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EVALUATION OF RADIANT HEAT STRESS

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The heat radiation stress is usually measured in terms of the »corrected effective temperature«. This index like many others serving to evaluate the heat radiation stress involves the globe temperature resulting from the mean radiant temperature and air temperature. Man is supposed to react in the same way when exposed to the same globe temperature, provided that the vapour pressure, air speed, metabolism and clo values do not change.

A series of experiments were performed on a single subject. At the same globe temperature the heart rate, rectal temperature and sweat loss increased in accordance with the increased air temperature and the corresponding mean radiation temperature.

In two other experiments on male subjects the heat component of the pulse rate was found to be different at numerically equal effective and corrected efective temperatures. If these experimental results are confirmed in the future, all indices, involving the globe temperature become questionable.

With small but powerful sources of heat radiation a formula of the heat radiation exchange between the heat source and man is proposed.

The problem of different surfaces irradiated at different working postures, and the more sophisticated problem of the »shady« zones of the body are discussed.

Bodies, which have a temperature higher than zero Kelvin, emit electromagnetic waves λ ranging from 100 to 1 μm. The wavelength depends on the temperature of the radiant heat source:

$$\lambda_{\max} = \frac{2900}{\mathrm{T\ K}} \mu\mathrm{m}$$

which emits a heat energy:

$$Q = \sigma\varepsilon S T^4 \quad \mathrm{Wm}^{-2}$$

where

σ = Stefan-Boltzmann's constant 5.67 x 10^{-8} $Wm^{-2}K^{-4}$
ε = emission coefficient
S = area of the radiant heat source in m^2
T = temperature of the object in K

The surface of the human body exchanges the radiant heat with the surroundings depending on the heat gradient in the direction from the warmer to the cooler object. It behaves almost like a black body with an emission coefficient of about 0.97. In a short infrared or visible light spectrum (i.e. 0.3—9.0 μm) the waves are to some extent reflected, and the body emission coefficient diminishes.

The mean radiant temperature ($\overline{T}_r$) is usually measured with a globe thermometer (1, 2) and may be computed according to *Bedford's* formula (3):

$$\overline{T}_r = [(t_g + 273)^4 + 0.247 \times 10^9 \times v^{0.5} (t_g - t_a)]^{0.25} \text{ K}$$

where

t_g = globe temperature °C
t_a = air temperature °C
v = air velocity (ms^{-1})

The globe thermometer exchanges the radiant heat with different heat sources and yields a mean value, which may be the famous »comfortable« average of one foot bathing in ice-cold and the other in boiling water. The problem becomes apparent for instance with small but powerful radiant heat sources as is, for instance, the aperture of a foundry furnace.

Also, the subject is surrounded by many areas each defined by the surface, temperature, emissibility and room angle in relation to the subject. All angles taken together equal 1.

The temperature may be measured by a contact thermometer or by a radiant thermometer, where the radiant flux is concentrated in a cone shaped reflector and transmitted to a chain of thermocouples. While, in practice, the reflected radiation can be neglected, the mean radiant temperature of the surroundings is expressed by the formula (4):

$$\overline{T}_r = (\varepsilon_1 T_1^4 F_{p-1} + \varepsilon_2 T_2^4 F_{p-2} + \ldots \varepsilon_N T_N^4 F_{p-N})^{0.25} \text{ K}$$

where

ε_N = emission coefficients
T_N = temperature of the object K
F_{p-N} = angle factor between the radiating surface and the subject

