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A transient thermal sensation equation fit for the modified Stolwijk model

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ABSTRACT
There are different thermal perception models linked to a mathematical thermophysiological human model, with which the thermal sensation under stationary and/or dynamic conditions can be evaluated. Each of these perception and thermophysiological models have their own field of application. Stolwijk developed a thermophysiological human model without an associated thermal perception model, which today is still the basis for other mathematical thermophysiological models. Fiala developed the FPC model, also based on the Stolwijk model, and is one of the latest developments in the field of thermophysiological human models. In the FPC model, an equation is included with which the thermal sensation under stationary and dynamic conditions can be assessed; the so-called Dynamic Thermal Sensation (DTS). The DTS equation is, however, specifically developed for use in combination with the FPC model. In contrast to the Stolwijk model, the source code of the computer programs of the later developed thermophysiological human models is not freely available, which limits the use and applicability of the models in practice. It is precise because of the availability of the source code that the Stolwijk model is still used in industry and the research world. The question, therefore, arises: 'To what extent can a human transient thermal sensation equation be derived, combined with the Stolwijk model, in a similar way to that used for the DTS equation in the FPC model?'.

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Mathematical modeling; thermal comfort; indoor environmental quality; workplace; computer simulation

Introduction

In order to improve the assessment of thermal comfort in the built environment in practice, it is not always necessary to rely on the latest and most advanced thermophysiological human models. Sometimes it is enough to provide the models that are used in practice, because they have been made easily accessible, with a few new methods and approaches in order to overcome their shortcomings.

There are different thermal perception models linked to a mathematical thermophysiological human model, with which the thermal sensation under stationary and/or dynamic conditions can be evaluated. Each of these perception and thermophysiological models have their own field of application. Thermophysiological human models, with an associated thermal perception model, are for example:

Steady state condition[1]

- Fanger/NEN-EN-ISO 7730 model (Fanger 1972; NEN-EN-ISO-7730 2005).

Transient condition

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[1] This is not an exhaustive list.

- Berkeley Comfort Model (Huizenga, Hui, and Arens 2001).
- Wang model (Wang 2003).
- FPC model (Ergonsim 2016).

Stolwijk developed a thermophysiological human model (Stolwijk 1971), which today is still the basis and inspiration for other mathematical thermophysiological models (Katic, Zeiler, and Boxem 2014); such as the aforementioned Berkeley Comfort Model and Wang model. Partly due to Munir's recommended adjustments (Munir, Takada, and Matsushita 2009), the Stolwijk model appears to be suitable for simulating human thermophysiology, under non-stationary conditions, particularly in sedentary activities (Munir et al. 2010). Fiala developed the Fiala Thermal Physiology and Comfort (FPC) model, also based on the Stolwijk model, and is one of the latest developments in the field of thermophysiological human models. In the FPC model, an equation is included with which the thermal sensation under stationary and dynamic conditions can be assessed; the so-called Dynamic Thermal Sensation (DTS) (Fiala, Lomas, and Stohrer 2003). Currently, the DTS, combined with the FPC model, appears to be the thermal sensation model with the widest application range. The DTS is based on the general temperature sensation of test subjects in previous experiments at the Kansas State University and their simulated average skin temperature and core temperature with the Fiala thermophysiological human model (Zhang 2003; Fiala 1998). The DTS equation is, therefore, specifically developed for use in combination with the FPC model. The original Stolwijk model is not equipped with clothing and temperature perception. This has been adjusted by Roelofsen (Roelofsen and Vink 2016), by using the Gagge model for the clothing aspect and by using the Fiala DTS equation for the temperature perception (Roelofsen 2016). In certain cases, the DTS equation appears to be usefully combined with the Stolwijk model (Roelofsen 2019), despite the fact that the DTS equation was not developed for use in other models than the FPC model.

In contrast to the Stolwijk model, the source code of the computer programs of the later developed thermophysiological human models is not freely available, which limits the use and applicability of the models in practice. It is precise because of the availability of the source code that the Stolwijk model is still used in industry and the research world, among others by NASA (Miskovish, Byerly, and Miller 2014), the army (Berglund, Yokota, and Potter 2013), and the universities (Munir, Takada, and Matsushita 2009; Munir et al. 2010; Ingegneria medica Universita' di Tor Vergata Roma 2016; Roelofsen and Vink 2016). The question arises: 'To what extent can a human transient thermal sensation equation be derived, combined with the Stolwijk model, in a similar way to that used for the DTS equation in the FPC model?'.

Before doing this, we will successively discuss the Stolwijk and Fiala model, the experiments that have been used, the thermal sensation model that has been chosen, and finally, the comparison of the calculation results with the experimental results.

Stolwijk model

Passive part

The passive part of the model consists of five cylinders and a sphere with adjusted dimensions (the dimensions are determined by measurements on subjects, Figure 1). The cylinders represent the trunk, arms, hands, legs, and feet, and the sphere represents the head. Each element consists of four concentric layers or compartments that comprise the core, the muscle tissue, the fat, and the skin layers. The model also contains a central blood compartment, which represents the large arteries and veins. The model assumes that the body is symmetrically built up; the legs are represented by one cylinder. The total passive system consists of 25 nodes: five cylinders and a sphere, each consisting of four layers and one central blood compartment.

Active part

The active part of the model is the thermoregulation system (Figure 2) which perceives the ambient temperature and consists of an integrated and regulatory system. It is a simplified representation of the actual human thermoregulation system and is based on set point values. The set point value is basically the temperature for each node that a node would have in a neutral condition. If the value in a node is different from this set point value, then the regulatory mechanisms are used.

