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Thermal Comfort Prediction of Aged Industrial Workers Based on Occupants' Basal Metabolic Rate

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ABSTRACT

The increasing workforce ageing brings benefits and challenges in industrial structures. Industries consider aged workers as essential resources thanks to their experience and skills. Conversely, the aged workers' progressive functional and cognitive decline reduce their tolerance to industrial environmental conditions, negatively impacting performance. In particular, after age 30, there is a progressive inefficiency in the physiological response to temperature changes. Therefore, thermal discomfort conditions have a worse impact as the workers' age increases. The Predicted Mean Vote (PMV) methodology is conventionally used to predict the human sensation of thermal comfort on a seven-point thermal sensation scale. Such methodology does not take account of progressive decline in thermoregulation capacity with age. This paper aims to fill this gap by proposing an analytic model for the prediction of thermal comfort. The Metabolic rate (M) parameter in the PMV equation is calculated from the Harris-Benedict equations revised by Mifflin and St Jeor (1990) for the Basal Metabolic Rate (BMR), including the age factor for a more accurate evaluation of the workers' thermal sensation. The aim is to safeguard the aged workers' health and well-being to enhance their performance during work.

Keywords: Ageing workforce, Thermal comfort, Metabolic rate, Occupational health and safety, performance

INTRODUCTION AND LITERATURE REVIEW

People are living longer. The increase in life expectancy and the decline in fertility rates lead to an increase in the share of aged people in the total population and, consequently, in the working population (Caporale et al. 2022). Statistics on workforce ageing estimate that nearly one-fifth of workers will be over 50 by 2050. Although everyone ages differently, a characteristic distinguishing the age factor is the progressive health decline (Varianou-Mikellidou et al. 2019). The cardiovascular and respiratory systems change after age 30, altering the thermoregulation phenomenon and limiting tolerance to environmental stresses. At the same time, the inability of individuals to respond to prolonged environmental stress results in cardiovascular diseases

Table 1. Seven-point thermal sensation scale, from UNI EN ISO 7730:2005.

+ 3	Hot
+ 2	Warm
+ 1	Slightly warm
0	Neutral
− 1	Slightly cool
− 2	Cool
− 3	Cold

(Isa & Atim 2019). Proper thermoregulation requires that the Metabolic rate (M), i.e., the heat generated from energy in the human body, balances the heat that the human body is losing. A decrease in the efficiency of the physiological response to changes in temperature (e.g., the release of sweat to decrease the temperature) prevents the achievement of thermal comfort. Thermal comfort depends on environmental parameters (i.e., air temperature, mean radiant temperature, relative humidity, and ventilation rates). At the same time, it expresses a subjective satisfaction with the thermal environment (Sun et al. 2019). The indices used to evaluate thermal comfort derive from a theoretical approach based on the application of the energy balance equation to the human body. In 1960 Ole Fanger proposed the Predicted Mean Vote (PMV) methodology to predict the average thermal sensation of large populations on a seven-point thermal sensation scale (Fanger, 1970). The adaptability of the Fanger model makes it fundamental in the thermal comfort analysis of large populations, representing, on the other hand, one of its limitations. In 2019, Broday et al. reported the presence of substantial disparities when comparing the PMV values to the actual thermal sensation reported by occupants. These discrepancies underline the differences in the thermoregulatory response of individuals in a given environmental condition. More recently, Arakawa Martins et al. (2022) reported that people with lower thermal sensitivity, such as aged workers, present thermal management and adaptation difficulties. The highlighted discrepancies suggest that one of the Fanger model limitations relates to an incorrect determination of the users' M value (Broday et al. 2019). This paper aims to fill this gap by proposing a thermal comfort prediction model including the operators' age and considering M as a junction between changes in body thermoregulation and PMV calculations.

PREDICTED MEAN VOTE

The PMV represents the mean value of the thermal sensation votes of a group of people occupying a specific environment on a 7-point thermal sensation scale from −3 (cold) to 3 (hot) (see Table 1). The Predicted Percentage of Dissatisfied (PPD) index quantifies the percentage of occupants whose thermal sensation vote differs from the PMV value.