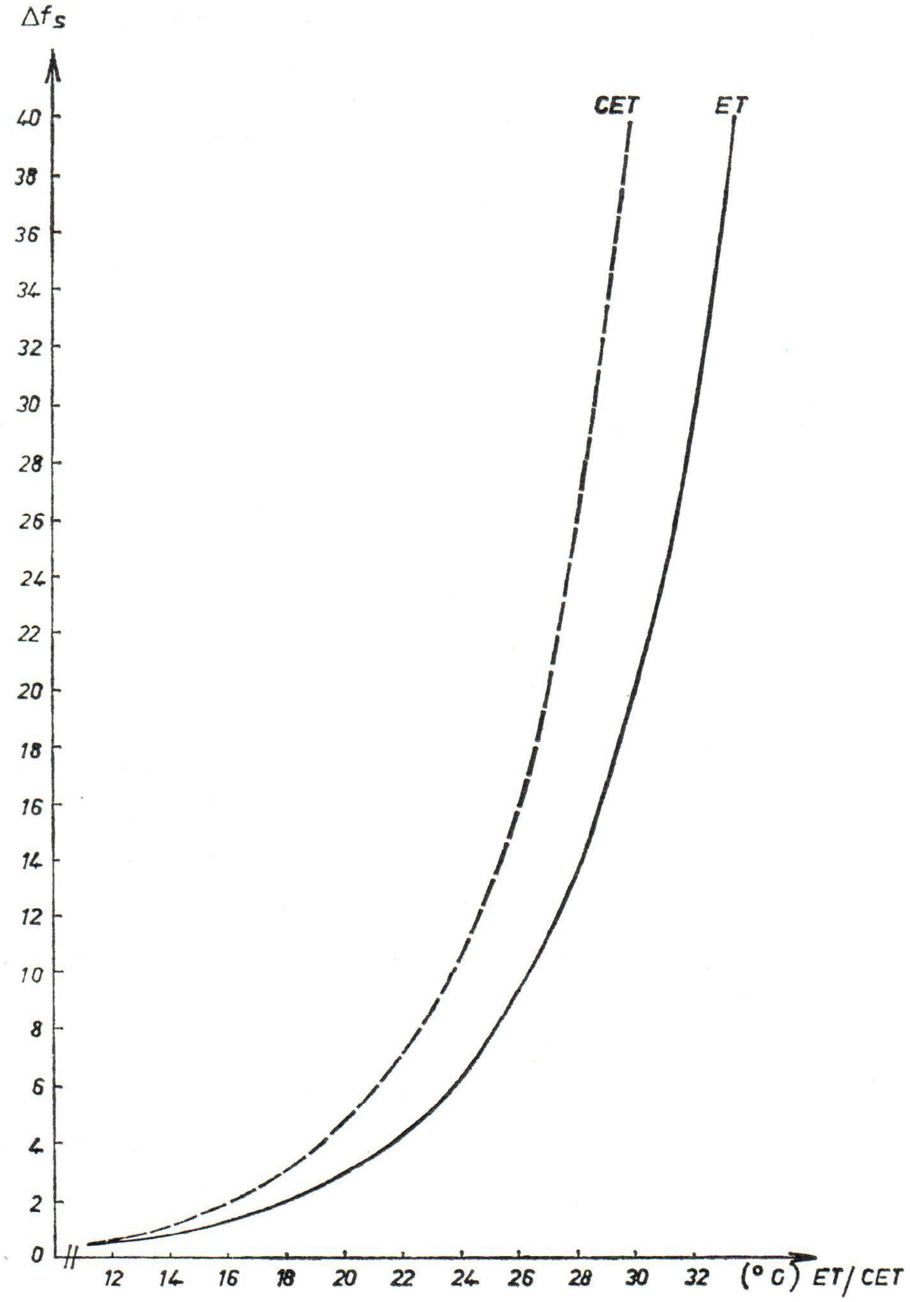

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Fig. 1 — *Heat component of the pulse rate* (Δ_{fH}) *as a function of the effective temperature (ET) and the corrected effective temperature (CET).*

According to *Fanger* the angle factors are determined by the use of diagrams (4), involving a series of simple but time-consuming operations. The emission coefficients are arrived at experimentally or approximated by applying data from the tables.

