THEORETICAL MODEL OF DRAUGHT THERMAL SENSATION PART 1. STEADY-STATE CONDITIONS

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A b s t r a c t

Sensation of local thermal discomfort caused by draught has been commonly evaluated by draught rating DR, determined experimentally and defining the percentage of the occupants reporting the sensation of draught as a function of the air mean velocity, air temperature and turbulence intensity. This assessment includes neither the air temperature fluctuations in the room nor the occupants' particular sensitivity to the frequencies of 0.3÷0.8 Hz of the air velocity periodical changes, confirmed by experiments [1].

The paper presents a model, which simulates the sensation of cold caused by draught in moderate environment. The model is based on principles of thermoreception and heat transfer between a human skin element and its surroundings. Thus, the sensation of local thermal discomfort is expressed as draught rating depending on the frequency of impulses generated by cold thermoreceptor. By validating the model parameters in steady conditions good correlation between cold thermoreceptor response (impulse frequency) and thermal sensation of cold expressed by draught rating DR has been acquired. Further research on the model development was aimed at its validation in transient conditions for periodical and stochastic changes in the air temperature and velocity.

S t r e s z c z e n i e

Odczucie lokalnego dyskomfortu cieplnego, spowodowanego przez przeciąg, ocenia się za pomocą wskaźnika przeciągu DR, definiowanego jako odsetek osób odczuwających przeciąg w pomieszczeniu. Wskaźnik ten wyznaczony został na drodze czysto eksperymentalnej jako funkcja średnich wartości prędkości i temperatury powietrza oraz intensywności turbulencji i nie uwzględnia ani fluktuacji temperatury powietrza w pomieszczeniu ani szczególnej wrażliwości ludzi na częstotliwości okresowych zmian prędkości powietrza z przedziału 0.3÷0.8 Hz, potwierdzonej eksperymentalnie [1].

W artykule przedstawiono opracowany dla środowiska umiarkowanego model teoretyczny, symulujący odczucie chłodu spowodowanego przez przeciąg. Model stworzono w oparciu o zasady termorecepcji i wymiany ciepła pomiędzy skórą człowieka a otoczeniem, co umożliwiło ocenę odczucia lokalnego dyskomfortu cieplnego za pomocą wskaźnika przeciągu przedstawionego jako funkcja częstotliwości impulsów generowanych przez termoreceptor zimna. Dobierając odpowiednio parametry modelu dla warunków stanu ustalonego osiągnięto silną korelację pomiędzy reakcją termoreceptora zimna (częstotliwością impulsów) a odczuciem cieplnym chłodu, wyrażonym przez wskaźnik przeciągu, DR. Dalsze prace nad rozbudową modelu prowadziły do jego weryfikacji w warunkach nieustalonych, dla periodycznych i stochastycznych zmian temperatury i prędkości powietrza.

K e y w o r d s: **Draught rating; Local thermal discomfort; Thermoreceptor; Heat transfer; Impulse frequency.**

1. INTRODUCTION

Draught is the most often reported reason for complaints because of local thermal discomfort. Methods used to evaluate local thermal discomfort caused by draught are based only on the results of experiments with people and their subjective evaluation of thermal environment. During experiments with pulsating airflow, directed to the back of the neck, *Fanger and Pedersen* found that the discomfort response had frequency dependence and the people's maximum sensitivity to the air velocity variations was for the frequencies of about 0.3÷0.8 Hz [1].

The model of draught rating, developed in 1988, defines draught rating DR as the percentage of occupants sensing draught in the room [2]. Draught rating is calculated from the empirical equation as a function of the air mean velocity $\overline{v}$, air temperature t_a and turbulence intensity Tu (Eq.1).

$$DR=(34-t_a)\,(\overline{v}-0.05)^{0.62}\,(0.37\,\overline{v}\,Tu + 3.14) \qquad (1)$$

where

$$Tu = \frac{\sqrt{\overline{v'^2}}}{\overline{v}}\,100\%$$

The model, fitted to the experimental data, may be applied within the following ranges of the parameters: $20<t_a<26°C$, $0.05<\overline{v}<0.4$m/s and $0<Tu<70\%$.

