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NEW MEASUREMENTS OF THE CONVECTIVE HEAT TRANSFER COEFFICIENT: INFLUENCES OF TURBULENCE, MEAN AIR VELOCITY AND GEOMETRY OF THE HUMAN BODY

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SUMMARY

Measurements of the convective heat transfer coefficient have shown that air velocities with low turbulence must be evaluated independently of the turbulence. For air velocities with mean and high turbulence, starting at about 40 %, the product out of turbulence intensity and mean air velocity is decisive. Using earlier psycho-physical measurements and a heat balance equation, the physical measurements lead to curves of admissible mean air velocities, depending on room temperature and turbulence intensity. At room temperatures about 23 °C there is a good agreement with earlier results of P.O. Fanger, whereas for lower room temperatures there are lower admissible air velocities and for higher room temperatures respectively higher air velocities.

Results of measurements were independend on measuring it at the forehead of a man or a manikin, at the forehead of a heated artificial head or at a plain surface, size of a hand.

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INTRODUCTION

Draught problems often are the reason for low acceptance in air conditioned rooms. Physical investigations in the Fraunhofer-Institut für Bauphysik (IBP) proved, that the evaluation of air motion according to mean air velocity and air temperature is not sufficient. The decisive physical value to judge the "character of draught" is really the convective heat transfer coefficient. This value integrates the evaluation factor used up to now - mean air velocity - as well as the instationary behaviour of air motion, characterized by turbulence and frequency [1]. This originally purely physical finding can also be applied to draught sensation of man, as confirmed in psycho-physical research by Prof. Fanger, TU Denmark, as well as in the IBP [2, 3].

The measurements described in [2] and [3] were carried out in varying ambient conditions with different anemometers.
However, before this new evaluation value can be introduced in standard works (f.i. DIN 1946, part 2 [4], Raumlufttechnik and ISO 7730 [5]), further investigation was required. The following questions had to be answered first:

- how is the convective heat transfer coefficient influenced by turbulence intensity, by mean air velocity, by the geometry of the body (of man)?
- are the former results, described in [1] vaild for all turbulence intensities?
- how can the criteria of evaluation of admissible air motion known at present be generalized for different room temperatures?

MEASURING THE CONVECTIVE HEAT TRANSFER COEFFICIENT

Draught problems are caused by too high convective cooling down of body surfaces, see [3]. The corresponding formula is:

$$q_K = \alpha_K (\vartheta_0 - \vartheta_L),$$

or $\vartheta_0 = \vartheta_L + q_K / \alpha_K$

with

q_K : density of convective heat stream
α_K : convective heat transfer coefficient
ϑ_0 : surface temperature of the body emitting heat (skin temperature)
ϑ_L : air temperature

The heat stream, caused by physical activity, being constant, skin temperature is falling if the air temperature is lowered, and/or if the convective heat-transfer coefficient is rised.

A heated artificial head and a heated measuring manikin were used to determine the influence of the geometry of bodies on the convective heat loss. The indoor climate measuring device developed in the Fraunhofer-Institut für Bauphysik (IBP), described in [6], was also applied. In the first two cases the convective heat transfer coefficient was measured by means of the NTC-ladder, developed in the IBP, see [3], the indoor climate measuring device (RKM) registers the coefficient via the q_K-meter which is part of the RKM. To analize the air motions, i.e. to measure mean air velocity and turbulence intensity an air flow probe developed in the IBP was applied. In a comparative test with other air flow probes this one proved to be non directional and had the shortest time of response: 30 ms.