CORRECTED EFFECTIVE TEMPERATURE AND OTHER CLIMATIC INDICES INVOLVING HEAT RADIATION

About forty years ago *Bedford* (5) introduced the »corrected effective temperature« (CET). Later he wrote: »During the Second World War it became necessary to measure warmth in hot compartments in war ships, and allowance had to be made for radiant heat. It was impossible at the time to undertake the prolonged research which would have been necessary to establish a new scale of warmth ...« (3). The same author described experiments of *Humphrey and colleagues* (3), who in the climatic index »effective temperature« (6) replaced the air temperature with the globe temperature. They observed that the rectal temperature, supposed to be a relevant physiological parameter, remained almost the same at the same »corrected effective temperature«, although the latter was composed of different values of globe temperature, air velocity and vapour pressure. Bedford continued cautiously: »It could scarcely be expected that this adjustment of effective temperature by the simple expedient of using globe thermometer readings would give absolutely correct results, nor has it been claimed that it does so ... but until further research makes it possible to put forward a better scale, the method does provide a better index of warmth than the uncorrected effective temperature in situations in which radiation is of significance«. We would do well to keep in mind Bedford's precautions. Unfortunately, his hopes have not been fulfilled; on the contrary, reports on heat radiation stress are extremely rare.

Some years later *Hettinger* (7) published an equation expressing the heat component of the pulse rate (Δf_H), as a function of the corrected effective temperature.

$$\Delta f_H = 0.0562 \times e^{0.22\,CET}$$

He took data on male workers working in situations where heat radiation was intense. The curve, constructed according to this formula and evading statistical evaluation, may be compared with another curve, constructed in laboratory experiments carried out on young male acclimatized subjects, clothed in clothing of 0.6 clo, performing dynamic work of 21 kJ min^{-1} and exposed to different climatic combinations, where t_g equals t_a (8):

$$\Delta f_H = 0.06 \times e^{0.194\,ET}$$

The difference between $\Delta f_{H\,CET}$ and $\Delta f_{H\,ET}$ increases evidently with increasing CET or ET. Basically, the Δf_H reacts differently, although the CET and ET are numerically equal.

At a given temperature, vapour pressure and air velocity, the physiological reactions are assumed to be equal, although different combinations of air temperature and mean radiant temperature may exist. After Humphrey's research work, this assumption obviously was not confirmed, until *Wenzel and co-workers* (9) recently initiated the first series of experiments in the very sophisticated climatic chamber of the Institute for Work Physiology in Dortmund, FGR.

