

Estimation of Lighting in Steel-rolling Shops through Integral Characteristics of the Light Field

S I Chikota¹

¹Institute of Construction, Architecture and Art, Nosov State Technical University, Lenin av., 38, Magnitogorsk, Chelyabinsk reg., 455000, Russian Federation

E-mail: asp_mgtu@mail.ru

Abstract. The organization of the light situation in the interior of steel-rolling workshops has been depicted in the presented research, where the visual operators' activity is characterized by discomfort which is caused by a self-luminous metal. To estimate the illumination, it is suggested to use the integral characteristic of a light area with an exactly distinguished direction functionality – that is, a quarter-spherical illumination. The theoretical argumentation for the quarter-spherical illumination and its calculation method from a single - point light source are subjected here.

1. Introduction

One of the main tasks to design the buildings for the metallurgical enterprises is to provide working conditions which are promoted to prevent the professional diseases. Management of the most technological operations at modern enterprises is distantly carried out from the fixed workplaces, which are protected from the harmful effects of the operation factors by cabs. In the hot workshops of metallurgical enterprises, operators' visual activity is characterized by the presence of the highly-profiled equipment in their sight field as well as hot or molten metal, which brightness, under certain conditions, gives rise to visual discomfort..

In the steel-rolling workshops of the metallurgical industry, the highly-profiled equipment significantly influences the organization of natural illumination [1], as it has a shadowing effect and pre-determines the presence of the vertical working surfaces. In such a case, it is emphasized that the human personal perception of the illumination level in a space location is determined primarily by the brightness of the interior vertical surfaces [2]. It is also pointed out, that in the cases where low and high brightness are being simultaneously present in the sight field, to make the introduction norms of the illumination is considered to be irrational [3]. Due to the above mentioned positions, it follows that in the cross-section of the particular workshop spaces, the illumination should be differentiated according to the internal space zoning (Figure 1). Under the workshop conditions, it is necessary to reduce the blinding effect of the glowing metal by creating favorable surface luminosities where the incandescent metal can be observed in contrast with them [4].

2. Scientific significance of the issue

Thus, when estimating the lighting conditions in buildings, it is important to have an estimation criterion that takes into account the particular circumstances of visual work to the fullest extent possible: significant interior space inspections while the vision line in a specific range is in the moving process. For this purpose, the highly bright or spatial (integral) characteristics of the illuminative environment are considered to be the best. This is indicated by the works of A.A. Gershun [5], V.A. Drozdov and N.M. Gusev [6], L. Bloch [7], who believe that the quantitative and qualitative illumination aspects that identify its visual estimation are primarily measured by the brightness distribution over the space-limiting surfaces. Whereby, A.A. Geshun introduces the concept of "body's distribution of brightness" for the first time, and this concept directly and completely identifies the



visual perception that an eye will be getting in a specified light field single-point.

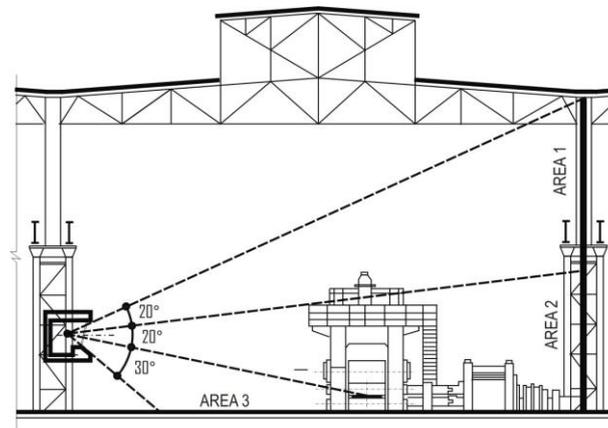


Figure 1. The sight field of the rolling mill operator.

The distribution of brightness, within the sight field of the operators in hot-rolling workshops, is determined by the difference in the luminance coefficients (reflection coefficients) in the particular areas of the coverage sectors (floor, wall, equipment, etc.), and additionally, by the distribution of the light flux over the illuminated surfaces and by the self-luminous metal existence in the sight field.

