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# REQUIRED THERMAL COMFORT CONDITIONS INSIDE HOSPITAL OPERATING ROOMS (ORS): A NUMERICAL ASSESSMENT

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# ABSTRACT

This paper presents a computational model along with a thermal comfort criterion aimed at assisting the design of operating rooms (ORs) from the perspective of meeting suitable flow patterns and thermal comfort conditions for the occupants. The computational model is based on the finite volume method (FVM) to describe the air inside ORs along with the human thermoregulation model implemented in virtual mannequins for thermal comfort. The air model considers turbulent fluid motion, species transport and the conservation of energy, including thermal radiation. The human thermoregulation model incorporates two interacting systems of thermoregulation. Namely, the passive system and the active system. The comfort criterion is based on the effective temperature of body parts which is a more suitable indicator than the commonly utilized predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) for body segments. The focus of the study is placed on the influence that the inlet thermal conditions provided by the air conditioning (AC) system have on the flow pattern and thermal comfort of the occupants. The results show that, for the selected conditions, lower air inlet temperatures than previously reported are required to operate at satisfactory comfort standards. It was also observed that smaller inlet temperatures bring about several improvements in the flow pattern inside the OR such as the size reduction of several recirculation zones (RZs). Nonetheless, smaller inlet temperatures bring about some drawbacks such as the size reduction of the ultra-clean ventilation (UCV) zone and the need of extra air-cooling power.

**Keywords**: Operating rooms (ORs); indoor environmental quality (IEQ); heat, ventilation and air conditioning (HVAC); thermal comfort; computational fluid dynamics (CFD).

# 1. INTRODUCTION

Hospitals and health care buildings are complex facilities where the indoor environmental quality in multiple areas such as ORs, ancillary work zones and interconnection hallways is a key factor related to the well-being, safety and health of the medical staff and patients (Sajadi, Saidi y Ahmadi 2020). ORs represent the areas where the strictest air quality standards inside the health care facility must be met (Nastase I., Croitoru C., Vartires A., Tataranu L. 2016). In addition, ORs are high percentage occupancy areas for the medical staff with about 50% of the total number of doctors and 10% of the medical staff working in the ORs (Balaras C., Dascalaki E., Gaglia A. 2007).

There are four strategies proposed for the health protection regarding indoor environmental quality (IEQ) including the number of air changes per hour (ACH), the air distribution, the room pressurization and the filtration. In general, all international guidelines recommend a low velocity unidirectional flow, which has been proven to be a solution to minimize the spread of airborne contaminants. A comprehensive review of IEQ in ORs can be found in reference (Nastase I., Croitoru C., Vartires A., Tataranu L. 2016).

The IEQ in ORs is controlled by AC systems, which should provide an adequate thermal comfort sensation for their occupants (Massarotti, Mauro y Mohamed 2020). According to ASHRAE 55 (ASHRAE 55 1992), the thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is essentially an interaction between six parameters: air temperature, mean radiant temperature (MRT), relative air movements, air humidity, activity level and thermal properties of clothing and seat. In addition, thermal comfort is divided in two categories including local and whole-body thermal comfort. The whole-body value only consists of a mean value, while the local values take into consideration effects on different body parts.

Thermal comfort has been investigated both experimentally and numerically with the aid of real and virtual manikins respectively. Experimental methods make use of full-size, man-shaped manikins with the surface covered by heating wires and temperature sensors, in order to measure in a realistic way the heat exchange over the whole body (Wyon D, Larsson S, Forsgren B & Lundgren I 1989), (Wyon D 1989), (Nilsson H & Holmér I 2000), (Saheb, H. A., Mahdi, A. A., Al-amir, Q. R. 2021) whereas computer simulations are based on mathematical models in virtual environments (Zhang B., Xue T., Hu N. 2017), (Murakami S, Kato S & Zeng J 1997), (Murakami S, Kato S & Zeng J 1998), (Malik y Šormaz 2019), . A thorough review of these technologies and their evolution can be found in reference (Danca P., Vartires A., Dogeanu A. 2016). In numerical models, time dependent flow, energy and species transport equations are solved in the ORs using CFD.

Recently, Liu et al. (Liu C., Zhou G., Li H. 2015) have evaluated the thermal comfort in ORs for a unique operation condition by using CFD along with the PMV and PPD criteria for body parts. In another study by Sanchez-Barroso & Sanz-Calcedo (Sánchez-Barroso G. & Sanz-Calcedo J. G. 2019), the indoor environmental conditions inside ORs are investigated under the application of three different standards

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The present work builds on the contributions made by Liu et al. (Liu C., Zhou G., Li H. 2015) and Sanchez-Barroso & Sanz-Calcedo (Sánchez-Barroso G. & Sanz-Calcedo J. G. 2019). The computational model presented here utilizes CFD to account for the turbulent fluid motion, species transport and energy balance, including thermal radiation, inside a fairly detailed geometry of a typical OR. The CFD model works along with a computer implementation of the human thermoregulation model in virtual mannequins to assess the thermal response of the occupants.

Different from previous work (Ding, Guo y Guo 2017), (Cao, Kvammen y Zhang 2021), (Wagner, y otros 2019), we evaluate different operation conditions and show their effect on the flow pattern and thermal comfort of the occupants (Fan, Cao y Pedersen 2021). In particular, we show the effect of the inlet temperature on the size of unwanted recirculation zones (RZs) and the ultra-clean ventilation (UCV) zone. We also show that the required operation conditions for thermal comfort inside ORs are better determined if the effective temperature of body parts is utilized as the thermal comfort criteria as opposed to the utilization of the PMV and PPD for body parts criteria.

# 2. DESCRIPTION OF THE SYSTEM TO BE MODELED

To compare the results of the present work with the literature, the same operating room considered by Liu et al. (Liu C., Zhou G., Li H. 2015) was examined. It is an OR with dimensions of 7.0 m x 6.0 m x 3.0 m. The OR has an air supply diffuser at the top, whose dimensions are 2.6 m x 2.4 m. The area projection of the air supply inlet inside the OR defines the UCV zone.

In the reference case, the air supply diffuser delivers a mass flow rate of 2.186 kg/s at a temperature of  $24.5 \,^{\circ}\text{C}$  and  $50 \,^{\circ}\text{K}$  relative humidity. The air is evacuated out of the OR by means of eight vents located at the floor level on two of the side walls.

The medical staff is composed by six members: patient, surgeon, first assistant, second assistant, anesthetist, instrumentalist and circulating nurse having an average height of 1.8 m. The equipment inside the OR consists of an operating table, an anaesthesia machine, an apparatus rack, instrument tables and surgical lamps.