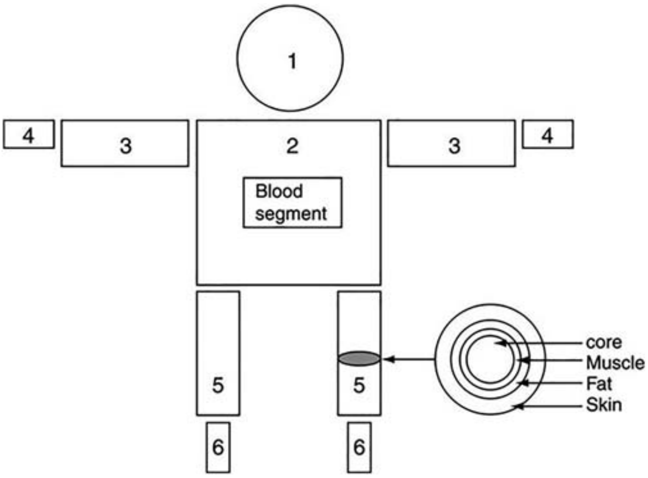

Figure 1. Schematic representation of the passive part of the Stolwijk model (Stolwijk and Hardy 1977).

Modifications Stolwijk model

Skin temperature

The characteristics of the multi-segmented human thermal model of Stolwijk were evaluated by Munir, Takada, and Matsushita (2009) using skin temperature measurements at low activity in transient environments by comparing the results of two series of experiments involving ten and seven subjects. The subjects were exposed to stepwise changes in environmental conditions, including neutral, low, and high ambient temperatures. It was concluded that the original Stolwijk model accurately predicted the absolute value of and the tendency of the transient mean skin temperature. This suggests that the original Stolwijk model was valid for the prediction of the transient mean skin temperature of an 'average' person in low

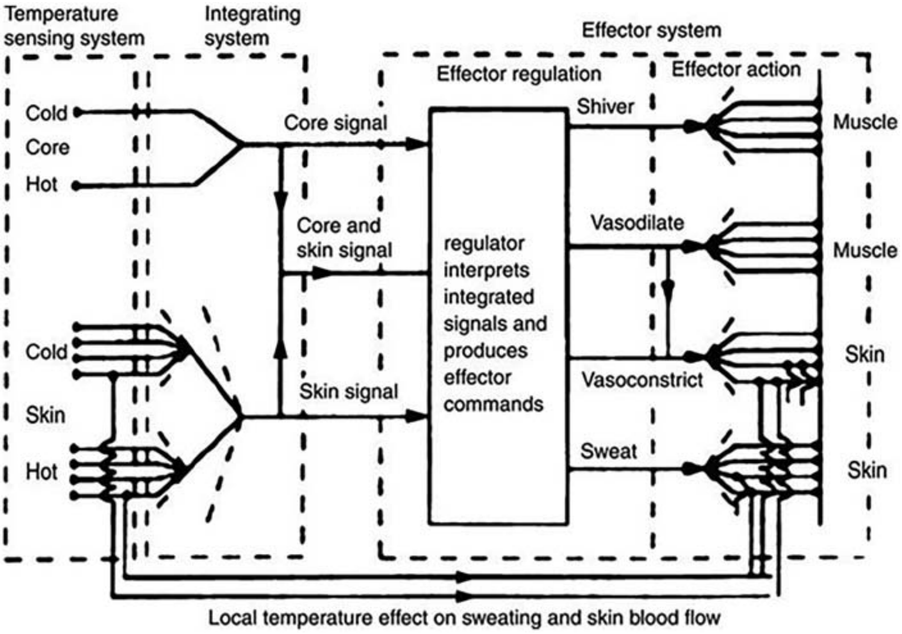

Figure 2. Schematic representation of the active part of the Stolwijk model (Stolwijk and Hardy 1977).

activity conditions. Some of the body segments showed deviations of local skin temperature. Modification of the distribution of the basal skin blood flow and the distributions of vasoconstriction and workload significantly improved the predicted results of both thermally neutral conditions and thermal-transient conditions (Munir, Takada, and Matsushita 2009). The above-mentioned modifications are displayed in (Munir, Takada, and Matsushita 2009) and included in the modified Stolwijk model (Roelofsen and Vink 2016).

Clothing

The original Stolwijk model was not equipped with clothing. In order for the model to be useful in the evaluation of the thermal comfort within the built environment, it is necessary that clothing can be included in the assessment. For that reason, the Stolwijk model, for all body segments, is modified, as described in (Roelofsen and Vink 2016). In this study, the calculation of the clo value is executed with a computer program based on a model of J. Lotens (Woerlee 1982). It calculates the clothing insulation values for a four cylindrical model of the human body. The model is covered with a clothing layer except for the head and hands.

Fiala model

In 1998 Fiala developed a thermophysiological model (Fiala 1998), based on the Stolwijk model. As with the Stolwijk model, the model of Fiala is split into passive and active parts. The original model of Fiala also assumes a standard male person weighing 73.5 kg, a body fat percentage of 14%, a Dubois area of 1.9 m^2, and a basal metabolic rate of 87.1 W.

The current FPC model (version 5.4), however, has undergone significant changes, modifications, and extensions. In the FPC model, the human body is modeled as 20 compartments consisting of 366 tissue nodes; the active system has been further developed and optimized. The passive system incorporates a humanoid reference model, which reproduces an average person obtained from anthropometric field studies. The new reference model represents a 35 years old, unisex person weighing 71.4 kg, 169.7 cm tall, with a skin surface of 1.83 m^2, and body fat content of 22.6% (Ergonsim 2016).

Dynamic thermal sensation (DTS)

In the FPC model, an equation is included to predict the thermal sensation under dynamic conditions, the so-called Dynamic Thermal Sensation (DTS), based on the simulated core temperature and the mean skin temperature. The equation for predicting the thermal sensation in thermally uniform environments is based on a large number of independent experiments. Using a multivariate analysis, it was found that the mean skin temperature, the core temperature, and the rate at which the mean skin temperature changes are the parameters affecting the thermal sensation under dynamic conditions. The thermal sensation was assessed on the basis of the ASHRAE seven-point scale. Experiments showed that the predicted DTS and the PMV (NEN-EN-ISO-7730 2005) were in agreement (Fiala 1998). In the studies of Fiala, two versions of the dynamic thermal sensation were published. The latest version is published in (Fiala, Lomas, and Stohrer 2003).

