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Human body exergy consumption models' evaluation and their sensitivities towards different environmental conditions

Hongshan Guo [a], Yongqiang Luo [a, d], Forrest Meggers [a, b, *], Marco Simonetti [c]

[a] School of Architecture, Princeton University, Princeton, NJ, United States
[b] Andlinger Center for Energy and the Environment, Princeton University, Princeton, NJ, United States
[c] DENERG, Politecnico di Torino, Turin, Italy
[d] School of Environmental Science and Engineering, Huazhong University of Science and Technology, Wuhan, 430074, PR China

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ABSTRACT

We can use the concept of exergy to analyze a human body as a heat emitter: while generating heat continuously, the body remains at roughly the same temperature through physiological responses such as shivering, sweating, breathing thus raising/decreasing the core and/or skin temperature to maintain effective heat dissipation. Existing literature provides an estimated exergy consumption rate of the human body ranging from 2 to $5W/m^2$, while nearly unanimously agreeing on a local exergy consumption minima points to potential individual thermal comfort. To clarify the underlying assumptions used in the existing human body exergy models, we analytically and numerically reviewed the terms used for assessing metabolism, radiation, evaporation, and convection exergy changes of the human body in this paper. We observed overestimations of exergy from metabolism, underestimations of exergy change through radiation, and some caveats in the signage of convective exergy losses in the results we obtained. We were also able to propose an improved expression to estimate human body radiation exergy exchanges as well as selecting reference temperatures that are more process-specific. Future studies that provide experimental verification of these models were also deemed necessary.

1. Introduction

Analyzing the human body as a heat exchanger has not been very common in the building sector up until very recently. Originating from longer-term entropy analysis of living organisms [1–3], the first attempts to quantify thermal comfort thermodynamically used entropy analysis to describe human physiology [4,5]. Batato improved the entropy analysis of the human body by first implementing the exergy approach on analysing the balance of the human body [6].

The exergy balance model was later introduced to thermodynamically quantify thermal comfort. Initially considered a more straightforward method to describe the physiological responses from the human body towards the surrounding environment [7–9], both analytical and experimental studies showed promising results on reflecting the human physiology [9,10]. A couple of researchers were able to equate the exergy minima with the state of thermal equilibrium, i.e. individual thermal comfort [8,11,12]. This can be explained thermodynamically as the state of the smallest system irreversibilities, which corresponds to the state with the smallest entropy generation, i.e. exergy destruction rate [8]. The evolution of the human body exergy models have led to a few specific sets of contemporary models [8,10,13] sharing the same underlying physiological model [14,15]. Despite the similarities between these human body exergy models, there are many inconsistencies between them, ranging from expressions of specific terms to magnitudes of exergy destruction rates at the respective local minimas. It is important that a systematic approach should be taken when assessing the performance of the models, where not only the expressions themselves, but also their underlying assumptions are examined and compared against each other to identify potential problems and rooms for improvement.

In this paper, we want to present such a systematic review that examines the assumptions, the methods that also includes the critique of the existing models. Building on the numerical results from the analysis, we will also propose changes to the existing expressions as well as selection of reference temperatures and

* Corresponding author. School of Architecture, Princeton University, Princeton, NJ, United States.
E-mail address: fmeggers@princeton.edu (F. Meggers).

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compare the proposed changes to the existing methods. Beginning with metabolic rate, which is the fundamental assumption of all existing human body exergy models, we tested the possibility of incorporating the metabolic rate of different age, build and gender, attempting to explain the gender and age-specific proclivity of thermal environments. We then examined the radiation exergy losses which are the second largest contributor to exergy balance and compared results from existing methods against a new expression with varying effective radiation areas and reference temperatures. The convection and evaporation exergy changes were subsequently shown to be also heavily influenced by the selection of reference temperatures and states. Experimental data on occupant responses and environmental conditions could increase the credibility of the numerical comparison, and should therefore be considered as crucial future work.

2. Background

Many conventional approaches used to predict the thermal comfort of the occupants originates from the PMV/PPD model developed by P.O. Fanger in 1970 [16]. Using both heat balance equations and empirical physiological studies, this model disregards the differences between the individuals and eventually contributed to an engineering mindset that the indoor heating/cooling is only about the set point of air temperatures [17]. The adaptive thermal comfort model, on the other hand, allows the calculation of ranges of acceptable environmental conditions under different weather and metabolic rates/clothing levels [18].

The human body exergy models are built on the same theoretical foundation of the PMV/PPD model when it comes to describing the thermoregulatory systems. A more prevailing one is the two-node model from Gagge et al. where the differences between core and skin temperatures can be interpreted into cold/hot signals triggering responses from the thermoregulatory systems [15]. Gagge furthered this claim in a 1981 publication by developing a series of heat transfer coefficients for both sensible and latent heat transfer [14]. The sensible heat loss was calculated via a combined heat transfer coefficient (CTC) which includes both radiation (R) and convection (C). Fanger, on the other hand, attempted to quantify the heat balance between the human body and the surrounding environment quantitatively by using empirical data collected through Gagge's model [16] and became a primary force in the analytical modeling of thermal comfort.

Results obtained by Fanger and Gagge encouraged the proposition of the human body exergy model proposed by Isawa & Shukuya and was further elaborated and clarified by Shukuya through a series of different studies [19]. Before publishing a book on exergy in 2012, Shukuya concisely laid out the groundwork, in particular the 'warm/cool' and 'wet/dry' exergy [8] as well as showcasing the relationship between MRT (mean radiant temperature) and air temperature with Isawa in 2002 [19]. This was further developed in the collaborative work between Shukuya and Tokunaga in 2011 where the expression of human body exergy remained unchanged, and real data collected from participating students (occupants) were used to verify the exergy models, with a particular interest in mechanical conditioning system against natural ventilation [20]. Ala-Juusela brought this investigation slightly further by building on the existing research but focused specifically on the relationship between the different climate types and insulation levels and was able to demonstrate a significant variation of exergy consumption rate under different climate conditions in Finland [21]. Schweiker worked with Shukuya to investigate the adaptive comfort or specifically the PMV values against the exergy consumption rate of the human body with existing experimental data [12]. This investigation was brought further in 2016 [11] were they proposed a method to calculate the unsteady state human body exergy consumption rate and applied this method to three existing sets of data, where the core and skin temperatures were derived from the indoor MRT, air temperature, humidity and air velocity via Gagge's model [14]. This study also included the full R-script that was used to calculate the steady and unsteady human body exergy consumption rate, which later was published as the *comf* package for R [22].

A somewhat different yet similar branch of investigation came from Prek since 2004 where the human body exergy consumption rate was derived from the results obtained by Gagge et al. [9], demonstrating a similar local minima of exergy consumption rate as was identified by Isawa et al. and Shukuya, but at a specific set of air temperature and MRT at $T_a = 19.2\ ^\circ C$ and $T_{mr} = 23.9\ ^\circ C$, assuming the core and skin temperature has a neutral point of 36.8 and 33.7 $^\circ C$. A further investigation published in 2005 provided a more elaborated explanation on how the exergy consumption rate of the human body was calculated and provided a T_a vs. T_{mr} contour plot for the human body exergy consumption rates [13]. This was similar to the contour plot obtained by Isawa and Shukuya but are different quantitatively as the reference temperature - against which the exergy can be calculated - was set to the outdoor air temperature instead of indoor air temperature. A further publication from Prek in 2010, however, provided an additional contour plot with air temperature versus mean radiant temperature, but showed different results despite limited changes in expressions of human body exergy consumption rate [23]. Latest publication from Butala and Prek submitted that the human body exergy model can be constructed in such a way that no longer requires inputs that indicates environmental parameters of the environment outside of the human body but rather the heat transfer between the core and shell of the body. Therefore, the core temperature and skin temperature's accuracy could significantly affect the exergy consumption results. As this is heavily reliant on the results obtained by Gagge et al., in 1981, it might be a problematic approach to quantify the human body exergy consumption from an indoor environmental sensing, despite the latter are now equipped with unprecedented data availability [24].

Additionally, Mady et al. developed a human body exergy consumption model that allows the human body to be analyzed as a multi-cylinder system upon the work of Ferrreira & Yanagihara [25]. Recognizing the differences between the thermal sensing capacity of different body parts, Mady suggested every single cylinder to be modelled independently before the overall exergy consumption rate can be calculated [25]. To investigate the exergy destruction rates of the human body under different levels of physical activities and the thermal comfort influence with different combinations of environmental parameters [26], hypothermia [27], as well as targeting the human heart [28], the research conducted by Mady and associated researchers concentrated on the exergy consumption rate for runners/athletes [29].