Top, front, side and 3D views of the CAD model of the operating room are shown in Figure 1 The origin of coordinates was set at the center of the floor with the axis orientation shown in the figure.



Figure 1.a Top view of the operating room.



Figure 1.b Front view of the operating room.



Figure 1.c Side view of the operating room.



Figure 1.d 3D view of the operating room.

# 3. PHYSICAL MODEL

#### 3.1 Description of the Air inside the OR

In the present work, the flow and thermal conditions of the air inside the OR are determined by solving the general transport equation:

$$\frac{\partial}{\partial t}(\rho\phi) + \mathbf{V} \cdot \nabla(\rho\phi) = \nabla \cdot (\Gamma_{\phi}\nabla\phi) + S_{\phi}$$
(1)

In this equation,  $\emptyset$  is the transported quantity;  $\rho$  is the density; **V** is the velocity vector with components u, v and w;  $\Gamma_{\emptyset}$  is the diffusion coefficient for the transported quantity and  $S_{\emptyset}$  is the source term. The value of the transported quantity  $\emptyset$  depends on the equation being solved. That is,  $\emptyset = 1$  for mass transport;  $\emptyset = u$ , v or w for momentum transport;  $\emptyset = e$  for energy transport, where e is the internal energy; and  $\emptyset = Y_i$  for species transport, where  $Y_i$  is the local mass fraction of the specie *i*.

The Reynolds number at the inlet for all the cases tested in this work is circa 160,000, which is far beyond the laminar flow regime, even when relaminarization devices such as honeycombs are utilized and upstream disturbances may be damped by viscosity (Kühnen, J., Scarselli, D., Hof, B. 2019), (Kühnen, J., Song, B., Scarselli, D., Budanur, N., B., Riedl, M., Willis, A. P., Avila, M., and Björn Hof, B. 2018). Nonetheless, relaminarization flow devices such as honeycombs provide a more

unidirectional flow which is the desired condition for the UCV zone. Consequently, the Reynolds Averaged method for the Navier-Stokes equations (RANS) is utilized to solve for the mean values of the transported quantities while accounting for the effects of turbulence on mean flow properties. The k-E model of Launder and Spalding, (Launder, B. E., Spalding D. B. 1972) is utilized for turbulent closure. This model is utilized due to its robustness, economy and reasonable accuracy for a wide range of applications (Moukalled F., Mangani L., Darwish M. 2016). The modeling of turbulence close to the wall region is performed by using standard wall functions developed by Launder and Spalding (Launder, B. E., Spalding, D. B. 1974) for near-wall treatment. Radiative heat transfer is accounted by utilizing the Surface-to-Surface (S2S) radiation model described in Howell, Siegel, & Pinar (Howell, J., Siegel, R., Menguck, M. 2011) and is coupled to the formulation of the energy equation by means of a source term. The S2S radiation model makes possible to account for the radiative heat transfer exchange for a nonparticipating media in an enclosure of gray-diffuse surfaces, as is the case in the present work.

In the calculation method of the S2S model all the radiative internal boundaries are subdivided in patches, each emitting a radiative beam over the enclosing hemisphere with solid angles. The solid angles are also discretized using an angular quadrature. Each beam is traced through the computational domain until it intercepts an opposing patch, thus defining a pair of patches that exchange radiative energy. The radiation energy transfer to or from each patch is then calculated from the radiative heat transport equation and the boundary conditions. The radiative heat transfer equation is given by:

$$\frac{dI(\bar{r},\bar{s})}{ds} + (a + \sigma_s) \cdot I(\bar{r},\bar{s}) = an^2 \frac{\sigma T^4}{\mu} + \frac{\sigma_s}{4\mu} \int_0^{4\mu} I(\bar{r},\bar{s}') \Phi(\bar{s},\bar{s}') d\Omega'$$
(2)

Where  $\bar{r}$  is the position vector;  $\bar{s}$  is the direction vector;  $\bar{s}'$  is the scattering direction vector; s is the path length; a is the absorption coefficient; n is the refractive index;  $\sigma_s$  is the scattering coefficient;  $\sigma$  is the Stefan-Boltzmann constant; I is the radiation intensity which is a function of the position vector,  $\bar{r}$  and the direction vector  $\bar{s}$ ; T is the local temperature;  $\Phi$  is the phase function; and  $\Omega'$  is the solid angle.

#### 3.2 Human Thermoregulation System

The human thermoregulatory system incorporates two interacting systems of thermoregulation. Namely, the active system and the passive system. The passive system, described in detail by Fiala et al. (Fiala D., Lomas K. J., Stohrer M. 1999), is a multi-segmental, multi-layered representation of the human body with spatial subdivisions. The layer subdivisions considered are bone (core), muscle, fat, inner skin, and outer skin. The model includes a detailed representation of the anatomic, thermophysical and thermophysiological properties of the human body and accounts for phenomena of human heat transfer that occur inside the body. That is, blood circulation, metabolic heat-generation, conduction heat transfer and energy storage. The model also considers phenomena occurring at the human body surface. That is, free and forced surface convection, long and shortwave thermal radiation, skin moisture evaporation, diffusion, and accumulation.

In the passive system, the heat transfer, generation and storage occurring inside the living tissue are described by the bioheat equation developed by Pennes (Pennes, H. H. 1948):

$$k_{ts} \left[ \frac{\partial^2 T_t}{\partial r_i^2} + \frac{\omega_i}{r_i} \frac{\partial T_t}{\partial r_i} \right] + \rho_{bl} w_{bl} c_{bl} (T_{bl,a} - T_t) + q_m$$

$$= \rho_t c_t \frac{\partial T_t}{\partial t}$$
(3)

In this equation, the first term on the left-hand side accounts for the radial heat flow from warmer to colder tissue regions. In this term,  $k_{ts}$  is the thermal conductivity of the tissue;  $T_t$  is the tissue temperature;  $r_i$  is the radius of the multi-segmental, multi-layered representation of the human body with spatial subdivisions and  $\omega_i = 1$  for polar coordinates and  $\omega_i = 2$  for spherical coordinates (head).

The convective term on the left-hand side represents the blood perfusion and is made of the product of the blood density  $\rho_{bl}$ , the blood perfusion rate  $w_{bl}$ , the blood heat capacity  $c_{bl}$  and the temperature difference between the arterial blood temperature  $T_{bl,a}$  and the tissue temperature  $T_t$ . The third term on the left-hand side is the metabolism  $q_m$ .

The combined effect of the three terms on the left-hand side of the bio-heat equation is balanced by the right-hand side, that is, by the rate of change of heat storage within the tissue. In this term,  $\rho_t$  and  $c_t$  are the density and heat capacity of the tissue respectively.

