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PHYSICAL CAUSES FOR DRAFT: SOME NEW FINDINGS

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ABSTRACT

This paper deals with some laboratory and field researches to elucidate the physical causes for draft. By the use of some new instruments, the correlation between air velocity and the convective surface-heat-transfer coefficient of a heated artificial head was measured. It could be shown that this coefficient results directly from the thickness of the temperature boundary layer. From these preliminary measurements it is concluded that there is a parabolic correlation between the product of mean air velocity and turbulence degree on the one side and the coefficient on the other. Using the dry heat balance of a heated body and the inclination of the human surface temperature for feeling cold discomfort, a simplified comfort equation reveals the mutual relation of the coefficient and air temperature with respect to draft. These statements are in accordance with the results of some field measurements of air velocities and inquiries in different ventilated buildings.

INTRODUCTION

It is well known that draft is one of the most frequent complaints about the indoor climate (Bolinder et al. 1971; Arbejdsmiljøgruppen 1974; Cakir et al. 1978; Pütz et al. 1980; Nemecek and Grandjean 1982; Kröling 1985). It is caused by a too high, mostly local convective cooling of the human surface. That is, in a more exact way, by a too great reduction of the surface temperature. To find out appropriate technical improvements, a better understanding of the physical causes for draft is necessary.

Neglecting moist heat loss (less important in air-conditioned rooms in a steady state of man), the heat balance, e.g., for the forehead is:

$$120\ \mathrm{W/m^2} = \underbrace{\alpha_c\ (RST-t_a)}_{q_c} + \underbrace{\text{const.}\left[\left(\frac{RST+273.2}{100}\right)^4 - \left(\frac{t_{sf}+273.2}{100}\right)^4\right]\ \mathrm{W/m^2}}_{qr} \qquad (1)$$

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where

$120\ W/m^2$ = forehead heat flow density produced by metabolism (body resting)

q_c = convective heat loss density

q_r = radiant heat loss density

α_c = convective surface-heat-transfer coefficient

RST = Resultant Surface Temperature, the surface temperature of the skin resulting from the thermal conditions of the body and the surrounding room, which according to Benzinger (1979) is decisive for cold discomfort

t_a = air temperature

t_{sf} = temperature of the surrounding surfaces

The decisive influence exerted by the convective surface-heat-transfer coefficient on thermal comfort becomes obvious when representing Equation 1 in a graph (see Figure 1). More detailed laboratory and field analyses of the convective surface-heat-transfer coefficient, the quantity that describes draft physically, are reported in the following section.

LABORATORY RESEARCHES

To investigate the correlation between air velocity and the convective surface-heat-transfer coefficient, preliminary researches were done in the Fraunhofer-Institut für Bauphysik. In its climatic test chamber, an artificial heated head (34°C) was exposed to different airstreams with constant temperature (22°C), where the airstreams differed mainly by their mean values and turbulences (see Figure 2). For measuring the air movements correctly, an anemometer for non-directional fast measurements (time-constant 10 ms) of low air velocities was developed (Mayer 1981). For measuring the convective surface-heat-transfer coefficient without influencing the measuring results, a laser differential interferometer was built up (see Figure 3). The instrument provides the gradient of the air temperature in front of the forehead and is described in more detail by Mayer (1983). From this you can calculate the wanted coefficient as follows.

It is known that the heat loss by convection is equal to the transmission heat flux through the resting air layer just in front of the heated body, see Equation 2.

$$\alpha_c\ (RST-t_a) = \lambda_a\ (dt/dx)_{x=0} \qquad (2)$$

where

α_c, RST, t_a = see Equation 1

λ_a = thermal conductivity of a resting thin air layer (here 0,026 W/m·K

$t(x)$ = air temperature at the distance x from the heated surface (forehead)

While in Equation 2 the variables RST, t_a, and λ_a easily can be measured or are known, this is not the case for dt/dx and t (x). For this we used the laser differential interferometer and found out:

$$t(x) = (RST-t_a)e^{\frac{-x}{d}} + t_a \qquad (3)$$

where
$t(x)$, RST, t_a = see Equations 1,2
d = thickness of the temperature boundary layer

Combination of Equations 2 and 3 leads to

$$\alpha_c = \frac{\lambda_a}{d} \tag{4}$$

where
α_c, λ_a, d = see Equations 1, 2, 3

That means, to find out the convective surface-heat-transfer coefficient, it is necessary only to measure the thickness of the temperature boundary layer. This was done by the above described method and led to the results in Figure 4.

