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NOTE

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Paul Roelofsen, Kaspar Jansen and Peter Vink

Industrial Design Engineering, Delft University of Technology, Delft, The Netherlands

ABSTRACT

This paper has the objective to initiate a discussion on potential improvements or extension of the validity of the original equation of the Predicted Percentage of Dissatisfied (PPD), according to (NEN-)EN-ISO 7730. This paper is to be regarded as a supplement to a paper on a re-derivation of the PMV equation in the Fanger model (Roelofsen, Jansen, and Vink 2021). In practice, in scientific research it regularly appears that the PMV (Predicted Mean Vote), and by extension the PPD, are applied outside the range based on which the PMV and the PPD equation are 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. As it turns out, 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 that reason, Roelofsen has adapted the PMV equation in the (NEN-)EN-ISO model. But to what extent should the PPD equation also be adjusted? After all, the PPD is also derived from and limited to a PMV of −2 to 2, according to (NEN-)EN-ISO 7730.

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Introduction

For sedentary activities, the PPD equation, as well as the PMV equation,.derived by Fanger (Fanger 1972) and published in the standard (NEN-)EN-ISO 7730 (NEN-EN-ISO-7730 2005), is to a great extent based on the research of Nevins et al. (720 test subjects) (Nevins et al. 1966). Nevins' experiments were later on repeated by Fanger, but with 128 college-age Danish subjects and 128 elderly Danish subjects, instead of American subjects (Fanger 1972). Rohles (1971) did the research from Nevins et al again, but over a more extensive temperature range (i.e. $15.6 \leq T_{operative} \leq 36.6$°C instead of $18.9 \leq T_{operative} \leq 27.8$°C) and more, namely 1600, test subjects. Rohles' research results have been partly (i.e. 320 test subjects) included in the derivation of the PPD equation, as published in (NEN-)EN-ISO 7730, but not in total (i.e. 1600 test subjects) (Fanger 1972). The results of the experiment of Rohles are published at a later time than the publication of the thesis of Fanger. Based on the research results of Rohles, Roelofsen, Jansen, and Vink (2021) have adapted the PMV equation in the Fanger model, with a wider application than −2 to 2 for the PMV, for sedentary activities. It is therefore obvious, based also on the research results of Rohles, to determine to what extent the PPD equation in the Fanger model needs to be adjusted too. After all, the PPD equation, as published in (NEN-)EN-ISO 7730, is also derived from and limited to a PMV between −2 and 2 (i.e. $18.9 \leq T_{operative} \leq 32.2$°C). This paper is to be regarded as a supplement to the paper on a re-derivation of the PMV equation in the Fanger model (Roelofsen, Jansen, and Vink 2021). In the same way as Fanger described in his thesis (Fanger 1972), and using the results of Rohles' experiment, this study is limited to the derivation of a PPD equation with a wider PMV range than −2 to 2, for sedentary activities. In his thesis (Fanger 1972), Fanger shows that the difference between men and women, in a stationary preferred thermal environment, is statistically insignificant and is too small to be of engineering significance. Like Fanger, no distinction was made between men and women for a further derivation of the PPD equation. The differences

CONTACT Paul Roelofsen c.p.g.roelofsen@tudelft.n

in thermoregulatory response between sexes and the elderly and non-elderly become apparent especially under fluctuating temperature conditions (Roelofsen 2016). In the present situation, however, we limit ourselves to the stationary thermal situation, without addressing the limitations of the (NEN-)EN-ISO model.

Research of Rohles

The experiment of Rohles on subjective assessment of thermal sensation using 800 male and 800 female subjects in a special climate chamber at the Institute for Environmental Research, Department of Mechanical Engineering, Kansas State University (KSU) yields a very valuable and complete set of thermal sensation votes for temperatures from 15.6°C to 36.7°C in increments of 1.1°C and for a relative humidity from 15% to 85% in increments of 10%. The subjects were sedentary and wore a standard clothing ensemble of thermal resistance 0.6 clo. The air velocity was constant at 0.1 m/s and the mean radiant temperature was equal to the air temperature. Each subject was exposed to the conditions once only. They voted on a seven-point scale of thermal sensation 1–7 as follows: 1 – cold, 2 – cool, 3 – slightly cool, 4 – comfortable, 5 – slightly warm, 6 – warm, 7 – hot (Ballantyne, Hill, and Spencer 1977).

The seven thermal sensation scale used in the experiment can be converted to the seven-point psychophysical ASHRAE scale, from −3 to 3, used by Fanger, by subtracting 4 from the above thermal sensation values.

The Kansas State University (KSU) results on 1600 subjects reported by Rohles, as described here above, are used in this study. The tabulation of thermal sensation assessments for the 1600 subjects of the Kansas State University experiment is displayed in Table 1.