Thermal sensation in a steady state situation from human subject studies

Experiments of Nevins et al. (1966)

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 ten persons (five males and five females). The exposure period was three hours. The students were clothed in cotton shirts and trousers and woolen socks; the intrinsic clo value was 0.6 clo (effective clo value: 0.52 clo) (Fanger 1972). The students were seated during the test and their average metabolism was 58.15 W/m^2 (1.0 Met). The average air velocity was 0.10 m/s (Fanger 1972).

Experiments of McNall et al. (1967)

McNall et al. have studied the effect of activity levels on thermal sensation and thermal comfort. The activity levels used in the experiment, specified by Fanger (1972), represented metabolic rates of 93 W/m^2 (1.6 Met), 123 W/m^2 (2.1 Met), and 157 W/m^2 (2.7 Met). The activity levels were created using a modified step test, where the test individual was walking up and down a flight of stairs. For the low activity level, the walking cycle was standing for 25 min – walk for 5 min, for the medium activity level stand for 10 min – walk for 5 min, and for the high activity level stand for 5 min – walk for 5 min. The subjects (in total 210 males and 210 females) of the experiment were ten university students, five males and five females. They wore a thin cotton shirt, trousers, and their own underwear. The intrinsic clo value was 0.6 clo (effective clo value: 0.52 clo) (Fanger 1972). 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. The measurements were made with three different relative humidities: 25%, 45%, and 65%.

Experiments of Rohles (1971)

To determine the full range of thermal conditions at which sedentary subjects report feeling comfortable, 1,600 college-age students were exposed by Rohles in groups of ten subjects each, five men and five 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%; subjects were required to report their thermal sensations on a seven-point scale every half-an-hour. The results showed that for sedentary subjects exposed for three hours in standard clothing with an intrinsic clo value of 0.6 clo, the ‘comfortable’ votes were distributed over the temperature range of 16.7–36.7°C.

Thermal sensation in a transient situation from human subject studies

Experiments of Xiuyuan Du et al. (2014)

This paper reports on studies of the effect of temperature step-change (between a cool and a neutral environment) on human thermal sensation and skin temperature. Experiments with three temperature conditions were carried out in a climate chamber during the period in winter. Twelve male subjects (age: 20–30 years) participated in the experiments simulating moving inside and outside of rooms or cabins with air-conditioning. Skin temperatures and thermal sensation were recorded. Results showed overshoot and asymmetry of the thermal sensation vote due to the step-change. Skin temperature changed immediately when subjects entered a new environment. When moving into a neutral environment from cool, dynamic thermal sensation was in the thermal comfort zone, and overshoot was not obvious. Air-conditioning in a transitional area should be considered to limit temperature difference to not more than 5°C to decrease the unacceptability of temperature step-change. The linear relationship between thermal sensation and skin temperature or gradient of skin temperature does not apply in a step-change environment. Different cool conditions (12–15°C and 17°C; air velocity < 0,1 m/s; RH ≈ 54–58%) were created in the climate chamber (4 m*3 m*2.7 m, Room 1, and a neutral environment (22°C; air velocity < 0,1 m/s; RH = 44–51%) was created by air-conditioning in next door observing room (4m*3 m*2.7 m, Room 2), both of which could be individually controlled for environmental variables. A typical uniform clothing combination (1.17 clo) was adopted for subjects to avoid the effect of the difference in clothing insulation. During the experiment, the sedentary subjects could read newspapers and magazines (M = 1 met) (Du et al. 2014).

Experiments of Hong Liu et al. (2014)

Experiments were conducted in a climate chamber (Room 1, 4 m*3 m*2.7 m) and an adjacent air-conditioning room (Room 2, 4 m*3 m*2.9 m) with a door connecting them. The environmental variables for these two rooms can be individually controlled. The climate chamber was used to create three temperatures, 32°C, 30°C, and 28°C which were selected to represent the ambient temperatures that occur in the warm seasons, while the air-conditioning room was used to maintain a neutral one of 25°C. The temperature differences between the two rooms are 7, 5, and 3 K, respectively. The relative humidity (RH) in both rooms was controlled to be approximately 60%, and air velocity was less than 0.1 m/s. A total of 20 healthy male college students ranging in age from 22 to 25 years participated in the experiments. All the students were not currently taking a prescription medication and had no history of cardiovascular disease. Subjects were asked to avoid caffeine, alcohol, and intense physical activity at least 12 h prior to tests. Each subject provided his or her basic information (e.g. age, height, and weight) prior to the tests and participated voluntarily in all three tests. They were briefed on the purpose of the tests, were familiar with experimental procedures, and were trained to know the test procedure well. During the experiment period, they were required to wear uniform clothing, including a short-sleeved T-shirt, short trousers and socks with an insulation level of 0.33 clo (1 clo = 0.155 m^2 K/W) referenced from clothing garment checklists in ASHRAE Standard 55. All experiments were conducted in summer from June to July in 2012, but not immediately after breakfast or lunch. Each test experience lasted for 2 h. In each test, the subject arrived at Room 2 and rested for about 20 min, then entered the climate chamber (Room 1) and put on uniform clothing. Before the beginning of the experiment, subjects were given sedentary activities (reading) for 30 min for acclimation to the thermal environment and keep the metabolism stable. The thermal sensation survey and skin temperature measurements were performed simultaneously. Subjects were asked to report their perception in a questionnaire every 10 min. After 30 min, the subjects moved into the cooler chamber (Room 2). The subjects voted for their thermal sensation immediately after entering Room 2. Next, the subjects completed a 60-min test in Room 2 where they voted for their thermal sensation every 2 min in the early 10 min and then every 10 min for the rest 50 min. Finally, the subjects returned back to Room 1, remaining for 30 min. In the final 30 min, they voted every 2 min in the early 10 min and every 10 min for the rest 20 min. The skin temperature was recorded every minute in the whole test (Liu et al. 2014).

