METABOLIC RATE ESTIMATION IN THE CALCULATION OF THE PMV FOR CHILDREN

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Abstract. Metabolic rate (MET) mainly corresponds to the heat production of the human body which is used in the calculation of the Predicted Mean Vote (PMV) of thermal sensation. Metabolic rates for various activities are tabulated in most of the commonly used standards. However, existing tables for determination of metabolic rate are based on average adult values and do not specifically include values for children. Moreover, previous studies indicate poor agreement on the estimation of metabolic rate for children. Children’s metabolism differs from that of adults, and this is not only limited to the relation between body surface area and estimated MET value. This implies that the influence of metabolic rate on the PMV calculation for children requires more research; also the way metabolism is included in the PMV equation may need to be changed for children. This study examines the metabolic rate of children during sedentary activity in the classroom and its influence on PMV-PPD predictions. Intervals of activity and resting metabolic rates (RMR) for children (10-12 years) are derived from the literature and PMV predictions are investigated based on application of these divergent RMR values both in a reference thermal condition and through incorporating empirical data.

Keywords. Activity metabolic rate; resting metabolic rate; children’s MET value; PMV-PPD.

1. Introduction

Metabolic heat production is of great importance in the determination of thermal comfort. It relates to the biochemical activity required to maintain an internal body temperature of 36.7°C (Goulding et al, 1992, p.112). Metabolic heat production varies with activity, person, and the physical condition of the environment (ASHRAE, 2009), and is measured in units of watts per square meter (W/m²) (ISO 7730, 2005). By convention, the unit MET is
used, where 1 MET represents the metabolic heat production rate of a quiet seated person (1 MET = 50 kcal/ (h.m²) = 58.15 W/m²) (ASHRAE, 2009).

In the study of thermal comfort, the metabolic rate is regarded as equivalent to the rate of heat generated from the human body. It is a key variable in Fanger’s PMV equation (Fanger, 1970) where it is given as the ratio of the activity metabolic rate to the resting metabolic rate. Since PMV was originally developed based on adults’ physiology, resting metabolic rate (RMR) in the PMV equation corresponds to the RMR of an average adult, designated as 58.15 W/m². According to ASHRAE (2009), tabulated values for estimation of metabolic rate are sufficiently accurate for well-defined activities with metabolic rates lower than 1.5 such as reading. However, ASHRAE suggests direct physiological measurement when higher accuracy is required; i.e. measurement of the rate of respiratory oxygen consumption and carbon dioxide production.

The paper reports on the sensitivity of Predicted Mean Votes of thermal comfort, to assumptions of metabolic rates. It is part of a larger study which examines the thermal comfort of children in classrooms, and expects to refine, with specific reference to this part of the population, the now accepted adaptive comfort models. The outcome of this study will be of significance in framing future standards, considering the role of thermal comfort in enhancing indoor environmental quality, the interaction between building performance and energy consumption, and comfortable and productive environments in school buildings.

2. Methods for determination of the metabolic rate in ISO 8996 and ASHRAE 55

ISO 8996 (2004) Ergonomics of the thermal environment provides four levels of accuracy and eight methods for estimation of metabolic rate in which accuracy and cost increase in distinct increments. A time-weighted average metabolic rate is suggested for conditions where the level of activity varies over time during a work cycle. However, according to the standard this leads to underestimation of metabolic rate when the activity period is short and rest periods are long.

ISO 7730 (2005), ISO 8996 (2004), and ASHRAE 55 (2010) variously tabulate metabolic rates. Of particular relevance is that the ISO standards refer to an “average” adult (male 30 years old 70kg, 1.75m, 1.8 m² body surface area; female 30 years old 60 kg, 1.70 m, 1.6 m² body surface area). The skin surface area of an average adult (A_{Du}=1.8 m²) (ASHRAE, 2009; ASHRAE 55, 2010) is also the basis of the estimated metabolic rate provided in other commonly used standards.
Generally children’s body mass and surface area are lower than those of adults. In a study by Havenith (2007) body surface areas for children 9-10 and 10-11 year old are taken as $1.23 \pm 0.11 \text{ m}^2$ and $1.29 \pm 0.12 \text{ m}^2$ respectively, as estimated by the Dubois formula (Du Bois and Du Bois, 1916). The reduced body surface area of children suggests that standard tabulated data may not be applicable for a younger population.