A few additional models influenced by those three major branch of researches: Wu et al. proposed both radiation and latent heat correction to the Shukuya's model and qualitatively compared the resulting exergy consumption curve with that from Shukuya in 2013 [30]. Buyak further simplified the method to obtain mean radiant temperature from Shukuya's model and proposed an overall methodology to obtain comfortable air temperatures while the rest of the required inputs are the rest of the six required parameters to calculate the PMV values as well as the reference temperature and relative humidity [31]. Dovjak et al. expanded the landscape of human body exergy analysis from thermoregulation physiology to different climates and found significant variations of in the occupants' exergy balances due to the usage of different combinations of outdoor temperatures and indoor clothing values

[32]. Upon examining the existing literature, despite inherent similarities and differences, very few of the human body exergy models share enough assumptions to be compared against each other. More importantly, much of assumptions that are being used in the underlying models rely on highly empirical models and simplifications for convection and radiation. This could lead to the drastic different conclusions of the breakdown of sources of exergy: Mady suggested that the combined contribution of radiation and convection to the total exergy generated makes up of only 0.7% of the total exergy generated by metabolism, while according to Caliskan, this combined number could contribute more than 1.9% [33]. Additionally, the selection of the reference states between different studies (e.g. air temperature suggested by Prek et al. [23] or the outdoor air temperature selected by Shukuya and many other researchers [8]). We propose a in-depth study that builds on top of the existing modeling methods, rethinks the benefits limitations of the model of human body exergy consumption.

3. Method

From a physiological stand point, thermal comfort can be maintained when the heat generated by the human metabolism is dissipated at a reasonable rate such that the dissipation of heat does not strain our systems. This requires accurate modeling of the metabolic rate which is the source of heat generation [10]. A simple breakdown of sources of exergy for a human body and the corresponding exergy losses/storages can be found in Fig. 1 following a specific set of assumptions made on the occupant in the original research [8] and valid only for the indoor/outdoor conditions as specified in the caption. Exergy generated by metabolism is obviously the main source of exergy when the physical activities [34] are limited [35] and needs to be addressed to maintain an overall exergy balance while other sources (radiant exergy from heat exchange and inhaled air) contributes significantly less. This is followed by the radiation exergy loss, and subsequently convection and exhalation/evaporation. We will therefore start with examining the largest contributor, metabolic rate of the occupants and then examine the sensitivities of radiation, convection and evaporation towards changes in the selection of reference state in this paper.

3.1. Basal metabolic rates' sensitivity to gender and age

The largest contributor to the human body exergy balance is the metabolic rate of the human body. Existing assumptions of the human body exergy balance ranges from 58.2W/m^2 (ASHRAE Handbook [8]) to 43.94 W/m^2 [36]. The assumption of 58.2 W/m^2 basal metabolic rate that has now been adapted in a significant range of ASHRAE publications appears to be first made popular by Fanger in 1970 [16] in his key publication to the field of thermal comfort. Upon carefully reviewing a wide range of the existing literature, Fanger set the resting metabolic rate at 50 kcal/hm^2 (i.e. 58.15 W/m^2). While this may have been a more than valid assumption back in 1970, more and more researchers were able to demonstrate a clear differentiation of metabolic rates [37] with respect to gender [38], age [39] as well as build [40], which appears to signal an overestimated metabolic rates in the assumption of 1 MET = 58.2 W/m^2. This meant overestimating female metabolic rate by up to 35% according to Kingma & Lichtenbelt, who argued the need to accurately represent the thermal demand of all occupants can lead to improved energy savings predictions in actual environments - and demonstrated the shift of thermal-neutral zones under standard and measured metabolic rates [41].

Their findings did not seem to have affected the state-of-the-art human body heat budget calculations - or the exergy models that were subsequently built upon them. The most conventional method of describing the resting energy expenditure has since then became the basal metabolic rate (BMR), in particular within the medical and pharmaceutical sciences. Many comparative studies have demonstrated the influence of gender, age, weight and stature on BMRs, resulting in significant variations between the metabolic rate assumptions that should go into the thermal comfort balance of the human body. To cope with said variations, Mady pointed out that [25] it was possible to introduce a variable metabolic rate with respect to gender and age citing the canonical expressions from Harris & Benedict (1918): The total heat produced throughout an entire day can be expressed with Equation (1) for men and Equation (2) for women.

$$h = 66.4730 + 13.7516w + 5.0003s - 6.7550a \quad (1)$$

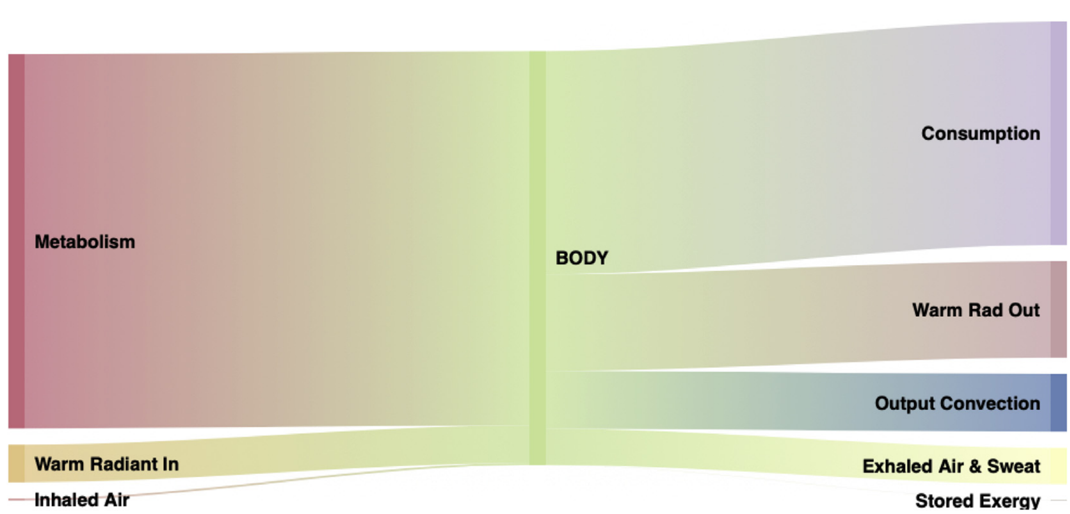

Fig. 1. Sources of incoming and outgoing exergy for a human body reproduced from excel tool published by Annex49 [8] when $T_a = 21°C$, RH = 30%, $T_{mr} = 20°C$ for the indoor environment, and $T_o = 0\ °C$, RH = 55% for the outdoor environment.

$$h = 655.0955 + 9.5634w + 1.8496s - 4.6756a \quad (2)$$

where h is the total heat produced every 24 h in kiloCalories, w is the weight in kilograms, s is stature in centimeters and a is age in years. Harris & Benedict tabulated the results for people weight between the age of 21–70 years of age with a stature between 151 and 200 cms. It is important to mark the significant differences between the expressions between men and women in Equation (1) and Equation (2) have caused Benedict himself to question the accuracy of this model. Daly et al. later confirmed Harris & Benedict overestimated BMR by 10–15% [42]. We therefore aspired to identify a different set of equations describing the BMR, and selected the formulas from Lorenzo et al., where the expressions for the metabolic rates can be written in Calories per day as Equation (3) for male and Equation (4) for females with different weight, stature and age. Note here we selected a model that outputs Resting Metabolic Rate (RMR) instead of BMR, which is considered to be a better indicator of daily energy needs than BMR, since BMRs are obtained in a much more controlled manner hence less indicative of the real-world energy requirements. This approach has also previously been used on determining a more appropriate MET value for children, which did not extend to adults and different body builds [43].

$$RMR_m = 53.284 \times w + 20.957 \times s - 23.859 \times a + 487 \quad (3)$$

$$RMR_f = 46.322 \times w + 15.744 \times s - 16.66 \times a + 944 \quad (4)$$

Attempting to illustrate how the conventional expression of metabolic rate with respect to physiology, we will first plot the metabolic rate of a hypothetical male (178 cm, 67 kg) and a female occupant (168 cm, 58 kg) against the change of age. This will, however, not accurately reflect the change of metabolic rate with respect to different bodily shapes, i.e. the change of surface areas of the occupants. Since the surface area is instrumental in the human body exergy model to account for the exergy losses for both convection and radiation heat transfer, we will introduce a model that predicts the body surface area for male and female occupants with given weight and height(stature). We will do so by incorporating this with the body surface area calculation from Schlich et al. [44] as shown in Equation (5) and Equation (6) as the following:

$$A = 0.000579479 \times w^{0.38} \times s^{1.24} \quad (5)$$

$$A = 0.000975482 \times w^{0.46} \times s^{1.08} \quad (6)$$

We thus were able to derive RMRs as a function of weight and stature in W/m^2 after converting Equation (3) and 4 from Calories per day to Watts. Dividing this with the surface area obtained in Equations (5) and (6), thus obtaining Equation (7) and 8. Here w is the weight in kg, s is the stature in cm, a is the age in years.

$$M_m = 2798.93s^{-1.24}(-0.276a + 0.243s + 0.617w + 5.64) \quad (7)$$

$$M_f = 1840.90s^{-1.08}(-0.193a + 0.182s + 0.536w + 10.92) \quad (8)$$

This enabled us to compare the metabolic rate between different genders, stature, weight at different ages, which we will present the results for male and female occupants at 35 and 55 years of age.