Proposed transient thermal sensation (TTS) equation

In 2003 Zhang (2003) published a more advanced thermal sensation model than the DTS equation of Fiala (Fiala 1998; Fiala, Lomas, and Stohrer 2003). More advanced in the sense that it was applicable for thermally non-uniform environments and suitable for the evaluation of the thermal sensation per body part. The model is only validated for sedentary activity and in practice, combined with a different thermophysiological model than the Berkeley Comfort Model, can differ considerably from experimental results. Nevertheless, it seems an interesting model to start from. For this study, the TTS equation is a derivative of the human thermal sensation model of Zhang, suitable for the evaluation of a thermally uniform environment.

- $\mathrm{TTS} = f_{sk} + \psi\ [-]$

Herein is:

- $f_{sk} = 4*(2/(1+\exp(-\mathrm{a}_1*\Delta \mathrm{T}_{\mathrm{sk,m}})) - 1)$ [K]; for $\Delta \mathrm{T}_{\mathrm{sk,m}} < 0$
- $f_{sk} = 4*(2/(1+\exp(-\mathrm{a}_2*\Delta \mathrm{T}_{\mathrm{sk,m}})) - 1)$ [K]; for $\Delta \mathrm{T}_{\mathrm{sk,m}} > 0$
- $\Delta \mathrm{T}_{\mathrm{sk,m}} = (\mathrm{T}_{\text{mean skin,actual}} - \mathrm{T}_{\text{mean skin,neutral}})$ [K]
- $\psi == \tau_- + \tau_+ + \mathrm{c}_1*\mathrm{dT}_{\mathrm{hy}}/\mathrm{dt}$ [K/min]
- $\tau_- = \mathrm{b}_1*\mathrm{dT}_{\mathrm{sk,m}}/\mathrm{dt}$ [K/min]; for $\mathrm{dT}_{\mathrm{sk,m}}/\mathrm{dt} < 0$
- $\tau_+ = \mathrm{b}_2*\mathrm{dT}_{\mathrm{sk,m}}/\mathrm{dt}$ [K/min]; for $\mathrm{dT}_{\mathrm{sk,m}}/\mathrm{dt} > 0$
- $\mathrm{dT}_{\mathrm{sk,m}}/\mathrm{dt}$ = mean skin temperature change [K/min]
- $\mathrm{dT}_{\mathrm{hy}}/\mathrm{dt}$ = hypothalamic temperature change [K/min]
- $\mathrm{T}_{\text{mean skin,neutral}} = 35.757 - 0.0248*\mathrm{M}$ [°C]; $\mathrm{R}^2 = 0.98$
- M = Metabolic rate [$\mathrm{W/m^2}$]; $58 \le \mathrm{M} \le 157$

TTS = Transient Thermal Sensation

The coefficients a1 to c1 are obtained via regression analysis. For the above-mentioned regression coefficients (a_1–c_1), the values apply, as in Table 1.

Table 1. Regression coefficients, combined with the modified Stolwijk model.

		Metabolic rate [met]			
	Regression coefficient	1.0	1.6	2.1	2.7
f_{sk}	a_1	0.449	0.358	0.240	0.632
	a_2	1.135	0.611	0.425	0.428
ψ	b_1	8.931	Further investigation required		

N.B.: Intermediate metabolic rates can be determined by linear interpolation. It is recommended to use the TTS equation mostly in the area: $-2.0 \le \mathrm{TTS} \le 2.0$.

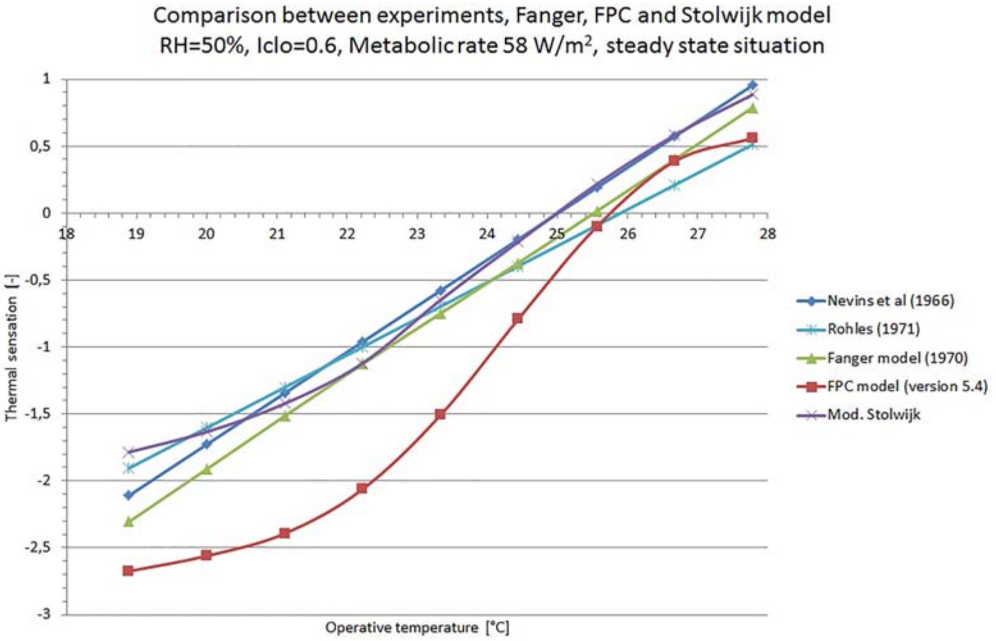

Figure 3. Thermal sensation. Metabolic rate 58 W/m^2. Steady state situation.

A comparison between the experimental results, the DTS and the TTS

In the following, the experimental results, the DTS, calculated with the FPC model (version 5.4), and the TTS, calculated with the modified Stolwijk model, are compared. TTS results are represented by the legend 'Modified Stolwijk'. They are exchangeable.