According to this curve, it is the product of the turbulence degree and the mean air velocity that determines the convective coefficient, where turbulence degree means the standard deviation of the fluctuating air velocity divided by the mean air velocity. As you can see, the correlation between this product and the coefficient is a parabola, starting with the value of own-convection.

FIELD RESEARCHES

In some earlier measurements of air velocity in buildings with different systems of air conditioning (bureaus and clean rooms), distinct differences of the mean air velocity and the turbulence intensity were detected (Mayer 1978).

In Figure 5 the dots represent the measured combinations of these two characteristic quantities of air movements. Supposing that the ventilation in the studied rooms only just avoided draft, the curve represents the margin between thermal comfort (below) and thermal discomfort (above the curve). The curve represents the product of mean air velocity and turbulence intensity - in accordance with the laboratory results in Figure 4. This means: to guarantee absence of draft, turbulence should be small when air velocity is high and vice versa. While Figure 5 refers to an air temperature of 22°C, similar curves for different air temperatures are shown in Figure 6, using Figures 5, 4, and 1 as follows:

In Figure 5, the calculated product of turbulence degree and mean air velocity of 0.06 m/s corresponds to a convective surface-heat-transfer coefficient of 11.5 $W/m^2 \cdot K$ according to Figure 4. In Figure 1 this corresponds to a resultant surface temperature (RST) of 29°C (see dashed line, air temperature 22°C). If you call for RST-values of not less than 29°C to avoid draft, the coefficient has to be maximal 8 $W/m^2 \cdot K$ at 20°C and 5.5 $W/m^2 \cdot K$ at 18°C. Because this is hard to achieve, it is a simple explanation for draft, especially in summer when outlet temperatures are low. Completing Figure 1 with curves of further air temperatures (not done here) you would get the curves of Figure 6 (again using Figure 4 too). For simplification, the same temperature of air and surfaces was assumed here.

Further field measurements of air motion and inquiries in five unair-conditioned and in six air-conditioned buildings confirm these statements (Kröling 1985; Mayer 1985). The results are represented in Figure 7. The mean air velocities and turbulence intensities were converted here in convective surface-heat-transfer coefficients by the help of Figure 4 and marked in dependence of the respective surrounding temperature. Furthermore, a marginal comfort curve was drawn according to Figure 6.

Practically all air motions measured in buildings without air conditioning were within the range of "thermal comfortable." Also, the main part of air motions measured in buildings with air conditioning was "thermal comfortable." Almost half of the measuring values were within the range of "thermal uncomfortable"; many were close to the marginal comfort curves, some even above those. This result conforms to the statement that in rooms with air conditioning, there were significantly more complaints about draft than there were in rooms without air conditioning.

DISCUSSION AND CONCLUSIONS

Up to now, laboratory and field researches of physical causes for draft have revealed:

1. The convective surface heat transfer increases the same as the result of turbulence degree and average air velocity, equal to the standard deviation of air speed variations, that is,
2. beginning with the self-convection, the convective surface-heat-transfer coefficient rises parabolically with increasing standard deviation.
3. The convective surface-heat-transfer coefficient is inversely proportional to the thickness of the boundary temperature layer of air heated by the body.
4. Decisive for the convective loss of heat is the disturbance - more or less strong - of the heated air close to the body, rising due to self-convection, consequence of pulsation (variation) of air motions, of exterior influences (e.g., inlet of air through air conditioning).
5. In future, the statement "free of draft" will have to fulfill different requirements than it has up to now.
6. These new requirements must comprise marginal values of mean air velocity as well as of temporal dynamic behavior of air movements, that is, the turbulance intensity and, possibly, its frequency.
7. This includes that low turbulence - as in clean rooms - allows air velocities higher than those acceptable to date.
8. The present requirements, according to German standard DIN 1946, Part 2 (1983), will not be sufficient with higher turbulence and with temperatures below 22°C.
9. In future, the convective surface-heat-transfer coefficient should be taken as the basis for the judgement of thermal comfort instead of mean air velocities.