The metabolism  $q_m$  is made of the contributions of the basal value  $q_{m,bas,0}$  and the additional heat  $\Delta q_m$ . That is:

$$q_m = q_{m,bas,0} + \Delta q_m \tag{4}$$

Where the basal metabolic rate  $q_{m,bas,0}$  is equal to 87 W, which agrees with the standardized value for the whole body metabolism of a reclining average human, according to ASHRAE 55 standard (ASHRAE 55 1992) and the additional heat  $\Delta q_m$  accounts for changes in the basal metabolism  $\Delta q_{m,bas,0}$  and additional changes in metabolism due to shivering  $q_{m,sh}$  and working  $q_{m,w}$ :

$$\Delta q_m = \Delta q_{m,bas,0} + q_{m,sh} + q_{m,w} \tag{5}$$

The change in the basal metabolism  $\Delta q_{m,bas,0}$  is the difference between the actual basal rate and the basal rate corresponding to neutral thermal conditions. It appears also in non-muscular tissues where  $q_{m,bas,0}$  is present and where the tissue temperature differs from its setpoint  $T_0$  the chance in the basal metabolism is given by:

$$\Delta q_{m,bas} = \Delta q_{m,bas,0} [2^{(T_t - T_0)} - 1]$$
(6)

The shivering term  $q_{m,sh}$  is given as a portion of the overall regulatory response obtained by the active system (Fiala D., K.J. Lomas, and M. Stohrer 2001) and the term  $q_{m,w}$  is obtained from the expression:

$$q_{m,w} = \frac{\partial(a_{m,w}H)}{\partial V_{mus}} \tag{7}$$

Where  $a_{m,w}$  is a coefficient distributing to body elements the overall extra metabolism due to exercise,  $V_{mus}$  is the corresponding bodyelement muscle volume, and H is the internal whole-body workload. The workload H represents the fraction of the overall extra energy that is produced by muscular activity, but which is not converted to external work. The H value can be estimated from the literature (ASHRAE 55 1992), (Fiala D., Lomas K. J., Stohrer M. 1999), for different activity levels.

Blood circulation is essential for heat dissipation and warming of body parts. The model of Fiala et al. (Fiala D., Lomas K. J., Stohrer M. 1999), accounts for the human blood circulatory system based on three main concepts. Namely, a central blood pool, countercurrent heat exchangers (CCX) and pathways to individual tissue nodes. In this model, body parts are supplied with warm blood from the central pool by the major arteries. Nonetheless, before blood is perfused into the extremities, it is cooled due to heat transfer interchange with the countercurrent bloodstreams in the adjacent veins as is accounted in the convective term of the bioheat equation. From the analysis of the CCX, the values of the arterial blood temperature  $T_{bl,a}$  and venous blood  $T_{bl,v}$  can be expressed as:

$$T_{bl,a} = \frac{(\rho_{bl}c_{bl}\int w_{bl}\,dV)T_{bl,p} + h_x T_{bl,v}}{\rho_{bl}c_{bl}\int w_{bl}\,dV + h_x}$$
(8)

$$T_{bl,\nu} = \frac{\int w_{bl} T_t dV}{\int w_{bl} dV}$$
<sup>(9)</sup>

In these expressions,  $T_{bl,p}$  is the blood pool temperature;  $T_{bl,v}$  is the venomous blood temperature before CCX and  $h_x$  is the countercurrent heat exchange coefficient which is zero for central body elements since no countercurrent heat exist. Reliable values of  $h_x$  for legs, feet, arms, hands and shoulders are reported in the literature (Fiala D., Lomas K. J., Stohrer M. 1999). The integral term represents the blood flow in the veins as the volume-integral of capillary blood flows  $w_{bl}$  over the body element.

At the surface of the manikin, the heat exchange with the environment  $q_{sk}$  is the result of the combined effects of convection heat transfer  $q_c$ ; radiation heat transfer with surrounding surfaces  $q_R$ , which is classified as long-wave radiation; irradiation from high-temperature surfaces  $q_{sR}$ , which is classified as short-wave radiation; and evaporation of moisture from the skin  $q_e$ . That is:

$$q_{sk} = q_c + q_R + q_{sR} + q_e \tag{10}$$

The convective heat exchange is given by the product of the combined convection coefficient  $h_{c,mix}$ , which accounts for natural and forced convection, and the temperature difference between the manikin surface  $T_{sf}$ , and the air  $T_{air}$ :

$$q_c = h_{c,mix}(T_{sf} - T_{air}) \tag{11}$$

The long-wave radiation heat transfer with surrounding surfaces is given by the product of the radiative heat transfer coefficient  $h_R$  and the difference between the manikin surface temperature  $T_{sf}$ , and the MRT of the surrounding surfaces  $T_{sr.m}$ :

$$q_R = h_R (T_{sf} - T_{sr,m}) \tag{12}$$

Where  $h_R$  is expressed as the product of the Stefan-Boltzmann constant  $\sigma$ ; the emission coefficient of the body surfaces sector  $\varepsilon_{sf}$ considered; the emission coefficient of the surrounding surfaces  $\varepsilon_{sr}$ ; the view factor between the body surfaces and the surroundings  $\varphi_{sf-}$  and factorized temperature terms in absolute units:

$$h_R = \sigma \varepsilon_{sf} \varepsilon_{sr} \varphi_{sf-sr} (T_{sf}^2 + T_{sr,m}^2) (T_{sf} + T_{sr,m})$$
(13)

The MRT is determined from the S2S model by equating the actual heat flux on the enclosure surface with that of an imaginary room at a uniform temperature and with unity emissivity.

The human thermoregulation model considers the effect of multilayer clothing insulation by the estimation of a local effective heat transfer coefficient  $U_{cl}$  for a j-layered clothing ensemble worn on a body-element sector:

$$U_{cl} = \left[\sum_{j=1}^{n} (I_{cl})_j + \frac{1}{f_{cl}(h_{c,mix} + h_R)}\right]^{-1}$$
(14)

The factor is calculated with information of the clothing insulation  $I_{cl}$  and the clothing area factor  $f_{cl}$ . Although the local effective heat transfer coefficient account for multilayer clothing, in this work, a unique

layer of clothing is considered for each body part with an equivalent clothing insulation value.

The local effective heat transfer coefficient  $U_{cl}$  quantifies the influence of clothing in the "dry heat". That is, the heat transfer that is not due to evaporation. To account for the effect of clothing in evaporation, the human thermoregulation model utilizes the evaporative heat transfer coefficient  $U_{e,cl}$ :

$$U_{e,cl} = L_{air} \left[ \sum_{j=1}^{n} \left( \frac{I_{cl}}{i_{cl}} \right)_{j} + \frac{1}{f_{cl} \cdot h_{c,mix}} \right]^{-1}$$
(15)

Where  $i_{cl}$  is the moisture impermeability index and  $L_{air} = 0.0165 \text{ K/Pa}$  is the Lewis constant for air (Fiala D., Lomas K. J., Stohrer M. 1999).