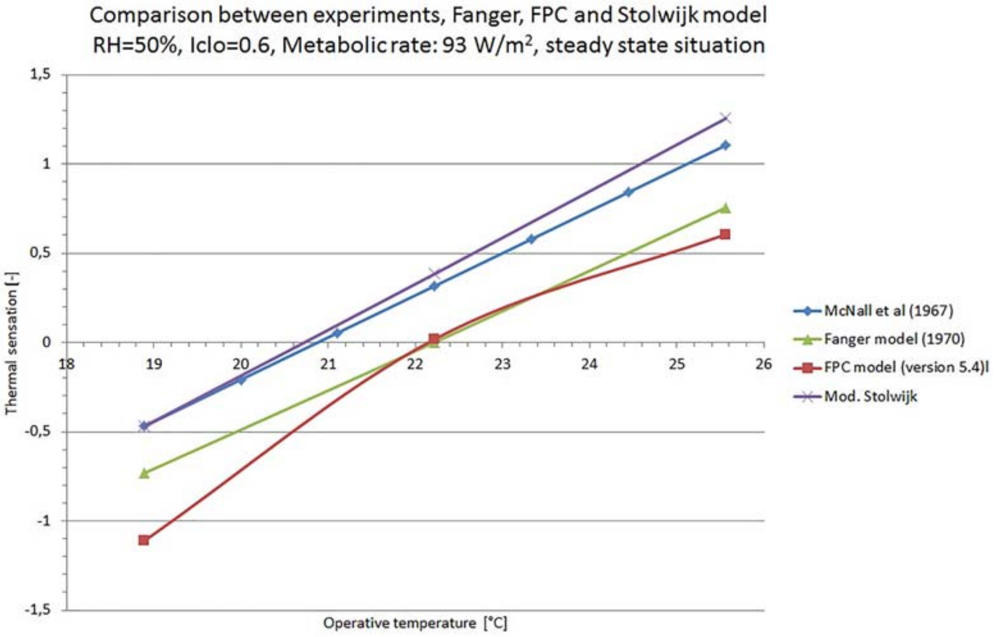

Figure 4. Thermal sensation. Metabolic rate 93 W/m^2. Steady state situation.

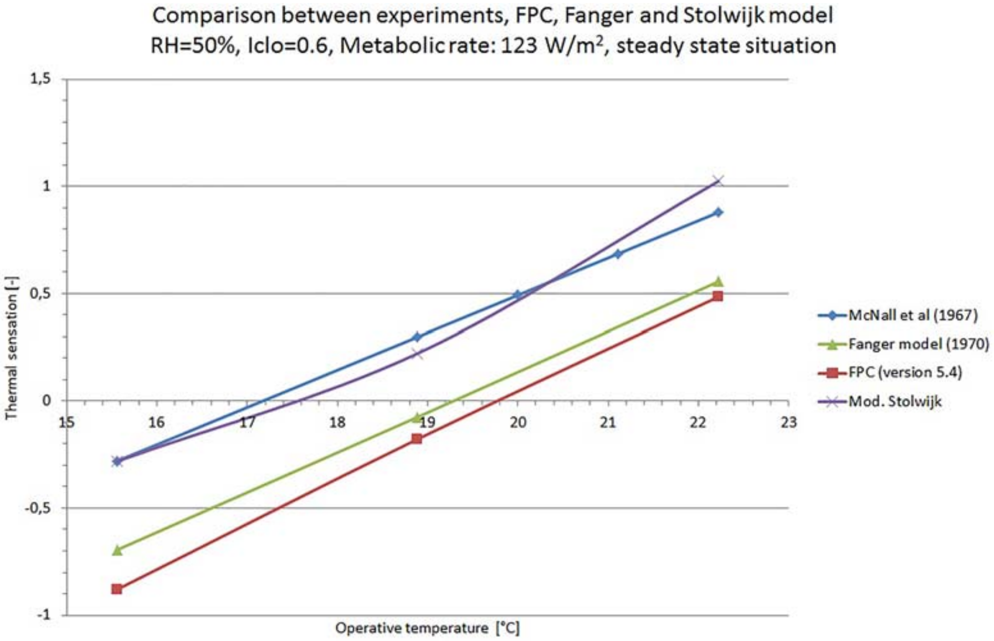

Figure 5. Thermal sensation. Metabolic rate 123 W/m². Steady state situation.

Steady state condition

Below simulated thermal sensation in steady state conditions is compared to the experimental results of Nevins et al. (1966), McNall et al. (1967), and Rohles (1971). The published regression equations of the experiments of Nevins et al., McNall et al., and Rohles are in this study graphically represented in

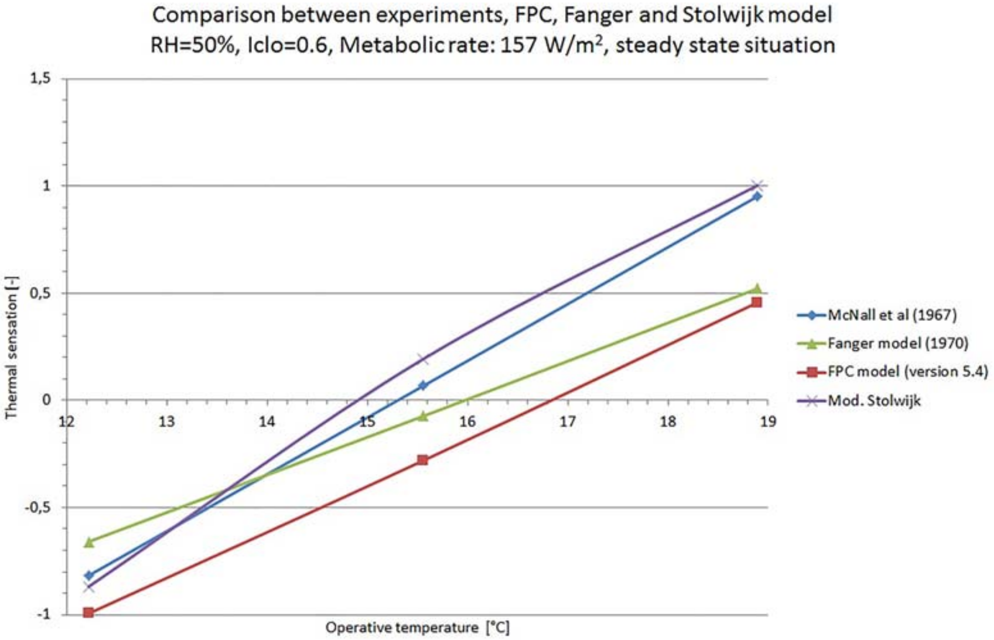

Figure 6. Thermal sensation. Metabolic rate 157 W/m². Steady state situation.