3. **Estimation of activity and resting metabolic rate for children**

Children’s metabolism is mainly discussed in children’s nutritional and physiological literature (e.g. Torun, 1989; Spadano et al, 2003); data are typically used to calculate mean metabolic rate over a day and often expressed per kg of body weight rather than the per m$^2$ value required for PMV calculation. In this domain, MET is the unit used for metabolic equivalent which is regarded as “the energy cost of physical activities as multiples of the resting metabolic rate (RMR)” (Spadano et al, 2003); hence for a certain activity it can be defined by dividing the measured activity energy expenditure by the measured or estimated RMR. One MET corresponds to the energy expended when sitting quietly (Ainsworth et al, 1993; Ainsworth et al, 2000; Spadano et al, 2003). For an average adult, 1MET is approximately equivalent to resting oxygen intake of 3.5 ml of oxygen.kg$^{-1}$.min$^{-1}$ (Ainsworth et al, 1993 p. 72).

The *Compendium of Physical Activities* (Ainsworth et al, 1993; Ainsworth et al, 2000; Ainsworth et al, 2011) provides a coding system which represents the energy cost of various activities of adults in MET based on the type and intensity of work. It improves comparability between studies but does not contain MET values for children’s physical activities. Given the lack of available data on the energy cost of children’s physical activities (Torun, 1989), different approaches have been presented to adjust adult metabolic rate values to apply to children.

Correcting adult data for children can result in considerable errors (Torun, 1983), which can be explained by the non-linear relationship between body weight and metabolic rate (Rogers et al, 1995). Similarly, values per unit of body surface area for adults cannot be converted to children’s values because the body surface area per unit of mass ratio changes with age (Havenith, 2007). This highlights the need for child specific data as simple size-corrected approaches do not produce reliable values for children.

A number of studies investigate the energy costs of activities in children. According to Harrell et al (2005) “energy expenditure per kilogram of body mass at rest or during exercise is greater in children than adults and varies with pubertal status”. However this study finds that the ratio of activity ener-
Energy expenditure to resting energy expenditure is similar in children and adults. Ridley and Olds (2008) suggest “using adults METs, combined with child resting metabolic rates, as the best existing technique to assign EE to children when measured values are not available”.

A compendium of energy costs for children and adolescents developed by (Ridley et al, 2008) lists MET values for 244 activities of which 35% were measured and the remainder estimated based on the adult compendium mentioned above. This youth compendium assigns a MET value of 1.4 for the energy cost of activities entitled “sitting quietly” and “writing-sitting”, measured in 9 and 5 child studies respectively. A MET value of 1.3 is assigned to “reading-sitting” derived from the adult compendium (Ainsworth et al, 2000).

Havenith (2007) has suggested metabolic rates for various age groups and classroom types based on a study of 25 primary school children. He found the metabolic rate of primary school children 9-11 years old during different lessons and classroom activities ranges from 52 to 64 W/m² and that of senior primary school children 10-11 years old for sedentary activities in the classroom varies from 62 to 64 W/m². These ranges are close to the lower limit of ASHRAE 55 (2010) for adults doing clerical work and are 10-20% lower than ISO 7730 (2005) and ISO 8996 (2004) values for office sedentary activity (i.e. 70 W/m²). According to Havenith (2007), the lower metabolic rate of school children per unit of surface area can be explained by their body size and the larger ratio of body surface area to mass.