RESULTS AND DISCUSSION OF MEASUREMENTS

Results of measurements of the convective heat transfer coefficient α_K at the front of the heated manikin are presented in fig. 1. Air stream from front, turbulence intensities are about 5 %, 20 %, 50 % and 70 %. At first we can see the expected rise of α_K related to air velocity. Further we find increase in convection with rising turbulence, already stated in earlier tests [2, 3]. Differing from these results fig. 1 shows, that this increase becomes only clear in higher turbulence intensities. Obviously, the warm layer of air near to the body is noticably troubled only with higher turbulence intensities. This leads to the conclusion that the dependence of the convective heat transfer coefficient from the product out of turbulence intensity and mean air velocity - as supposed earlier [1] - is valid only for higher turbulence intensities. This becomes more clear in another presentation of the results shown in fig. 1. In fig. 2, the product of turbulence intensity and mean air velocity was chosen to be the independent variable instead of mean air velocity. From both pictures we can conclude that in low turbulence, air velocity only is sufficient to evaluate air motion with regard to draught. For air motion with mean and high turbulence, from about 40 %, the product of turbulence intensity and

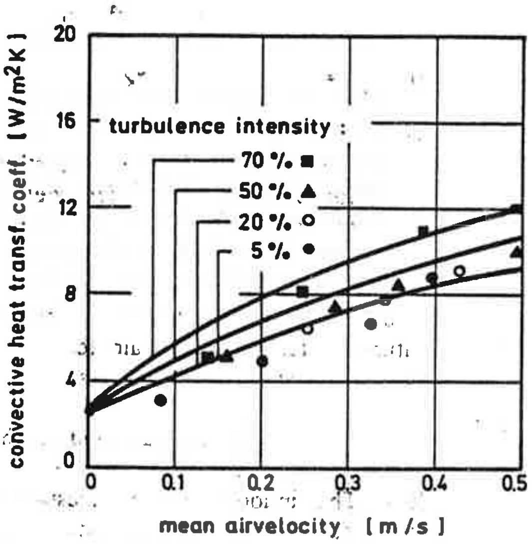


Fig. 1. Convective heat transfer coefficients at the forehead of a heated manikin as a function of mean air velocity, air stream from front and turbulence intensity of c. 5 %, 20 %, 50 % and 70 %. In turbulence intensities up to 40 onvective heat transfer mainly depends on air velocity, the influence of turbulence is minor.

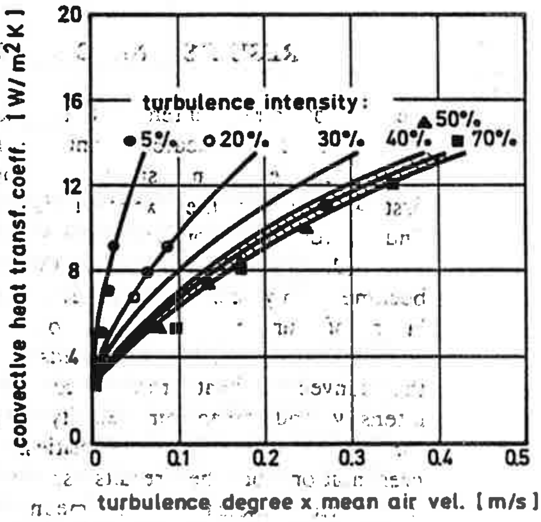


Fig. 2. Convective heat transfer coefficients as a function of product of turbulence intensity and mean air velocity. Only with higher turbulence there is clear dependence from the product (dotted section); in low turbulence only air velocity is important (see fig. 1).

mean air velocity is decisive.

Now, to answer the question of how far the geometry of the tested body influences the convective loss of heat, the α_K measurements at the completely heated test manikin were compared to those at the heated artificial head. The results for the head found in [3] are shown in fig. 3. Conformity of fig. 2 to fig. 3 makes clear that at the forehead - air stream from front - the presence of the complete body is of no influence on the convective loss of heat. The same applies to heating of the whole body surface compared to heating of the head only.