More measurements will be required to make a more detailed and comprehensive statement on the effect of air motions on the convective loss of heat and, thus, on the thermal comfort of man.

Turbulence and average values of air velocity should then be varied more than is done now; furthermore, direction of flow and geometry of the heated body and - last but not least - the influence of frequencies of air motions on the convective surface-heat-transfer coefficient, which have not been considered yet, must still be examined.

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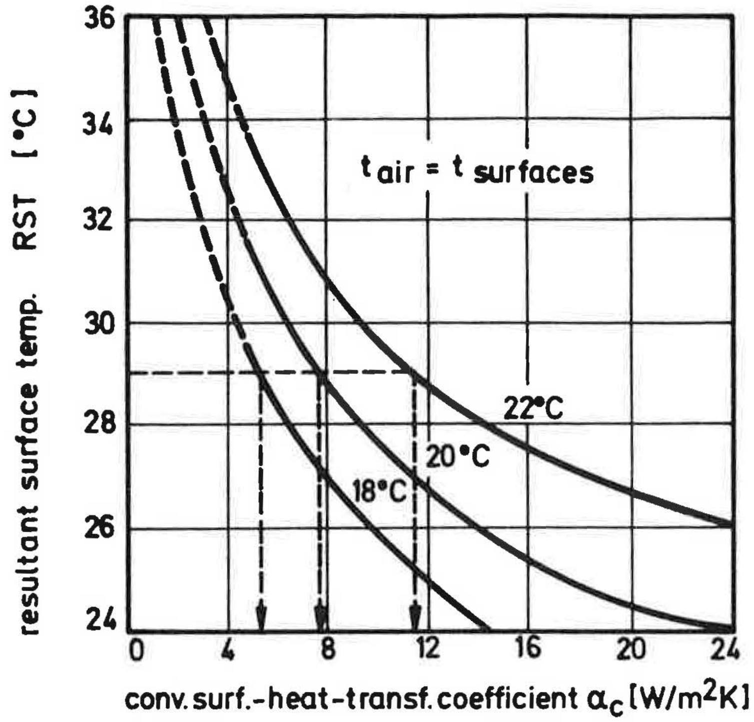

$$120\,\mathrm{W/m^2} = \alpha_c(RST - t_a) + 4.9\cdot\left[\left(\frac{RST+273.2}{100}\right)^4 - \left(\frac{t_{sf}+273.2}{100}\right)^4\right]\,\mathrm{W/m^2}$$

Figure 1. *Calculated resultant surface temperature, RST, of a 120 W/m^2 heated body as a function of the convective surface heat-transfer coefficient, α_c, when air temperature, t_a, and temperature of surrounding surfaces, t_{sf}, are equal*