As we want to ultimately link this back to the human body exergy consumption, we employed the R module published by Schweiker and Shukuya [11] and predicted the variation of overall exergy consumption rate with respect to operative temperature. We eliminated the effect of weight and stature by assuming the same set of weight and height for male and females (male at 178 cm, 67 kg and a female at 168 cm, 58 kg) and varied the ages between 15 and 75 years of age with 20 years' step increase. Assuming the same set of optimal indoor environment condition as identified by Prek [23], it is possible to plot the exergy consumption rate E_{cons} against operative temperature T_{op}. The assumptions and environmental parameters used during the simulations are listed out in Table 1.

The operative temperature is defined via Equation 9, where h_c and h_r are, respectively. The linearized radiation heat transfer coefficient and the convection heat transfer coefficient. As we will further expand on h_r in the following section, we assume both as constant values for the investigation of metabolic rate following the recommended overall value of $h_c = 3.5\ W/(m^2K)$ and $h_r = 4.5\ W/(m^2K)$ [45].

$$T_{op} = \frac{h_c \cdot T_a + h_r \cdot T_{mr}}{h_c + h_r} \quad (9)$$

Other assumptions used in achieving the relationship between the exergy consumption and the operative temperature include assuming a typical summer condition where the outdoor air temperature is assumed to be 30 °C with a relative humidity of 80%, while the indoor air remains at a constant 40% relative humidity, while the indoor air velocity was maintained at 0.1 m/s. The resulting ranges of exergy consumption rate can be used to showcase the potential of variation in thermal comfort of the occupants, as well as the limitation of not only existing human body exergy models, but also thermal comfort models.

3.2. Exergy of radiation heat exchange

As the second largest contributor to exergy change within the human body, radiation heat transfer and the resulting exergy loss of the human body varies significantly due to the discrepancies within how radiant exergy should be expressed analytically. Radiant

Table 1
Parameters/Assumptions used in calculating the discrepancies between the different terms of radiation.

Expressions	Definition	Value	Unit
f_{cl}	Factor of body clothed	0.7	Dimensionless
T_0	Reference temperature	23	$^\circ C$
f_{eff}	Effective radiation ratio area factor of body	0.72 (Fanger)	Dimensionless
ε	Surface emissivity	0.95	Dimensionless
T_{cr}	Neutral temperature at core	36.8	$^\circ C$
T_{sk}	Neutral temperature at skin	33.7	$^\circ C$
σ	Stefan-Boltzmann Constant	5.67×10^{-8}	Dimensionless
T_a	Indoor Air Temperature	23	$^\circ C$
T_{mr}	Mean radiant temperature	25	$^\circ C$

energy always require both a sender and a receiver to calculate the radiant energy transfer between two objects, as was shown by Berglund in Equation (10) [46]. This is unlike chemical or thermal energy which can be measured directly or easily quantifiable since inherently a reference state is already built in (absolute zero at 0 Kelvin or 0 $^{\circ}C$ (273.15 K)-zero degree Celsius, also known as the temperature of the water/ice mixture). For any radiation process, it is necessary to calculate the exergy independent to the radiation as a such that the exergy can be quantified.

A typical case of solving the conundrum of radiation heat transfer is known as the linear heat transfer coefficient due to radiation as h_r, and combining that with the convective heat transfer coefficient h_c, can be written as combined coefficient h_{cr} [14]. In general, the radiation heat transfer from a person in an enclosed space can be classically modelled with Equation (10) [46]. A linearized version can therefore be derived as Equation (12) where h_r can be expressed as Equation (11):

$$Q_r = A_D \varepsilon \sigma f_{cl} f_{eff} \left(T_{cl}^4 - T_{mr}^4\right) \tag{10}$$

$$h_r = \varepsilon \sigma f_{cl} f_{eff} \left(T_{cl}^4 - T_{mr}^4\right) \Big/ (T_{cl} - T_{mr}) \tag{11}$$

$$Q_r = A_D h_r (T_{cl} - T_{mr}) \tag{12}$$

By assuming $T_{cl} - T_{mr} \approx 0$, i.e. the radiant heat transfer is held at minimum, expression of h_r in Equation (11) can be further simplified to Equation (13), whose derivation was explained in details by Berglund [46], which was also adopted by Gagge et al. [14] also into what was later known as the J.B. Pierce two-node model [47].

$$h_r = 4 f_{cl} f_{eff} \varepsilon \sigma \left(\frac{T_{cl} + T_{mr}}{2}\right)^3 \tag{13}$$

This expression has since been introduced into the ASHRAE Fundamentals as the radiation heat transfer coefficient without the assumption that it was based on and accepted as the state-of-the-art expression [48]. Within the context of human body exergy consumption, this has influenced the branch of research that was led by Ferreira, Yanagihara and Mady [36] where the combined heat transfer coefficient was used to account for the radiation and convective heat transfer between the human body and the surrounding environment.

Additionally, there are also a collection of simplified linear radiation heat transfer coefficients. ASHRAE Handbook [49] suggested a reasonable value to substitute any calculation would be 4.70 W/m^2K, hence a constant radiation heat transfer coefficient was adopted by a few researchers including Shukuya [50], Mady et al. [36] as well as Caliskan [33]. The linear approximation was obtained by converting the radiation heat transfer relationship directly in some research [30]. Since this is, by the law of radiation heat transfer, and per the derivation from Petela on the exergy of radiation heat transfer [51], the most accurate account of the actual exergy loss during radiation, we will therefore divide its exergy term with the temperature difference between clothing and mean radiant temperature ($T_{cl} - T_{mr}$) to obtain a h_r-like term to also be documented in Table 2 for comparison.

Existing literature appears to have difficulty to come to agreement towards the extent of how to properly account for the exergy available in the radiation heat transfer. Since radiation was identified to be the most important factor influencing the total human body exergy consumption other than metabolism rate by multiple studies [8,36], we will be comparing the influences and deviations of expressions of h_r and E_x from the actual radiation heat transfer coefficient and exergy consumption as derived by Petela [51], where the exergy of radiation heat transfer between two objects can be written as Equation (14) to calculate the amount of exergy from surface A at T_A to surface B at T_B Kelvin where the temperature of the surrounding environment is held at T_0. This points to an expression such as Equation 15 when accounting for the radiation exergy between the clothing surface at T_{cl} and the mean radiant temperature of the surrounding environment at T_{mr}. It's important to point out the temperature of the surrounding environment from Petela's original research in fact points to the environmental surface temperature T_0 instead of the environmental air temperature T_a. Unlike convection and evaporation where the reference temperature needs to be set to a specific reference temperature of the air to illustrate its total thermal potential, the thermal potential of surfaces to be involved in radiant heat exchange should not be affected by the air temperature, and hence T_0 should not have been set to T_a according to our interpretation of Petela's work.

$$Ex_r = \varepsilon \sigma A \left[\left(T_A^4 - T_B^4\right) - \frac{4}{3} T_0 \left(T_A^3 - T_B^3\right)\right] \tag{14}$$

$$Ex_r = f_{cl} f_{eff} \varepsilon \sigma A \left[\left(T_{cl}^4 - T_{mr}^4\right) - \frac{4}{3} T_{mr} \left(T_{cl}^3 - T_{mr}^3\right)\right] \tag{15}$$

The expression Wu et al. [30] used, as shown in Equation (16), where the air temperature was used for T_0 instead of T_{mr} should therefore be considered an understandable misinterpretation. We will be comparing the resulting radiation exergy function of both the original expression from Wu et al. and its corrected version where T_{mr} is used instead of T_a.

$$Ex_r = f_{cl} f_{eff} \varepsilon \sigma A \left[\left(T_{cl}^4 - T_{mr}^4\right) - \frac{4}{3} T_a \left(T_{cl}^3 - T_{mr}^3\right)\right] \tag{16}$$

The clothing temperature, also commonly known as the temperature of the overall human body, can be calculated using the two-node model that was outlined by Gagge et al., where the neutral temperature at the core and skin are respectively $T_{cr,n} = 36.8$ and $T_{sk,n} = 33.7$ °C, such that the temperature of the clothing T_{cl}, or the whole body T_b can be obtained by solving the

Table 2
Expressions for linearized radiant heat transfer coefficient h_r.