The model of draught rating takes into account neither the air temperature fluctuations in room nor the particular sensitivity to the air velocity fluctuations within the frequency range mentioned. It is also purely empirical and does not involve analyses of heat transfer and physiology of human thermal sensation

When considering all these shortcomings, one can see a need to develop another model simulating the sensation of local thermal discomfort caused by draught. This model should incorporate the impact of thermal environment (by describing the heat transfer between a man and his immediate surroundings), human physiology (by taking into account skin thermal parameters) and thermal sensation (by describing the response to a change in the environment thermal conditions). It should also reproduce the conditions assumed in the modern measurement equipment used to measure thermal environment parameters and yield results consistent with the results of the experiments. By combining elements of physics, physiology and psychophysics the model ought to be more reliable than the empirical equation.

2. BASIC IDEAS OF THERMORECEPTION

Elements of the thermoregulatory system sensitive to variations in the environment temperature are thermoreceptors. They are the nerve endings, placed under the skin surface, which are sensitive to cold and warm and provide information both of the absolute temperature value and temperature changes to the thermoregulation centre. The information is transferred by means of bursts (impulses) of different frequencies and a single thermoreceptor response to temperature stimulus is always a change in the impulse frequency [3, 4]. Research into properties of cutaneous thermoreceptors [3] proved that when considering their dynamic response they could be divided into cold and warm receptors responding to the temperature decrease or increase i.e. informing of the sensation of cold or warm, respectively. When measuring the depth of thermoreceptors, Hensel found that the layer of cold thermoreceptors was immediately beneath the epidermis at the minimum and maximum depth of 0.18 mm and 0.22 mm, respectively. The results of previous measurements, which he referred to, placed warm thermoreceptors at the depth of about 0.3÷0.6 mm, in the upper layers of the corium. According to *Hensel* both cold and warm thermoreceptors reveal the following features:

- They exhibit a static discharge with constant impulse frequency at constant skin temperatures within the normal range.
- Dynamic response to sudden temperature changes $dt_R/d\tau$ is always observed with either a negative temperature coefficient (cold thermoreceptors, responding with a transient overshoot in frequency to sudden cooling) or a positive coefficient (warm thermoreceptors), regardless of the initial temperature.
- They are not excited by mechanical stimuli.
- They are active only in the non-painful or innocuous temperature range.

Thermoreceptor activity is only indirectly related to the environment temperature effect – the factor, which is a direct reason for thermoreceptor activity, is the change in the thermoreceptor temperature itself [3, 5]. The value of the neutral skin temperature, at which neutral thermal sensation and thermal comfort are observed, is about 34°C, whereas the sensation of cold and discomfort appears for the skin temperature lower than about 30°C [6]. Excitation of a single thermoreceptor depends on the absolute thermoreceptor temperature tR and on the rate of thermoreceptor temperature change $dt_R/d\tau$ (temporal gradient) and spatial temperature gradient dt_R/dx is not a stimulus for thermoreceptor [3]. The threshold of thermoreceptor response to changes in thermal conditions, defined as the smallest temperature difference, which may be clearly detected, depends on the initial skin temperature, the part of the body and the surface of skin on which the temperature stimulus is directed. Excitation of cold thermoreceptors appears when the temperature decreases by 0.004K/s [4].

3. HEAT TRANSFER BETWEEN A SKIN ELEMENT AND THE ENVIRONMENT

In moderate thermal environment, in a relatively narrow temperature range including thermal comfort temperature, the energy balance of human body is equalised. The only form of the latent heat transfer through the skin in a moderate environment is water vapour diffusion through the skin (*perspiratio insensibilis*), which does not cause the effect of moisture on the skin surface and therefore does not have any cooling effect [7]. The sensible heat flow for a clothed man includes convection, radiation and conduction. However, on a bare skin surface it is equal to the heat loss occurring only by convection and radiation. The sensible convective loss and radiant heat loss from the skin element surface to its immediate surroundings are expressed as functions of the skin temperature ts and the mean radiant temperature $\overline{t_r}$, respectively (Eq. 2 and Eq.3).

$$C = h_c \cdot (t_s - t_a) \quad W/m^2 \tag{2}$$

$$R = h_r \cdot (t_s - \overline{t_r}) \quad W/m^2 \tag{3}$$

where:

h_c –convective heat transfer coefficient W/m^2K,

h_r –radiative heat transfer coefficient W/m^2K.