Re-derived PPD equation

Using the results of Rohles' experiment, the modified PPD equation is derived in the same way as Fanger describes in his thesis on page 130 (Fanger 1972):

> The dissatisfied are defined here as those who vote −2 or −3, 2 or 3. One could perhaps object that those voting −1–1 were not included also, but as evidenced by Gagge et al (Gagge, Stolwijk, and Hardy 1976), real discomfort is first expressed by those voting higher that 2 or lower than −2. It has therefore been decided here to describe as dissatisfied, only those persons who feel discomfort according to the above definition.

In addition, the same PDD formula form, as published in (NEN-)EN-ISO-7730, has been used.

Table 1. KSU assessments of thermal sensation as a function of temperature after 3 h exposure (for all humidities and both sexes) (Ballantyne, Hill, and Spencer 1977).

Temperature	Thermal sensation [–]							Total
[°C]	1	2	3	4	5	6	7	[–]
15.6	58	21	1	0	0	0	0	80
16.7	40	26	12	2	0	0	0	80
17.8	31	29	17	3	0	0	0	80
18.9	38	21	17	3	1	0	0	80
20.0	25	36	10	8	1	0	0	80
21.1	12	24	35	9	0	0	0	80
22.2	14	22	22	22	0	0	0	80
23.3	9	6	38	25	2	0	0	80
24.4	1	6	19	47	7	0	0	80
25.6	0	2	13	46	16	3	0	80
26.7	0	1	5	48	18	6	2	80
27.8	0	0	3	32	31	10	4	80
28.9	0	0	0	22	28	21	9	80
30.0	0	0	1	27	31	15	6	80
31.1	0	0	0	13	26	26	15	80
32.2	0	0	0	5	19	36	20	80
33.3	0	0	0	6	6	27	41	80
34.4	0	0	0	1	12	29	38	80
35.6	0	0	0	1	6	17	56	80
36.7	0	0	1	3	13	21	42	80
Total [–]	228	194	194	323	217	211	233	1600

Table 2. Sedentary activity. Comparison $PPD_{experiment}$, $PPD_{(NEN-)EN-ISO\ 7730}$ and the re-derived PPD.

$T_{operative}$ [°C]	$PMV_{experiment}$ [(1)] [–]	$PPD_{experiment}$ [(2)] [%]	$PPD_{(NEN-)EN-ISO\ 7730}$ [%]	$PPD_{re\text{-}derived}$ [%]
15.6	−2.8	98.8	97.9	87.4
16.7	−2.5	82.5	93.6	83.8
17.8	−2.2	75.0	85.2	78.2
18.9	−1.9	73.8	72.3	70.2
20.0	−1.6	76.3	56.5	59.4
21.1	−1.3	45.0	40.3	46.3
22.2	−1.0	45.0	26.1	32.0
23.3	−0.7	18.8	15.2	18.8
24.4	−0.4	8.8	8.3	9.2
25.6	−0.1	6.3	5.2	5.7
26.7	0.2	11.3	5.9	9.1
27.8	0.5	17.5	10.5	18.5
28.9	0.8	37.5	18.9	31.7
30.0	1.1	26.3	31.2	46.0
31.1	1.4	51.3	46.4	59.2
32.2	1.7	70.0	62.8	70.0
33.3	2.0	85.0	77.7	78.1
34.4	2.3	83.8	89.0	83.8
35.6	2.6	91.3	95.7	87.4
36.7	2.9	78.8	98.7	89.4
Mean deviation from the experiment	–	0	7.8	5.5
R^2	–	–	0.92	0.93

Based on Rohles' research results, shown in Table 1, and the definition of the number of dissatisfied people, by Fanger, the following PPD equation can be derived:

$$PPD = 100 - 94.3086*EXP(0.01883*(PMV + 0.08985)^4 - 0.411661*(PMV + 0.08985)^2)$$

Herein is:

PPD: Predicted Percentage of Dissatisfied [%] and PMV: Predicted Mean Vote [–].

Table 2 gives an overview of the PPD, for sedentary activity, in accordance with the experiment of Rohles, the original PPD equation and the re-derived PPD equation in this study. For the shaded cells, it is recommended, in accordance to (NEN-)EN-ISO 7730, not to use the original PMV- and PPD equation.

1) PMV = $0.2718*T_{operative}$ − 7.039 at relative humidity = 50% (Rohles 1971)
2) In accordance with the definition of Fanger (Fanger 1972), see above.

The re-derived PPD equation is shown graphically in Figure 1. It also contains a category II comfort zone, in green hatched, in accordance with EN-ISO 15251 (NEN-EN-15251 2007), as well as the experiment of Rohles and the original PPD equation, in accordance with (NEN-) EN-ISO 7730.

Conclusion

Using Rohles' experimental results and the re-derived PPD equation in the (NEN)-EN-ISO 7730 model the following conclusions can be drawn:

- By including Rohles' experimental results in the derivation of the PPD equation, the statistical basis of the equation has been increased (namely 1600 test subjects instead of 1296 test subjects).
- The application of the results of the experiment of Rohles, in the derivation of the PPD equation, broadens the scope of the PPD equation, in the case of sedentary activity (namely $-3 \leq PMV \leq 3$ instead of $-2 < PMV < 2$).
- The calculation results of the re-derived PPD equation differ less from the results of the experiment of Rohles than the calculation results of the original PPD equation (see Table 2).