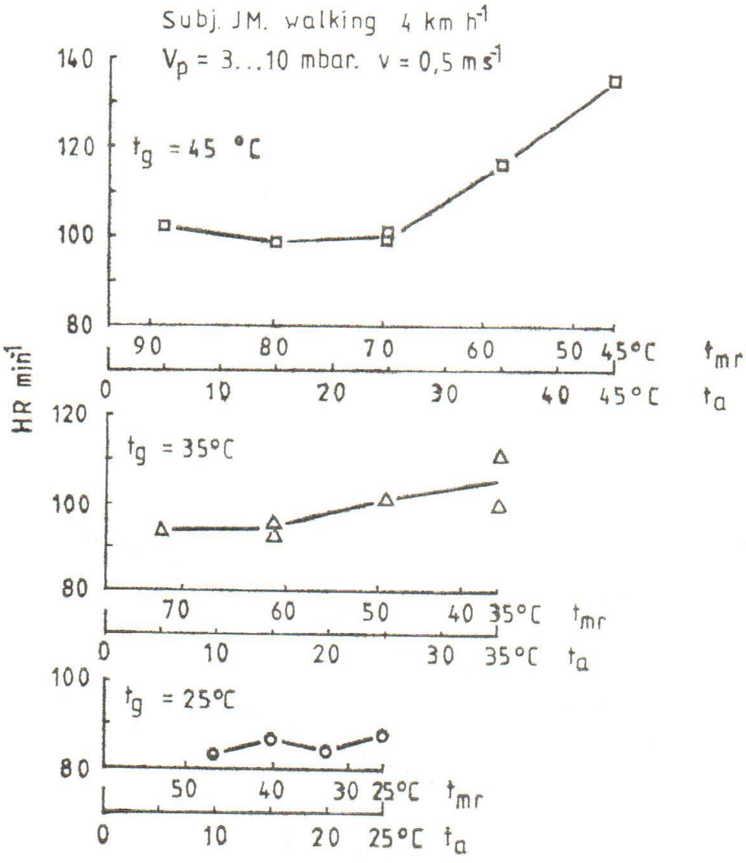

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Fig. 2 — *Heart rate at three different globe temperatures (25, 35 and 45 °C). The globe temperatures are results of air temperatures and corresponding mean radiant temperatures. Subject J. M., walking on the treadmill 4 km h—¹, at vapour pressure 3 ... 10 mbar and air speed 0.5 m s—¹.*

In this series of experiments a young, unacclimatized, unclothed male subject performed for some hours a day a moderate dynamic exercise on a treadmill at 0.5 ms^{-1} air speed and 3—10 mbar vapour pressure. In some experiments the globe temperature was kept at 25 °C, and in other at 35 and 45 °C respectively. At first the air temperature was equal to the mean radiant temperature, but afterwards the air temperature was lowered stepwise and the mean radiant temperature raised to keep the globe temperature constant. The extreme values that could be reached in the chamber were 5 °C air temperature and 89 °C mean radiant temperature.

The physiological response (heart rate, sweat loss, rectal temperature) should — according to the concept of the corrected effective temperature — remain constant at a given globe temperature, given air speed and given vapour pressure. In the described experiment, however, the physiological parameters systematically followed a decrease in the air temperature (Figs. 2 and 3).

Wenzel wrote in the report: »Die Meinung, das Globethermometer ein für physiologische Beurteilungen brauchbares Klimasummenwertgerät ist, erwies sich bei diesen Versuchen als falsch ... eine Überprüfung an weiteren Probanden ist notwendig ...«

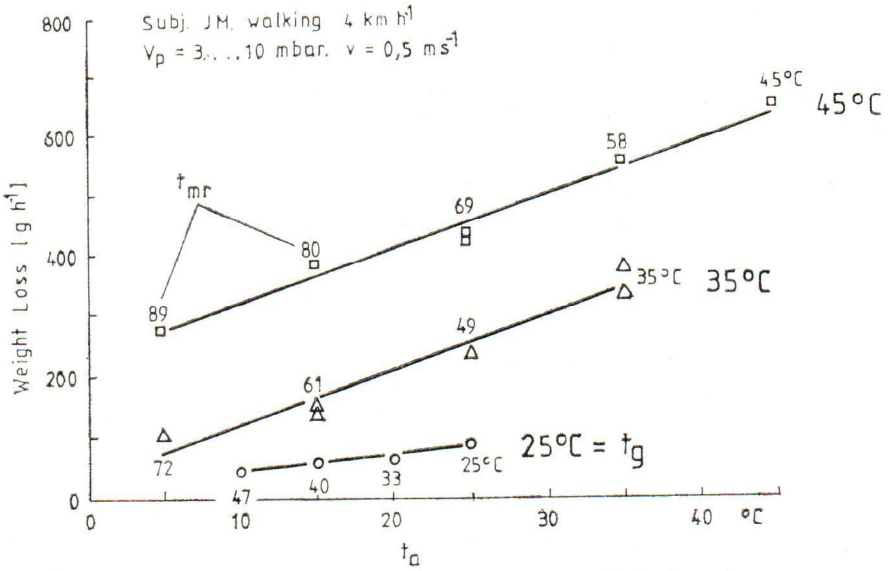

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Fig. 3 — *Weight loss (g h^{-1}) at experimental conditions described in Figure 2.*