The researches have proved that, for a fixed vision line, the adaptation brightness is mainly governed by the surface brightness to which the observer's eye is directed to. [8]. For visual activities with a non-fixed vision line, the adaptation processes may not be taken into consideration because of their short duration, however, the adaptation brightness at each moment will depend upon the visual surface brightness and on the simultaneous (inductive) action of much more brighter periphery.

Nowadays, a number of countries (Britain, Germany, Russia, Japan, etc.) use integral characteristics as the criteria to assess the illumination quality: spherical illumination - $E_{4\pi}$, semispherical illumination - $E_{2\pi}$, cylindrical illumination - E_C , light vector - ε . This is connected to the fact that in a number of industrial practice cases, the illumination data on a horizontal or in any other way located level surface are considered to be subnormal to decide the fact as far as the illumination quality is concerned. The similar process deals with the illumination of the adaptation area [9].

The theoretical fundamentals of the light field were developed by A.A. Gershun [5]. The largest works relating to the spatial characteristics calculation belong to N.G. Boldyrev [10], M.M. Gurevich [11], M.M. Gutorov [12-14] and I. Gabel [15]. Practical use of spatial characteristics is devoted to the researches of N.M. Gusev [16], M.M. Epaneshnikov and T.N. Sidorova [17], H.N. Nuretdinov [18], V.I. Petrov [19], A.K. Soloviev [20], C. Cuttle, W.B. Valentine, J.A. Lynes, W. Burt [21], A.R. Bean [22] and to other scientists. Measurement and photosensor methods were developed by N.S. Ivanova, R.L. Folb, A.M. Fomina [23], L.E. Weis, S.I. Petrova [24], L.V. Kovalsky and M.U. Sakhnovsky [25].

Let's provide only some of the summaries we are being interested in, and which are contained in the research works listed above:

- horizontal illumination can not be taken as a characteristic for the light of the space;
- in spaces, where the visual line is considered to be the most possible, and the visual line and which is located in the horizontal surface or at a small angle to the horizon, the medium cylindrical illumination the most correctly characterizes the transferred sensation of the space saturation with the light;
- the average spherical illumination level does not always correctly reflect the developing perception of the light saturation;
- it is useful, in some cases, to have an integral characteristic where the function of the direction would be expressed more exactly than in the cylindrical or hemispherical illumination (this condition is

satisfied by semicylindrical and quaterspherical illumination);

- at present, the integral (spatial) characteristics of the light happen to have the limited application in the practice of designing and evaluating the light environment;

- researchers' experience illustrates that it is possible to develop recommendations to use these challenging criteria only after a careful study of specific types of visual activity.

3. Problem statement

We have developed the comfort index of visual sensations p [26] and have normalized its practical importance to work out the aims to assess the quality and to normalize the illumination of visual work areas for operators in hot workshops of metallurgical enterprises [27]. The above mentioned indicator is considered to be a function of several variables:

$$p=f(L_1, L_2, L_3, L_M, \omega_M), \quad (1)$$

L_1, L_2, L_3 - brightness of the upper, middle and lower of the interior areas, cd/m^2 ;

L_M - brightness of luminous metal, cd/m^2 ; ω_M - is the angular size of the glowing metal, sr.

For the specific workshop sections, the quantities L_M и ω_M have fixed values, thus, the function (1) is being simplified:

$$p=f(L_1, L_2, L_3). \quad (2)$$

At the same time, the integral characteristics of the light space E_{int} are also considered to be functions of the interior surfaces' brightness:

$$E_{int}=f(L_1, L_2, L_3). \quad (3)$$

Along with this, every characteristic integrates the brightness of the interior surfaces according to a particular law which is peculiar only to the very characteristic. And, it is quite possible, that among the set of integral characteristics it will be possible to single out the one, which reaction to the changing process of the interior areas brightness will be adequate to the sensitivity of parameter p to the similar brightness changes. In this case, it is possible to accept the E_{int} as a normalized quantity, while the quality control of the lighting should be reduced to the E_{int} measurement only in one point of the light field- to the location point of the operator's eyes.