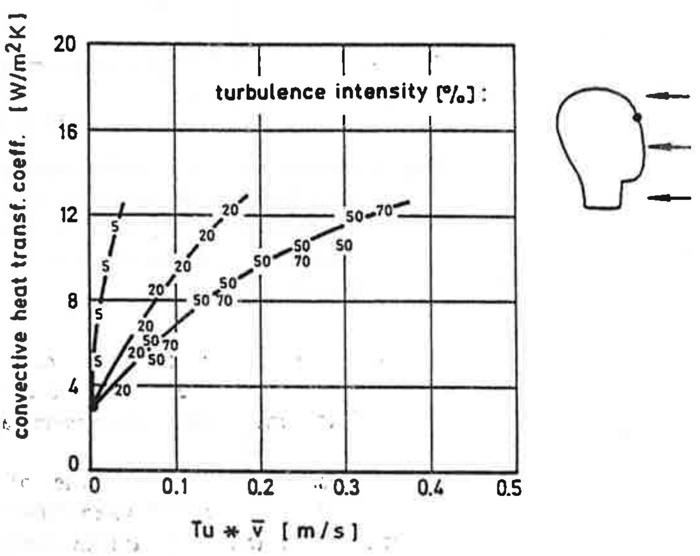


Fig. 3. Convective heat transfer coefficients of the forehead of the artificial head as a function of product of turbulence intensity T_u and mean air velocity $\bar{v}$, air stream from front and turbulence intensities of c. 5 %, 20 %, 50 % and 70 % (measuring points).

Differing herefrom, the position of the measuring point at the tested body is decisive. Fig. 4 makes this clear. In the example of the head, air stream from front. Constant air velocity and resting air, the α_K-values are marked for forehead, top of head, neck and temple. At forehead and top of head the α_K-values were almost identical whereas the result at the temple is clearly lower. This can be explained by means of the air stream next to the head, due to low turbulence. The air streaming along the heated head is warming up, thus increasing the thickness of the temperature boundary

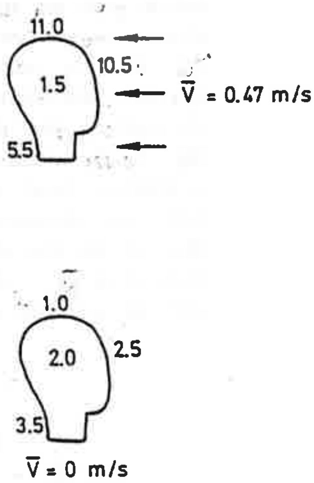


Fig. 4. Convective heat transfer coefficients in W/m^2K at forehead, top of head, neck and temple of the heated artificial head, air stream from front with low turbulence (c. 5 %) and resting air.

layer. Result hereof is decrease of α_K. This effect also shows only about half of the α_K-value. Supplementary in fig. 4, the convective conditions for resting air of the head are marked. The mean α_K-value being 2,5 W/m^2K, there are only minor local differences. The low value of 1,0 W/m^2K at the top of the head can also be explained with the above mentioned effect. Comparative measurements of the convective heat transfer coefficient applying the indoor climate measuring device of IBP (RKM) have also shown good agreement with the artificial head and the test manikin.

EVALUATION OF THE RESULTS FOR ASSESSMENT OF DRAUGHT

In the climatic test chamber of the IBP psycho-physical measurements were taken with air stream from front, turbulence intensity under 5 %, at 23 °C room temperature. This is described in detail in [3]. The results are in fig. 5. The percentage of those persons is shown who complain about draught sensation in the face, air velocity between 0 and 0,5 m/s. Connecting the physical results of fig. 1 and the psycho-physical results of fig. 5, we receive the percentage mentioned above as a function of the convective heat transfer coefficient in fig. 6. Based on these experiments [3], the connection of the α_K and the evaluation of draught does not depend on the direction of air stream and turbulence, in other words, the convective heat transfer coefficient integrates the colling effect of mean air velocity and the time-dynamic behaviour of air motion.