Authors	Radiation exergy loss Ex_r (W/m^2)	h_r $(W/(m^2K))$
Mady et al. [25]	$f_{cl} h_r (T_{cl} - T_{mr})\left(1 - \frac{T_o}{T_{sk}}\right)$	4.7
Schweiker et al. [11]	$f_{cl} f_{eff} \varepsilon_{cl} h_r [(T_{cl} - T_o)^2 / (T_{cl} + T_o)]$	$6.13 \frac{A_r}{A_D} \times \varepsilon$
Wu [30]	$f_{cl} f_{eff} \varepsilon \sigma A \left[(T_{cl}^4 - T_{mr}^4) - \frac{4}{3} T_a (T_{cl}^3 - T_{mr}^3)\right]$	$f_{eff} \varepsilon \sigma A [(T_{cl}^4 - T_{mr}^4)] / (T_{cl} - T_{mr})$
Mady [36]	$f_{cl} h_r (T_{cl} - T_{mr})\left(1 - \frac{T_0}{T_{sk}}\right)$	$4 f_{eff} \varepsilon \sigma \left(\frac{T_{cl} + T_{mr}}{2}\right)^3$

following set of equations:

$$WSIG_{cr} = max[(T_{cr} - Tcr, n)] \tag{17}$$

$$CSIG_{sk} = max[(T_{sk} - Tsk, n)] \tag{18}$$

$$\dot{m}_{bl} = [(6.3 + 200 \cdot WSIG_{cr})/(1 + 0.5 \cdot CSIG_{sk})]/3600 \tag{19}$$

$$\alpha = 0.0418 + 0.745/(3600 \cdot \dot{m}_{bl} + 0.585) \tag{20}$$

$$T_{cl} = \alpha \cdot T_{sk} + (1 - \alpha)T_{cr} \tag{21}$$

This is also commonly known as the J.B. Pierce two-node model, which is an alternative human thermoregulation model that describes the qualitative thermal comfort through quantitative analysis.

$$0.905A_D\frac{T_{sk} - T_{cl}}{I_{cl}} + 0.095A_D\left(\left(T_{sk}^4 - T_{mrt}^4\right) + h_c(T_{sk} - T_a)\right) = 0.905A_D\left(\varepsilon\sigma\left(T_{cl}^4 - T_{mrt}^4\right) - h_c f_{cl}(T_c l - T_a)0.905A_D\right. \tag{24}$$

The effective radiation factor f_{eff} was determined by Fanger [16] using a projection-based photographic method and recommended. They were able to find good agreement between their results and the results from Winslow et al., where through a heat balance model, the radiation intensity were found to exhibit a somewhat linear relationship with the algerbraic sum of metabolism, evaporation and storage, which points to a ratio of effective radiation area being approximately 70–75%. We were therefore able to determine that the effective radiation factor applies to the overall body.

$$f_{cl} = 1 + 0.3I_{cl} \tag{22}$$

The clothing area factor, f_{cl}, on the other hand, is assumed to have a linear relationship with the level of insulation, and can be alternatively viewed as the surface increase ratio from the nude skin from added insulation [52]. Therefore, as was pointed out in a review on the estimation of f_{cl} from I_{cl}, the correlation in Equation (22) is an acceptable estimate for indoor ensembles [53]. The expression for T_{cl} in Equation (21) estimates the clothing temperature from empirical physiological studies, while as pointed out by Silva [54], the clothing temperature can be considered as an inferred concept that treats the overall body and clothing as a whole by iteratively solving a heat balance equation between the skin and clothing surfaces as shown in Equation (23).

$$\frac{T_{sk} - T_{cl}}{I_{cl}} = \varepsilon\sigma f_{cl}\left(T_{cl}^4 - T_{mr}^4\right) + f_{cl}h_c(T_{cl} - T_a) \tag{23}$$

Aside from using a linearized h_r to characterize the potential of radiant heat transfer, another issue with the original method of estimating the exergy loss in radiation is that the f_{cl} should be combined only with the clothed surfaces on a human body. To reflect both the exergy loss from the clothed body and the exposed skin, it is necessary to redefine the method used to obtain the clothing temperature to recognize the simultaneous heat exchange between the clothed skin surfaces and exposed skin surface and their relationship to the surrounding environment. We have developed a new expression to address this explicitly. As shown in Equation (24), the clothing temperature can be calculated iteratively at a steady-state condition when the total heat loss from the skin (left hand side) equals the heat loss from the clothing surface (right hand side). Providing an artificial value to initiate the calculation, the new clothing temperature can now be obtained as the result converges during the iterations. We could alternatively write the radiant exergy loss per squared meter as Equation (25) by using the newly obtained T_{cl} in Equation (24).

According to Equation (25), the heat exchange between the human body and the surrounding environment can be approximated by taking into account both the clothing temperature and the skin temperature without differentiation. Albeit a reasonable estimation with the limited data that can be collected on the occupants, Expression 23 effectively eliminates the influence of skin temperature fluctuation on the prolonged simulation of thermal responses. More importantly, with improved sensing capabilities on both the clothing temperature and the skin temperature (through thermal-imaging, for example), it is important to differentiate the two variables, as was proposed in Equation (24).

$$Ex_r = \varepsilon\sigma\left(f_{cl}f_{eff}0.905\left[\left(T_{cl}^4 - T_{mr}^4\right) - \frac{4}{3}T_{mr}\left(T_{cl}^3 - T_{mr}^3\right)\right] + 0.095\left[\times\left(T_{sk}^4 - T_{mr}^4\right) - \frac{4}{3}T_{mr}\left(T_{sk}^3 - T_{mr}^3\right)\right]\right) \tag{25}$$

We arrived at the expression in Equation (25) by examining the existing literature, particularly on the definitions for both the effective radiation area factor f_{eff} and the ratio of the clothed body to the surface area of the body. Additionally, since we are assuming that the hands and head (0.5% [55] and 9.0% [56], respectively) are fully exposed, hence their respective effective radiation factor and clothing factor were assumed to be 1. Arguably the gesture of the hands of the occupants could vary significantly when performing different tasks It is therefore possible to derive an updated effective radiation factor for the rest of the body as 0.68 to be used in Equation (25). We will be comparing this proposed expression against the expressions listed out in Table 1 to quantify the potential differences via solving the two-node model with respect to a wide range of skin and core temperature until they converge. Addition to the parameters listed in the table, we will be assuming a surface area of 1.8 m^2 and a metabolic rate of 46.3 W/m^2 and a range of 18–40 °C for the value of T_{mr}.

3.3. Convection

As we proceed onto the next large contributor of exergy changes and re-examined the existing methods of calculating the exergy losses, one specific issue arises since the sign of exergy losses does not change despite the direction of heat exchange, i.e. convection only results in exergy losses regardless of the direction of heat transfer. Consider, for example the heat conduction from the core to the skin in a Gagge two-node model [30], where the exergy losses due to heat conduction can be calculated via the following Equation (26):

$$E_{x-C} = f_{cl}h_c(T_{cl} - T_a)\left(1 - \frac{T_a}{T_{cl}}\right) \tag{26}$$

In this expression, regardless of whether $T_a > T_{cl}$ or $T_a < T_{cl}$, the resulting exergy loss from convection is always positive. However, when considering the direction of heat transfer, the body can only dissipate heat in the latter scenario, which is in fact loss of exergy. The prior scenario, where $T_a > T_{cl}$ is in fact exergy gain via convection. The signage of the exergy loss term appears to be at constant positive regardless of the direction of heat transfer happening within the human body.