The experiments to identify the integral characteristics with the properties which we are interested in, have been carried out on the laboratory device that we constructed ourselves [26]. For experiments, out of the theoretically substantiated integral characteristics, were selected the ones, where the function of direction in the horizontal direction have been more clearly expressed and, what is more, that function of direction corresponds to the characteristics of the visual operators' activity: E_V - vertical illumination; $E_{2\pi}$ - hemispherical illumination at the vertical position of the base and the hemisphere orientation towards the observation sector; E_{SC} - hemi-cylindrical illumination under the vertical location of the rectangular base, and under the horizontal arrangement of the bases in the form of semicircles and of the semi-cylindrical orientation towards the observation sector.

The integral characteristics' values of the light spaces were measured at the operator's eye location (viewing window) through the specially manufactured sensory device. To determine the dependencies (3) for integral characteristics, the experiment planning method was used. The researches have been made in the accordance with the three — factor plan by Box-Benkin [27].

The experiments has resulted in the following [28, 29]:

- the integral characteristics of E_V , $E_{2\pi}$ and E_{SC} have been significantly affected by the brightness of the interior lower zone;

- the brightness effect of the middle and upper zones of the interior is less significant, however, the effect of the middle zone's brightness is slightly stronger than the effect of the upper zone's brightness;

- the nature reaction of the E_V and E_{SC} to brightness changes in the interior areas is identical;

- for $E_{2\pi}$ is distinguishing a significantly lower reaction degree to changes in the brightness of the upper and middle interior areas;

- indicator p is characterized by a weak response to changes in the brightness of the upper zone and an active reaction to changes in the brightness of the middle and lower interior zones, notably, the brightness impact of the middle zone is the most colossal;

- as far as the degree of response to brightness changes of the upper zone $E_{2\pi}$, is concerned, it is much more preferable, however, to the extent of the reaction $E_{2\pi}$ and p to changes in the middle and lower zones' brightness, the required consistency hasn't been evidenced.

The analysis of the obtained results presented the foundations for the further researches and theoretical substantiation of the integral characteristic with a more exactly defined functionality of the direction line that measures the average illumination within a quarter of the sphere.

4. Theoretical part

For a quarter-spherical light receiver, the radiation function value is:

$$f(\beta) = \frac{1}{4}(\cos \alpha + \sin \alpha)(1 + \cos \beta); \text{ or } f(\beta) = \frac{1}{2}(\cos \alpha + \sin \alpha) \cos^2 \frac{\beta}{2}; \quad (4)$$

where α - is the angle between \vec{n} of one base and the direction of the light rays;

β - the angle between \vec{n} of the other base and the projection of the light rays' direction on this base.

While using N.G. Boldyrev's proposal [10] concerning the mathematical description of spatial luminous-technical characteristics as the functions of the single-point and of the direction, the formula for a quarter-spherical illumination can be represented in the following form:

$$E_{\pi} = \int_{\omega} L(\alpha, \beta) \frac{1}{4}(\cos \alpha + \sin \alpha)(1 + \cos \beta) d\omega = \frac{1}{2} \int_{\omega} (\cos \alpha + \sin \alpha) \cos^2 \frac{\beta}{2} dE_H \quad (5)$$

Under the average quarter-spherical illumination one means the average illumination of the spherical surface of the sphere quarter, in which the radius r tends to zero. In this case, the mathematical expression of the average quarter-spherical illumination produced by N with the single-point light sources is:

$$E_{\pi} = \lim_{r \rightarrow 0} \sum_N \frac{\Delta F_i}{\pi \cdot r^2}; \quad (6)$$

where ΔF_i - is the light flux, impinging upon the spherical surface of the quarter - sphere from the i light source,

πr^2 - is the area of the spherical quarter-sphere surface.

The quarter - sphere's position in space is being definitely determined by the directions of the sphere axis \vec{n}_O and the normals to semicircular bases \vec{n} directed toward the spherical surface.