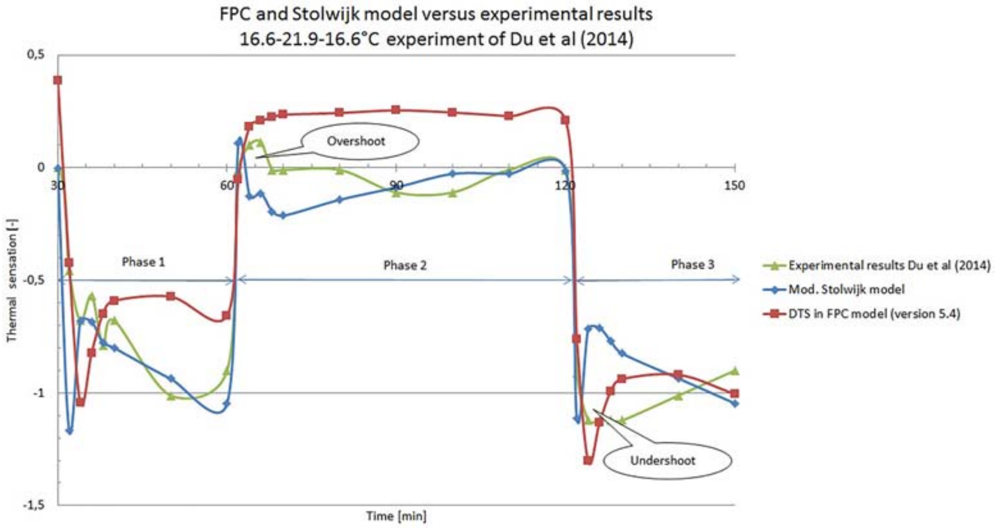

Figure 7. Thermal sensation. Slightly Cool: 16.6°C/RH = 54.3%, Neutral:21.9°C/RH = 49.1%, and Slightly Cool: 16.6°/RH = 54.3%.

Figures 1–4. In the steady state situation (Figures 1–4), the PMV value calculated with the Fanger model (NEN-EN-ISO-7730 2005; Fanger 1972) is for completeness also taken into account (Figures 5 and 6).

In the steady state situation, the TTS equation, calculated with the Stolwijk model, appears to correspond best with the experimental results, compared to the Fanger/NEN-EN-ISO-7730 and FPC model. In the case of the FPC model, the calculation results based on a metabolic rate of 58 W/m² are particularly striking (red curve in Figure 3). It is unclear why the DTS, calculated with the FPC model, is structurally lower than the experimental results.

Transient conditions

In order to find out to what extent the DTS calculation results and TTS calculation results deviate from the experimental results, a number of variant calculations were carried out. Two well-described and known

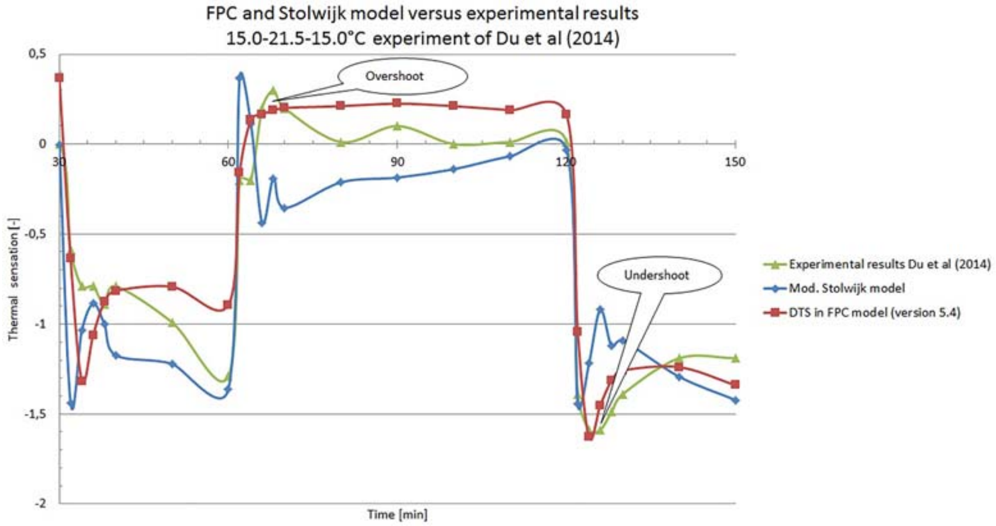

Figure 8. Thermal sensation. Slightly Cool: 15.0°C/RH = 58.2%, Neutral: 21.5°C/RH = 51.0%, and Slightly Cool: 15.0°C/RH = 58.2%.

