Evaluation of radial component of thermal load at workplaces in hot shops

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Abstract
The theoretical evaluation of impact of thermal radiation on staff of hot shops considering constant of radiation of heated material, temperature of the radiating surface, and distance to workplace is performed. Consideration of impact of the reflected radiation with reflecting or diffusion nature on workers is new. Joint effect of straight and reflected beams at the levels of legs and head of person is considered.
Key words: HOT SHOP, WORKPLACE, THERMAL RADIATION, THERMAL LOAD

Relevance

The heating microclimate is considered to be workplace condition where the total thermolysis of person to the environment is less than thermolysis of body that leads to accumulation of heat in the body.

Places where the thermal emissions connected with technological processes exceed the level of heat losses of the body (20 kcal / h*m^3) are called hot shops irrespective of ways of emissions insertion to this place (convection or radiation). Heat flows there from the heated objects and surfaces, hot or boiling masses. Such conditions are formed at workplaces in metallurgical production during metals treatment under pressure in the deep horizons in openings, in hot shops of the food processing plant in case of fire-fighting operations and some other productions. Under conditions of heating microclimate, thermal effect on workers, such as burns, body overheat, consciousness loss, heat strokes are quite frequent. From our standpoint, the reason which determines emergence of this sort of accidents is absence of reliable information about external thermal load of workers that generates insufficient level of application of antithermal means at the enterprises. Therefore, scientific reasons and enhancement of regulatory documents regarding development of solutions on application of means of individual and group protection of the production from heat are relevant task. According to authors, objective evaluation of external thermal load of workers who are exposed to external thermal impact is a basis for selection of ways of enhancement of antithermal protection. The primary source of heating microclimate at the majority of technological processes is thermal radiation which directly affects workers, and also is the reason of their subsequent convective and conductive heating.

State of problem

In hot shops, the major climate factor is infrared radiation from the objects heated up to 500 … 1300 °C and more. The higher subject temperature is, the more heat it gives to the environment by radiation. For example, in the open-hearth plant of steel works 62 … 67% of heat is transferred to the workplaces due to infrared radiation, and 33…38% is transferred by convection transfer of heat. Infrared beams as primary sources of heat accumulation in the room are partially absorbed by objects and equipment, heat them and turn into secondary sources of thermal emission. More rarely, the microclimate of hot shops can be formed by convection heat accumulation when transition of mechanical, electric energy into heat, emission of heat by the people who are in this place, conditions of the external atmosphere etc.

Study of conditions of climatic indicators at various workplaces has shown the following [1]. At workplaces of blast-furnace plant due to radiation, air temperature fluctuates from 32,9 to 26,7 °C and more. Such severe thermal conditions take place at workplaces in case of converter steel production (Table1).

Table 1. Microclimate at workplaces of converter shop

Workplace	Outside temperature, °C	Temperature of working rooms, (average / maximum) °C	Thermal radiation, cal / cm^2 • min., (average / maximum)
Near ladle, pouring	21,3	33,0/40,0	6,1/ 6,9
Near throat	15,0	30,0 /37,0	1,5 /2,2
Near tuyere	16,0	32,0 /45,0	0,7/ 1,0
Cabin of pouring	13,7	19,4 /24,2	1,5 /2,9
Near mould	13,7	28,0 /33,4	2,2 /2,6
Crane cabin	23,0	38,7/ 40,0	-- /2,9

In papers devoted to research of external thermal load under the conditions of heating microclimate, only the effect of direct thermal beams is considered. It leads to understating of results, underestimation of impact of convective heating and reflected beams. Above mentioned can be illustrated with the data of results [2] obtained at Lviv University of Health and Safety at thermal effect of the low-power center of gasoline burning (Figure 1).

From our standpoint, it is explained not by consideration of others (except direct radiation) components of heating, such as action of reflected beams and convective flows.

The Polish researchers did not consider these factors when developing calculation models of thermal condition of thermal protective garments at different types of tests [3,4].

The variety of types of thermal impact on the person is not taken into account during the developing, testing and recommendations on application of protective clothes in the USA and Russia [5-7].