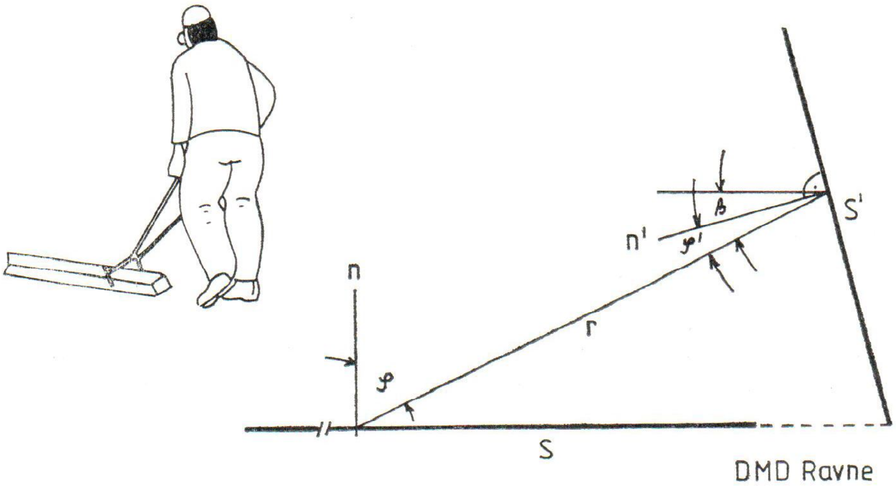

Fig. 4 — *The radiant heat transfer between the worker and the red hot bar in a rolling mill. S = bar surface, S' = worker's surface (A_p), r = distance between the bar centre and the worker's centre, φ and φ' angles between the nS and r and nS' and r, respectively.*

It is too early to generalize the initial data, but they promise to throw light on the confusing matter. It seems that the globe temperature has been overestimated in relation to the air temperature, which has been underestimated.

Then, of course, all climatic indices involving the globe temperature are questionable. Besides, comparing man with a black sphere (i.e. globe thermometer) does not seem to be a suitable simplification. *Madsen* (10) at least compares man to a doubly rotated ellipsoid.

EVALUATION OF LOCAL RADIANT HEAT SOURCES

The exchange of radiant heat between a person's surface and the surrounding surfaces is a physical process. Human beings exposed to small but powerful heat sources, suffer more from local effects than from general thermoregulation effects. In such cases the climatic indices do not express the prevailing heat load. One should rather start with the computing of the thermal flux, according to the simplified formula (11, 12):

$$\Phi = \frac{5.67 \varepsilon S \cos\varphi \varepsilon' S' \cos\varphi'}{r^2 \pi} \left[\left(\frac{t + 273}{100} \right) - \left(\frac{t' + 273}{100} \right) \right] \mathrm{Wm}^{-2}$$

where

ε = emission coefficient of the heat source
S = surface of the heat source (m^2)
φ = angle between nS and r (^{0})
t = temperature of the heat source (^0C)
ε' = emission coefficient of the exposed person
S' = a person's surface exposed to a heat source (m^2)
φ' = angle between nS' and r (^{0})
$\bar{t}_s$ = mean surface temperature of the exposed person (skin)
r = distance from the centre of S to the centre of S' (m)

In the equation, a person's surface is expressed as the product S' cosφ. *Fanger* is closer to reality with his »projected area« (A_p) (4):

$$A_p = f_{ef} f_p A_{Du}$$

where

f_{ef} = relation of irradiated surface to total body surface (m^2), assumed for nude or clothed, male or female, standing or seated persons to be 0.71
f_p = projected area factor given in Fanger's nomograms for standing or seated persons depending on altitude and azimuth of the radiant heat source
A_{Du} = body surface (m^2) according to *Dubois's* formula (13)

Accordingly, the formula should read:

$$\Phi = \frac{5.67\, \varepsilon\, S \cos \varphi\, \varepsilon' A_p}{r^2 \pi} \left[\left(\frac{t + 273}{100}\right)^4 - \left(\frac{\bar{t}' + 273}{100}\right)^4\right] Wm^{-2}$$

The method is explained by the following example (see Figure 5):

Red hot bar:

S = 0.30 m^2
φ = 64^0
ε = 0.70
t = 1130 ^0C
r = 1.97 m

Worker:

