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Application area of the PMV equation

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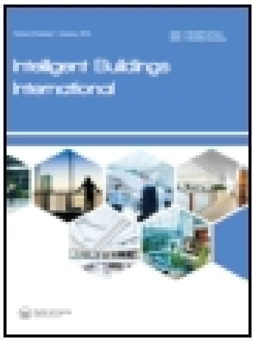

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NOTE

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A larger statistical basis and a wider application area of the PMV equation in the Fanger model: application area of the PMV equation

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ABSTRACT

For sedentary activities, the PMV equation, derived by Fanger, is mainly based on the research of Nevins et al. (720 test subjects). Nevins' experiments were later on repeated by Fanger, but with 128 college-age Danish subjects and 128 elderly Danish subjects, instead of American subjects. Rohles did the research from Nevins et al. again, but over a more extensive temperature range and more, namely 1600, test subjects. Rohles' research results have been partly included in the derivation of the PPD equation, but not in the derivation for the PMV equation. Rohles' experimental results are published at a later time than the publication of the thesis of Fanger. The question arises: 'If Rohles' experimental results were included in the derivation of the PMV equation, instead of Nevins' experimental results, to what extent does that change the PMV equation and the application area of the PMV equation, with regard of validity, for sedentary activities?'. In the same way, as Fanger described in his thesis, and using the results of Rohles' experiment, this study is limited to the derivation of a PMV equation with a wider PMV range than −2 to 2, for sedentary activities.

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Introduction

It is important to further develop thermophysiological models allowing the assessment of thermal comfort in the built environment. This includes not only the searching of new methods and approaches (Mayer 1997; Fiala 1998; Yao, Li, and Liu 2009) but also reviewing and revisiting the old research (Mayer 1998; Fanger and Toftum 2002; Roelofsen 2019; Roelofsen and Vink 2016).

This paper has the objective to initiate a discussion on potential improvements or extension of the validity of the original equation of the Predicted Mean Vote (PMV) (Fanger 1972; NEN-EN-ISO-7730 2005).

Fanger's work (Fanger 1972; NEN-EN-ISO-7730 2005) is of great value for evaluating comfort in different fields of study (e.g. construction, automotive, shipbuilding and aeronautics). The human model in combination with the PMV and Predicted Percentage of Dissatisfied (PPD) equations (Fanger 1972; NEN-EN-ISO-7730 2005), derived by him, are used in the world on a daily basis. In practice, but also in scientific research (Mohamed and Korb 2002; Mohamed and Korb 2003; Feriadi and Wong 2004; Backes, Trenktrog, and Eckstein 2019; Zang and Lin 2021) it regularly appears that the PMV equation is applied outside the range on the basis of which the PMV equation is derived. In practice, this can occur, for example, in the evaluation of the measurement or calculation of temperature exceedances in a room, for sedentary activities (Gao, Wang, and Wargocki 2015; Baglivo et al. 2017). Evidently, there is a need for a PMV equation with a broader application than −2 to 2, in accordance to NEN-EN-

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ISO-7730 (2005). A PMV equation with an application of −3 to 3, for at least sedentary activities, would be useful in the different fields of study.

For sedentary activities, the PMV equation is mainly based on the research of Nevins et al. (1966). Nevins' experiments (720 test subjects) were later on repeated by Fanger, but with 128 college-age Danish subjects and 128 elderly Danish subjects (Fanger 1972), instead of American subjects. Rohles (1971) did the research from Nevins et al. again, but over a more extensive temperature range and more, namely 1600, test subjects. Rohles' research results have been partly included in the derivation of the PPD equation (NEN-EN-ISO-7730 2005), but not in the derivation for the PMV equation (Fanger 1972). The results of the experiment of Rohles are published at a later time than the publication of the thesis of Fanger (1972).

The question therefore arises:

> If the results of the experiment of Rohles were included in the derivation of the PMV equation, instead of the results of the experiment of Nevins et al, to what extent does that change the PMV equation and the application area of the PMV equation, in terms of validity, for sedentary activities?.

In the same way, as Fanger described, on page 113, in his thesis, and using the results of Rohles' experiment, this study is limited to the derivation of a PMV equation with a wider PMV range than −2 to 2, for sedentary activities.