To better illustrate this issue, the exergy losses terms for convection, radiation, as well as evaporation of the human body will be plotted against the actual heat transfer to observe the influence of defined exergy signage with respect to a range of possible environmental conditions as contour plots in order to identify the scope of the signage issues. None of the existing human body exergy calculations model addresses the possibility of exergy losses happening in different directions, i.e. exergy could also be generated by absorbing the thermal energy from the surrounding environments except one absorption term form Shukuya [8].

One viable solution to this appears to be Shukuya's definition of warm/cool and dry/wet exergy as proposed by Shukuya [8]. Shukuya suggested that exergy can be compared to the outdoor environment as a 'dead' reference state to ascertain the direction of the heat and mass transfer. The 'warm' speaks to the capability of heat being dissipated while 'cool' points to the capability of heat being absorbed from the surrounding environment. The 'wet', similarly, speaks to the capability of targeted system/components' capability of losing water/vapor to the surrounding environment, while 'dry' suggests the opposite. Despite the strength in vividly painting the nature of the direction of potential heat transfer, it is uncommon for this concept to be easily grasped by researchers that do not form direct collaborations with researchers who are already familiar with this concept [33]. Specifically relating to the terms we will be comparing, the exergy loss terms and the corresponding convection heat transfer coefficient h_c are listed in the following Table 3:

3.4. Evaporation

As the last contributor to exergy balance of the human body, for evaporation, we compare the expressions from Shukuya [50] (Equation (27)), Mady [36](Equation (30)), Prek [23](Equation (29) and Wu [30](Equation (28)). Shukuya assumed a volumetric rate of liquid water being generated in the body shell as sweat $V_{w-shell}$ at $(m^3/s)/m^2$, essentially calculating the exergy of the water vapor generated by sweat, which is derived from Gagge two-node model.

$$V_{w-shell}\rho_W\left(c_{pv}\left[\left(T_{cl}-T_a-T_a ln\frac{T_{cl}}{T_a}\right]+\frac{R}{M_W}\right.\right.$$
$$\left.T_a\left[ln\frac{p_{sk}}{p_{va}}+\frac{P-p_{sk}}{p_{sk}}ln\frac{P-p_{sk}}{P-p_{va}}\right]\right) \tag{27}$$

Wu pointed out that this expression does not account for the heat of phase change as water is evaporated into water vapor, and therefore derived a new expression using the definition of exergy related to liquid water and water vapor in Equation (28).

$$c\frac{\dot{m}_{w,sk}}{A_D}\left\{W_{sk}c_{pv}\left[\left(T_{sk}-T_a-T_a ln\frac{T_{sk}}{T_a}\right]+W_{sk}RT_a\left(ln\frac{1+1.608W_a}{1.608W_{sk}}+\right.\right.\right.$$
$$\left.\left.ln\frac{W_{sk}}{W_a}\right)-RT_a ln(1+1.608W_{sk})\right\}-\frac{\dot{m}_{w,sk}}{A_D}\left[h_{fg}\left(1-\frac{T_a}{T_{sk}}\right)+c_{pv}\left[T_{sk}-T_a-T_a ln\frac{T_sk}{T_a}\right]-RT_a ln\phi_a\right] \tag{28}$$

This is a very similar expression comparing to the expression from Prek [23] as Equation (29) or a simplified version from Mady in Equation (30), where the enthalpy of the liquid water at skin h_{sk} and the reference enthalpy of air h_o were eventually obtained via ASHRAE Handbook through equations that populated Equations (29) and (28).

$$\frac{\dot{m}_{w,sk}}{A_D}\left(W_{sk}c_{pv}\left[\left(T_{sk}-T_a-T_a ln\frac{T_{sk}}{T_a}\right]+W_{sk}RT_a\left(ln\frac{1+1.608W_a}{1.608W_{sk}}+ln\frac{W_{sk}}{W_a}\right)-\right.\right.$$
$$\left.RT_a ln(1+1.608W_{sk})+h_{fg}\left(1-\frac{T_a}{T_{sk}}\right)-c_{pv}\left[T_{sk}-T_a-T_a ln\frac{T_{sk}}{T_a}\right]-2RT_a ln\phi_a\right) \tag{29}$$

Table 3
Expressions for exergy loss via convection and convection heat transfer coefficient.h_c

Authors	Radiation exergy loss Ex_c (W/m^2)	h_c $(W/(m^2K))$
Prek et al. [23]	$h_c(T_{sk}-T_a)\frac{T_{sk}-T_0}{T_{sk}}$	$\max(2.38\lvert T_{cl}-Ta\rvert^{0.25}, 12.1\cdot\sqrt{\upsilon})$
Wu et al. [30]	$f_{cl}h_c(T_{cl}-Ta)\left(1-\frac{T_a}{T_{cl}}\right)$	$\max(\max(1.16\lvert M-50\rvert^{0.39}, 8.6\upsilon^{0.53}), 3)$
Mady et al. [36]	$f_{cl}h_c(T_{cl}-Ta)\left(1-\frac{T_a}{T_{sk}}\right)$	3.3 OR $[14.8\ \upsilon^{0.69}]$
Shukuya [8]	$f_{cl}h_c(T_{cl}-T_a)\left(1-\frac{T_o}{T_{cl}}\right)$	$\max(2.38\lvert T_{cl}-Ta\rvert^{0.25}, 12.1\cdot\sqrt{\upsilon})$

$$\dot{m}_{w,sk}(h_{sk}-h_o)+\dot{m}_{w,sk}R_W T_o ln\frac{P_{w,sk}}{P_{w,o}} \tag{30}$$

Assuming constant neutral temperature at core and skin, it is possible to obtain the two groups of contour plots of exergy losses during convection and evaporation process. To assess whethere there are any sign-convention related issues, the colors of the contour lines are arranged such that the minus signs are always expressed with bright or dark red, while the transitioning ones near zero are light pink.

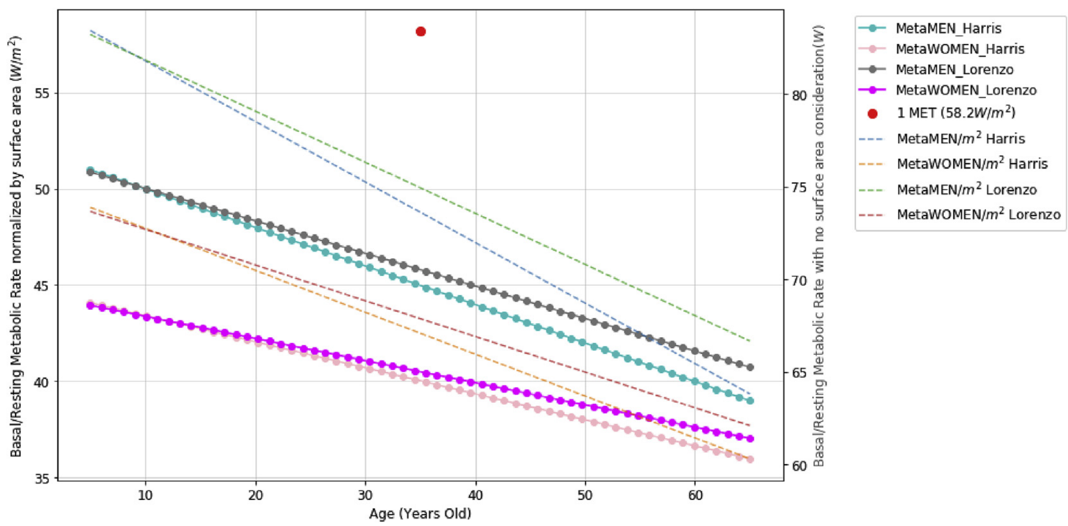

Fig. 2. Variation of Metabolic rate among different sub-group of occupants normalised by body surface area.

4. Results and discussions

4.1. Influence of gender and age

Following the sequence of our subject of interests, we will show how the metabolic rate varies with respect to gender, age and build, and how this ultimately affects the resulting exergy consumption rate as a proxy of thermal comfort. As Mady pointed out in 2013, the contribution from the metabolic rate makes up to 97.5% of the total exergy expenditure. To ascertain this influence, we can plot the two referenced variable basal/resting metabolic rate expressions from Harris & Benedict [57] as well as Lorenzo et al. to be normalised by body surface area as the following in Fig. 2. Both Harris & Benedict as well as Lorenzo et al.'s model, regardless of whether normalised by the surface area or not, does not agree with the 58.2 W/m^2 assumption proposed by Fanger. In fact, the basal metabolic rate appears to only go above 50 W/m^2 when the age of a boy around 10 years old, and drops even further as the subject under study ages.