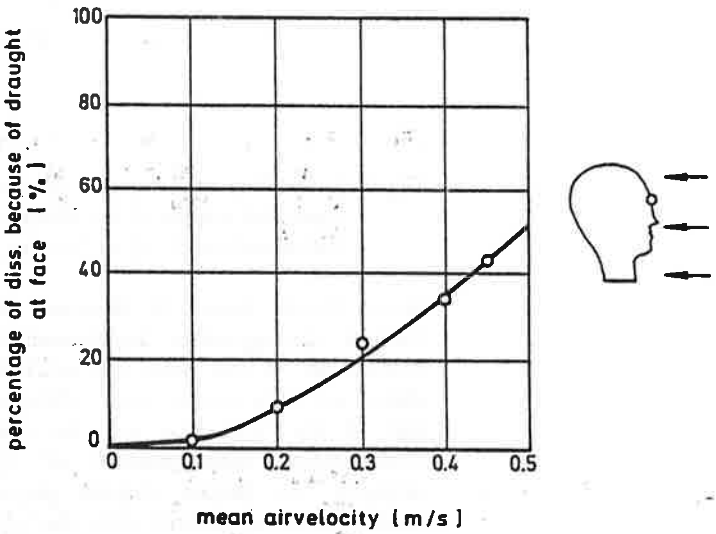


Fig. 5. Percentage of those complaining about draught sensation in the face, air stream from front, as a function of air velocity, turbulence intensity below 5 % and room temperature of 23 °C. Measuring values for seated test persons dressed with training suits.

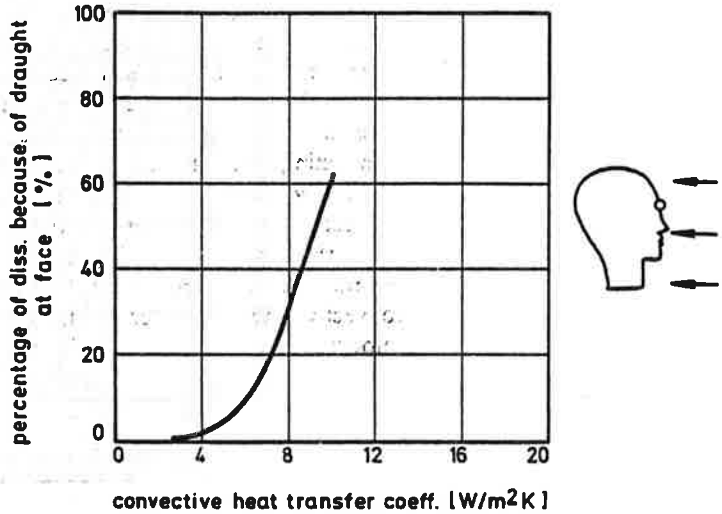
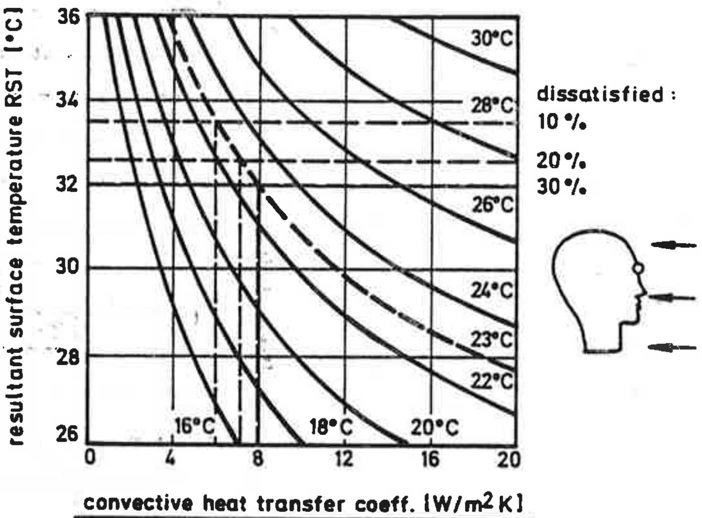


Fig. 6. Percentage of those complaining about draught sensation as a function of convective heat transfer coefficient at the forehead, 23 °C room temperature, air stream from front and turbulence intensity below 5 %, of figures 1 and 5.