Research of Nevins et al., McNall et al. and Rohles

As mentioned in the introduction, the PMV equation in the Fanger model is above all based on the research of Nevins et al. (1966), for sedentary activities, as well as the research of McNall et al. (1967), for non-sedentary activities. Nevins et al. has measured the thermal sensation of college students (360 males and 360 females), who were exposed to each thermal condition (T_{db} = 18.9–27.8°C; RH = 15–85%) in groups of 10 persons (5 males and 5 females), at a metabolic rate of 1 Met. McNall et al. (1967). have studied the effect of activity levels on thermal sensation and thermal comfort. The subjects (in total 210 males and 210 females) of the experiment were 10 university students, 5 males and 5 females. The activity levels used in the experiment, and specified by Fanger (1972), represented metabolic rates of 1.6, 2.1 and 2.7 Met. The surrounding temperatures were for the low activity test: 18.9°C, 22.2°C and 25.6°C, for the medium activity test: 15.6°C, 18.9°C, 22.2°C and 25.6°C, and for the high activity test: 12.2°C, 15.6°C and 18.9°C. In other words, rather limited temperature ranges. The measurements were made with three different relative humidities: 25%, 45% and 65%.

Rohles (1971) exposed 1600 college-age students in groups of 10 subjects each, 5 men and 5 women, to 20 dry-bulb temperatures ranging from 15.6°C to 36.7°C in increments of 1.1°C. at each of eight relative humidities: 15%, 25%, 35%, 45%, 55%, 65%, 75% and 85%, to determine the full range of thermal conditions at which sedentary subjects (1 Met) report feeling comfortable. In fact, Rohles did the research from Nevins et al. again, only over a more extensive temperature range and more test subjects.

Experimental results Nevins et al., McNall et al. and Rohles

The published regression equations of the experiments of Nevins et al., McNall et al. and Rohles are in this study graphically represented in Figures 1–4. The figures also show graphically the published regression equations derived by Fanger, which were used to derive the PMV equation in the Fanger model. In his thesis, Fanger shows that the difference between men and women, in a preferred thermal environment, is statistically insignificant and is too small to be of engineering significance. For a further derivation of the PMV equation the combined equations, for men and women, have been used, like Fanger has done too.

Upon closer examination of the derivation of the PMV equation in the Fanger model, with regard to the experiment of McNall et al., one notices two possible omissions:

- In the case of a metabolic rate of 93 W/m², Fanger did take into account the published regression line regarding the thermal sensation for men, only apparently not that of women
- In the case of a metabolic rate of 123 W/m², the published regression line derived by Fanger has indeed the same slope angle as the published regression line for males and women, derived by McNall et al., but a different intercept.

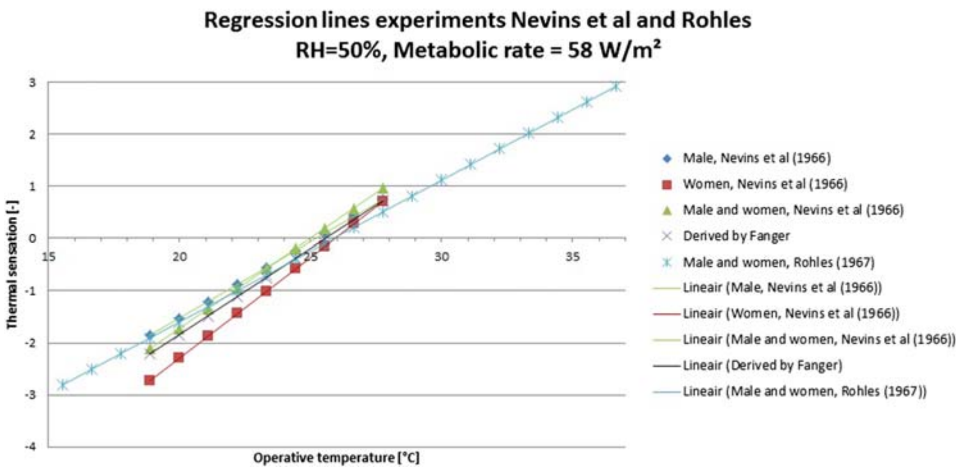

Figure 1. Experimental results Nevins et al. and Rohles.