It is relatively easy to determine the right value of the radiative heat transfer coefficient. However, the values of the convective heat transfer coefficient available in the literature are only experimental ones and differ from each other substantially. Discrepancies are found already for the mean heat transfer coefficient values, calculated for the whole body. The values of local heat transfer coefficient are even less certain.

The most general relationship between the mean value of heat transfer coefficient, calculated for the whole body, and the air velocity measured in a flow without disturbances is the equation $h_c = B \cdot v^n$. The best estimation of *n* is 0.6 but for velocities $v \leq 4$m/s the error from taking n = 0.5 is small [8].

When there is no air movement (v = 0) the heat loss from the body to the surroundings occurs in the way of natural (free) convection. As a result of natural convection a rising plume of warm air is produced near the body surface. The thickness of the boundary layer of warm air increases as the air moves up over the body. For a standing man the thickness of the boundary layer at the head level may be of 20 cm and the upward airflow velocity reaches 0.2÷0.3 m/s at the level of the chest [9]. When the air velocity around a hot body is reduced, natural convection becomes more important to finally become a predominant form of convection. When the skin surface temperature is 5 K higher than the ambient temperature, the transition begins at the air velocity of about 0.15 m/s. The transition is not abrupt and thus a mixed convection region usually occurs between natural and forced convection regions [8].

The type of convective heat loss is not the same for the whole body. It is the highest on the surface facing into the air stream directly and the least at the sides. At the rear surface of the body unstable eddies occur which increase the convection. The heat loss depends not only on the airflow direction but it depends on the size and shape of the hot body as well. Thus the differences in the values of local convective heat transfer coefficient e.g. for hands and back of a person are obvious [10].

Convective heat transfer coefficient depends not only on the air mean velocity but also on the turbulence intensity. Laminar airflow of constant velocity seldom occurs in real conditions. If the air velocity changes relatively slowly, the average heat loss may be determined from the time average of the square root of the air velocity. Rapid variations of the airflow velocity or direction may increase the heat loss significantly and the values of local convective heat transfer coefficient can be even about two times higher than the values determined for the whole body [9, 11].

4. THE MODEL ASSUMPTIONS

When constructing the model the following assumptions were made:

- The model will describe human thermal sensation in a moderate environment, i.e. in the conditions of neutral thermal equilibrium, in which the organism itself is able to equalise the body energy balance and human thermal sensation is proportional to thermoreceptor response to temperature variations – the frequency of impulses generated by thermoreceptor.

- The model will incorporate heat diffusion through the skin and heat transfer from the skin surface to the surroundings
- The change in the cold thermoreceptor temperature will determine the relevant thermal sensation of cold.
- The right values of the skin element thickness and convective heat transfer coefficient to be used in the model will be acquired by validating the model for steady state conditions i.e. steady air temperature, steady radiant temperature and steady air velocity (laminar flow)
- Having obtained the values of cold thermoreceptor temperature, it will be possible to simulate generation of impulses sent by the thermoreceptor and determine their frequency.

The structure of the model, including subsequent steps of the model validation, is shown in Fig. 1.

5. THE MODEL VALIDATION IN STEADY STATE CONDITIONS

5.1 Skin element thickness

After [8], three skin element layers (epidermis, dermis and fatty layer) of different thickness and thermal properties were assumed in the model (Table 1).

Table 1.
Thermal parameters of the skin element assumed in the model

Thickness of layer [mm]	Thermal conductivity [W/mK]	Density [kg/m^3]	Specific heat [J/kgK]
0.125	0.25	1000	4200
0.7	0.4	1000	4200
7.75	0.15	800	2000