GENERALISATION OF THE RESULTS FOR DIFFERENT ROOM TEMPERATURES

The results found at a room temperature of 23 °C are to be applied also to other temperatures. For this purpose a heat balance equation was used, for the dry loss of heat of man. This shows fig. 7. As a function of convective heat transfer coefficient α_K the surface temperatures RST of a surface heated with 120 W/m^2 are marked, each of the same temperature ϑ_L and surrounding surface temperature ϑ_{UF} (room temperature) between 16 °C and 30 °C. The heating power corresponds almost to the total heat emission of the resting human forehead (which is especially considered in the experiment) and is equaled with convective loss of heat and loss of



$$120\,W/m^2 = \alpha_K (RST - \vartheta_L) + 4.9 \left[\left(\frac{RST + 273.2}{100}\right)^4 - \left(\frac{\vartheta_{UF} + 273.2}{100}\right)^4\right]$$

Fig. 7. Resultant surface temperature RST of a surface heated with 120 W/m^2K as a function of the convective heat transfer coefficient α_K as well as of room temperature (air temperature ϑ_L and surrounding surfaces temperature ϑ_{UF} equal) and only dry heat emission. The resultant surface temperature was determined by means of the heat balance equation. The α_K- values at 23 °C room temperature were taken from figure 6 for 10 %, 20 % and 30 % persons dissatisfied due to draught.

heat by radiation. The α_K-values of 10 %, 20 % and 30 % of persons dissatisfied due to draught sensation in the face, air stream from front at 23 °C, were taken from fig. 6, that is roughly 6 W/m^2K, 7 W/m^2K and 8 W/m^2. Assuming that equal sensation of draught can be described by equal skin surface temerpature, the RST-values for 10 %, 20 % and 30 % were marked by horizontal lines. From the points of intersection of these lines and the temperature curves fig. 8 directly results. In order to receive statements on admissible air velocities with horizontal air stream from front, the fig. 1 and 8 were combined and respresented graphically in fig. 9. Mean air velocities for 15 % of persons dissatisfied due to draft sensation in the face as a function of room temperature for turbulence intensities between 0 % and 70 % are mentioned.

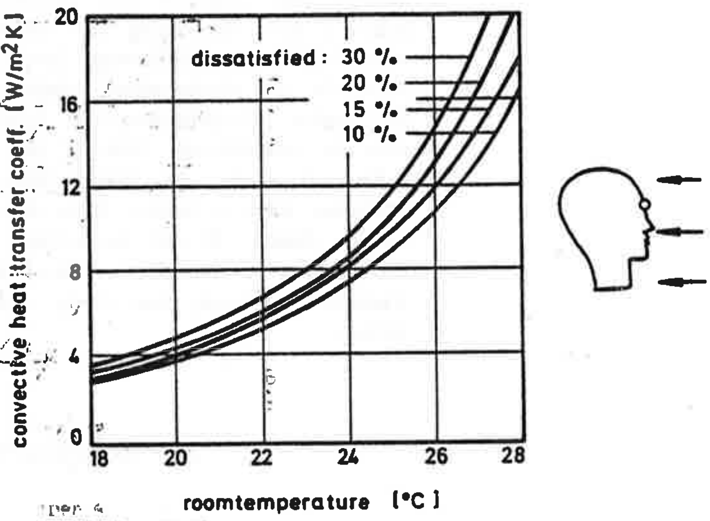


Fig. 8. Convective heat transfer coefficients taken from figure 7 correspond to 10 %, 15 %, 20 % and 30 % of persons dissatisfied due to draught as a function of room temperature.