A_{Du} = 1.87 m^2
f_{ef} = 0.71
f_p = 0.318
ε' = 0.90
$\bar{t}_S$ = 34.5 ^0C

The radiant heat transfer equals:

$$\Phi = \frac{5.67 \times 0.70 \times 0.30 \times 0.438 \times 0.90 \times 1.85 \times 0.71 \times 0.320}{1.97^2 \times 3.14}$$

$$\left[\left(\frac{1130 + 273}{100}\right)^4 - \left(\frac{34.5 + 273}{100}\right)^4\right] \mathrm{Wm^{-2}}$$

$$\Phi = 625.84 \quad \mathrm{Wm^{-2}}$$

Diagrams (14) and tables (12) containing tolerance limits for the radiant heat transfer, expressed as endurance time are given as evaluation standards. The tolerance limit is above 50 min. During the working cycle the bar is kept at a standstill for only 6 s.

The red hot bar has an elongated form. Connecting both surfaces (S, S') with one distance r and corresponding angles — as shown in Figure 5 — appears to be a rough approximation. Therefore we divided the bar in 12 sections ($S_1 \ldots\ldots S_{12}$) and defined each section with a corresponding angle ($\varphi_1 \ldots\ldots \varphi_{12}$) and distance ($r_1 \ldots\ldots r_{12}$). We determined the angles ($\beta_1 \ldots\ldots \beta_{12}$) and introduced them in Fanger's nomogram for the projected area factor (f_p). Figures 6 and 7 show the radiant heat energy for each section of the bar. The sum ($\Phi_1 \ldots\ldots \Phi_{12}$) amounts to 1050.61 $\mathrm{Wm^{-2}}$, or about 400 $\mathrm{Wm_{-2}}$ more in relation to the first, simplified result.

The tolerable exposure times are not referred clearly to the exposed body surfaces (the uncovered face or the mostly covered whole body?) (Fig. 4).

The measured corrected effective temperature was in our case 27.1 °C, which is the tolerable limit for moderate physical work (7).

THE DISTANCE BETWEEN THE RADIANT HEAT SOURCE AND A SUBJECT'S IRRADIATED AREA

Two important problems concern the distance between the radiation source and the irradiated person, and the body irradiated area.

Workers often move from one place to another, diminishing or increasing their distance from the heat source and accordingly the intensity of exposure. *Hettinger* (7) for instance proposed to divide the area around the heat source into circular zones, in which the radiant heat has to be measured repeatedly, and related to the time of the worker's presence in a particular zone. This method is considered to be a better approach than the trivial reading of instruments — as is common practice.

The workers do not only vary the distance, but also the body position in relation to the heat source, and in doing so, they change the irradidiation angle. Fanger's estimation of the projected area (A_p) provides for

