefore, proposed future research is to develop a model that calculates the heat loss and gain to achieve thermal comfort considering the sudden changes of wind speed, also called pumping effect, in non-stationary conditions.

Data availability statement

Has data associated with the study been deposited into a publicly available repository? No. Data included in article/supp. material/referenced in article.

CRediT authorship contribution statement

Ivan Oropeza-Perez: Writing – original draft, Validation, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nomenclature

A	Area of heat transfer [m^2]
B	Coefficient of volume expansion of the fluid [K]
C	Mass concentration of the water [kg/m^3]
Clo	Clothing thermal resistance [0.155 m^2-K/W]
C_p	Heat capacity of the air [kJ/kg-K]
h	Dynamic coefficient of convection [W/m^2-K]
h_e	Thermal exterior surface conductance, vertical flux [13 W/m^2-K]
h_i	Thermal interior surface conductance, horizontal flux [8.1 W/m^2-K]
h_{cloint}	Coefficient of heat transfer by convection of the clothing inner surface [W/m^2-K]

h_{cloext} Coefficient of heat transfer by convection of the clothing inner surface [W/m^2-K]
h_{skin} Coefficient of heat transfer by convection of the skin surface [W/m^2-K]
g Acceleration due to gravity [9.81 m/s^2]
Gr Grashof number [dimensionless]
k Material conductivity [W/m-K]
k_{air} Thermal conductivity of the air [W/m-K]
L Cross-sectional length [m]
L_{zone} Length of the zone between the skin and the clothing layer [m]
l Length of the vertical surface [m]
m Mass of the air between the skin and the clothing [kg]
met Metabolic rate generated by the physical activity of the body (infrared radiation) [58 W/m^2]
N Local mass flux by diffusion [m^2/s]
Nu Nusselt number [dimensionless]
Q Volumetric flow rate of the water [m^3/s]
q_{cond} Local heat flux by conduction in x,y,z direction [W/m^2]
q_{conv} Local heat flux by convection in x,y,z direction [W/m^2]
q_{rad} Local heat flux by radiation in x,y,z direction [W/m^2]
Pr Prandtl number [dimensionless]
Pb–Pa Pression drop across the porous media [Pa]
Ra Rayleigh number [dimensionless]
RA Rate of the water vapor [kg/m^3-s]
T_d Temperature of dew point [°C]
$T_{confort}$ Temperature resulting on the numerical model [K]
T_{cloext} Temperature of the external face of the clothing [K]
T_{cloint} Temperature of the internal face of the clothing [K]
T_{outair} Temperature of the outdoor air [K]
T_{solid} Temperature at the boundary of the solid body (ultraviolet radiation) [K]
T_{skin} Temperature of the human skin [K]
T_{zone} Temperature of the zone between the skin and the clothing layer [K]
U Global coefficient of heat transfer by conduction of the clothing [W/m^2-K]

Greek letters
$\beta =$ Local air velocity [m/s]
$\varepsilon_{sb} =$ Emissivity of the surface [dimensionless]
$\kappa =$ Air permeability of the clothing layer [cm^3/s/cm^2]
$\rho_{air} =$ Density of the air [kg/m^3]
$\rho_{clo} =$ Solar reflectivity of the clothing [dimensionless]
$\rho_{water} =$ Density of the water [kg/m^3]
$\rho_{confort}$ Density of water vapor in the zone [kg/m^3]
$\rho As =$ Saturation vapor density [kg/m^3]
$\varphi =$ Relative humidity between the skin and the clothing layer [%]
$\mu_{air} =$ Viscosity of the air [N-s/m^2]
$\mu_{water} =$ Viscosity of the water [N-s/m^2]
$\sigma =$ Stefan-Boltzman constant [5.670367(13) x 10^{-8} W/m^2-K^4]

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