The skin surface temperature is expressed according to Eq.4:

$$t_s = t_d - R_\lambda (C + R) \tag{4}$$

where: t_d – deep body temperature,

$$C + R = (h_c + h_r)(t_s - t_a), \quad \text{since } \bar{t}_r = t_a, \tag{5}$$

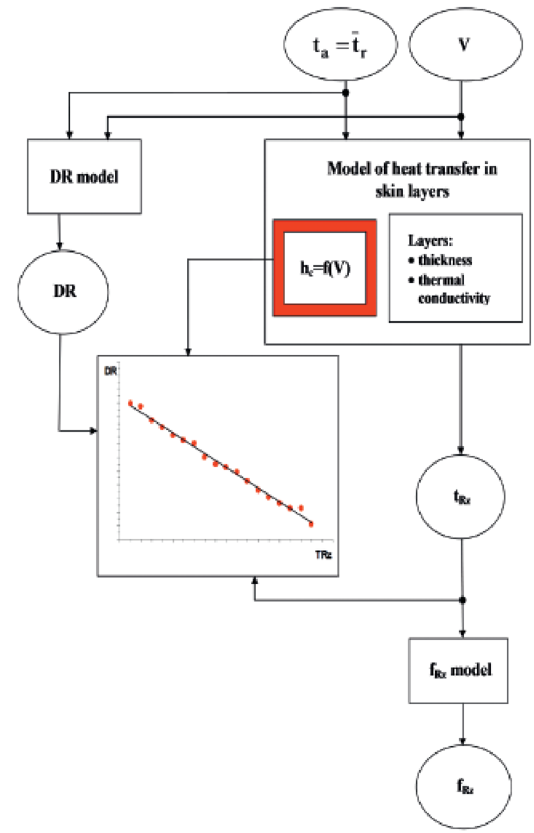

Figure 1.
The structure of the model, including subsequent steps of its validation in steady-state conditions where: t_a – air temperature, $\bar{t}_r$ – mean radiant temperature, V – air velocity, DR – draught rating, h_c – convective heat transfer coefficient, t_{Rz} – cold thermoreceptor temperature, f_{Rz} – static impulse frequency

R_λ – thermal resistance for the whole skin element:

$$R_\lambda = \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \frac{d_3}{\lambda_3} \tag{6}$$

where

d_1, d_2, d_3 – thickness of each layer, respectively,

λ_1, λ_2, λ_3, – thermal conductivity of each layer, respectively.

The thicknesses of epidermis and dermis were assumed according to the literature data [8]. When setting the fatty layer thickness it was assumed that in the steady state conditions i.e. at constant air velocity, the equation of human body thermoregulation should be fulfilled [12] (Eq.7).

$$t_s = 36.4 - 0.054\left(C + R\right) \qquad (7)$$

where 36.4°C is the average core temperature value, t_d.

Thus, R 0.054 and the thickness of the third layer can be calculated from Eq.(6).

5.2. Heat transfer coefficients – correlation between the draught rating and cold thermoreceptor temperature

The values of radiative heat transfer coefficient assumed in the model were calculated for different skin temperature values ts ranging 28°C÷32°C and different mean radiant temperature values $\overline{t_r}$ = 20°C÷26°C, equal to the temperature of the ambient air: $\overline{t_r} = t_a$. Then, the mean value obtained from the calculations: h_r=5.5 W/m^{2}K was assumed in the model. This value is the same as the radiative heat transfer coefficient value for human head in the environment where $\overline{t_r} = t_a$ [6].

The question how to choose the proper distribution of the convective heat transfer coefficient was answered by analyses of the correlation between the draught rating and cold thermoreceptor temperature assuming constant temperature of the ambient air. In steady-state conditions thermoreceptor temperature is constant and thus the frequency of the generated impulses is constant too. Since thermal sensation depends on the impulse frequency there should be good correlation between the cold receptor temperature t_{Rz} and thermal sensation of cold expressed by draught rating DR.

When analysing the correlation between the receptor temperature and draught rating, laminar, non-fluctuating airflow was assumed and the changes in the cold thermoreceptor temperature were considered. The flow velocities varied from 0.1 to 0.4m/s by 0.025m/s, the ambient temperature changed from 20°C to 26°C by 0.5°C for each velocity value [13].

The temperature of the skin surface was determined for all the ambient temperature values from thermoregulation equation according to Eq. 8.

$$t_s = 36.4 - 0.054(h_c + h_r)(t_s - t_a) \qquad (8)$$

Then the cold thermoreceptor temperature was calculated for all the ambient temperature values (Eq. 9),

$$t_{Rz} = t_s + (36.4 - t_s)\frac{\frac{d_1}{\lambda_1} + \frac{x}{\lambda_2}}{R_\lambda} \qquad (9)$$

where x = 0.075 mm was assumed (distance between the cold thermoreceptor and the dermis layer).