The ANSI/ASHRAE Standard 55-2020, the UNI EN ISO 7730:2005, and the UNI EN 16798-1:2019 recommend that the optimal indoor temperature is defined when PPD is lower than 10%, which corresponds to PMV values

Table 2. Default categories for designing a mechanical heated and cooled building, defined in Annex B "Default criteria for the indoor environment" in the UNI EN 16798-1:2019 standard.

Category	Thermal state of the body as a whole	
	Predicted percentage of dissatisfied PPD [%]	Predicted mean vote PMV
I	<6	$-0.2 < \text{PMV} < +0.2$
II	<10	$-0.5 < \text{PMV} < +0.5$
III	<15	$-0.7 < \text{PMV} < +0.7$
IV	<25	$-1.0 < \text{PMV} < +1.0$

between −0.5 and 0.5. Table 2 highlights the matches between PMV, PPD, and the reference categories.

METHOD

The analytic model proposed in this paper addresses the thermal comfort prediction of industrial operators, using the Equation proposed by Harris-Benedict (1919) and revised by Mifflin and St Jeor (1990) for calculating the Basal Metabolic Rate (BMR) of individual workers. The model proposes a detailed evaluation of PMV and PPD, considering the BMR values in

Table 3. Index and parameters for revised PMV model.

Index	
i	Activity index, $i = 1 \ldots n$
Parameters	
M	the Metabolic rate $[W/m^2]$
W	the effective mechanical power $[W/m^2]$
BMR	the Basal Metabolic Rate in watts $[W]$
PAR	the Physical Activity Ratio
PAL	the Physical Activity Level
BSA	the Body Surface Area $[m^2]$
w	the person weight $[kg]$
h	the person height [cm]
y	the person age $[years]$
t_i	the duration of activity i $[min]$
T	the duration of the work cycle considered $[min]$, equal to the sum of the partial durations t_i
P_a	the water vapor partial pressure $[Pa]$
t_a	the air temperature [°C]
f_{cl}	the clothing surface area factor
t_{cl}	the clothing surface temperature [°C]
t_r	the mean radiant temperature [°C]
h_{cl}	the convective heat transfer coefficient $[W/(m^2 \times K)]$
V_{ar}	the relative air velocity $[m/s]$
RH	the Relative Humidity expressed as the percentage [%]of the water vapor pressure to the saturation vapor pressure at a given temperature
Icl	the clothing thermal insulation [clo]
MET	the Metabolic Equivalent of Task [met]

relation to the operators' age within the M parameter in the Fanger model. The aim is to improve aged workers' health and well-being and enhance their performance at work.

Table 3 shows the index and parameters used in the proposed model.

The analytic formulations of the models' functions are as follows.

$$\begin{aligned}\mathrm{PMV} = {} & [0.303 \times \exp(-0.036 \times M) + 0.028] \times \{(M - W) - 3.05 \times 10^{-3} \\ & \times [5733 - 6.99 \times (M - W) - p_a] - 0.42 \times [(M - W) - 58.15] \\ & - 1.7 \times 10^{-5} \times M \times \left(5867 - p_a\right) - 0.0014 \times M \times (34 - t_a) \\ & - 3.96 \times 10^{-8} \times f_{cl} \times [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} \\ & \times h_{cl} \times (t_{cl} - t_a)\,\}\end{aligned} \tag{1}$$

$$M = \frac{BMR \times PAL}{\mathrm{BSA}} \tag{2}$$

$$\mathrm{BMR_{men}} = 10 \times w + 6.25 \times h - 5 \times y - 5 \tag{3a}$$

$$\mathrm{BMR_{women}} = 10 \times w + 6.25 \times h - 5 \times y - 161 \tag{3b}$$

$$PAL = \frac{\sum_{i=1}^{n} t_i \times PAR_i}{\sum_{i=1}^{n} t_i} = \frac{1}{T} \times \sum_{i=1}^{n} t_i \times PAR_i \tag{4}$$