Fanger model

In the Fanger model, it is assumed that the degree of discomfort is greater, the more the load on the effector mechanisms deviates from the comfort condition. Therefore, it is assumed that the thermal load of the body (L), defined as the difference between the internal heat production (H) and the heat loss to the actual environment for a human hypothetically kept at the comfort values of the mean skin temperature and the sweat secretion at the actual activity level. In the comfort condition, the thermal load will be equal to zero. In other environments, the body's effector mechanisms will change the mean skin temperature and sweat secretion in order to maintain the heat balance of the body. The thermal load is therefore an expression for the physiological strain upon the effector mechanisms of the body, and it seems reasonable to assume that the thermal sensation (Y) at a given activity level is related to this strain. This relationship

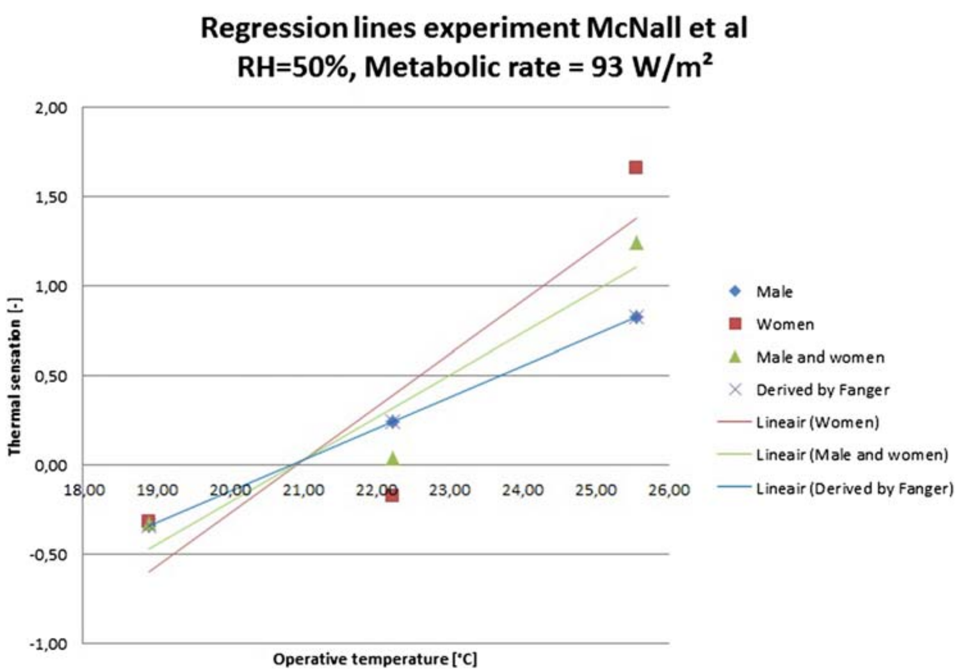

Figure 2. Experimental results McNall et al., metabolic rate of 93 W/m^2.