In order to find the best possible correlation between the draught rating and cold thermoreceptor temperature, different types of relations between the local convective heat transfer coefficient and the air velocity were taken into account [13]. The analyses showed strong dependence of the correlation between the draught rating and cold thermoreceptor temperature on the function relating local convective heat transfer coefficient and the air velocity. In result of the analyses the value of local convective heat transfer coefficient was assumed according to Eq. 10.

$$h_c = h_{nc} + B\sqrt{v}\,\frac{1}{2}\left(1 + \mathrm{erf}\left(\frac{v - c}{\sqrt{2}b}\right)\right) \qquad (10)$$

where: h_{nc}=3 W/m^{2}K, B = 25, error function parameters: c = 0.233, b = 0.072.

The value of the local convective heat transfer coefficient, calculated in this way, changes smoothly from the constant value, characterising domination of natural convection to the value characterising the prevailing effect of forced convection. The values of the error function coefficients were assumed in result of computer optimisation in which maximum value of the correlation coefficient was sought for the correlation between the draught rating DR and cold thermoreceptor temperature t_{Rz}. Fig. 2 shows the distribution of the local convective heat transfer coefficient, determined after Eq. 10 and correlation between the draught rating and cold thermoreceptor temperature obtained for this distribution in steady-state conditions. In this case the value of the determination coefficient was $R^2 = 0.97$ and was the highest acquired when considering different types of distributions of the local convective heat transfer coefficient.

5.3. Model of impulse generating in steady-state conditions

The model of impulse generating is based on the assumption that in steady-state conditions cold receptor response is proportional to the difference between the actual receptor temperature and its neutral temperature i.e. temperature in which no thermoreceptor response is observed.

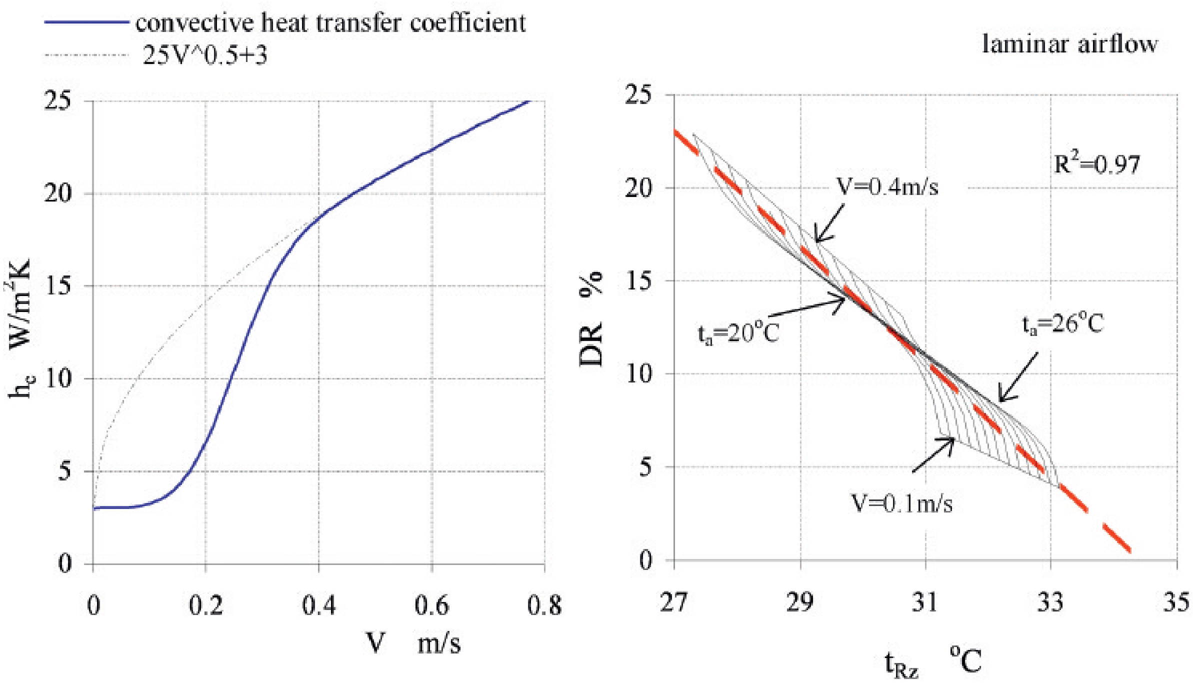

Figure 2.
Distribution of the local convective heat transfer coefficient assumed in the model and correlation between draught rating DR and cold thermoreceptor temperature t_{Rz} obtained for this distribution in steady-state conditions