The dimensions of a quarter-sphere are assumed to be infinitely little, so one can assume the fact that the light rays to be flowing from the single-point source will be parallel (Figure 2).

$$E_{\pi} = \frac{I_{\alpha} \pi r^2 (\cos \alpha + \sin \alpha)(1 + \cos \beta)}{l^2 4\pi r^2} = \frac{1}{2} E_{\perp} (\cos \alpha + \sin \alpha) \cos^2 \frac{\beta}{2}. \quad (7)$$

If the quarter-spherical light detector is oriented in accordance with Figure 3, then:

- illumination in point A horizontal plane is

$$E_{Ah} = E_{\perp} \cos \alpha; \quad (8)$$

- illumination in point A of the vertical plane which is said to be normal to the axis of the spherical surface \vec{n}_O

$$E_{Av} = E_{\perp} \sin \alpha \sin \beta \text{ or } \frac{E_{Av}}{\sin \beta} = E_{\perp} \sin \alpha. \quad (9)$$

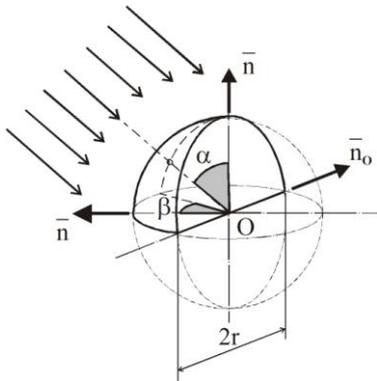


Figure 2. Calculation scheme to determine the function of the radiation value for a quarter-spherical illumination

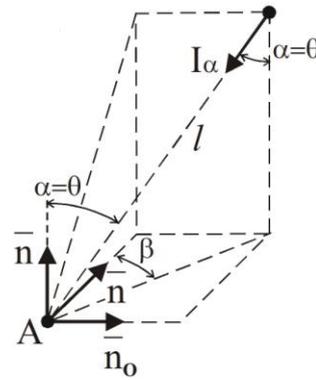


Figure 3. Calculation scheme to determine the quarter-spherical illumination from a single-point source of light

Taking into account the well-known expression for cylindrical illumination [13]

$$E_C = \frac{I_\alpha \sin \alpha}{\pi l^2}; \quad \frac{E_{Av}}{\sin \beta} = E_\perp \sin \alpha = \frac{I_\alpha \sin \alpha}{l^2} = \pi E_C. \quad (10)$$

The obtained mathematical dependence is used to generate the well-known expression for semicylindrical illumination [14]

$$E_{SC} = E_C + \frac{E_{Av}}{\pi}; \quad \pi E_{SC} = \pi E_C + E_{Av}; \quad E_{SC} = E_C + E_C \sin \beta = E_C (1 + \sin \beta). \quad (11)$$

While using the above demonstrated formulae, for the average quarter-spherical illumination $E_{\pi H}$ with the horizontal arrangement type of the axis for the spherical surface's fourth of the sphere, one can set down the following variants of the mathematical expressions:

$$E_{\pi H} = \frac{1}{2} \left(E_{Ah} + \frac{E_{Av}}{\sin \beta} \right) \cos^2 \frac{\beta}{2}; \quad (12)$$

$$E_{\pi H} = \frac{1}{2} (E_{Ah} + \pi E_C) \cos^2 \frac{\beta}{2}; \quad (13)$$

$$E_{\pi H} = \frac{1}{2} \left(E_{Ah} + \frac{\pi E_{SC}}{1 + \sin \beta} \right) \cos^2 \frac{\beta}{2}; \quad (14)$$

$$E_{\pi H} = \frac{1}{2} (E_{Ah} - E_{Av} + \pi E_{SC}) \cos^2 \frac{\beta}{2}. \quad (15)$$

5. Conclusion

The completed theoretical substantiation of the quarter-spherical illumination and the developed formulae to calculate it from a single-point light source, can be taken as the bases for further researches to develop the methods for calculating the quarter-spherical illumination from the luminous lines and from the large surfaces, and besides, to conduct the laboratory experiments with the quarter-spherical illumination.

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