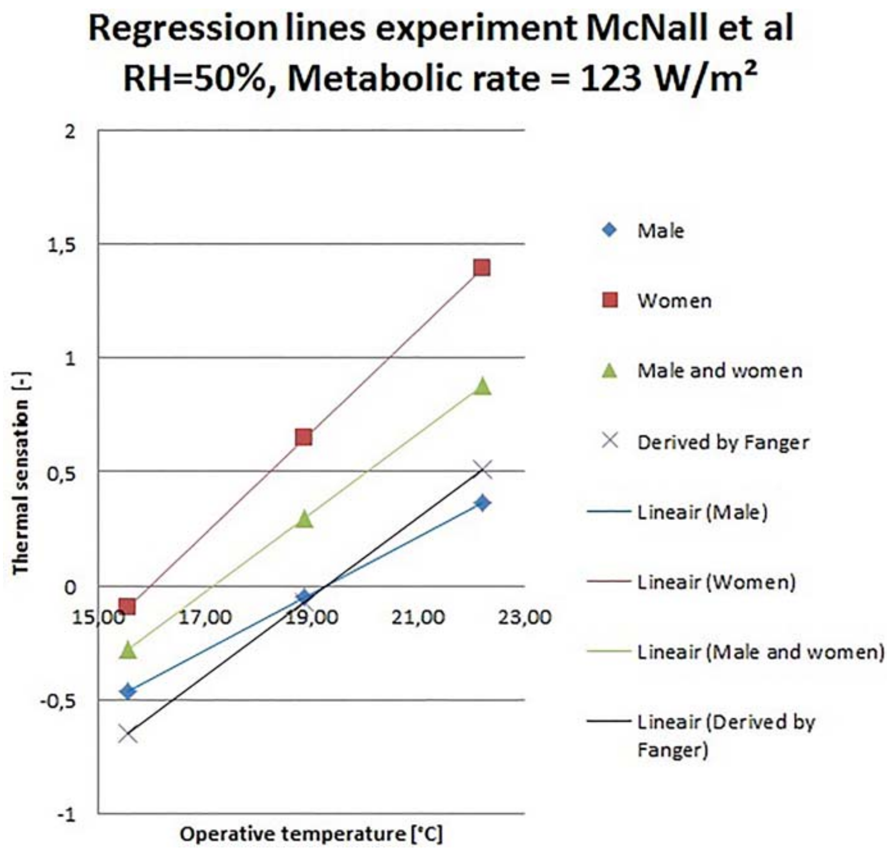

Figure 3. Experimental results McNall et al., metabolic rate of 123 W/m^2.

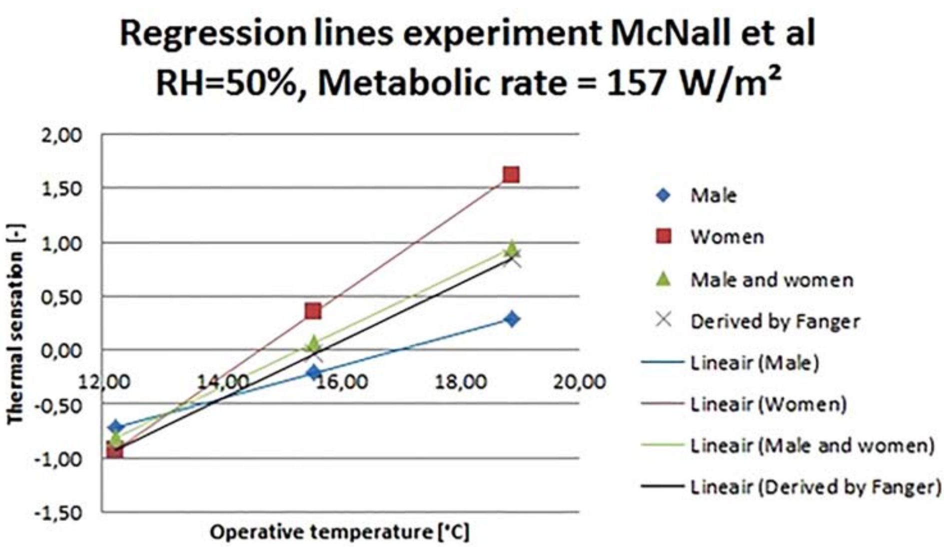

Figure 4. Experimental results McNall et al., metabolic rate of 157 W/m^2.

can be expressed mathematically as follows:

$$Y = f(L, H/A_{du})$$

Herein is:

$$A_{du} = \text{DuBois area } (m^2)$$

where the thermal sensation is expressed by the mean vote Y on the seven-point psycho-physical ASHRAE scale. The proviso is here made that the functional connection between the thermal sensation (the mean vote Y) and the thermal load L might vary with the internal heat production H/A_{du}. It is clear that the aforementioned equation for Y can only be quantified on the basis of experiments where the subjects cast thermal sensation votes, and where the clothing, activity and all the surrounding variables have been carefully controlled so that the thermal load can be calculated. In order to obtain a reasonable statistical basis for the quantification of the equation for Y, it is necessary that a large number of subjects have participated in the experiments. Fortunately, results are available from experiments of Nevins et al., McNall et al. and Rohles, which satisfy the above-mentioned demands and which therefore can be used to determine the functional dependence in the equation for Y.