To account for heat transfer due to evaporation, the skin evaporation model considers the balance of heat and mass transfer at each sector of the body element. The transport of latent energy from a skin sector of area  $A_{sk}$  can be expressed by the skin evaporation model as:

$$U_{e,cl}(P_{sk} - P_{air}) = \frac{\lambda_{H2O}}{A_{sk}} \frac{dm_{sw}}{dt} + \frac{P_{osk,sat} - P_{sk}}{R_{e,sk}}$$
(16)

In this expression, the term in the left-hand side is the energy transfer due to the evaporative potential between the skin and the air. In this term,  $P_{sk}$  is the water vapor pressure at the skin surface and  $P_{air}$  is the vapor pressure of the ambient air. The first term in the right-hand side represents the evaporation of sweat from the skin surface. In this term,  $\lambda_{H20}$  is the heat of vaporization of water and  $dm_{sw}/dt$  is the rate of swet production over a skin sector of area  $A_{sk}$ . The last term represents the heat transport by moisture diffusion through the skin. In this term,  $P_{osk,sat}$  is the saturated vapor pressure within the outer skin layer of the body sector considered and  $[R_{e,sk}]^{-1} = 0.003 W \cdot m^{-2}Pa^{-1}$  is the skin moisture permeability (Fiala D., Lomas K. J., Stohrer M. 1999).

Although most of the heat is lost through the body surface, heat exchange by the environment is also due to respiration, which has the contribution of evaporation and convection. Both contributions are calculated according to Fanger (Fanger, P. O. 1973). For evaporation, the latent heat exchange  $E_{rsp}$  is estimated from the pulmonary ventilation as a function of the whole-body metabolism; the latent heat of vaporization of water; and the difference between the humidity ratio of the expired and inspired air, which depends on the ambient temperature  $T_{air}$  (°C) and the partial vapor pressure of the ambient air  $P_{air}$  (Pa):

$$E_{rsp} = 4.373 \int q_m (0.028 - 6.5 \times 10^{-5} T_{air} - 4.91 \times 10^{-6} P_{air}) dV$$
(17)

Where the relationship of the enthalpy of the expired air with the inspired air at  $T_{air}$  and  $P_{air}$  can be observed.

For convection, the dry heat loss  $C_{rsp}$  is also calculated as a function of the pulmonary ventilation rate and the air environment conditions:

$$C_{rsp} = 1.948 \times 10^{-3} \int q_m (32.6 - 0.066T_{air} - 1.96 \times 10^{-4} P_{air}) dV$$
(18)

The active system model simulates responses of the human thermoregulatory system such as suppression (vasoconstriction) and elevation (vasodilatation) of the cutaneous blood flow, sweat moisture excretion and changes in the metabolic heat production by shivering thermo-genesis. The active system was developed by means of statistical regression analysis using measured responses obtained from steady and transient exposures to cold stress, cold, moderate, warm and hot stress conditions, and exercise intensities between 0.8 - 8 metabolic rate (met), where one met is equal to  $58.2 \text{ W/m}^2$ .

Several authors have developed active system models for thermal regulation (Hussain, Agarwal y Hafiz 2020), (Ho, S. H., Rosario, L., Rahman, M. M. 2009), (Alsved, M., Civilis, A., Ekolind, P., Tammelin, A. 2018). Complete descriptions can be found in the work of Stolwijk & Hardy (Stolwijk, J.A.J. and Hardy, J.D 1966) and by Fiala et al. (Fiala D., K.J. Lomas, and M. Stohrer 2001). Nonetheless, all are based on the same approach, where the active system is modeled as a central controller whose inputs correspond to temperature signals which are processed to produce four controlled variables. The input signals are the skin body temperature for all body segments and the head core temperature. The head core temperature corresponds to the temperature of the hypothalamus which is the center of the temperature regulation. The four controlled variables are vasodilation and transpiration during heat load and vasoconstriction and shivering during cold load. That is, the central controller provides blood flow rates and heat fluxes in respond to the thermal stimuli of the environment.

A first step in the estimation of the active system response is to determine the temperature deviations from their reference values. In the case of the head core, the temperature deviation is given as:

$$\theta_{hy} = T_{hy} - T_{hy,ref} \tag{19}$$

Where,  $\theta_{hy}$  is the temperature deviation of the hypothalamus which is estimated as the difference between the actual temperature  $T_{hy}$  and a reference value  $T_{hy,ref}$ .

In the case of the body segments, the temperature deviation is given as:

$$\theta_{sk,j} = T_{sk,j} - T_{sk,ref,j} \tag{20}$$

Where,  $\theta_{sk,j}$  is the deviation of the skin temperature of the body segment *j*, which is estimated as the difference between the actual temperature of the skin for the body segment *j*,  $T_{sk,j}$  and the reference temperature for that body segment  $T_{sk,ref,j}$ . These deviations are estimated differently for the cold and warm conditions as:

$$\theta_{wa,sk,j} = \theta_{sk,j}$$
 for  $(\theta_{sk,j} \ge 0)$  (21)

$$\theta_{co,sk,j} = -\theta_{sk,j}$$
 for  $(\theta_{sk,j} < 0)$  (22)

Where,  $\theta_{wa,sk,j}$  and  $\theta_{co,sk,j}$  are the deviations for the warm and cold cases respectively. Then, the total signal of the skin temperature for warm and cold stimulus is estimated as a weighted average that considers the area fraction of each body element:

$$\theta_{wa,sk,Tot} = \sum_{j=1}^{14} \left( \theta_{wa,sk,j} \cdot w_{wa,ref,j} \right)$$
(23)

$$\theta_{co,sk,Tot} = \sum_{j=1}^{14} \left( \theta_{co,sk,j} \cdot w_{co,ref,j} \right)$$
(24)

In these expressions,  $\theta_{sk,Tot}$  is the combined signal for the whole body of the skin temperature deviation and  $w_{ref,j}$  is the weighting factor for each body element as described in reference (Stolwijk, J.A.J. and Hardy, J.D 1966). Then, the controlled variable for thermal transpiration,  $S_{tt}$ , is estimated from the expression (Stolwijk, J.A.J. and Hardy, J.D 1966):

$$S_{tt} = 372.2\theta_{hy} + 33.7(\theta_{wa,sk,Tot} - \theta_{co,sk,Tot})$$
(25)

Which clearly shows that the influence of the head core temperature is an order of magnitude higher than that of the skin temperature. Then, the local transpiration heat transfer for the body segment j,  $q_{tt,j}$ , is estimated from:

$$q_{tt,j} = (w_{tt,j} \cdot S_{tt}) \cdot 2^{(\theta_{sk,j}/10)}$$
(26)

Where  $w_{tt,j}$  is the weighting factor for the distribution of sweet formation across the skin surface and the two factor accounts for the local amplification effect of the temperature deviation for the body part *j*.