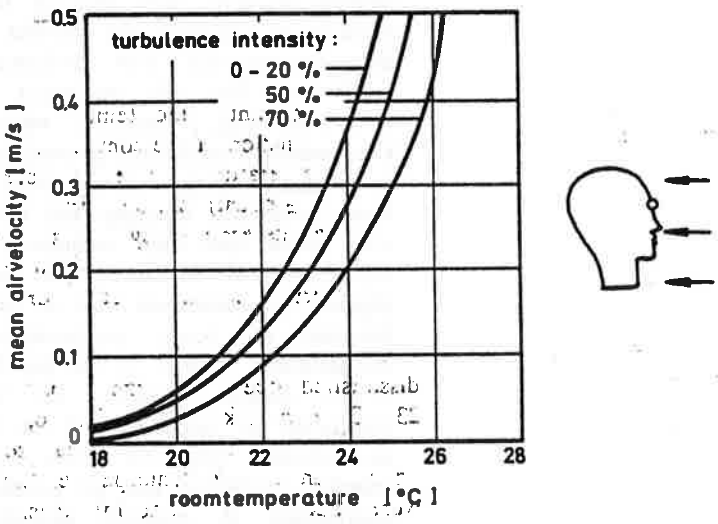


Fig. 9. Mean air velocities corresponding to 15 % of persons dissatisfied due to sensation of draught in the face, air stream from front, turbulence intensities between 0 % and 70 % as a function of room temperature (taken from figures 1 and8). Basis hereof are psycho-physical measurements at seated test persons dressed with training suit at 23 °C (figure 5), physical measurements of the convective heat transfer coefficient (figure 1) as well as the application of a heat balance euqation (figure 7).

Further conditions for these curves are: air stream from front, sedentary activity and clothing, the thermal insulation corresponding to that of a training suit. Regarding the course of curve for higher temperatures we must make the following limitation. The heat balance equation shows correctly the physiological relations for temperatures under 23 °C, whereas for higher temperatures the humid heat emission via evaporation should also be considered. This is the reason why the curves in fig. 9 were calculated again, also taking into consideration the portion of humid heat emission, already known from literature. However, the course of curves did hardly change. It will be subject to further research to find out how far the portion of humid heat emission increases with increasing convective heat transfer coefficient, thus taking influence on the course of curves mentioned above.

SUMMARY AND OUTLOOK

The present study shows that besides mean air velocity also the turbulence of air motions has an effect on the convective loss of heat of man. Air temperature and convective heat transfer coefficient are the variables to measure the integral effect of mean air velocity and turbulence on the cooling of skin, thus also on thermal comfort. A correct analysis of air motions is condition for correct assignment of air velocity and turbulence intensity to the new evaluation value, the convective heat transfer coefficient. For this we need anemometers registering air motion non directional and, if possible, without delay. Measurements of the convective heat transfer coefficient proved, that air velocities with low turbulence must be evaluated independently from turbulence regarding draugt. The product from turbulence intensity and mean air velocity is decisive for air velocites with mean and high turbulence (above 40 %). With the aid of earlier psycho-physical measurements and using a heat balance equation, the physical measurements lead to curves of admissible mean air velocities as a function of room temperature and turbulence intensity. For room temperatures around 23 °C we find good agreement with earlier results of P. O. Fanger, however, for lower room temperatures we find lower admissible air velocities and for higher room temperatures higher admissible air velocities (fig. 10). The experiments proved that the convective heat transfer coefficient can be measured and, together with air temperature, is appropriate to evaluate draught. Before this new evaluation value is introduced in standard literature, there should be supplementary psychophysical measurements at 20 °C and 26 °C.

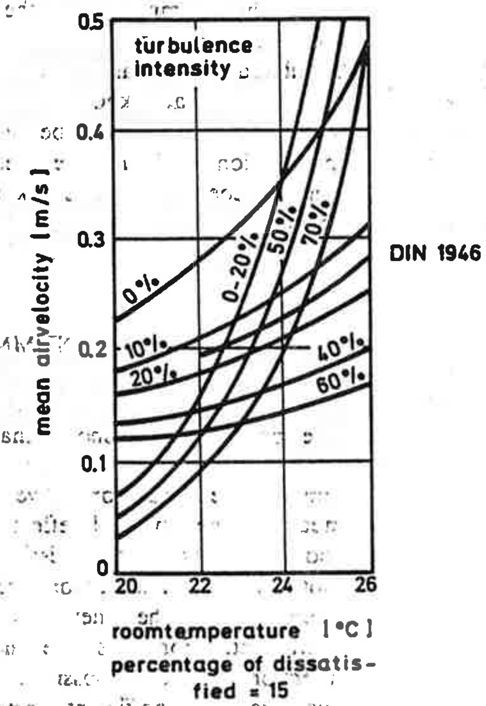


Fig. 10. Mean air velocities corresponding to 15 % of persons dissatisfied due to sensation of draught as a function of room temperature:
- according to Fanger [2], flat curves
- according to figure 9, steep curves
- according to DIN 1946 [4].

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