It appears that Fanger's MET could be an over-estimation of the metabolic rate of the human body when compared to the existing physiological models. Normalisation by the surface area derived from weight and stature of the body normalises the RMR slightly by reducing the slope of the metabolic rates. However, as a non-linear function that has hyperbolic performance when being calculated as a function of weight, stature and age, the change of metabolic rate normalised by surface as being expressed by Equations (7) and (8) can be plotted for male and female subjects as surface plots with varying age, weight and stature as in Fig. 3.

The resulting metabolic rate for male ranges from 58.1 W/m^2 to 43.9 W/m^2, while for females, this value ranges from 49.5 W/m^2 to 40.3 W/m^2, varying by 16.2% and 11.4% respectively if a single(mean) resting metabolic rate is assumed for either gender. Comparing to the 58.2 W/m^2 from Fanger's model, the over-estimation could be as high as 32.6% for male occupants and 44.4% for female occupants. This can be further analyzed by comparing the variation of exergy consumed by using the resulting metabolism rate as input and assuming constant environmental temperature, through which Fig. 4 was obtained.

Elderly female occupants could have an exergy consumption rate that is as low as 4.0 W/m^2 while the high could go up to 6.2 W/m^2 when calculating the exergy generated by metabolism. As a 3D plot that showcases the relationship between the exergy consumption rates and weight and stature of individuals, Fig. 4 is very

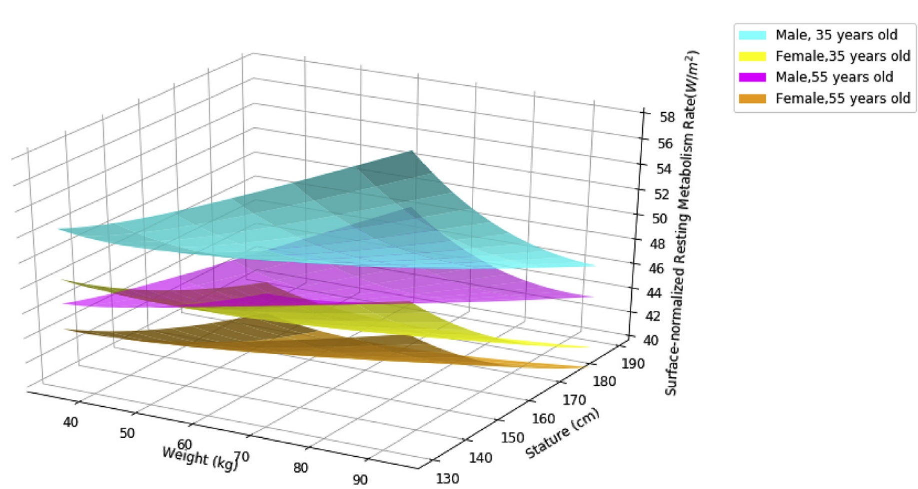

Fig. 3. Surface-normalised Resting Metabolism Rate for male and female occupants that are 35 and 55 years of age.

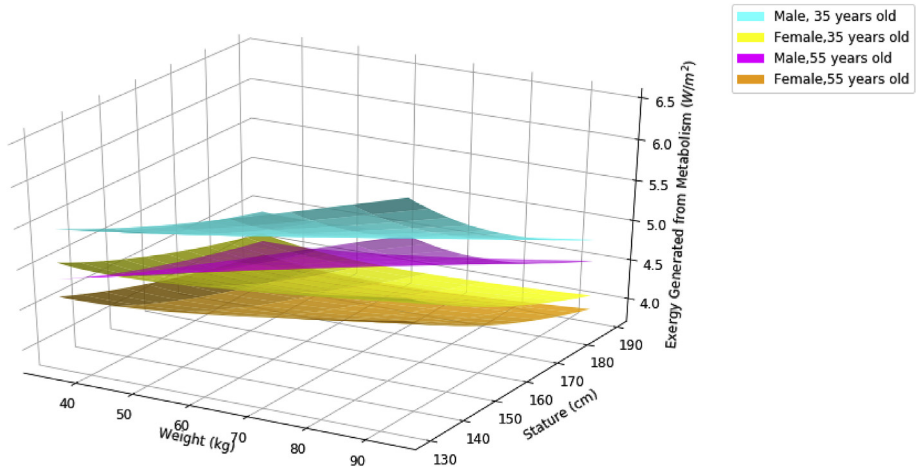

Fig. 4. Exergy Generated from Metabolism for male and female occupants that are 35 and 55 years of age.

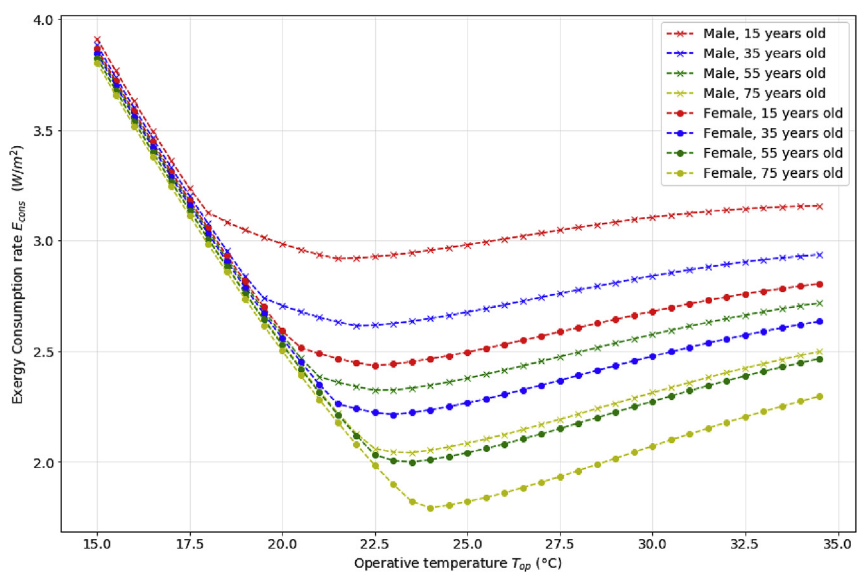

Fig. 5. Exergy consumption rate of human body E_{cons} plotted against a range of operative temperature T_{op} for male and female occupants of different age group.

difficult to comprehend in 2D and or as an interactive plot. Also, since the rate of exergy destruction is only relevant to thermal comfort when there is an observable minima, it cannot be easily observed in 3D plot either.

We therefore compare said exergy consumption rate minima by varying the indoor environmental conditions within an operative temperature range of 14 °C–35 °C, where the resulting curve of exergy consumption rate can be observed as shown in Fig. 5. In general, the exergy consumption rate of the younger people are much higher than that of the elders, while the male occupants tend to experience a much larger exergy consumption rate than the females occupants. Additionally, it is worth noticing that the exergy consumption rates shows a consistent steeper decline when the operative temperature is lower than 18 °C, but begins to climb back up at different minima across different genders and ages. The minima of the youngest male is the lowest while the oldest female's minima corresponds to the highest operative temperature and a lowest exergy consumption rate. Assuming the model is fully reliable, this points to a clear differentiation between the preferred environmental conditions varying between genders and ages. This is consistent with the existing reviews that examines the relationship between gender and thermal comfort [58], the diversity of perceived thermal comfort [59] as well as actual thermal comfort [60] among all individuals.

Adopting the same hypothesis as previous studies where the minima corresponds to the thermal neutral points, the results in Fig. 5 appears to coincide with the physiological observations where the elderly population prefers slightly warmer environments, since the minima could be as low as 22 °C for 15-year-old male and as high as 24.0 °C for 75-year-old female.

Additionally, the exergy consumption rate at a lower operative temperature also appears to be rather consistent across different age and gender group, potentially pointing to limitation of existing models limitations. Also, despite we are using operative temperature as the x-axis to show the local minima, the inherent complexities caused by the selection of convection and radiation coefficient could both lead to changes in the resulting operative temperature, and this is to build on the assumption that mean radiant temperature can be accurately obtained - which is in its own a problematic assumption.