4. Adjustment approaches for calculation of PMV

A number of thermal comfort studies in schools applied various adjustments for calculation of PMV to better represent children’s metabolic heat production.

Al-Rashidi et al (2009) adjusted children’s metabolic rate for sedentary activities downwards by 10% based on the findings of (Havenith, 2007). This ‘PMV_{10}’ is only applied to the input MET value, and the outcome indicates that both standard PMV and PMV10 fail to predict actual mean vote of children. Moreover, the reduced metabolic rate in PMV_{10} predicts a neutral temperature 1.3°C higher than the PMV prediction.

In Wargocki and Wyon (2007) the metabolic rate of children in schools was assumed to be higher than of adults in office buildings mainly because of the higher activity level of students during the school breaks. The study set the metabolic rate of an average 10-12 year old child as 40% higher than adults’ office work (i.e. 1.7 MET) because children’s body size was assumed to be 40% smaller than that of adults.
Mors et al (2011) multiplied the mean adult MET value of 1.26 by 1.7/1.14 to correct PMV for reduced body surface area of children 9-11 years old, with 1.7 m$^2$ and 1.14 m$^2$ representing body surface area of an average adult and a 10-year old child respectively. The derived mean metabolic rate of children in Mors et al (2011) is 109 W/m$^2$, which is much higher than adults’ metabolic rate during sedentary activity (i.e. 70W/m$^2$). The investigation found that corrected body surface area for calculation of PMV underestimates actual thermal sensation of children by 0.5 to 1.5 scale points during summer.

Teli et al (2012) investigate PMV model predictions with four different stepwise adjustment approaches to address the metabolic rate of primary school children aged 7-11 years. In the first approach the PMV equation remains unchanged and the input MET value for children is estimated as MET=1.2, the same as the metabolic rate of adults during office sedentary activity (ISO 8996, 2004). The results underestimate actual thermal sensation of children in the classroom.

In the second approach, the metabolic rate was corrected for reduced surface area and both PMV and RMR remained unaltered. The metabolic rate of adults during sedentary activity was taken in accordance with ISO 7730 (2005), i.e. 70W/m$^2$, and corrected for body surface area by multiplying it by 1.73/1.14 = 1.5; the resulting MET value =1.8. In this case PMV underestimates thermal sensation votes but with better agreement than the first approach. The third approach adjusts the adult sedentary activity metabolic rate and RMR for reduced body surface area to derive a MET value for children. In addition, PMV is corrected by substituting RMR inside the PMV equation with corrected RMR for children (taken as 88.25 W/m$^2$). The result introduces a better match between PMV and TSV compared to other approaches, although PMV still overestimates TSV.

The fourth adjustment approach used an input MET value derived from children’s activity metabolic rate in the classroom (Havenith, 2007) and children’s RMR (Amorim, 2007). PMV was modified using calculated RMR for children (i.e. 48.8 W/m$^2$). This led to a large difference between PMV and TSV, explained by the fact that the original PMV equation arose from experiments with adult subjects.

5. Determination of children’s metabolic rate in the present study

To enhance the validity of thermal comfort predictions in school environments and understand the effects of metabolic rate on PMV predictions, this study focuses on a range of child-specific metabolic rates for calculation of PMV as opposed to applying adult data.
5.1. ESTIMATION OF ACTIVITY MET VALUE

Although direct methods, result in more precise metabolic rates than tabulated values based on activities, in this study direct measurement of activity metabolic rate was not empirically possible. Therefore, it was decided to estimate activity metabolic rate and resting metabolic rate of children from the physiology, growth and development literature.

To improve the accuracy of estimation and examine the predictive value of PMV, a sensitivity analysis was conducted on part of the surveyed data. The analysis sets a range of MET rates and three different RMR values inside the PMV equation:

- **48.8 W/m²** in line with Teli et al (2012) where the RMR of children is determined based on (Amorim, 2007) (i.e. 1147 kcal/day), and normalized for body surface area of school children (i.e. 1.14m²).
- **88.25 W/m²**, which is the size-corrected adult resting metabolic rate. This is used in line with Teli et al (2012) mainly to enable comparison of comfort conditions between studies and to avoid differences caused by different internal RMR values.
- **58.15 W/m²**, which is the unchanged adult RMR of the PMV calculation.