In this study, for sedentary persons, the experimental data of Rohles will be used, instead of the experimental data of Nevins et al. For higher activity levels the experimental results of McNall et al. can be used, without the aforementioned omissions. These two investigations have covered 2020 subjects clothed in the Kansas State University (KSU)-standard uniform ($Iclo_{intrinsic} = 0{,}6$ clo) and exposed for three hours to constant environments, where all the variables have been well controlled. In the derivation of the original PMV equation of the Fanger model, 1396 subjects were involved. For the four activity levels investigated, connections between mean vote Y, and operative temperature were found as shown in Figures 1–4. By inserting the experimentally determined values of the different variables in the equation for the thermal load of the body (L) it is possible, for each of the four activity levels, to determine a connection between Y and L. After this, dY/dL can be determined graphically for $Y = 0$, since it is especially the relationship around the neutral point which is of interest (Fanger 1972).

In figure 5, the values of dY/dL found are plotted with the four activity levels.

> It can be seen that dY/dL is considerably higher for sedentary activity than it is for the other activities. In perusing the plotted points one could believe at first that dY/dL had a minimum value. This, however, is not likely. It seems more probable that dY/dL decreases monotonously with the activity and therefore an exponential curve has been drawn through the point, equivalent to a metabolic rate of 58 W/m², as this is based on a much larger number of subjects than the other points.

Fanger (1972) writes in his thesis. For this reason, the exponential curve is also used in this study.

In the same way, as Fanger described in his thesis (113), the equation of the curve becomes:

- $dY/dL = 0.337 * EXP(-0.051 * MR) + 0.033$ (m²/W)

By integration we then arrive at the re-derived PMV equation:

- $Y = PMV = (0.337 * EXP(-0.051 * MR) + 0.033) * L$ (–)

Since $Y = 0$ for $L = 0$.

The original PMV equation in the Fanger model is shown below for comparison:

- $PMV = (0.303 * EXP(-0.036 * MR) + 0.028) * L$ (–).

Table 1 gives an overview of the thermal sensation for sedentary activity in accordance with the experiment of Rohles, the original PMV equation, and the re-derived PMV equation in this study.

For the shaded cells, it is recommended, in accordance to (NEN-)EN-ISO 7730, not to use the original PMV equation, but in practice (Gao, Wang, and Wargocki 2015; Baglivo et al. 2017) it turns out that the PMV equation is often used beyond the validity of the equation (among others: $-2 < PMV < 2$).

Tables 2–4 give an overview of the thermal sensation for three higher activity levels in the case of the experiment of McNall et al., according to the original PMV equation and according to the re-derived PMV equation.

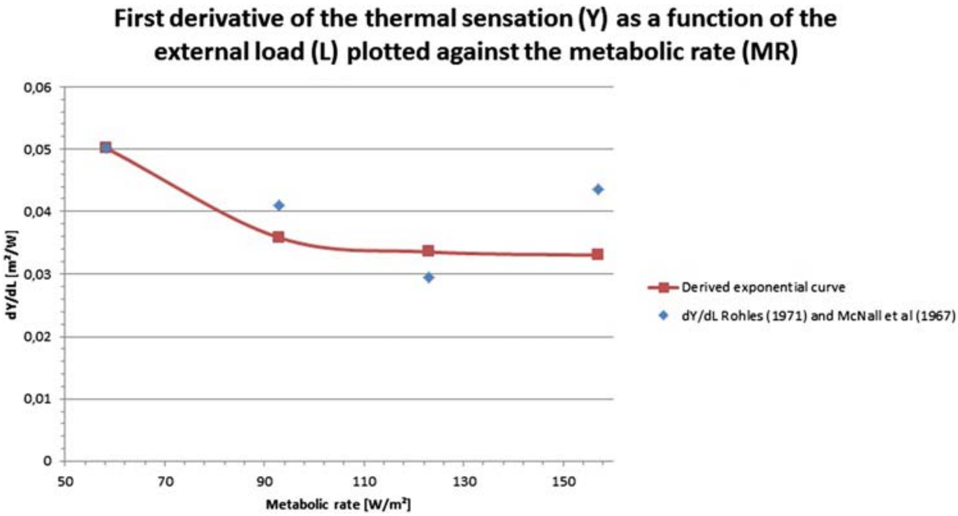

Figure 5. dY/dL as a function of the metabolic rate.