The two controlled variables for vasomotricity account for the ability of the human body to react to heat or cold loads. The controlled reaction variable for heat load is vasodilation,  $S_{VD}$ , which is given in m<sup>3</sup>/s as:

$$S_{VD} = (32.5 \times 10^{-6})\theta_{hy}$$
(27)  
+ (2.1 × 10^{-6})(\theta\_{wa,sk,Tot} - \theta\_{co,sk,Tot})

The controlled reaction variable for cold load is vasoconstriction,  $S_{VC}$ , which is given in m<sup>3</sup>/s as:

$$S_{VC} = -5 \left( \theta_{hy} + \theta_{wa,sk,Tot} - \theta_{co,sk,Tot} \right)$$
(28)

Then, the modified blood flow rate for the body segment j can be estimated from:

$$\dot{V}_{bl,j} = \left(\frac{\dot{V}_{bl,bas,j} + L_{VD,j}S_{VD}}{1 + L_{VC,j}S_{VC}}\right) \cdot 2^{(\theta_{sk,j}/6)}$$
(29)

Where  $\dot{V}_{b,bas,j}$  is the basal blood flow rate for the body element *j* and  $L_{VD,j}$  and  $L_{VC,j}$  are the local constants for vasodilation and vasoconstriction of the body segment *j* respectively. The values of these constants can be found in the work of Hertzman & Randall (Hertzman, A.B. and Randall, W.C. 1948). The two factor accounts for the effect that the decrease on the skin temperature has in the increase of resistance in the blood vessels.

When the body temperature drops, the shivering mechanism is activated. Shivering has the objective to maintain the inner temperature by activating the skeletal muscles. Thus, increasing the metabolic rate. The controlled reaction variable for shivering,  $S_{sh}$ , is calculated in Wats as:

$$S_{sh} = -24.425 \cdot \theta_{hy} \cdot \theta_{co\_sk\_Tot} \tag{30}$$

Then, the local heat transfer for the body segment j,  $q_{tt_j}$ , is estimated from:

$$q_{sh_j} = S_{sh} \cdot L_{SH_j} \tag{31}$$

Where  $L_{SH_j}$  is the weighthing factor that accounts for the heat distribution produced by shivering among the body parts.

## 3.3 Thermal Comfort Criteria

The set of equations described in sections 3.2.1 for the air inside the OR are solved iteratively along with the equations for the domain of the manikins. That is, for the human thermoregulation model described in section 3.2.2. Once the numerical stable solution is obtained, the thermal comfort criteria is estimated by evaluating the value of the effective temperature. The effective temperature is calculated by utilizing the empirical expression developed by Madsen et. al (Madsen T, Olesen B & Kristensen N 1984):

$$T_{eq} = 0.55T_{air} + 0.45T_{sr,m} + \frac{0.24 - 0.75\sqrt{v_{air}}}{1 + I_{cl}}(36.5 - T_{air}) \quad (32)$$

Which considers all the important variables affecting the thermal comfort. That is, the air temperature, the MRT, the air velocity  $v_{air}$ , and the clothing thermal resistance.

#### 4. COMPUTATIONAL METHODS

#### 4.1 Domain Discretization and Boundary Conditions

Governing equations for turbulent flow, heat and mass transfer as well as the equations describing the thermoregulation human system were solved using the FVM in structured grid systems. The simulations were performed in 3D domains in stationary flow regime. The grids were refined towards the manikins, equipment, inlet, outlet vents and walls. The grid convergence was analyzed until an adequate size of 2.2 +millions of cells was selected for the simulations. The model was built utilizing the Siemens PLM software STAR-CCM+.

The utilization of the thermal comfort model requires the body segmentation of manikins to provide the solution for the local thermal comfort of each of the body parts. Thus, each manikin was divided into 14 body parts which are listed in Table 1 along with their correspondent body segments IDs for identification of results. Figure 2 shows a closer view of the domain discretization for the OR including details of the grid refinement and body segment division for the manikins.



Figure 2 Domain discretization of the OR and body segmentation of the virtual manikins.

Table 1. Body segmentation and identification for the manikins.

Body Segment	Body Segment ID	Body Segment	Body Segment ID
Head	14	Right Hand	7
Torso	13	Left Upper Leg	6
Upper Left Arm	12	Right Upper Leg	5
Upper Right Arm	11	Left Lower Leg	4
Lower Left Arm	10	Right Lower Leg	3
Lower Right Arm	9	Left Foot	2
Left Hand	8	Right Foot	1

Boundary conditions for the reference case are summarized in Table 2. They can also be found in reference (Liu C., Zhou G., Li H. 2015). The

table includes the metabolic rate and clothing insulation for each of the occupants. Operating table, apparatus rack, anesthesia machine and instrument tables are adiabatic, whereas the heat dissipation capacity for the surgery lamps is 80 W total. Although most of the emissivity values for the surfaces of the OR are taken from Liu et al. (Liu C., Zhou G., Li H. 2015), those for the body parts are taken assuming that most of the surface of each occupant is covered by fabric. Thus, a value of 0.88 is considered based on the work of Belliveau et al. (Belliveau, R. G., DeJong, S. A., Boltin, N. D., Lu, Z., Cassidy, B. M., Morgan, S. L. and Myrick ML. 2020).

Table 2. Boundary conditions.

Boundary name	Conditions
Air supply inlet	Reference case: 2.186 kg/s, 24.5 °C, 50 % R.H.; emissivity 0.02; transmissivity 0.98.
Patient	Metabolic rate 0.8 met; clothing thermal resistance 0.20 $m^2$ K/W; emissivity 0.88.
Surgeon	Metabolic rate 2.4 met; clothing thermal resistance 0.22 m <sup>2</sup> K/W; emissivity 0.88.
Assistant 1	Metabolic rate 2.0 met; clothing thermal resistance 0.14 m <sup>2</sup> K/W; emissivity 0.88.
Anesthetist	Metabolic rate 1.9 met; clothing thermal resistance 0.14 m <sup>2</sup> K/W; emissivity 0.88.
Instrumentalist	Metabolic rate 2.0 met; clothing thermal resistance $0.14 \text{ m}^2 \text{ K/W}$ ; emissivity 0.88.
Assistant 2	Metabolic rate 0.8 met; clothing thermal resistance 0.20 m <sup>2</sup> K/W; emissivity 0.88.
Air outlet	Pressure outlet at standard pressure (101.325 kPa); emissivity 0.02; transmissivity 0.98.
Ceiling	Convection heat transfer coefficient 15 W/m <sup>2</sup> ·K, external environment temperature 28 °C; coefficient of thermal conductivity 1.74 W/m·K; emissivity 0.60.
Floor	Convection heat transfer coefficient 23 W/m <sup>2</sup> ·K, external environment temperature 28 °C; coefficient of thermal conductivity 1.74 W/m·K; emissivity 0.60.
Side walls	Convection heat transfer coefficient 23 W/m <sup>2</sup> ·K, external environment temperature 28 °C; coefficient of thermal conductivity 1.74 W/m·K; emissivity 0.60.
Astral lamp	Heat dissipation capacity 80 W; emissivity 0.60.