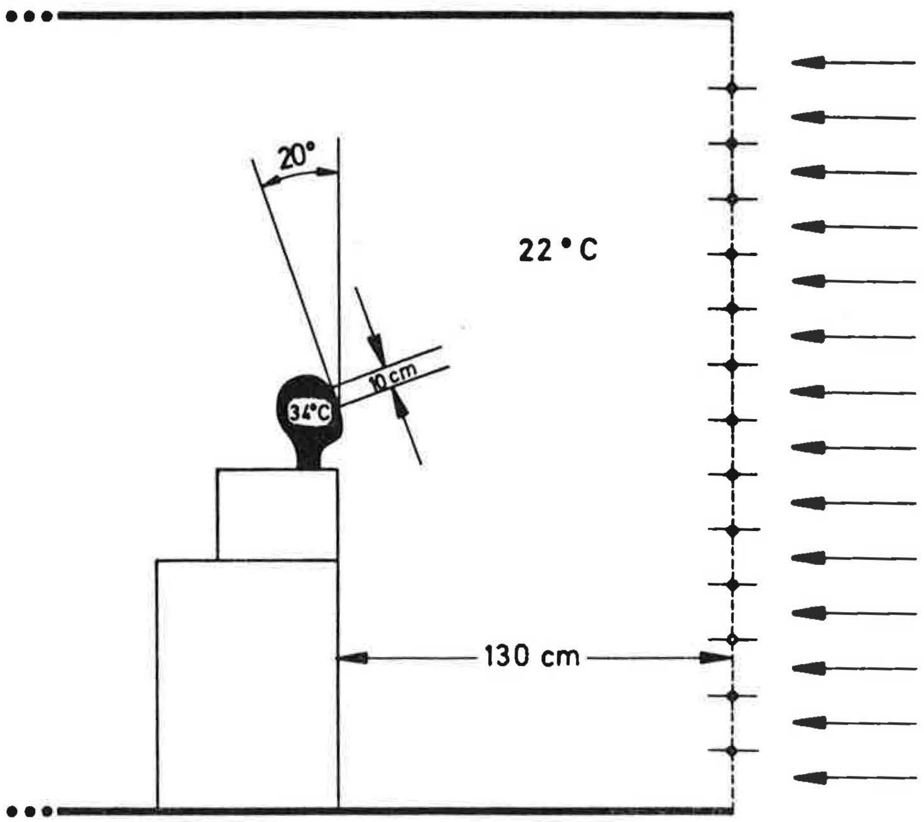

Figure 2. *Position of the artificial heated head in the climatic test chamber*

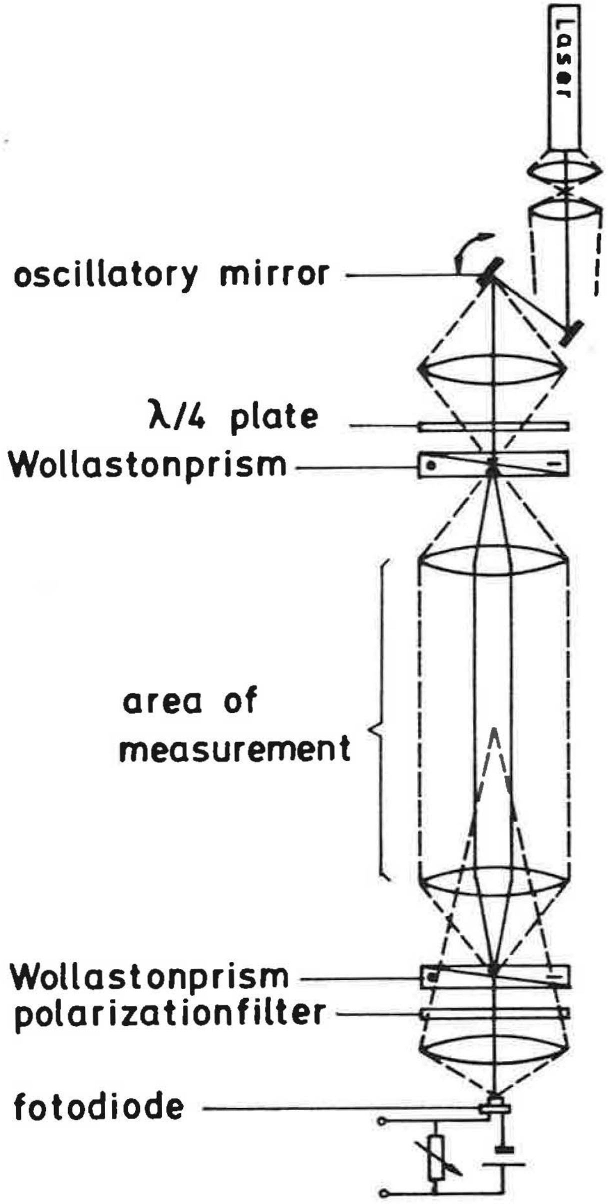

Figure 3. *Construction of the laser differential interferometer*

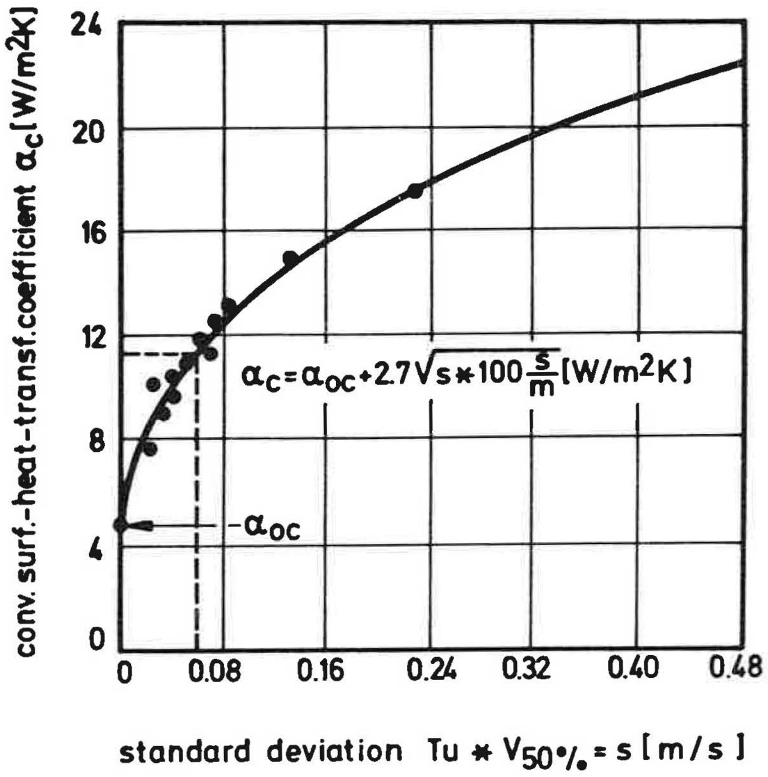

Figure 4. *Measured (dots) and calculated (curve) correlation between the product of turbulence intensity, Tu, and mean air velocity, $V_{50\%}$, that means standard deviation, s, on the one