$$BSA = (w^{0.425} \times h^{0.725}) \times 0.007184 \tag{5}$$

$$M_{men} = \frac{\left(10 \times w + 6.25 \times h - 5 \times y - 5\right) \times \sum_{i=1}^{n} t_{\mathrm{i}} \times \mathrm{PAR}_i}{T \times [(w^{0.425} \times h^{0.725}) \times 0.007184]} \tag{6a}$$

$$M_{women} = \frac{\left(10 \times w + 6.25 \times h - 5 \times y - 161\right) \times \sum_{i=1}^{n} t_{\mathrm{i}} \times \mathrm{PAR}_i}{T \times [(w^{0.425} \times h^{0.725}) \times 0.007184]} \tag{6b}$$

Equation (1) computes the PMV values, as in the ISO 7730:2005 standard. The relationship between the M, the BMR and the contribution of energy consumption derived from the Physical Activity Level (PAL) is in Equation (2). The product between these factors is subsequently divided by the Body Surface Area (BSA). Equations (3a) and (3b) are from the Mifflin and St Jeor's formulas for male and female BMR calculation, respectively (Mifflin et al. 1990). Equations (3a) and (3b) consider individual weight (w), height (h), and age (y) in the BMR definition. Equation (4) represents the time-weighted average of Physical Activity Ratio (PAR). PAR values represent the energy cost of physical activity expressed as a ratio of BMR. The Du Bois formula for the BSA calculation is in Equation (5), given the individual weight (w) and height (h) (Du Bois and Du Bois, 1989).

Table 4. Constrained individual and environmental parameters.

Individual parameters				Environmental parameters			
Gender	*w*[*kg*]	*h [cm]*	*Icl [clo]*	t_a [°C]	t_r [°C]	V_{ar} [m/s]	*RH [%]*
Male	79	176	0.5	24.5	27.5	0.10	50
Female	65	163	0.5	24.5	27.5	0.10	50

Equations (6a) and (6b) integrate Mifflin and St Jeor's formulas into the male and female M equation, respectively.

The following feasibility constraints give consistence to the model:

M 46 W/m^2 to 232 W/m^2 (0,8 met to 4 met) (7)
Icl 0 $m^2 \cdot K/W$ to 0,310 $m^2 \cdot K/W$ (0 clo to 2 clo) (8)
t_a 10 °C to 30 °C (9)
t_r 10 °C to 40 °C (10)
V_{ar} 0 m/s to 1 m/s (11)
P_a 0 Pa to 2 700 Pa (12)

The following Section applies the proposed model to three simulated work activities and discusses the main results and key findings.

CASE STUDY

This Section introduces the analytic model's application, proposing a multi-scenario analysis. This simulation involves the thermal comfort analysis of 12 operators involved in three different industrial processes. Specifically, the first Scenario investigates the operators' thermal comfort during office work. The second Scenario refers to an assembly activity. Finally, the third Scenario simulates the variation of operators' thermal comfort during a lifting activity. The aim is to analyze the impact of the age of the operators on their thermal sensation, defined with the PMV, based on the application of the Equations proposed by Mifflin and St Jeor (3a and 3b) in the calculation of operators' M value (6a and 6b). The multi-scenario analysis aims to compare the resulting PMVs to varying ages only. The environmental parameters, i.e., t_a, t_r, V_{ar}, RH, and the individual parameters, i.e., Icl, w, and h, are constant in each Scenario.

The following Table 4 collects the values of the constrained parameters for the evaluation of PMV in each Scenario.

Table 4 shows the environmental parameters and the thermal insulation provided by clothing, following the ranges described in the UNI EN 16798-1:2019. This standard defines the minimum quality criteria that the environmental parameters must respect to guarantee both the energy performance of the building and the operators' thermal comfort. In the three scenarios, the selected configuration simulates the optimal microclimatic conditions of an industrial environment during the summer period. Literature studies highlight the risks associated with the ageing of workers both

Table 5. Hourly BMR calculation in the reference multi-scenario analysis.