#### 4.2 Solution Method

In the solution method, the SIMPLE scheme (Versteeg, H.K., Malalasekera, W. 2007) was utilized for pressure-velocity coupling in conjunction with the second order scheme for pressure interpolation (Versteeg, H.K., Malalasekera, W. 2007). Turbulent flow, transport of species, and radiative heat transfer equations were solved using a second order upwind scheme (Versteeg, H.K., Malalasekera, W. 2007). Normalized residuals were set to values smaller than 1e-06. The convergence was verified by checking the energy balance as recommended by reference (Ansys, Inc. 2019) as well as monitoring the average outlet values of velocity, temperature and humidity.

The simulations were performed by utilizing computer parallelization in a typical lab workstation with a configuration of 32

processors running at a clock speed of 2.6 GHz and 64 MB of RAM. The approximated clock wall solution time per simulation was about 2 hours.

## 5. RESULTS AND DISCUSSION

This section shows the simulation results of the computational model. The results are shown for the flow and thermal conditions of the complete OR. Nonetheless, for the sake of brevity and clarity, those for the thermal comfort are shown for the main occupants inside the most critical location of the room. That is, for selected occupants inside the UCV zone: the patient, surgeon and surgeon assistant.

We focus on the effect of the inlet temperature of the air provided by the AC system. This is the easiest variable to control in the OR and was the variable that showed a major impact on the thermal comfort. The recommended relative humidity must be between 40 and 60 percent but a relative humidity of the inlet air close to either extreme of the scale may result in out of the range values once the air reaches the occupants. This is due to the heat sources and sweat production inside the OR. Thus, a value of 50 percent for the relative humidity of the inlet air is typically fixed. Finally, the thermal properties of clothing and the rate of transpiration are determined by the clothing requirements and the activity level of the surgical team.

The first stage of the work focused on the verification and validation of the model by comparing the simulation results against those obtained by Liu et al. (Liu C., Zhou G., Li H. 2015). Figure 3 and Figure 4 show the velocity contours and velocity vectors for the simulations. The planes shown correspond to the cuts at x = 0 and z = 1 m.

The velocity vectors shown in Figure 4 reveal the existence of several recirculation zones (RZs) which have been marked with red circles and capital letters. RZs such as A and E are the result of the flow driven pattern induced by the vertical flow coming from the inlet as well as the flow separating from the obstacles such as the operating table. RZs such as D occur around the lower extremities of the manikins and are caused by the flow driven condition induced by the flow that separates from the operating table.

Perhaps the most critical RZs are B and C, which are caused by the downward flow passing the lamps. This, since these RZs are inside the UCV zone and directly affect the patient and main surgical team. This effect has been recently investigated by Refaie R. et al. (Refaie R., Rushton P., McGovern P., Thompson D., Serrano-Pedraza I., Rankin K. S., Reed M. 2017). They conducted an experiment to identify the effect of surgical lamps on the flow pattern inside the UCV zone and recommended practical strategies to limit any negative effects. In their experiment, they utilized neutrally buoyant bubbles to visualize the flow pattern inside the UCV zone under different configurations of surgical lamps. They concluded that in the absence of surgical lamps, bubbles were cleared rapidly and did not accumulate. Nonetheless, if lamps are placed above the surgical field, RZs are formed between the operating table and the lamps.

Figure 5 shows the results for the thermal comfort of the occupants obtained following the same procedure utilized by Liu et al. (Liu C., Zhou G., Li H. 2015), that is, by utilizing the PMV and PPD of body parts. As it can be seen, our results are in good agreement with those reported by Liu et al. (Liu C., Zhou G., Li H. 2015). However, the thermal comfort condition of the head and hands based on the PMV appears to be warmer which is not consistent with the fact that such body parts are the less thermally insulated areas of the body as well as the more exposed to the cold flow provided by the AC system inside the UCV zone. To address inconsistency in previously applied PMV standard, thermal insulation garments such as rubber gloves, masks and caps for the hands and head of the surgical team must be considered in the analysis. In other words, if the skin temperature, which is higher than the effective temperature, is utilized to calculate the PMV value, the obtained value will be considerably warmer.



0.00 0.05 0.10 0.15 0.20 0.24 0.29 0.34 0.39 0.44 Velocity: Magnitude (m/s)

Figure 3. Velocity contours in the front plane (at x = 0) and the top plane (at z = 1 m).



Velocity: Magnitude (m/s)



PMV values between -0.5 and +0.5 are recommended (Nilsson, H.O. and Holmér, I. 2003), which led Liu et al. (Liu C., Zhou G., Li H. 2015) to suggest that most of the body parts, although slightly warmer, fall within acceptable values of the PMV.



Figure 5. PMV for each body segment of selected occupants and its comparison with Ref. (Liu C., Zhou G., Li H. 2015)

The results for thermal comfort of the occupants are shown in Figure 6, where the utilization of the effective temperature as a better estimation of the thermal comfort for the occupants can be observed. The plots show the division of the comfort zone in five regions: effective temperature values falling on the left of the blue line (region I) are unacceptable too cold conditions for each body part; effective temperature values falling between the blue and green lines (region II) correspond to cold but acceptable conditions for each body part; effective temperature values falling between the green and orange lines (region III) correspond to neutral comfort conditions for each body part; effective temperature values falling between the orange and hot lines (region IV) correspond to hot but comfortable conditions; effective temperature values on the right of the red line correspond to unacceptable too hot conditions. It can be noted that the neutral zone (region III) is further divided by a dashed gray line which defines the change from cold to warm neutral conditions. Details for the estimation of the five regions can be found in reference (Nilsson, H.O. and Holmér, I. 2003).

Three different cases were selected for comparison, each of them corresponding to a different value of the inlet air temperature with the case one corresponding to the reference case. Based on the results obtained for the reference case, in the present study, the effect of air inlet temperature on the thermal comfort conditions of the occupants is further explored. The cases are summarized in Table 3. The exploration process showed that smaller temperatures are required to provide a neutral thermal comfort.