It is possible to draw a conclusion that the known techniques do not fully consider all types of thermal impact on the worker body, for example, in metallurgical production. Under these conditions, three main types of external thermal impact act in parallel, namely: direct flows of thermal beams (radiation) blowing streams of hot gases (convection), heat transfer in case of contact with heated firm objects (conduction).

As a rule, initial parameters of sources of thermal radiation, such as boiling point of metal or heating of billets, sizes of radiation front, climatic conditions, namely, air temperature, its humidity, speed of air flows, dust content and others are known. Proceeding from these data, it is necessary to evaluate situation and develop measures of thermal safety of workers at the enterprises.

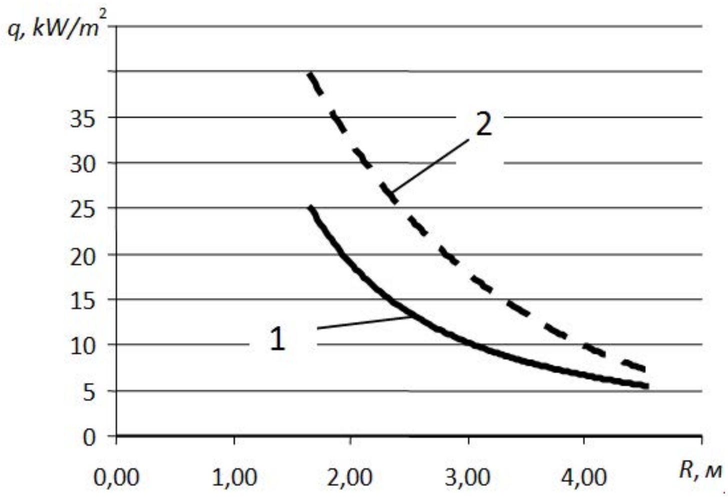

Figure 1. Theoretically (1) and experimentally (2) established thermal streams from flame of burning gasoline

The factors determining the internal heat generation depending on muscular load of worker are under control by selection of operating modes in zones of thermal load, application of protection means, mechanization of technological operations and other ways.

Influence of external factors is prevailing, caused objectively and hardly regulated. It is important to notice that the reflected and convective streams of heat are secondary, derivative from direct beams. Therefore, we consider that determination of level of radiation heating is the main objective in this paper; it will form a basis for development of technique of evaluation of thermal condition of workplaces in hot shops.

The work objective is to prove theoretically the approaches to evaluation of radiation impact on staff of hot shops that can form a basis for determination of secondary components of heating microclimate and selection of methods and means of antithermal protection of workers.

Results of researches

In metallurgical production, the main sources of external radiation are places where processes of boiling, heating of metal or other similar processes take place. Thermal beams when getting on a surface of workplaces and being partially absorbed transfer a part of energy to substance molecules forcing them to fluctuate intensively by heating up. Remaining energy is reflected from surfaces and dissipates in space.

At a workplace both the direct and reflected beams take place that should be considered when determining admissible time of workers stay in a zone of thermal injury (Figure 2).

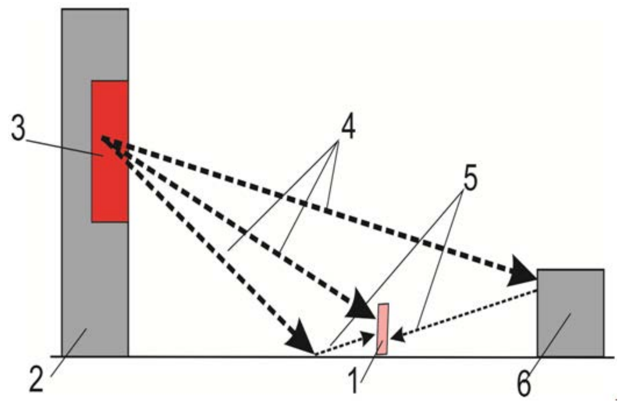

Figure 2. The diagram of the external beam streams taking place at a workplace: 1 - worker; 2 – technological installation; 3 – area of high temperature; 4 – direct thermal streams from the fire; 5 – reflected beams; 6 - reflecting surface

Convective flows emerge for two reasons. Firstly, it can be gaseous products, which evolve in course of burning and thermal destruction of combustible substances used in production. Considering that the majority of combustible solid, gaseous and liquid substances are organic compounds, the main part of products constitute carbon oxides, sulfurs, water vapor, gases of the organic nature, and also air nitrogen oxides in case of high (more than 1500 °C) temperatures. Another component of convective streams is the air, which is heated up in case of contact with the heated surfaces. The density of warm gases is smaller than of air; and it moves under the impact of buoyancy force. The vector of movement of convective streams is determined by the sum of this force and direction of ventilating streams.