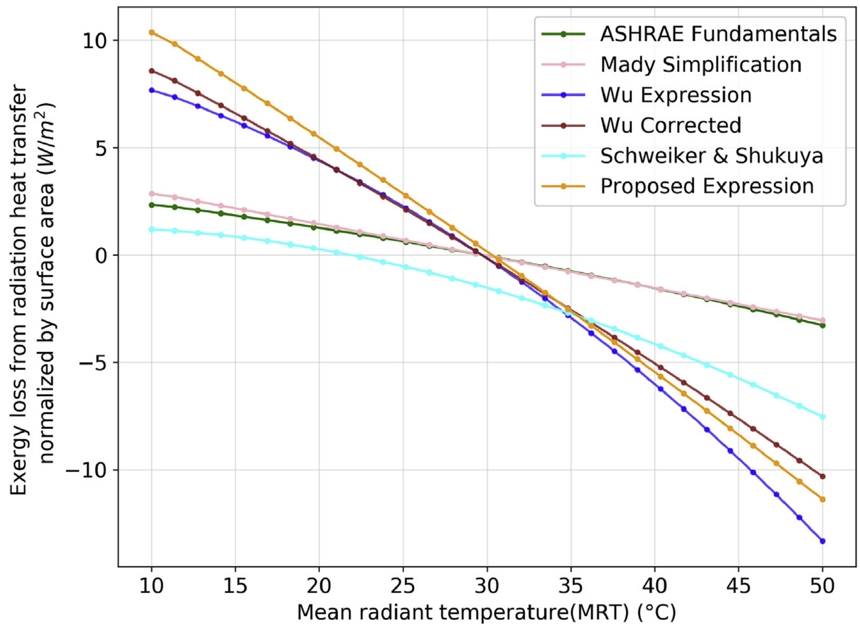

Fig. 6. Exergy loss during radiation heat transfer between human body and surrounding radiant environment assuming indoor air temperature $T_a = 23\,°C$.

4.2. Radiation terms

Following the metabolic rate, the next largest is the radiation, as is shown in Fig. 1. Using the assumptions parameters as presented in Table 1 such that the resulting Ex_r can be seen as plotted in Fig. 6.

All expressions exhibit a decrease from positive exergy loss at a mean radiant temperature of 18 °C to negative exergy loss (therefore exergy gain from radiation) as the mean radiant temperature increase to 40 °C. Neither the rate of decrease nor the overall magnitude appears to be consistent throughout the existing models. For the models that had a linearized radiation heat transfer coefficient, the resulting exergy loss during radiation heat transfer appears to be fairly small and linear regardless of the temperature gradient between the body and the mean radiant temperature. The expression from Wu et al., on the other hand, exhibit a much steeper rate of change with respect to mean radiant temperature and a more consistent drop of exergy consumption rate, which is partially dampened when replacing the reference temperature from T_a to T_{mr} to keep consistency with the expression from Petela as Equation (14).

Schweiker and Shukuya's expression appears to be decreasing at a much smaller rate with the change of mean radiant temperature but appears to have over estimated the exergy absorbed as the increase appears to be starting at T_{mr} at 22.76 °C, which is much lower than either the skin temperature T_{sk} at 32.05 °C, or the equivalent clothing temperature T_{cl} at 27.22 °C. Decreasing at a comparable rate to the Schweiker and Shukuya expression, our proposed exergy loss via radiation heat exchange remains positive until T_{mr} reaches 30.34 °C while T_{cl} and T_{sk} was estimated to be at 29.92 °C and 32.18 °C respectively. This is also comparable to the suggested linear coefficient from ASHRAE which suggests the body starts absorbing heat from the surrounding environment at $T_{mr} = 29.65\,°C$ while T_{cl} and T_{sk} were predicted to be at 32.17 °C and 29.67 °C. As the mean radiant temperature deviates away from the skin and clothing temperature, the variation appears to grow much larger, which could indicate the strength of the proposed model in environments that has a larger amount of radiation heat exchange.

4.3. Convection

Third group of exergy consumption contributor, are the runnder up of convection and evaporation, as is shown in Fig. 1. As we were able to pose the question of whether the current selection of reference state and governing equation could lead to reasonable representation of what is going on with respect to the overall understanding of the actual physical phenomena - or specifically whether the resulting exergy losses may have a change of signage when the direction of heat exchange varies. The convection-related exergy losses as discussed in the methodology sections can be plotted assuming constant clothing temperature (calculated at 29.8 °C following the aforementioned assumptions) in Fig. 7. Expressed in the plot are the exergy losses calculated by varying air velocity and air temperature without changing any other environmental parameters (MRT, RH, etc.).

It is important to recognize that despite the change in air (dry-bulb) temperature and air velocity, the values of the exergy loss with respect to the skin through convection remains positive in all expressions except the one from Shukuya. Mady's expression, owing to its convection heat transfer coefficient being independent of air velocity, reaches minima between clothing temperature at 30 and 33.8 °C. The rest of the three convection exergy loss terms from Wu et al., Prek et al. and Shukuya et al. shows similar trend. In particular between the Wu and Prek models, the minima and maximum exhibit comparable minima and maxima at consistent combination of air temperature and air velocities, with the Prek model outputting slightly larger exergy destruction rate at the higher end of air temperature and larger air velocity. The only plot that exhibit any change of sign in the exergy loss through convection is the model from Shukuya, which was consistent with the model from Prek except the selection of reference temperature in the Shukuya model was the outside air temperature instead of the indoor air temperature.

From the thermodynamics and thermoregulation theories, it is understandable that as the air temperature becomes higher than the skin temperature, the human body begins to receive the heat

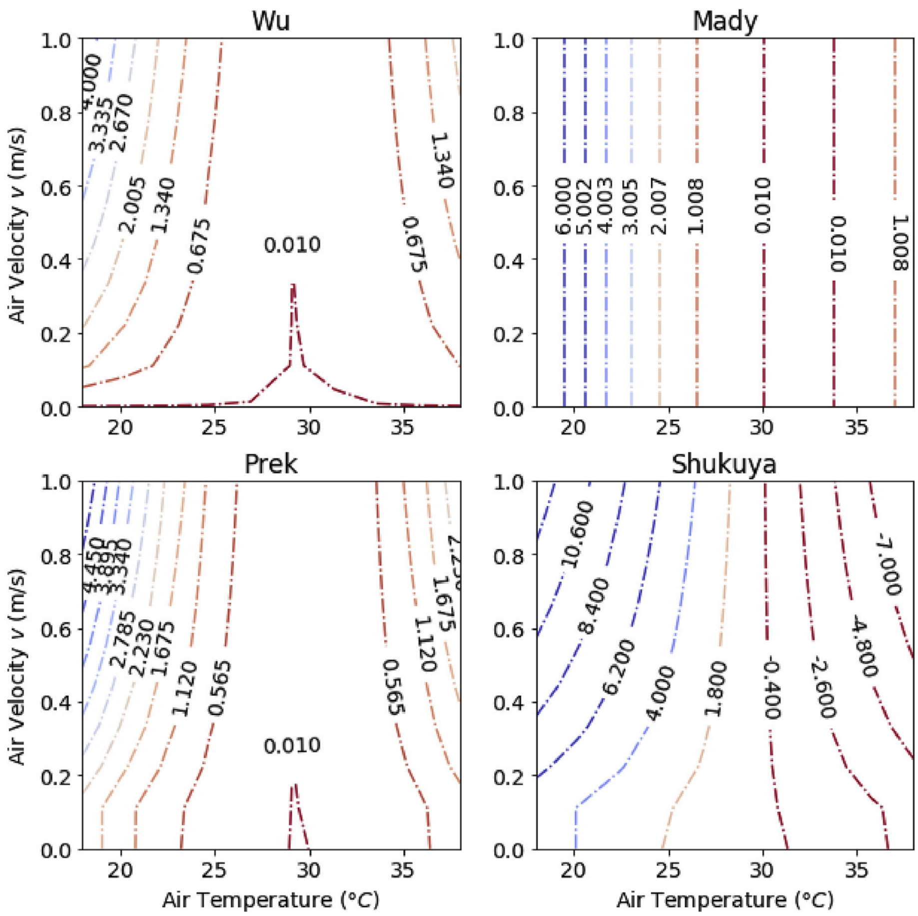

Fig. 7. Exergy loss through convection in W/m^2 plotted against air temperature and air velocities.

from the air rather than dissipate heat that was generated by work and metabolism. This should have increased the load of exergy consumption rather than decrease it as a form of exergy loss. However, choosing the outside air temperature also have its own shortcomings, since the amount of exergy loss being calculated by Shukuya's model does not agree with Prek,Wu or Mady's model with its order of magnitude and could become significantly smaller when the outside air temperature is comparable with the indoor air temperature. It might be beneficial to introduce a check of sign that compares the T_{cl} and T_a which ensures the exergy loss of the human body from convection becomes exergy gain from the expression when T_{cl} is smaller than T_a. Similar to Figs. 7 and 8 shows the exergy losses calculated by varying relative humidity and air temperature without changing any other environmental parameters (MRT, air velocity, etc.).