Gender	Male						Female					
Age	20	30	40	50	60	65	20	30	40	50	60	65
BSA [m^2]	1.95	1.95	1.95	1.95	1.95	1.95	1.70	1.70	1.70	1.70	1.70	1.70
BMR [W]	1785	1735	1685	1635	1585	1560	1407	1357	1307	1257	1207	1182
BMR/h [W/h]	74	72	70	68	66	65	58	56	54	52	50	49

Table 6. Calculation of metabolic expenditure for individual activities.

Gender	Male						Female					
Age	20	30	40	50	60	65	20	30	40	50	60	65
Scenario 1: Office work												
PAR	**1.5**											
M [W/m^2]	57	55	53	52	50	49	51	49	48	46	44	43
MET [met]	0.98	0.95	0.93	0.90	0.87	0.86	0.89	0.86	0.82	0.79	0.76	0.75
Scenario 2: Assembly activity												
PAR	**2.5**											
M [W/m^2]	95	92	89	87	84	83	86	83	80	77	73	72
MET [met]	1.64	1.59	1.54	1.50	1.45	1.43	1.48	1.43	1.38	1.32	1.27	1.24
Scenario 3: Lifting activity												
PAR	**4.0**											
M [W/m^2]	152	148	143	139	135	133	137	133	128	123	118	115
MET [met]	2.62	2.55	2.47	2.40	2.33	2.29	2.37	2.29	2.20	2.12	2.04	1.99

during the winter and in the summer due to their reduced ability to regulate the body temperature in hot and cold environments (Calzavara et al. 2020). This multi-scenario analysis considers the summer period and represents only a first verification of the importance of the age factor in achieving thermal comfort. The analysis of the age impact on the individual environmental comfort involved the definition of 12 ideal profiles. In Table 4, the operators' weight and height values were established following 50th mass and height percentiles of male and female Caucasian populations (Cassola et al. 2011). The six male operators share the values of weight (79kg) and height (176cm) and differ in age (i.e., 20y, 30y, 40y, 50y, 60y, 65y). In the same way, the six female profiles share equal values of weight (65kg) and height (163cm) and different values of age (i.e., 20y, 30y, 40y, 50y, 60y, 65y).

In Table 5, the BMR in watts [W] was calculated with Equations (3a) and (3b) for men and women, respectively.

Since this calculation derives the daily BMR, in the following line, this result has been divided by 24, resulting in hourly BMR. The Body Surface Area (BSA) in [m^2] was calculated with the Du Bois formula (5) starting from the operators' weight and height. Values of w and h are constant in this multi-scenario analysis; therefore, BSA values are common to six male ($1.95m^2$) and six female ($1.70m^2$) operators, respectively. Table 6 illustrates the M values of the 12 operators during the three scenarios.

M [W/m^2] was calculated using Equations (6a) and (6b) considering for each Scenario $t_i = 1h$ and the Physical Activity Ratio (PAR) value in Table 6.

Table 7. Change in PMV as worker's age increases.

Gender	Male						Female					
Age	20	30	40	50	60	65	20	30	40	50	60	65
Scenario 1: Office work												
PMV	− 0.13	−0.27	− 0.37	− 0.52	− 0.69	−0.75	−0.58	−0.75	−1.00	−1.20	−1.42	− 1.50
PPD [%]	5	7	8	11	15	17	12	17	26	35	47	51
category	I	II	II	III	III	IV	III	IV	IV	IV	IV	IV
Scenario 2: Assembly activity												
PMV	0.57	0.54	0.49	0.45	0.41	0.39	0.44	0.39	0.34	0.29	0.24	0.21
PPD [%]	12	11	10	9	8	8	9	8	7	7	6	6
category	III	III	II	II	II	II	II	II	II	II	II	I
Scenario 3: Lifting activity												
PMV	1.42	1.36	1.28	1.23	1.16	1.12	1.19	1.12	1.04	0.97	0.91	0.86
PPD [%]	47	43	39	37	33	31	35	31	28	25	22	21
category	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV

The PAR values used to represent the energy costs of the selected activities are from Ainsworth et al. (1993). The M $[W/m^2]$value was converted to the Metabolic Equivalent of Task (MET) using the conversion formula $1met = 58\ W/m^2$.