Conductive heating takes place in case direct contact of person with the heated surfaces or liquids. Most often, legs or only feet are subject to such thermal impact (Figure 3).

Thus, external thermal load (Q_{wt}) of person, who is at workplace, consists of the following main components:

- direct thermal streams from heated sources (Q_{fd}) which action is of direction from a source;
- reflected (Q_{fr}) primary sources streams from soil and walls, reflected beams, as a rule, are of reflecting and diffusion nature, which is disseminated because of roughness of reflecting surfaces;
- convective flows of heated gases (Q_k) caused by heating of surface or wind transfer of products of burning;
- conductive (Q_c) heating of parts of work clothes adjoining to heated surfaces or flame.

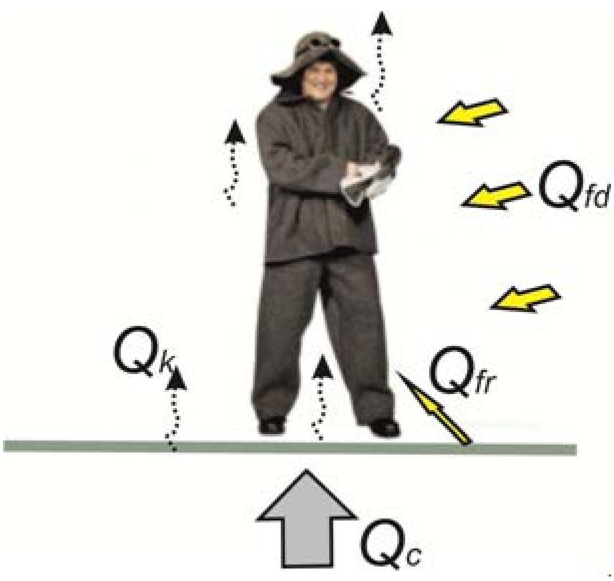

Figure 3. Diagram of impact of external thermal streams: direct and reflected beam (Q_{fd} and Q_{fr}) respectively; convective (Q_k); conductive (Q_c) on the metallurgist

The total amount of heat affecting the worker from the outside can be expressed by the equation:

$$(Q_{wt}) = Q_{fd} + Q_{fr} + Q_{\kappa} + Q_c \qquad (1)$$

Thus, it is necessary to remind that reflected, convective and conductive thermal streams are derivative of direct streams Q_{fd}, i.e.:

$$Q_{fr} + Q_{\kappa} + Q_c = f(Q_{fd}) \qquad (2)$$

Let us try to evaluate the value Q_{fd} on the basis of the following assumptions.

At a first approximation, the radiation source is close to a circle radius R by the form. The size of direct thermal stream from the melted or heated metal can be determined on the basis of area of the radiating space, temperature of radiating substance, distance to the front of radiation, transparency of air. The isotropic air medium where heat is generated is of half-space form. Proceeding from Saint-Venant principle, let us accept an assumption that at distance more than three linear sizes of the radiation front (3R) it is possible to consider that all emitted energy is concentrated in its center. The isosurface of thermal stream is radiation hemisphere Ω; its base is the circle of radius *r* equal to distance from a radiation source to workplace. The projection of some irradiated platform to surface of hemisphere is equal to *S* (Figure 4).

The specific capacity of radiated thermal flow R_{rad} referred to a surface in 1 m² according to Stefan and Boltzmann law can be provided by the following expression:

$$P_{rad} = \varepsilon \cdot \sigma_0 \cdot T^4, W/m^2 \qquad (3)$$

where: εε – radiating ability (radiation constant) of heated material;σ_0 - Stefan-Boltzmann constant equal to $5{,}67_*10^{-12}$, $W/(m^2{}_*K^4)$; T – temperature of radiating surface, *K*,(°*C* + 273).