side and convective surface heat-transfer coefficient, α_c, on the other, beginning with the value of own convection, α_{oc}*

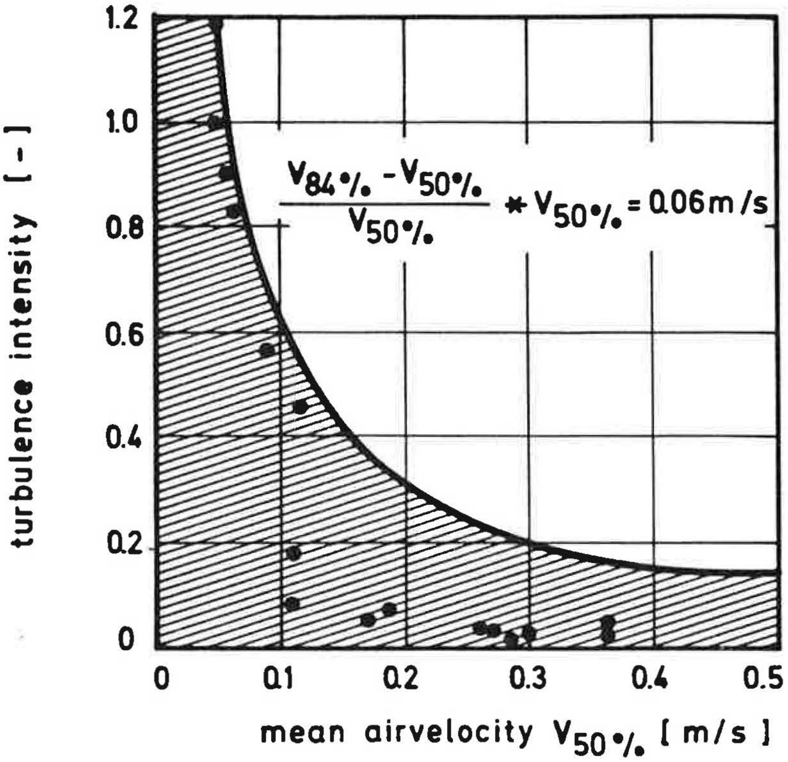

Figure 5. Combinations of mean air velocities, $V_{50\%}$, and turbulence intensities, $(V_{84\%} - V_{50\%})/V_{50\%}$, measured in heights of 0,2 m, 1,3 m, and 1,8 m in air-conditioned bureaus and in clean rooms. According to inquiries there was no draft beneath the curve (air temperature = 22°C)