Table 3 Evaluated cases for the OR model

Case number	Inlet air temperature (C°)
Case 1	24.5
Case 2	22
Case 3	18

It can be noted that for the reference case most of the body parts fall inside region IV. That is, within the region of hot but comfortable conditions, with the lower part of the body close to unacceptable too hot conditions. This is not surprising since the flow at the lower part of the body has a higher temperature and lower velocity with respect to the upper part of the OR. The lower velocity is caused by the presence of the obstacles such as lamps, occupants and the operating table which divert the flow away from the bottom part of the body of the occupants. The higher temperature is due to the heat absorption from the inlet down to the floor. That is, due to the heat provided by the lamps, the upper parts of the occupant's bodies and the thermal radiation from the environment.

Figure 7 and Figure 8 show the velocity contours and vectors for case 3 respectively. The density of the inlet air is higher with respect to the reference case due to the smaller temperature. This causes the

velocity of the air to be smaller at the inlet. Nonetheless, it can be observed that, because of a higher density, the flow becomes heavier and falls more rapidly as it approaches the operating table. This effect brings about several improvements in the flow pattern with respect the reference case. As it can be seen in Figure 7, the RZs inside the UCV zone (RZs B and C) decrease in size due to the higher momentum of the flow moving downwards. In addition, a reduction in the velocity field of the RZs A, D and E is also observed.



Figure 6. Comfort zones and effective temperature profiles for each body segment.

A downside in the flow pattern is that the higher momentum of the downward flow as well as its higher density also causes a decrease in the size of the UCV zone. As it can be seen in Figure 7, the UCV zone gets narrower with respect to the reference case (Figure 3). This negative effect must be considered when decreasing the temperature of the inlet air aiming at improving the thermal comfort of the occupants.

Figure shows the thermal quantities more relevant to the thermal comfort of the occupants. That is, temperature and relative humidity. The temperature below the plane of the operating table is considerable higher than above the plane. The temperature below the plane of the operating table rises 2 Celsius degrees in average inside de UCV zone. This is consequent with a warmer thermal comfort for the bottom part of the body of the occupants (Figure 6). As it can be observed in Figure , this temperature rise is mainly promoted by the occurrence of RZs below the operating table such as region D which cause the advection of the warmer flow outside of the UCV zone such as the flow close to the walls. The decrease in the size of the UCV zone can also be observed in terms of temperature in the front plane and is notorious in the top plane. Regarding the relative humidity, its value remains within the recommended range of 40 to 60 percent for most of the OR and for the complete workspace utilized by the occupants which of course is a positive point.

#### 6. CONCLUSIONS

A computational model was built to evaluate the required thermal conditions inside ORs. The computational model is based on the momentum, energy and species transport in the gas phase and the human thermoregulation model implemented in virtual mannequins. The model along with the effective temperature criteria and multi-zone comfort conditions can be utilized to assess the flow characteristics and thermal comfort of the occupants inside ORs. In particular, the model was utilized to explore the air inlet temperature value required to secure a neutral thermal comfort condition for the occupants.

The required conditions to meet the thermal comfort of each body part were based on a more suitable parameter than the PMV and PPD which has been typically utilized by previous authors. Namely, the



0.00 0.05 0.10 0.15 0.20 0.24 0.29 0.34 0.39 0.44 Velocity: Magnitude (m/s)

**Figure 7.** Velocity contours for case 3. Results are shown in the front plane (at x = 0) and the top plane (at z = 1 m).



0.00 0.05 0.10 0.15 0.20 0.24 0.29 0.34 0.39 0.44 Velocity: Magnitude (m/s)

Figure 8. Velocity vectors for case 3. Results are shown in the front plane (at x = 0) and the top plane (at z = 1 m).



**Figure 9.** Contours of temperature for case 3. Results are shown in the front plane (at x = 0) and the top plane (at z = 1 m).



Figure 10. Contours of relative humidity for case 3. Results are shown in the front plane (at x = 0) and the top plane (at z = 1 m).

effective temperature of body parts. It was found that smaller air inlet temperatures around 18 °C are required to provide a more adequate thermal comfort environment. It was observed that a smaller air inlet temperature brings about several improvements in the flow pattern with respect the reference case but has also a downside. That is, smaller air inlet temperatures contribute to the reduction of RZs, but they also decrease the size of the UCV zone. In addition, the extra power requirement necessary to achieve thermal comfort must be examined. For instance, considering a typical outdoor temperature of 30 °C in a warm day, the thermal power required to achieve thermal comfort will be amplified by a 2.2 factor with respect to the reference case. A thorough discussion about the impact of environmental factors on the power requirements of AC Systems is presented by Jaluria et al. (Jaluria, Y., Sunder, A., Benner, J. Z., 2020).

It is worth mentioning that, even when the movement of the occupants or equipment inside the OR may alter the flow field, such movement is limited throughout the operation. Thus, any flow disturbance caused by moving objects or the operation staff will dissipate in a relatively short period of time in contrast to the duration of the surgical procedure. As a result, the flow disturbance caused by moving items or the staff was deemed minimal in this study.

The model presented in this paper can also be utilized to explore the design or operation conditions of the OR that allow to avoid or alleviate the appearance of undesirable flow patterns such as RZs. For instance, by modifying the outlet location of the ports or adding more ports at higher elevation from the floor for RZs A and B; by utilizing a curtain covering the bottom part of the table for the RZ D and by modifying the inlet flow conditions or the location and configuration of the surgical lamps which promotes the formation of RZs B and C.

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# NOMENCLATURE

A	Area (m <sup>2</sup> )
а	Absorption coefficient (m <sup>-1</sup> )
$a_{m,w}$	Coefficient distributing to body elements the overall extra metabolism due to exercise
$a_{m,w}$	Coefficient distributing to body elements the overall extra metabolism due to exercise
С	Heat capacity (kJ ·kg <sup>-1</sup> ·K <sup>-1</sup> )
$C_{rsp}$	Dry heat loss (W)
dm <sub>sw</sub> /dt	Rate of sweet production over a skin sector of area $A_{sk}$ (kg·s <sup>-1</sup> )
$f_{cl}$	Clothing area factor
Н	Internal whole-body workload (W)
$h_x$	Countercurrent heat exchange coefficient (W·K <sup>-1</sup> )
h <sub>c,mix</sub>	Combined convection coefficient (natural and forced convection) $(W \cdot m^{-2} \cdot K^{-1})$
$h_R$	Radiative heat transfer coefficient (W·m <sup>-2</sup> ·K <sup>-1</sup> )
i <sub>cl</sub>	Moisture impermeability index
I <sub>cl</sub>	Clothing insulation
I	Radiation intensity (W·m <sup>-2</sup> )
k <sub>ts</sub>	Thermal conductivity of the tissue $(W \cdot m^{-1} \cdot K^{-1})$
Lair	Lewis's constant for air (0.0165 K·Pa <sup>-1</sup> )
L <sub>SH_j</sub>	Weighting factor for the heat distribution produced by shivering among the body parts
$L_{VC,j}$	Local constants for vasodilation and vasoconstriction of the body segment j respectively
n	Refractive index