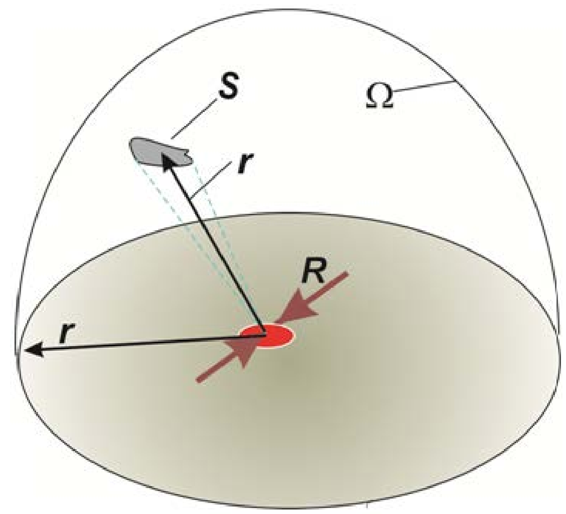

Figure 4. The diagram of determination of thermal load of the platform S located in radiation hemisphere Ω, which is at distance *r* from a source of heat of radius *R*: r – distance from a source to the center of workplace

The size of radiating ability of materials *ε* differs significantly in wave ranges. Infrared radiation is implemented in the range from 0,74 to 2000 microns. It is reasonable to evaluate the size of thermal streams as integrated for different intervals of radiation range (Table 2). For approximate evaluation, it is possible to use an average indicator with the help of reference value.

Table 2. Radiating ability of some materials of ferrous metals [8]

Material	Effective length of wave, microns			
	1	2.2	5.1	8-14
Iron oxide	0,7-0,9	0,7-0,9	0,6-0,9	0,5-0,9
Iron	0,35	0,1-0,3	0,05-0,25	0,05-0,2
Rough iron	0,35	0,6-0,9	0,5-0,8	0,5-0,7
Cold0rolled steel	0,8-0,9	0,8-0,9	0,7-0,9	0,4-0,6
Sheet steel	0,35	0,6-0,7	0,5-0,7	0,1
Polished steel	0,35	0,2	0,1	-
Cast steel	0,8-0,9	0,25-0,4	0,1-0,2	0,7-0,9
Oxidized steel	0,35	0,8-0,9	0,7-0,9	0,1-0,8
Stainless steel	-	0,2-0,9	0,15-0,8	-

Power of radiation of the source of circle form with radius R is:

$$I= P_{rad} \cdot \pi \cdot R^2,\ W \quad (4)$$

Specific energy (intensity) of radiation, which is evenly distributed on a surface of hemisphere, is:

$$E = I/\Omega = \varepsilon \cdot \sigma_0 \cdot T^4 \cdot R^2 \cdot (2 \cdot r^2)^{-1},\ W/m^2 \quad (5)$$

The energy passing to the surface of platform S, m^2, which is on a radiation hemisphere surface, is:

$$E_S = \varepsilon \cdot \sigma_0 \cdot T^4 \cdot R^2 \cdot S \cdot (2 \cdot r^2)^{-1}, W \quad (6)$$

If a projection of human shadowgraph to hemisphere (at human height h_h= 1,8 and width of shoulders of 0,6 m, S is about 1,1 m^2) is considered as the platform S, the obtained result of calculation will correspond to direct thermal stream (Q_{fd}) affecting the worker.

Besides direct beams *E*, the reflected E_m affects workers in hot shops. The amount of thermal radiation in a workplace should not exceed admissible safety rules level, intensity of thermal emission E_{sc}=5,6,*mJ/(m^2·h),=155,6,W/m^2* can be maintained without special protection during unlimited time, $E_{sc} = E+E_m$.

Therefore, limiting safe size of the reflected radiation will be:

$$E_m = E_{sc} - E. \quad (7)$$

Ratio of the reflected thermal radiation to the size of stream of the radiant energy on the surface is characterized by coefficient of reflection (k_o), it can vary in the wide range. Below, the data for certain types of medium (Table 3) are given.

Reflection of beams is of dual nature, namely, reflecting and scattered (diffusion). Under real conditions, there are reflected beams of both types. The ratio of the reflecting and scattered reflected light depends on a condition of the irradiated surface. Therefore, it is reasonable to consider both variants of reflection of infrared radiation separately.