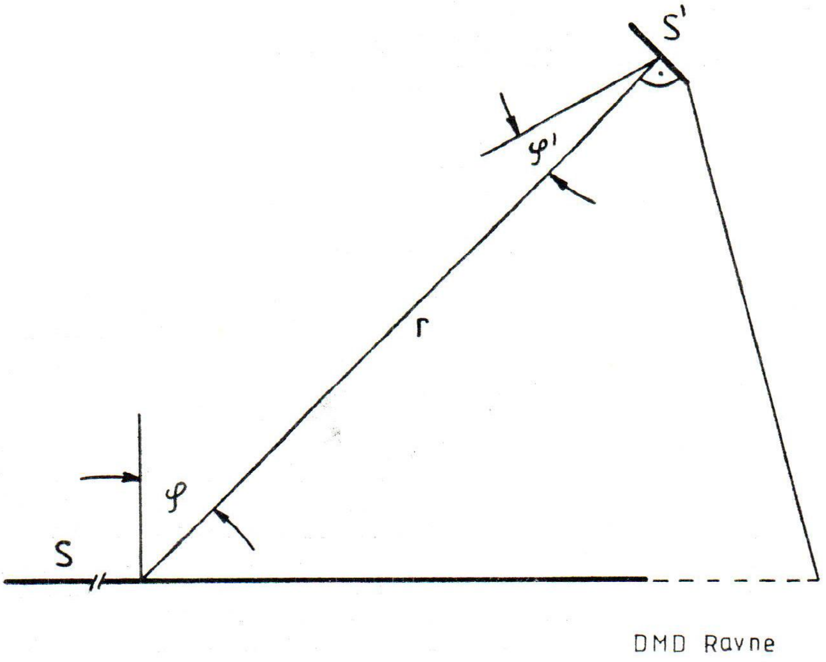

Fig. 5 — *The radiant heat transfer between the worker's face and the red hot bar in a rolling mill. Data as in Figure 4.*

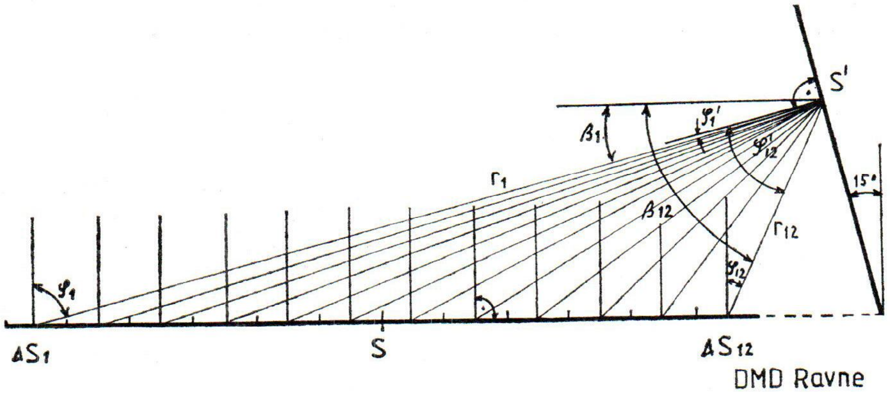

Fig. 6 — *The radiant heat transfer between the worker (S') and the red hot bar ($\Sigma \Delta S_1 \ldots\ldots \Delta S_{12}$) in a rolling mill. The bar is divided in 12 sections, with corresponding distances $r_1 \ldots r_{12}$ and angles φ_1, $\varphi'_1 \ldots \varphi_{12}$, φ'_{12}. The angles $\beta_1 \ldots \beta_{12}$ were used for the computation of A_p (4).*