$P_{osk,sat}$ Saturated vapor pressure within the outer skin layer of the body sector considered (Pa) $q_{tt,j}$ Local transpiration/shivering heat transfer for the body segment j (W·m <sup>-2</sup> ) $q_m$ Metabolic rate (W·m <sup>-3</sup> ) $q_{m,bas,0}$ Basal metabolic rate (W·m <sup>-3</sup> ) $q$ Heat exchange (W·m <sup>-2</sup> ) $q_{sk}$ Heat exchange with the environment (W·m <sup>-2</sup> )
$l osk,sat$ body sector considered (Pa) $q_{tt,j}$ Local transpiration/shivering heat transfer for the body $q_m$ Metabolic rate (W·m <sup>-2</sup> ) $q_m$ Basal metabolic rate (W·m <sup>-3</sup> ) $q_{m,bas,0}$ Basal metabolic rate (W·m <sup>-2</sup> ) $q_{sk}$ Heat exchange (W·m <sup>-2</sup> )
$q_{tt,j}$ Local transpiration/shivering heat transfer for the body segment j (W·m <sup>-2</sup> ) $q_m$ Metabolic rate (W·m <sup>-3</sup> ) $q_{m,bas,0}$ Basal metabolic rate (W·m <sup>-3</sup> ) $q$ Heat exchange (W·m <sup>-2</sup> ) $q_{sk}$ Heat exchange with the environment (W·m <sup>-2</sup> )
$q_{tt,j}$ segment j (W·m <sup>-2</sup> ) $q_m$ Metabolic rate (W·m <sup>-3</sup> ) $q_{m,bas,0}$ Basal metabolic rate (W·m <sup>-3</sup> ) $q$ Heat exchange (W·m <sup>-2</sup> ) $q_{sk}$ Heat exchange with the environment (W·m <sup>-2</sup> )
$q_m$ Metabolic rate (W·m <sup>-3</sup> ) $q_{m,bas,0}$ Basal metabolic rate (W·m <sup>-3</sup> ) $q$ Heat exchange (W·m <sup>-2</sup> ) $q_{sk}$ Heat exchange with the environment (W·m <sup>-2</sup> )
$q_{m,bas,0}$ Basal metabolic rate (W·m-3) $q$ Heat exchange (W·m-2) $q_{sk}$ Heat exchange with the environment (W·m-2)
$q$ Heat exchange (W·m <sup>-2</sup> ) $q_{sk}$ Heat exchange with the environment (W·m <sup>-2</sup> )
$q_{sk}$ Heat exchange with the environment (W·m <sup>-2</sup> )
$\bar{r}$ Position vector (m)
$R_{e,sk}$ Skin moisture permeability (Pa · m <sup>2</sup> · W <sup>-1</sup> )
$r_i$ Radius of the multi-layer body representation (m)
s Path length (m)
$S_{\phi}$ Source term in the general transport equation
$\bar{s}$ Direction vector (m)
$\bar{s}'$ Scattering direction vector (m)
$S_{tt}$ Controlled reaction variable for thermal transpiration
S Controlled reaction variable for coal load
$v_{VC}$ vasoconstriction (m <sup>3</sup> ·s <sup>-1</sup> )
T Temperature (K)
$T_{eq}$ Equivalent temperature (°C)
$T_{bl,v}$ Venomous blood temperature before CCX (°C)
$T_{hy}$ Actual temperature (°C)
$T_{hy,ref}$ Reference value temperature (°C)
Difference between the actual temperature of the skin for
$T_{sk,ref,i}$ the body segment j, $T_{sk,j}$ and the reference temperature
for that body segment (°C)
$T_{x,y}$ Difference between temperature x and y (K)
$U_{cl}$ Local effective heat transfer coefficient (W·m <sup>-2</sup> ·K <sup>-1</sup> )
$U_{e,cl}$ Evaporative heat transfer coefficient (W·m <sup>-2</sup> ·K <sup>-1</sup> )
v Velocity (m·s <sup>-1</sup> )
V Velocity vector (m·s <sup>-1</sup> )
$\dot{V}_{hl has i}$ Basal blood flow rate for the body element j
W Perfusion rate (s <sup>-1</sup> )
Weighting factor for the distribution of sweet formation
$W_{tt,j}$ across the skin surface
$w_{ref,j}$ Weighting factor for each body element

#### Greek symbols

Г	Diffusion coefficient
$\mathcal{E}_{sf}$	Emission coefficient of the body surfaces sector
E <sub>sr</sub>	Emission coefficient of the surrounding surfaces
$\theta_{hy}$	Temperature deviation of the hypothalamus (K)
$\theta_{sk,j}$	Deviation of the skin temperature of the body segment j (K)
$\theta_{sk,Tot}$	Combined signal for the whole body of the skin temperature deviation (K)
$\theta_{wa,sk,j}$	Temperature deviation for the warm condition for the body segment j (K)
$\theta_{co,sk,j}$	Temperature deviation for the cold condition for the body segment $j(K)$
$\lambda_{H2O}$	Heat of vaporization of water (J/kg)
ρ	Density (kg/m <sup>3</sup> )
$\sigma_s$	Scattering coefficient
σ	Stefan- Boltzmann constant (W·m ${}^{-2}$ ·K ${}^{-4}$ ) (= 5.67051 x $10^{-8}$ W·m ${}^{-2}$ ·K ${}^{-4}$ )
$\Phi$	Phase function
$\varphi_{x-y}$	View factor between x and y
Ø	Transported quantity
$\Omega'$	Solid angle (Sr)
Subscripts	

a	Arterial
air	Air

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Ы	Pland
Di .	Common officer
C	Convection
cl	Clothing
CO	Cold
е	Evaporation of moisture from the skin
hy	Hypothalamus
j	Segment j
mus	Muscle
MRT	Mean radiative temperature
0	Setpoint
р	Pool
R	Surrounding surfaces
ref	Reference
sf	Manikin surface
sh	Shivering
sk	Skin
sr	Surrounding surfaces
sr,m	Mean value of the surrounding surfaces
sR	High- temperature surrounding surfaces
SW	Sweat
t	Tissue
Tot	Whole body
v	Venomous
VC	Vasoconstriction
VD	Vasodilatation
w	Working
wa	Warm

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