Table 1. Sedentary activity. Comparison of thermal sensation experiment, original PMV and re-derived PMV.

$T_{operative}$	$Y_{experiment\ Rohles}$	Original PMV	Re-derived PMV
(°C)	(–)	(–)	(–)
15.6	−2.81	−3.49	−2.69
16.7	−2.51	−3.09	−2.38
17.8	−2.21	−2.70	−2.08
18.9	−1.91	−2.31	−1.78
20.0	−1.60	−1.91	−1.47
21.1	−1.30	−1.52	−1.17
22.2	−1.00	−1.13	−0.87
23.3	−0.70	−0.75	−0.58
24.4	−0.40	−0.37	−0.29
25.6	−0.09	0.01	0.01
26.7	0.21	0.40	0.31
27.8	0.51	0.79	0.61
28.9	0.81	1.18	0.91
30.0	1.12	1.58	1.21
31.1	1.42	1.98	1.52
32.2	1.72	2.38	1.83
33.3	2.02	2.79	2.15
34.4	2.32	3.20	2.46
35.6	2.63	3.62	2.78
36.7	2.93	4.04	3.11
Average deviation with regard to the experimental results	–	0,46	0,12

Table 2. Metabolic rate 93 W/m². Comparison of thermal sensation experiment, original PMV and re-derived PMV.

$T_{operative}$	$Y_{experiment\ McNall\ et\ al.}$	Original PMV	Re-derived PMV
(°C)	(–)	(–)	(–)
18.9	−0.33	−0.73	−0.68
22.2	0.03	0.00	0.00
25.6	1.24	0.76	0.70
Average deviation with regard to experimental results	–	0,31	0,31

Table 3. Metabolic rate 123 W/m². Comparison of thermal sensation experiment, original PMV and re-derived PMV.

$T_{operative}$	$Y_{experiment\ McNall\ et\ al.}$	Original PMV	Re-derived PMV
(°C)	(–)	(–)	(–)
15.6	−0.28	−0.69	−0.74
18.9	0.30	−0.07	−0.08
22.2	0.88	0.55	0.59
Average deviation with regard to experimental results	–	0,37	0,38

Table 4. Metabolic rate 157 W/m². Comparison of thermal sensation experiment, original PMV and re-derived PMV.

$T_{operative}$	$Y_{experiment\ McNall\ et\ al.}$	Original PMV	Re-derived PMV
(°C)	(–)	(–)	(–)
12.2	−0.82	−0.66	−0.75
15.6	0.07	−0.07	−0.08
18.9	0.95	0.52	0.59
Average deviation with regard to experimental results	–	0,24	0,19

Conclusion

With the modification of the PMV equation in the Fanger model the following conclusions can be drawn:

- By including Rohles' experiment in the derivation of the PMV equation, the statistical basis of the equation has been increased
- The application of the results of the experiment of Rohles, instead of the results of the experiment of Nevins et al., in the derivation of the PMV equation, broadens the scope of the PMV equation, in the case of a sedentary activity
- The calculation results of the newly derived PMV equation differ less from the results of the experiment of Rohles than the calculation results of the original PMV equation
- In the case of the higher activity levels, than the sedentary activity, the calculation results of the newly derived PMV equation are not inferior to the calculation results of the original PMV equation
- In the case of sedentary activity and with the newly derived PMV equation, the temperature limits at which the PMV exceeds the values −0.5 and 0.5 are somewhat further apart, in accordance with the experimental results, than calculated with the original PMV equation. This will influence the result of the design calculations (e.g. capacity calculations and the calculation of the temperature exceedances in a room). However, the evaluation of this influence on the design calculations is, for the time being, beyond the frame of this study
- It is worth considering including the newly derived PMV equation in an eventual re-evaluation of the standard (NEN-)EN-ISO-7730.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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