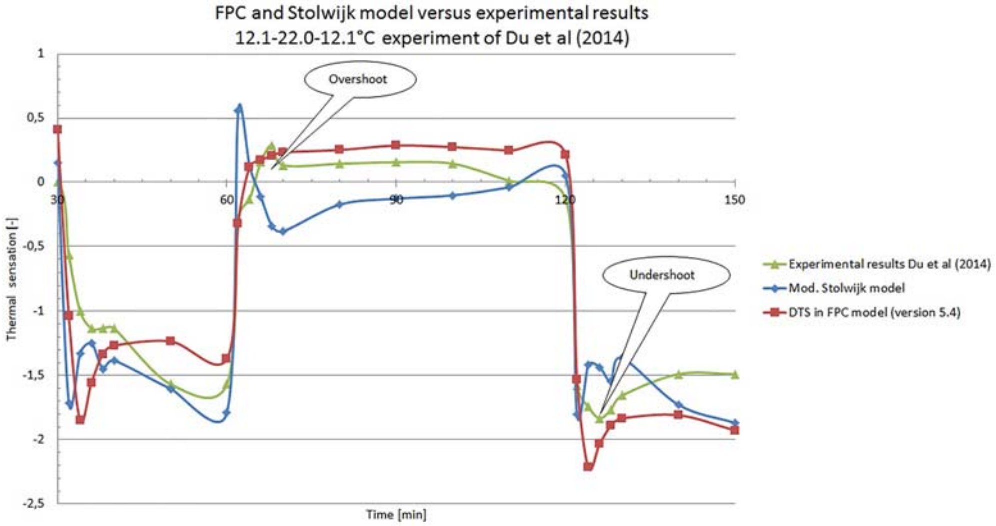

Figure 9. Thermal sensation. Cool: 12.1°C/RH = 57.4%, Neutral:22.0°C/RH = 43.9%, and Cool: 12.1°C/RH = 57.4%.

scientific experiments from the professional literature are used for the simulation of a homogenous step-change transient thermal environment and a sedentary activity. In all graphs below, three phases can be identified with an environmental condition that deviates from the environmental condition in the subsequent phase, as once explicitly shown in Figure 7.

The results of the (Slightly) Cool – Neutral – (Slightly) Cool experiments of Du et al. (2014), the DTS calculation results of the simulation with the FPC model as well as the prediction results of the modified Stolwijk model (TTS) are displayed in the Figures 7–9 of the temperature intervals 17–22–17°C, 15–22–15°C, and 12–22–12°C, respectively.

The results of the (Slightly) Warm – Neutral – (Slightly) Warm experiments of Liu et al. (2014), the DTS calculation results of the simulation with the FPC model as well as the prediction results of the modified Stolwijk model (TTS) are displayed in the Figures 10–12 of the temperature intervals 28–25–28°C, 30–25–30°C, and 32–25–32°C, respectively.

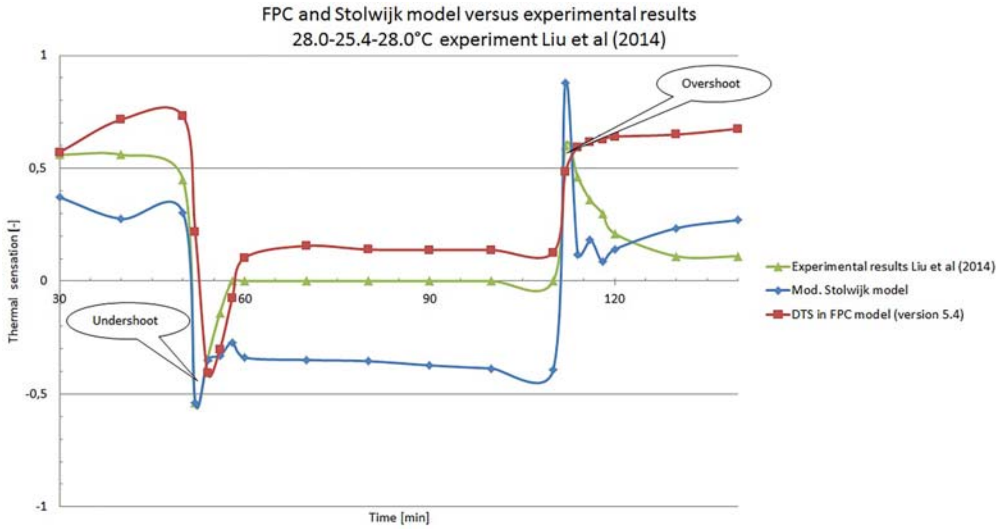

Figure 10. Thermal sensation. Slightly Warm: 28.0°C/RH = 61.0, Neutral: 25.4°C/RH = 60.9%, and Slightly Warm: 28.0°C/RH = 61.2%.

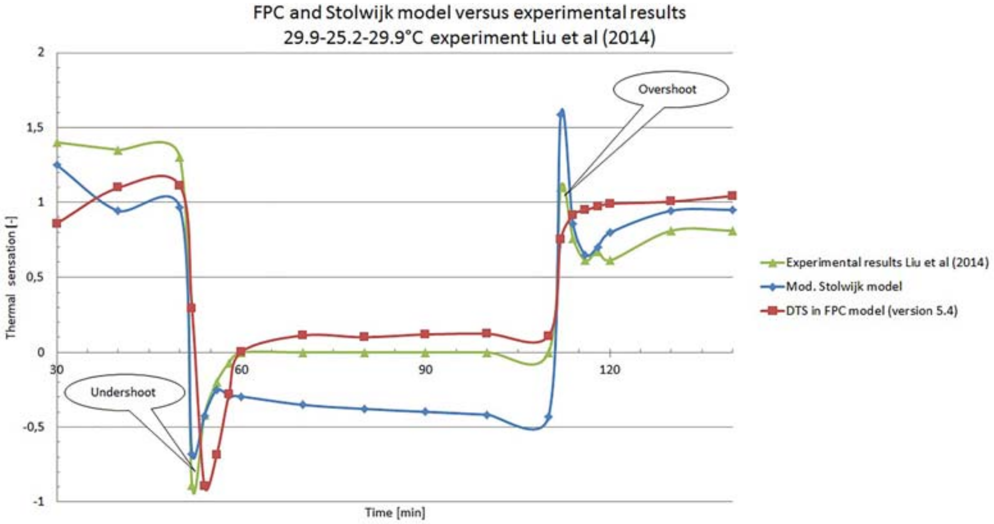

Figure 11. Thermal sensation. Slightly Warm: 29.9°C/RH = 59.5, Neutral: 25.4°C/RH = 58.1%, and Slightly Warm: 29.9°C/RH = 59.4%