The PMV values for each Scenario and operator are in the following Section.

RESULTS AND DISCUSSION

This Section introduces the results of applying the thermal comfort prediction model to the multi-scenario industrial case study. The aim is to verify the impact of workers' age on the individual response to the microclimatic conditions of an industrial environment during the performance of different activities.

Table 7 shows the individual parameters (i.e., gender and age) of the 12 operators involved, the values of PMV and PPD, and the reference scenario (i.e., office work, assembly activity, lifting activity).

The CBE thermal comfort tool (Tartarini et al. 2020) allowed the calculation of the comfort indices following the ASHRAE 55–2020, ISO 7730:2005, and EN 16798–1:2019 Standard. PMV, PPD, and category were calculated only by varying the MET values in Table 6. The values in Table 7 show that, for each of the three case studies, the age of workers significantly influences the response to the thermal environment.

The values in Table 5 show a condition of thermal neutrality for the 20-year-old male worker (PMV = −0.13) with a PPD equal to 5%, in the case of office work (Scenario 1). As age increases, PPD increases, reaching 17% (category IV) for the 65-year-old male operator. The PMV negative value (-0.75) highlights the workers' thermal sensation, changing from neutral to slightly cool, as indicated in Table 1.

The 20-year-old male worker experiences a condition halfway between thermal neutrality and slightly warm (PMV = 0.57) during the assembly activity (Scenario 2). These results place him in category III with a PPD of 12%.

In this case, the assembly activity produces a PAR of 2.5, increasing the operators' MET. For this reason, the PMV value of the 65-year-old operator in Scenario 2 is lower than the PMV values for the younger operators in the same Scenario. The increase in metabolic activity due to the activity carried out compensates for the cool feeling in Scenario 1.

The workers in Scenario 3 perform an intense activity (PAR 4), which places them in category IV with slightly warm to warm sensations. PMV and PPD variations are similar to those in Scenario 2. The feeling of thermal neutrality requires a warmer environment as worker age increases; because of the drop in the BMR values. The metabolic decline compensates for the increase in the MET when performing intense work activities.

The results for the 6 female workers in Table 7 show that these operators present lower PMV values than their male counterparts of the same age and in similar environmental conditions. The environmental conditions in Scenario 1 (Table 4) are insufficient to guarantee the thermal comfort of female operators over 50 years old. The UNI EN 16798-1:2019 standard does not consider PMV values equal to or lower than -1.20.

Conversely, the BMR values for the female operator ensure comfortable conditions in conjunction with the medium-intensity assembly activity in Scenario 2 (PAR values equal to 2.5). In Scenario 3, all the female workers are in category IV. However, the comparison of their PMV values with those of male operators shows a slight improvement.

CONCLUSION

The ageing of the working population and the strategies to protect the aged workers' well-being and productivity represent fundamental issues within industrial settings. The literature highlights that all workers need favorable environmental conditions. Aged workers need thermal comfort conditions to improve their health and to remain in the labor market. This paper proposed integration to the Predicted Mean Vote (PMV) methodology, including the age factor to calculate the Metabolic rate (M) of workers during the performance of three different work activities, i.e., office work, assembly activity, and lifting activity. The multi-scenario analysis introduced in this paper shows that the increase in age corresponds to a Basal Metabolic Rate (BMR) decline and a consequent decrease in M. The drop in BMR values implies that, as age increases, the feeling of thermal neutrality requires higher ambient temperatures. So, in a cold or slightly cold environment, aged workers suffer more than their younger colleagues. Finally, female workers have lower BMR values than male workers. Therefore, female workers suffer more from a cold environment than male counterparts of the same age and in similar environmental conditions. Considering the impact of changes in thermoregulation systems due to advancing age and gender in thermal comfort assessments allows for better plant management, work shifts definition, and the supply of appropriate clothing and tools. This study represents a preliminary assessment of the impact of age on workers' thermal comfort. Future developments of this study will include more in-depth evaluations and field analyses, extending the analysis sample, the reference period, and the monitored activities.

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