Table 3. Coefficient of reflection of some surfaces

Surface	k_o
Fresh snow	0,85
Sand	0,3
Forest	0,1…0,18
Green grass	0,26
Dry grass	0,19
Water	0,02…0,7**
Black velvet	0,005
Aluminium	0,8…0,9

** - depends on the angle of light falling β

For reflection, the surface must be smooth, for example, quiet water or polished materials, such as mirror, aluminium foil. Reflected thermal stream represents vector of beams. Criterion of specular reflection is image of radiation source on the irradiated surface. For the surfaces located close to the platform on which the beam (level of feet of the worker) falls, the size of reflected stream is:

$$E_{m1} = \varepsilon \cdot \sigma_0 \cdot T^4 \cdot R^2 \cdot (2 \cdot r^2)^{-1} \cdot k_{oz},\ W/m^2, \quad (8)$$

at the level of head this value is:

$$E_{m2} = \varepsilon \cdot \sigma_0 \cdot T^4 \cdot R^2 \cdot (2 \cdot r^2)^{-1} \cdot k_{oz} \cdot h_h^{-2},\ W/m^2, \quad (9)$$

Real surfaces, which prevail in workplaces, are rough; and ledges and holes can be of various sizes and orientation, therefore light is reflected in various directions that is scattered. Let us consider the variant of loss of heat - quasiuniform distribution in reflecting hemisphere Ω_r (Figure 5).

Under identical conditions of radiation, vector action of scattered radiation is significantly less than reflected one; however, integrating, acting from various directions together with direct beams, it affects workers negatively.

Generally, scattered beams are distributed in reflecting hemisphere with space angle Ω_r=2π, steradian and the basis in the form of circle with radius r_r and area of hemispherical surface $2\pi\ r_r^2$. The size of radius depends on the size of direct radiation E and coefficient of reflection k_o.

Thermal energy reflected quantitatively corresponds to thermal stream O = 1m² (falling on the single platform) multiplied by coefficient of reflection k_o and is

$$E_m = E \cdot k_o = \varepsilon \cdot \sigma_0 \cdot T^4 \cdot R^2 \cdot (2 \cdot r^2)^{-1} \cdot k_o, Bm \quad (10)$$

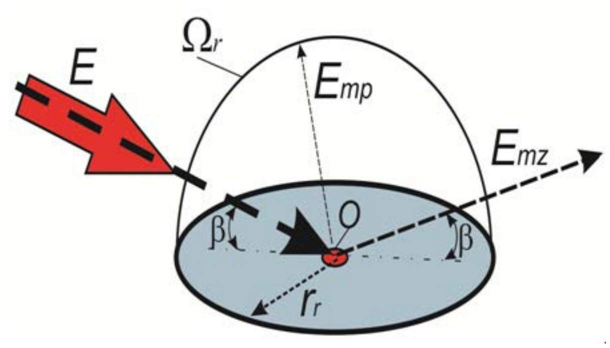

Figure 5. Diagram of specular and scattered reflection of thermal stream E of single platform O: *β* - angles of falling and reflection; E_{mz} - vector of reflected stream; E_{mp} – beam of scattered stream; r_z –radius of zone of scattered reflection; Ω_r - hemisphere where the main part of scattered energy is concentrated

Density of stream of the reflected light beams is inversely proportional to the square of distance to the irradiated object; therefore, they mainly affect close located surfaces. The closest things are feet of workers. From there, it is possible to establish the maximum radius of hemisphere, on which border the reflected beams influence the human with intensity of no more than E_{sc}. In such hemisphere, radiation exceeds admissible level.

Specific thermal load E_{tr} of reflection to hemisphere surfaces Ω_r is:

$$E_{mr} = E_o / \Omega_r = E k_o / (2\ \pi \cdot r_r^2),\ W/m^2 \quad (11)$$

The size of radius r_r forming hemisphere Ω_r, out of which thermal radiation does not exceed safe level, can be determined taking into account expression (7):

$$E_{sc} - E. = E k_o / (2\ \pi \cdot r_r^2),$$

from where:

$$r_r = \sqrt{\frac{Ek_o}{2\pi(Esc - E)}}. \quad (12)$$

From the obtained expression, it follows that the safe value of hemisphere of reflection can change depending on primary radiation, but it will be always proportional to root square from reflection coefficient value for this type of surface.