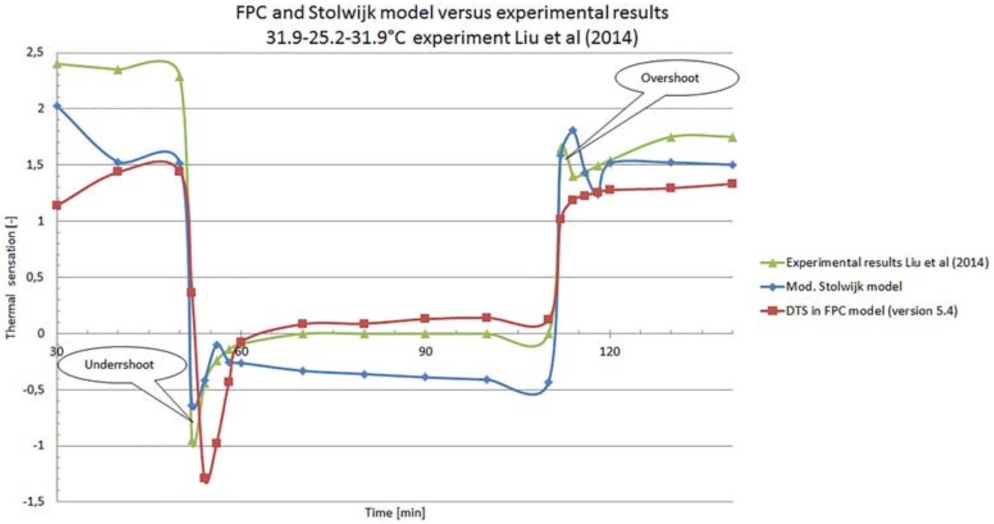

Figure 12. Thermal sensation. Warm: 31.9°C/RH = 59.1, Neutral: 25.2°C/RH = 58.1%, Warm: 31.9°C/RH = 59.0%.

In the Figures 10–12, it is striking to see that with a metabolic rate of 1 met (sedentary activity; 58 W/m^2) and a clothing resistance of 0.33 clo, the neutral situation (Thermal sensation = 0) is apparently at 25.2–25.4° C, according to the 20 male test subjects within the Liu et al. experiment. In a steady state situation, according to the NEN-EN-ISO-7730/Fanger model, the PMV value would be −0.6, instead of 0, based on 1,396 test subjects. In the studies by Nevins et al. and Rohles, the neutral situation for sedentary activity was respectively 25.0°C and 25.9°C, however with a clothing resistance of 0.6 clo, based on 2,320 test subjects. On the other hand, the neutral situation in the Du et al. study, based on twelve male test subjects, is almost confirmed by the PMV value (≈−0,14). In other words, the assumed neutral situation in the study of Liu et al. deviates from expectations, based on previous studies, with a larger amount of test subjects. This is the reason that the simulated thermal sensation (TTS), according to the modified Stolwijk model, is apparently too low at the beginning (phase1) and the middle (phase 2) of the graph in Figures 10–12.

Table 2. Average deviation DTS and TTS compared to the experimental results.

Figure	DTS in FPC model	TTS in Stolwijk model
7	0,23	0,24
8	0,22	0,37
9	0,31	0,41
10	0,30	0,26
11	0,38	0,28
12	0,60	0,37

Table 2 shows an overview of the average deviation in the figures of the calculated DTS and TTS value compared to the experimental results.

Conclusion

Based on the calculation results compared to the experimental results, it can be concluded that in a steady state situation for different metabolic rates or a homogenous step-change transient thermal environment and for sedentary activity:

- The calculation results of the DTS equation in the FPC model (version 5.4) and the TTS equation in the modified Stolwijk model approach the experimental results fairly accurate.

The calculation results of the TTS equation in the modified Stolwijk model, based on experiments with a total of 2,772 subjects, are not inferior to the calculation results of the DTS equation in the FPC model (version 5.4).

Furthermore, it can be concluded that:

- In the steady state condition, the TTS equation, calculated with the Stolwijk model, appears to correspond best with the experimental results, compared to the DTS equation in the FPC model, and even the PMV value of the Fanger/NEN-EN-ISO-7730 model.
- In the steady state condition, the lines of the PMV value (as well as the DTS value) appear to lie below the experimental results for the majority of the time. As a result, an indoor thermal climate, designed according to the Fanger/NEN-EN-ISO-7730 model, will be experienced slightly warmer than expected. This has also been noted in earlier studies by Clements-Croome (Clements-Croome, 1997) and Roelofsen (Roelofsen 2001).
- In the case of the FPC model, the situation with a metabolic rate of 58 W/m², and a steady state condition (red curve in Figure 3), differs considerably from the experimental results and the calculation results of the Fanger model.
- The assumed neutral situation in the experiment of Liu et al. (I clo = 0.33; $T_{neutral}$ = 25.2–25.4°C) deviates from expectations, based on previous experiments of Nevins et al. and Rohles (I clo = 0.6; $T_{neutral}$ = 25.0–25.9°C), with a much larger amount of test subjects.
- In the transient situation, the constant overshoot and undershoot in the experimental results, shown in Figures 7–12, is better represented by the TTS equation in the modified Stolwijk model than by the DTS equation in the FPC model.
- The TTS equation in the modified Stolwijk model shows no constant overestimating of the thermal sensation in the first phase of the graph in the Figures 7–9 in comparison to the experiments of Du et al., as is the case with the DTS in the FPC model.
- The course of the TTS in the third phase of Figures 10–12 seems to fit better with the experimental results of Liu et al. than the course of the DTS.
- By adding the TTS equation, besides the DTS equation (Roelofsen 2019), in the Stolwijk model, the Stolwijk model has become, once again, more valuable for use in the professional practice within the built environment.

Disclosure statement

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

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