In order to have a single value for children’s body surface area and enable comparison with the outcomes of recent studies reviewed above (Mors et al, 2011; Teli et al, 2012), 1.14m² is taken as the surface area of an average child and 1.73m² represents that of adults.

Finally, we note that the field study from which the thermal comfort perception and preference data for the sensitivity analysis is taken paid special attention to ensure MET levels return to a steady state condition following playground activities.

6. Analysis and results

The PMV equation given in (ISO 7730, 2005; ASHRAE 55, 2010) was re-coded in MATLAB computer software.

To understand the relationship between resting and activity metabolic rate intervals and PMV changes, a reference condition corresponding to PMV=0 was considered for preliminary analysis; air temperature 22°C, mean radiant temperature 23°C, air velocity 0.1m/s, relative humidity 50% RH, individual clothing value 0.85 clo, activity metabolic rate 1.2 MET, and resting metabolic rate 58.15 W/m². The resulting PMVs as a function of PPDs at various metabolic rates (RMR and METs) are calculated to compare predictions with the reference condition. As illustrated in Figure 1, using
children’s RMR values in the calculation of PMV-PPD indices results in clear departure from the neutral condition.

Children’s mean thermal sensation votes from 30 surveyed classrooms were then considered to investigate the PMV-TSV correlation. A total of 794 actual votes of students were taken in mid-autumn 2012 and winter 2013 in Shiraz, Iran. PMV in each classroom was calculated with a weighted average clo value and physical variables consistent with ISO 7726 (2001). Thermal neutrality (zero on the ASHRAE seven point scale) is derived based on the mean thermal sensation vote as a function of operative temperature. For each interval of MET and RMR value, one linear regression is generated to assess neutral temperature predicted by PMV and that governed by actual thermal sensation mean votes of the children (TSVmean).

![Figure 1. PMV as a function of PPD](image)

The outcome of the regressions (Figure 2) shows that children’s RMR values result in discrepancies in predictions of PMVs; RMR=44.85 W/m² leads to underestimation of PMV while RMR=88.25W/m² consistently falls above the regression line of actual thermal sensation of students.

PMV predictions based on adult values seem to be more robust in this study compared to other child specific values given in the literature. Linear regression analysis shows that among all RMRs used to explore the relations between PMV and TSV, fitted lines of PMVs with RMR=58.15W/m², MET=1.1, and RMR=48.8 W/m², MET=1.4 are close to the line representing the actual mean votes of the students.

The ranges for valid use of PMV to predict the mean thermal sensation are discussed in Humphreys and Nicol (2002). It is necessary to further study the validity of PMVs based on discrepancy analysis to assure the mean PMV-TSV discrepancy is within ±0.25 scale units as they propose. This ap-
proach should be coupled with application of actual RMR in the sensitivity analysis for future analysis in this study.

Figure 2. Linear regression calculation based on mean TSV and PMVs (vs.) operative temperature
7. Conclusion

Data from an autumn/winter field study in non-air conditioned primary schools in Shiraz, Iran, were used to examine sensitivity of PMV predictions for intervals of MET and RMR values derived from the literature relating to children. Linear regression of corresponding PMVs and TSVs (mean) as a function of operative temperature was derived to evaluate robustness of activity and resting metabolic rates in the PMV equation for children. The results suggest that changing RMR values for children at neutral temperature lead to deviations from actual neutral votes.

Even though this study shows a better match between actual data and PMV using RMR and MET values given in adult based standards, children’s resting metabolism, activity levels and their implications in the heat balance equation need more research.

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