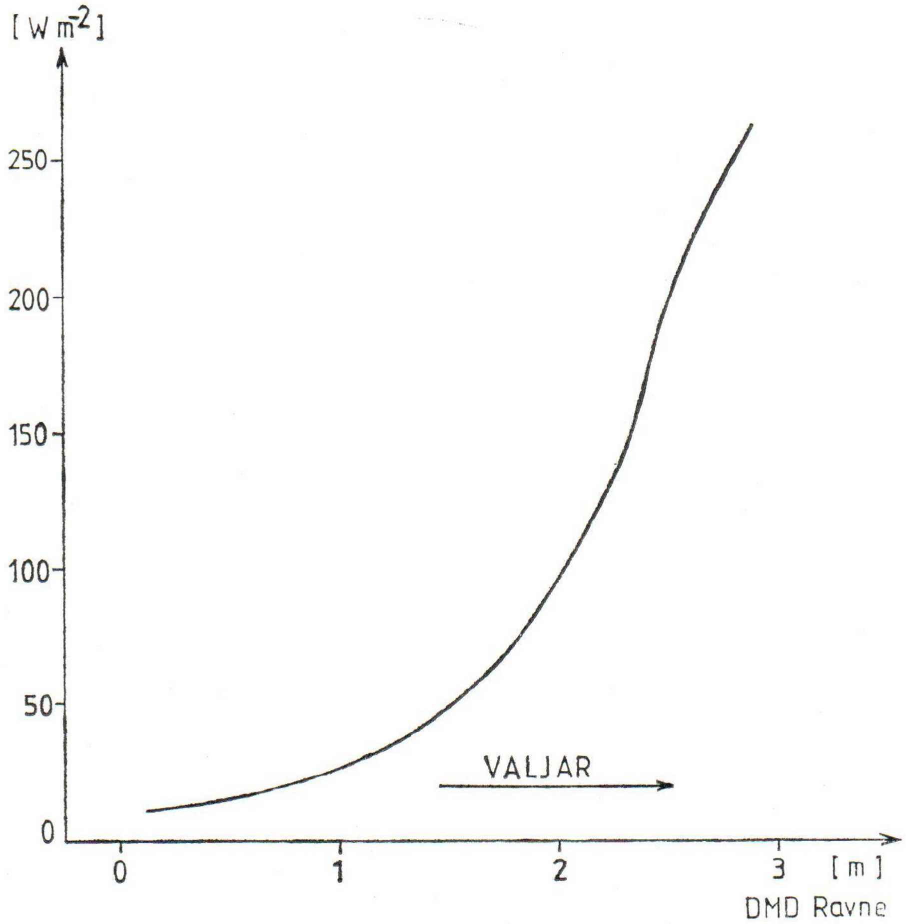

Fig. 7 — *Radiant heat energy (Wm—²) acting upon the worker in dependence on the bar section.*

upright standing and seated subjects, but not for other positions, for instance the inclined posture which appears very often in industrial practice. In a sophisticated investigation, one should also pay more attention to the »shady zones« between the arms and the thorax, and between the legs.

CONCLUSION

The evaluation of radiant heat load leaves more questions open than one would expect. One may argue about the well established »corrected effective temperature« and other climatic indices, which involve the globe temperature. These indices seem to overestimate the thermal load. Moreover, the methods are hardly appropriate for evaluating the effect of small but intense radiant heat sources, where the local influence predominates over the general effects of thermoregulation.

A physical model is shown by which the load is expressed in terms of endurance. Further, one claims the existing determinations of the body's irradiated surface to be insufficient, especially, since the distance of the subject to the heat source is not being taken into account satisfactorily.

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Sažetak

PROCJENA STRESA USLIJED TOPLINSKOG ZRAČENJA

Opterećenje toplinskim zračenjem se najčešće mjeri toplinskim indeksom »korigirana efektivna temperatura«. U korigiranoj efektivnoj temperaturi i nizu drugih toplinskih indeksa za registriranje toplinskog zračenja upotrebljava se temperatura globus termometra, koja je rezultanta srednje temperature zračenja i temperature zraka. Pretpostavlja se da čovjek kod jednake globus temperature uz jednaki tlak para, brzinu strujanja zraka, metabolizam i clo vrijednost odjeće, reagira tako da se fiziološki parametri ne mijenjaju. U radu je opisana serija pokusa na jednom muškarcu u klimatskoj komori. Rezultati su pokazali da su frekvencija srca, rektalna temperatura i gubitak znoja kod iste globus temperature rasli s rastućom temperaturom zraka i njom povezanim padom srednje temperature zračenja. Opisana su i druga dva pokusa na reprezentativnoj populaciji kod koje srčana frekvencija više poraste kod numerički iste korigirane efektivne temperature u usporedbi s efektivnom temperaturom. Ako se u daljim pokusima ovi rezultati potvrde, svi indeksi koji uključuju globus temperaturu dolaze pod znak pitanja.

U radu se dalje ističe potreba da se kod ograničenih ali jakih izvora toplinske radijacije primjenjuje fizikalna metoda za izračunavanje izmjene toplinske energije između izvora zračenja i eksponiranog radnika. Predložena je izmjena pojednostavljene jednadžbe koja točnije opisuje izloženu površinu čovječjeg tijela.

Izneseni su problemi koji nastaju u evaluaciji opterećenosti zračenjem zbog mijenjanja položaja radnika u odnosu na izvore toplinskog zračenja, kao sofisticirana pitanja zona u »sjeni«, na primjer između butina ili trupa i gornjih ekstremiteta.

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