In case of evaluation of thermal conditions at workplaces as radius, it is possible to consider such indicator as human height h_h. Thus, at the level of head, specific thermal load with the reflected heat will be

$$E_{m2} = E k_o / (2\ \pi \cdot h_h^2),\ W/m^2$$

The part of surface of human body turned to primary source of radiation is the most intense on radial load. It is affected by both direct and reflected beams, which create the high possibility of thermal injury. Diagram of distribution of beams on this site by the height of human body is presented in Figure 6. From the opposite "shadow" side, only the reflected component of scattered radiation takes place, in the diagram; it is limited by dashed line.

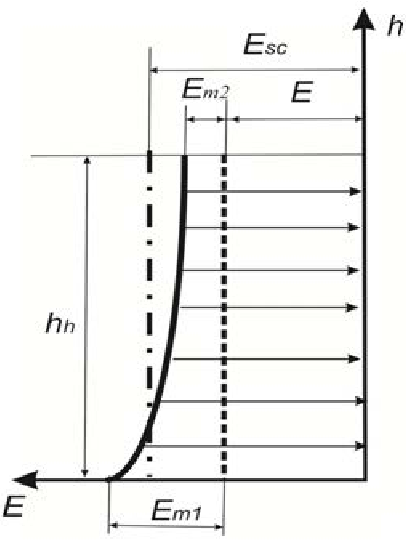

Figure 6. Distribution of straight (E) and reflected beams at the levels of feet (E_{m1}) and head (E_{m2}) along human body of height (h_h); the dotted line divides a straight line and reflected components of beam stream; $_{Esc}$ – the safe level of thermal radiation at a workplace

When determining thermal conditions at a workplace, it is necessary to consider the "hottest" place (it is the point located at feet). The beam stream affecting it is equal to the sum $E+E_o$ (see Figure 6):

$$E+E_{m1}=\varepsilon\cdot\sigma_0\cdot T^4\cdot R^2\cdot(2\cdot r^2)^{-1}+\varepsilon\cdot\sigma_0\cdot T^4\cdot R^2\cdot(2\cdot r^2)^{-1}\cdot k_o = \\ =\varepsilon\cdot\sigma_0\cdot T^4\cdot R^2\cdot(2\cdot r^2)^{-1}\cdot(1+k_o),\ W/m^2 \quad (13)$$

Near the head, thermal load is slightly lower and is $E+E_{m2}$:

$$E+E_{m2}=\varepsilon\cdot\sigma_0\cdot T^4\cdot R^2\cdot(2\cdot r^2)^{-1}+\varepsilon\cdot\sigma_0\cdot T^4\cdot R^2\cdot(2\cdot r^2)^{-1}\,k_o/2\,\pi\,h_h^2 = \\ =\varepsilon\cdot\sigma_0\cdot T^4\cdot R^2\cdot(2\cdot r^2)^{-1}\cdot(1+k_o\,(2\pi\cdot h_h^2)^{-1}) \quad (14)$$

It is necessary to consider that real surfaces of floors and walls in production rooms do not possess properties of specular or exclusively scattered reflection of beams. Therefore, in case of evaluation of thermal conditions on workplaces in hot shops, it is necessary to consider both variants of reflection, and to evaluate thermal impact.

Conclusion

Components of external thermal load of the worker, who is at a workplace in the hot shop, were determined. These are direct thermal streams from primary sources of radiation; the reflecting and diffusion beam streams reflected from soil and walls; convective gas streams; conductive heat transfer from heated surfaces or flame.

Theoretically, on the basis of classical theory of thermodynamics, the methodology of evaluation of beam impact on staff of hot shops considering constant of radiation of heated material, temperature of the radiating surface, distance to a workplace, was provided. In methodology, accounting of impact of the reflected radiation having reflecting or diffusion nature on workers is new. Joint impact of straight and reflected beams at the levels of legs and head was considered.

The obtained results can be used further for determination of secondary components of the heating microclimate (convection, conduction), evaluation of integrated external load, and justification of ways and means of antithermal protection of workers.

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