In addition, the exergy losses shown in Figs. 8 and 5 are both time rate change of exergy normalised by surface area, and can be converted to exergy when a specific occupants profile is selected. This could also be considered an important co-benefit of using exergy analysis for human occupants, where the dimension of exergy consumption rate is consistent with the dimension of energy consumption. As existing research has already made similar connections on connecting human body exergy analysis to the building envelopes [61], extending the analysis further to the district even city level could be both challenging and beneficial. Comparing with other thermal comfort metrics that are either vote-like (PMV) or temperature-like [62], exergy consumption rate of the human body has an inherent strength that it can be used to quantitatively analyze the comfort delivery efficiency of conditioning systems. Yet, as the experimental data on human body exergy consumption is still very limited comparing to other comfort metrics, future studies on associating exergy consumption rates with comfort delivery efficiency is necessary.

4.4. Evaporation

In the meantime, the exergy losses from the evaporation of sweats can be found plotted also as contour in Fig. 8. All expressions were consistently in showing a trend where the exergy loss was the largest when the indoor air temperature was the largest at the lowest humidity ratio. This is consistent with the physical phenomenon where the lowest relative humidity and the highest temperature provides the largest water vapor pressure differential that drives the evaporation process. The expressions used by Wu, Prek and Mady were also consistent in that the exergy consumption rate drops as the indoor air temperature decreases while the relative humidity increases, and exhibit negative exergy loss values when the air temperatures are above skin temperatures and at a higher relative humidity. Expressions from Wu and Mady agrees upon one another in their capabilities of also their maxima and minima of exergy losses, while the Prek model exhibit a consistent trend but a smaller overall value due to an extra term that was used to quantify the chemical exergy of the dry air, $RT_a ln\phi_a$, as can be observed between Equation (29) and Equation (30).

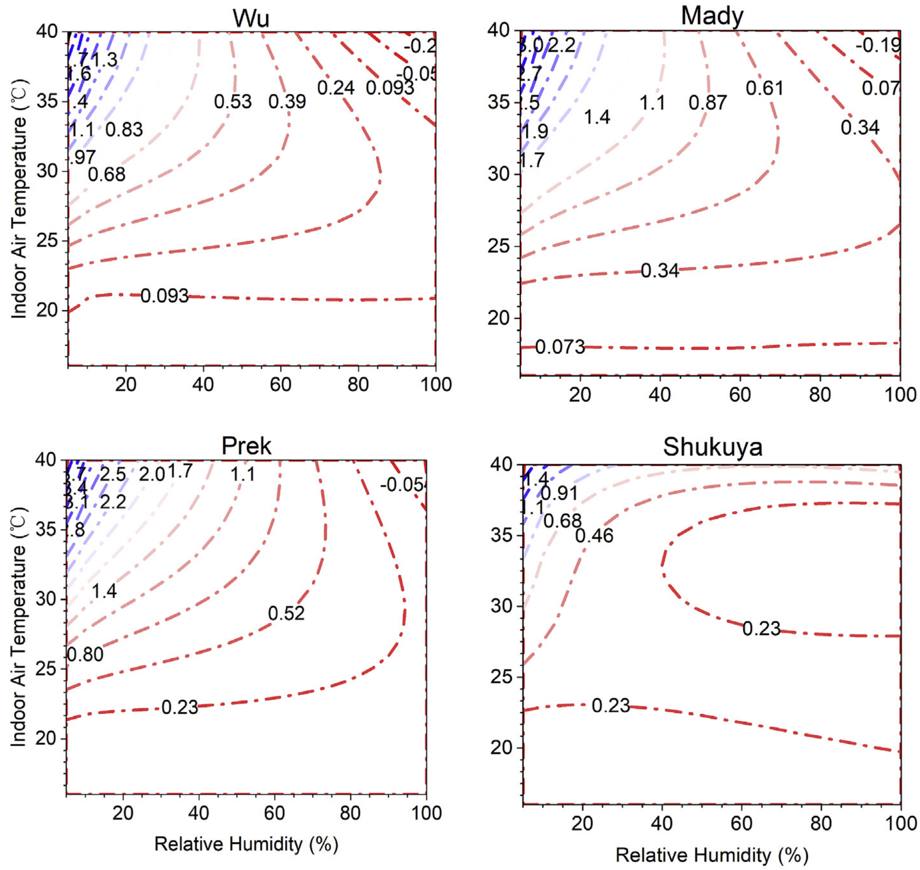

Fig. 8. Exergy consumption rate of skin evaporation E_{esk} and respiration E_{res} plotted against a range of operative temperature.T_{op}

4.5. Reference temperatures

Despite the differences between the various models we reviewed, our results indicated that they share a common problem that the choice of reference temperature could significantly affect the resulting exergy. As we are launching the exergy analysis for a human body, it is important to recognize that we are in fact conducting user-side exergy analysis, which does not necessarily require a 'dead' state to compare the exergy losses (or gains) with [63]. However, if included in an overall system analysis, it is important to choose one reference state that is relevant and comparable to all the components of the system, i.e. a universal 'dead' state. The selection of the reference temperature for the human body exergy model should, therefore, be considered the most critical parameter to be kept consistent across different models before their performances can be compared against each other.

Also relating to the convection term, since Prek did not specify their choice of h_c, we adhered to the same h_c of choice by Shukuya et al. [50] from the Fanger's comfort model, the only differences between the Prek and Shukuya model was the choice of the reference temperature term, which led to a change in the resulting exergy of both magnitude and signage as shown in Fig. 7.

For the radiation term of exergy, we used the corrected term from Wu et al. and showed a much better agreement with both our proposed method, and the simplification from Mady et al. as well as the ASHRAE mandate. This does not appear to be monumental as it can be observed by correcting the Wu expression via changing the reference temperature from T_a to T_{mr}, but could be important to account for radiation exergy within environments that have a larger T_{mr}. For the convection term, Mady switched from $Q_c\left(1-\frac{T_0}{T_{sk}}\right)$ to $Q_c\left(1-\frac{T_a}{T_{sk}}\right)$ from the year of 2012–2014, effectively changing the signage of the exergy term.

5. Conclusion

To better understand the existing human body exergy models, we followed a typical exergy consumption breakdown from Shukuya's published research and analyzed term-by-term the four biggest contributor to human body exergy consumption, i.e. metabolic rate, radiation exergy loss, convection and evaporation. Using the resulting visual breakdown of exergy gain/losses, we started with metabolism, the largest contributor of exergy generation and examined the rest of the large contributors term-by-term to numerically compare the models.

We found the metabolic rate to be constantly over-estimated by up to 20% using the 58.2 W/m^2 as suggested by ASHRAE and many other existing literature on indoor thermal comfort. Recent physiological research points to a much more varied range of resting metabolic rate, which could be considered as an alternative for explaining the thermal preference differences between occupants of different age, gender, build groups. We also proposed a new expression that quantifies human body radiation exergy by accounting for the head and hand surfaces exposed with respect to a new reference temperature. Our analysis on other exergy terms including convection and evaporation showed also the importance of selecting appropriate reference temperature as it may result in exergy losses that are constantly positive regardless of whether the body is emitting or absorbing heat. Exergy losses/gains of the human body during the convection process were also found more susceptible to the selection of reference temperature than during evaporation.

A key conclusion is that significant changes of the human body exergy consumption can be caused by the RMR (or BMR) variations caused by weight, stature, age or gender differences. We proposed a new expression for radiant exergy that differentiates the skin on hands and head with the rest of clothing surfaces. We were also able to demonstrate that it is essential to be aware of the potential change of sign when accounting for the exergy loss during convection, which currently will only exhibit a change of signage when the reference temperature is set differently. We propose to use mean radiant temperature as reference temperatures when quantifying radiant exergy - which is particularly important since the existing approaches tend to treat the radiant heat transfer as a process that is linear to the temperature difference between the body and air.

Additionally, we also believe it is crucial to conduct further empirical verification of the human body exergy models to increase the credibility of using them in the qualitative and potentially quantitative analysis of thermal comfort.

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