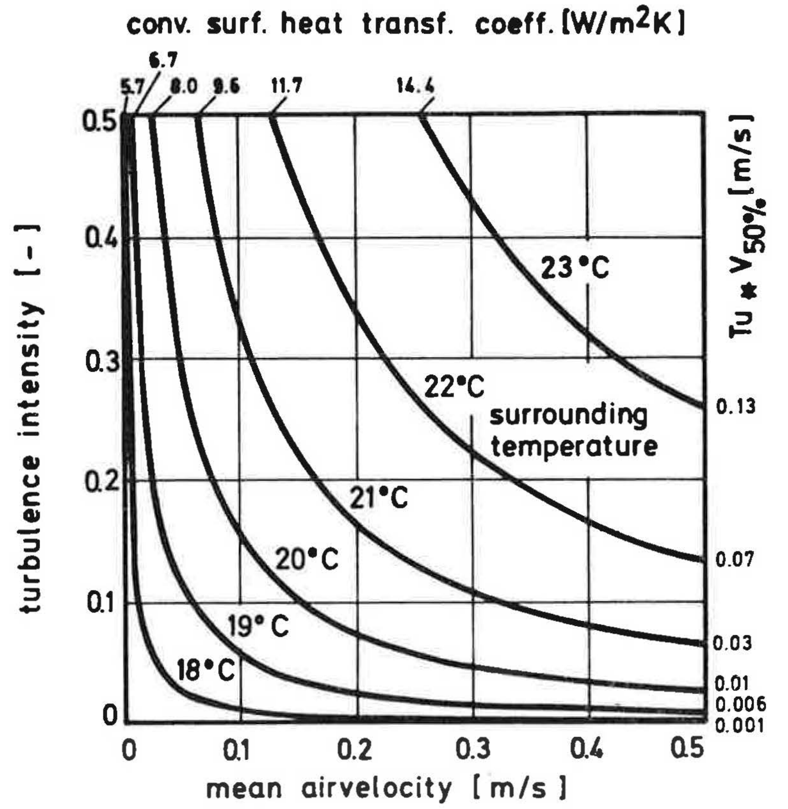

Figure 6. Preliminary marginal curves for thermal comfort (no draft)

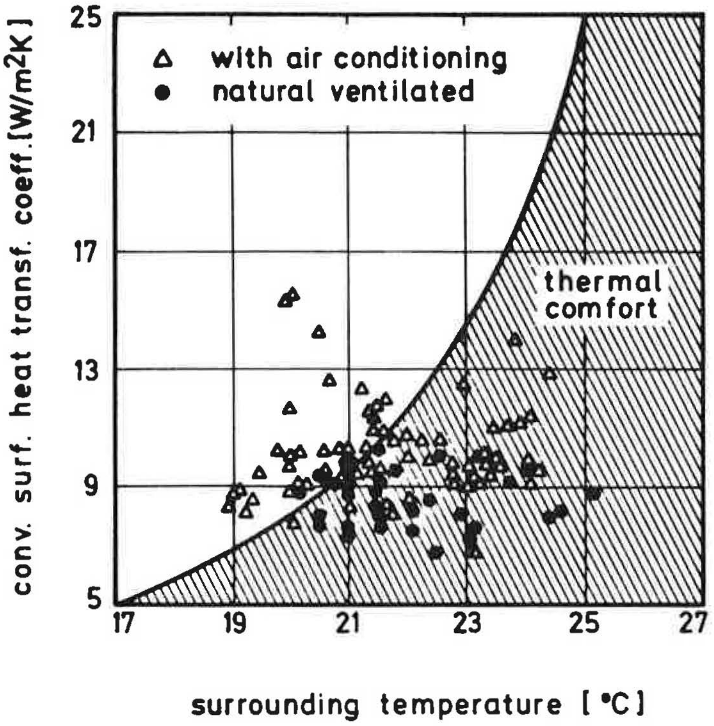

Figure 7. Results of measurements of air velocity in different ventilated buildings and preliminary marginal curve for thermal comfort (no draft)