The static frequency of impulses was expressed by Eq. 11.

$$f_{Rz} = K_s\,(t_{Rz} - t_n) \qquad (11)$$

where

K_s –proportionality constant for thermoreceptor static response,

t_{Rz} - cold thermoreceptor temperature,

t_n - cold thermoreceptor neutral temperature.

In steady-state conditions thermoreceptor generates impulses of constant frequency, producing thermal sensation of cold. Thus, the model of impulse generating described by Eq. 11 should yield good correlation between the impulse frequency f_{Rz} and thermal sensation of cold expressed by the draught rating DR in steady-state conditions.

In order to analyse the dependence between the draught rating and static frequency of impulses, generated by the cold thermoreceptor and calculated after Eq. 11, laminar airflow was considered. The flow velocities changed from 0.1 to 0.4 m/s by 0.025 m/s and the air temperature changed from 20°C to 26°C by 0.5°C for each velocity value.

The value of the neutral temperature in Eq. 11 (about 34°C) was determined more precisely as t_n = 34.4°C in Fig. 2, having assumed that the neutral temperature value was the cold thermoreceptor temperature in which there was no dissatisfaction because of cold (DR = 0 while draught rating was determined after the linear regression function y = 3.1352 x+107.7).

In order to find the proper value of the proportionality constant K_s, different K_s values were assumed and the impulse frequencies were calculated according to Eq. 11. These frequencies were then compared with the values of static frequency of impulses found in the literature [3, 14]. In result of these analyses K_s = -1 was assumed. Then, the values of static frequency of impulses generated by cold thermoreceptor for the laminar airflow analysed were calculated and the relation between the impulse frequency and draught rating was determined. This relation is shown in Fig. 3. Apparently, for steady-state conditions there is good correlation between the frequency of impulses, generated by cold thermoreceptor and calculated from the model, and thermal sensation of cold expressed by draught rating. The high value of correlation coefficient was acquired by validating the model in steady-state conditions i.e. choosing the right distribution of local convective heat transfer

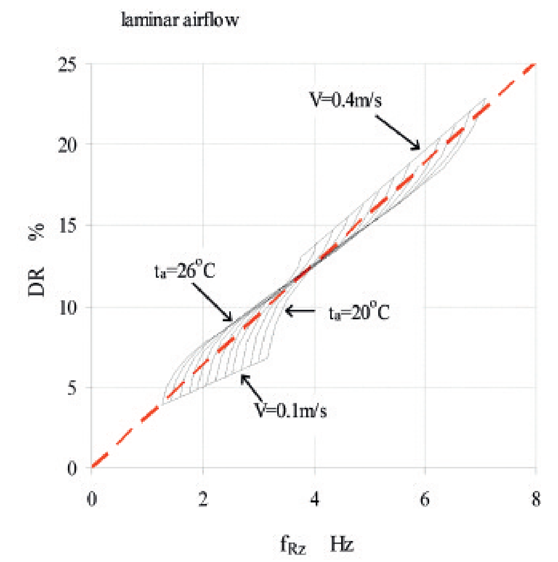

Figure 3.
Relation between the static impulse frequency f_{Rz} and draught rating DR

coefficient and the right value of the neutral temperature t_n in Eq. 11 after which static impulse frequency should be calculated.

6. CONCLUSIONS

In steady state conditions the suggested model of heat transfer in an element of human skin conforms both to the thermoregulation equation and to the draught rating model (good correlation between the draught rating and cold thermoreceptor temperature was acquired). The simulations of cold thermoreceptor response to laminar airflow have proved that in steady state conditions the suggested model of impulse generating yields also good correlation between the frequency of impulses generated by cold thermoreceptor and draught rating.

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