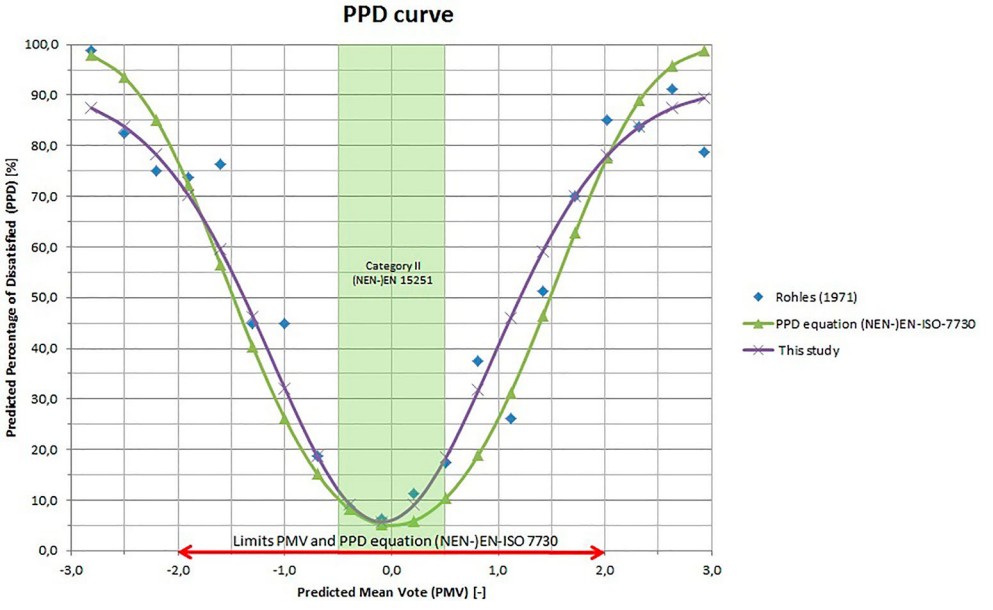

Figure 1. PPD according to Rohles' experiment, (NEN-)EN-ISO 7730 and this study.

- Outside the PMV interval −2 to 2, the PPD turns out to be lower than calculated with the original PPD equation, where the original PPD equation does not apply by the way.
- Within the interval −2 <PMV < 2, the PPD turns out to be higher than calculated with the original PPD equation.
- On the cool side of the comfort area (−2 < PMV < 0), the results of the original PPD equation and the results of the re-derived PPD equation appear to differ little.
- On the warm side of the comfort area (0 < PMV < 2), the results of the original PPD equation and the results of the re-derived PPD equation appear to differ significantly. The number of dissatisfied with general thermal comfort in this interval is higher, according to Rohles' experiments, than we now take into account in practice.
- The minimum of the re-derived PPD equation, according to Rohles' experiments, is approximately PMV = −0.1 and not PMV = 0, as is the case with the original PPD equation.
- In accordance with the research results of Rohles, with regard to the PPD as a function of the PMV, it is sensible to design a bit cooler than we are used to. However, it should be noted that the assessment of the operative temperature on the warm side of the comfort area by the test subjects in the experiment of Rohles was perceived as less warm than by the test subjects in the studies taken into account by Fanger. For this, reference is made to Roelofsen, Jansen, and Vink (2021). This should be further investigated.
- It will be clear that the discrepancy between the original and re-derived PPD equation, when used in practice, especially on the warm side of the comfort area (see Figure 1), can cause differences in relation to the category classification, as shown in (NEN-) EN 15251 and (NPR-)CR 1752. It is useful that the category classification, in terms of general thermal comfort, is to be judged again on its merits.
- In the situation of sedentary activity and for temperature exceedance calculations, it makes sense to use the PMV (Roelofsen, Jansen, and Vink 2021) and PPD equation, suitable for $-3 \leq \text{PMV} \leq 3$.
- It is worth considering including the re-derived PPD equation, combined with the re-derived PMV equation (Roelofsen, Jansen, and Vink 2021), 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).

Notes on contributors

Paul Roelofsen is a research fellow Healthy Urban Living & Working at the faculty of Industrial Design Engineering. His current research interests involve indoor environmental quality, wellbeing and human performance engineering.

Kaspar Jansen is professor of Emerging Materials at the faculty of Industrial Design Engineering. His current interests involve electronic textiles, smart materials, shape morphing materials and electroluminescence.

Peter Vink is professor of Environmental Ergonomics at the faculty of Industrial Design Engineering. His main research interests are interior design, comfort and vehicle seat design and their applications in mobility.

ORCID

Kaspar Jansen http://orcid.org/0000-0002-2172-9824

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