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Analysis of the selected optical parameters of filters protecting against hazardous infrared radiation

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The paper analyses the selected optical parameters of protective optic filters used for protection of the eyes against hazardous radiation within the visible (VIS) and near infrared (NIR) spectrum range. The indexes characterizing transmission and reflection of optic radiation incident on the filter are compared. As it follows from the completed analysis, the newly developed interference filters provide more effective blocking of infrared radiation in comparison with the currently used protective filters.

Keywords: optical filters; interference filters; infrared radiation

1. Introduction

Worksites in glass and metal works, foundries, rolling mills, in the vicinity of hardening furnaces, rotary kilns in the cement industry, high-temperature laboratory furnaces, as well as firefighting, are associated, in addition to common mechanical hazards (e.g., due to splashes of molten metals and slag), sparks and direct contact with open fires, with hazards caused by emission of harmful optic radiation within the visible (VIS) and infrared (IR) spectrum range. Excessive exposure to IR radiation leads to dryness of the mucous membranes, burns of the eyeball and development of cataracts.[1]

Protection against thermal hazards due to excessive amounts of IR radiation reaching the eyes is provided by protective optic filters installed in spectacles, goggles or face protections. Besides protecting the user against hazardous IR radiation, such filters should ensure that the object/area of work can be seen clearly. If the level of IR radiation is very high, the use of filters reflecting radiation is recommended, as it allows the temperature increase in the filter itself to be reduced.[2,3]

The filters currently used for the protection of the face and eyes against hazardous IR radiation are of metallic reflective type, made of glass or organic material (mainly polycarbonate) bases coated with a single metallic layer for reflectance of IR radiation or absorption filters.

Absorption filters are manufactured from dyed glass obtained in a mass staining process by introduction of a factor modifying the radiation within the VIS and near infrared (NIR) spectrum range passing through the filter.

The effect of a protective optical filter obtained as a result of this process is based on absorption of a large proportion of optic radiation, whereas only a small proportion of radiation the filter is exposed to is reflected. Absorption leads to an increase in the filter temperature. This is an undesirable phenomenon, contributing to deterioration of the filter user's comfort.[2]

Reflective metallic filters are obtained by deposition of a metallic layer of copper (Cu) or gold (Au) on mineral or organic bases. Such filters take advantage of the characteristic properties of the metals used in their production, i.e., significant reflection coefficient for IR radiation and significant transmittance for the VIS spectrum.

Despite the fact that the technique of deposition of interference layers has been known for many years [4,5] the application of thin film IR filters in eye protections to block IR radiation is a new approach. The previous papers published by the authors of this study [6,7] contain descriptions of the structure of interference filters designed for application in eye protections – highly effective in reduction of IR radiation with high level of transmission of the VIS spectrum. The authors investigated also the optical and mechanical parameters of the newly developed protective optic filters manufactured with the use of interference technologies. The analysis of the results of the conducted tests demonstrated numerous advantages of interference technology application in the construction of protective filters, including: improved resistance to damage of the external protective filter surface (cracking, scratching etc.) as well as high reflection coefficients for the NIR spectrum.

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The aim of the present study was to compare the optic properties of protective filters manufactured by taking advantage of the interference technology and those coated with a single metallic layer reflecting IR radiation. The coefficients characterizing their optic parameters, allowing to assess the protective properties within the VIS and IR spectrum range were compared. The following coefficients were analysed [8]:

- luminous transmittance (τ_V),
- IR transmittance within the 780–1400 nm range (τ_A),
- IR transmittance within the 780–2000 nm range (τ_N),
- IR reflectance within the 780–2000 nm range (R_N),
- IR absorptance within the 780–2000 nm range (A_N),
- shade number (N).

The level of protection (shade number) is determined on the basis of luminous transmittance (the higher protection level correlates with the higher level of IR radiation blocked and appropriately lower VIS light transmittance). Protection level consists of a code number (e.g., 4) for IR filters and a shade number (e.g., 3, 5, 7) calculated according to the following equation [9]:

$$N = 1 + \frac{7}{3} \times \lg \left(\frac{1}{\tau_V} \right), \quad (1)$$

where τ_V = luminous transmittance.

For the particular level of protection, the mean IR transmittance within the 780–1400 and 780–2000 nm ranges as well as the IR reflectance and absorptance within the 780–2000 nm range are determined.

2. Test samples – filters protecting against hazardous IR radiation

For comparative analysis of the metallic reflective filters available in the market versus the interference filters developed by the authors, the following samples were prepared for the tests:

- off the shelf metallic reflective filters on a polycarbonate base (flat parallel plate of 50 mm diameter and 2 mm thickness with a metallic layer of copper (Cu) – protection levels: 4-3, 4-5, 4-7);
- interference filters on a polycarbonate base (flat parallel plate of 50 mm diameter with interference coating made up of the following materials: aluminium, H4 – LaTiO₃ substance and silicon dioxide).

The protection levels, luminous transmittance and symbols used for marking the tested filters are presented in Table 1.

Table 1. Characteristics of the filters.

Symbol	Luminous transmittance τ_V (%)	Protection level	Filter type
Cu 4-3	14.133	4-3	Metallic reflective
ITF 4-3	9.082	4-3	Interference
Cu 4-5	2.021	4-5	Metallic reflective
ITF 4-5	1.470	4-5	Interference
Cu 4-7	0.353	4-7	Metallic reflective
ITF 4-7	0.160	4-7	Interference

Note: Protection level consists of code number (4) for infrared filters and shade number (3, 5, 7) calculated according to equation (1).

3. Testing methodology

Optical properties of the filters were measured with a Cary 5000 Spectrophotometer (Varian, Australia). The spectrophotometer enabled transmittance or reflectance of optical radiation within the VIS and NIR spectrum to be recorded with 1 nm steps and 0.001% resolution level. Spectral transmittance and reflectance measurements were carried out within the wavelength range of 780–2000 nm. The quartz halogen lamp was used as a source of radiation. To detect transmitted or reflected radiation the photomultiplier tube and lead sulphide detector were used for VIS and NIR spectrum, respectively. Spectral transmittance was measured with incident radiation falling normally on the filter surface in the visual centre (defined as in [9]). For spectral reflectance an integrated sphere was used. The measurements were taken every second owing to the high absorption of investigated filters within the NIR region. Since the minimum averaging time of the Cary 5000 Spectrophotometer was 0.0125 s, the values of transmittance or reflectance were measured 125 times for a given wavelength. The aforementioned coefficients were calculated from the following equations [10–12]:

- luminous transmittance

$$\tau_V = \frac{\int_{380 \text{ nm}}^{780 \text{ nm}} \tau(\lambda) \cdot V(\lambda) \cdot S_{D65\lambda}(\lambda) \cdot d\lambda}{\int_{380 \text{ nm}}^{780 \text{ nm}} V(\lambda) \cdot S_{D65\lambda}(\lambda) \cdot d\lambda}, \quad (2)$$

where $\tau(\lambda)$ = spectral transmittance, $V(\lambda)$ = spectral visibility function of the average human eye for daylight or night vision, [13] $S_{D65\lambda}(\lambda)$ = spectral energy distribution of Standard Illuminant D65 [13];

- IR transmittance within the 780–1400 nm range

$$\tau_A = \frac{1}{621} \int_{780 \text{ nm}}^{1400 \text{ nm}} \tau(\lambda) \cdot d\lambda, \quad (3)$$

where $\tau(\lambda)$ = spectral transmittance;

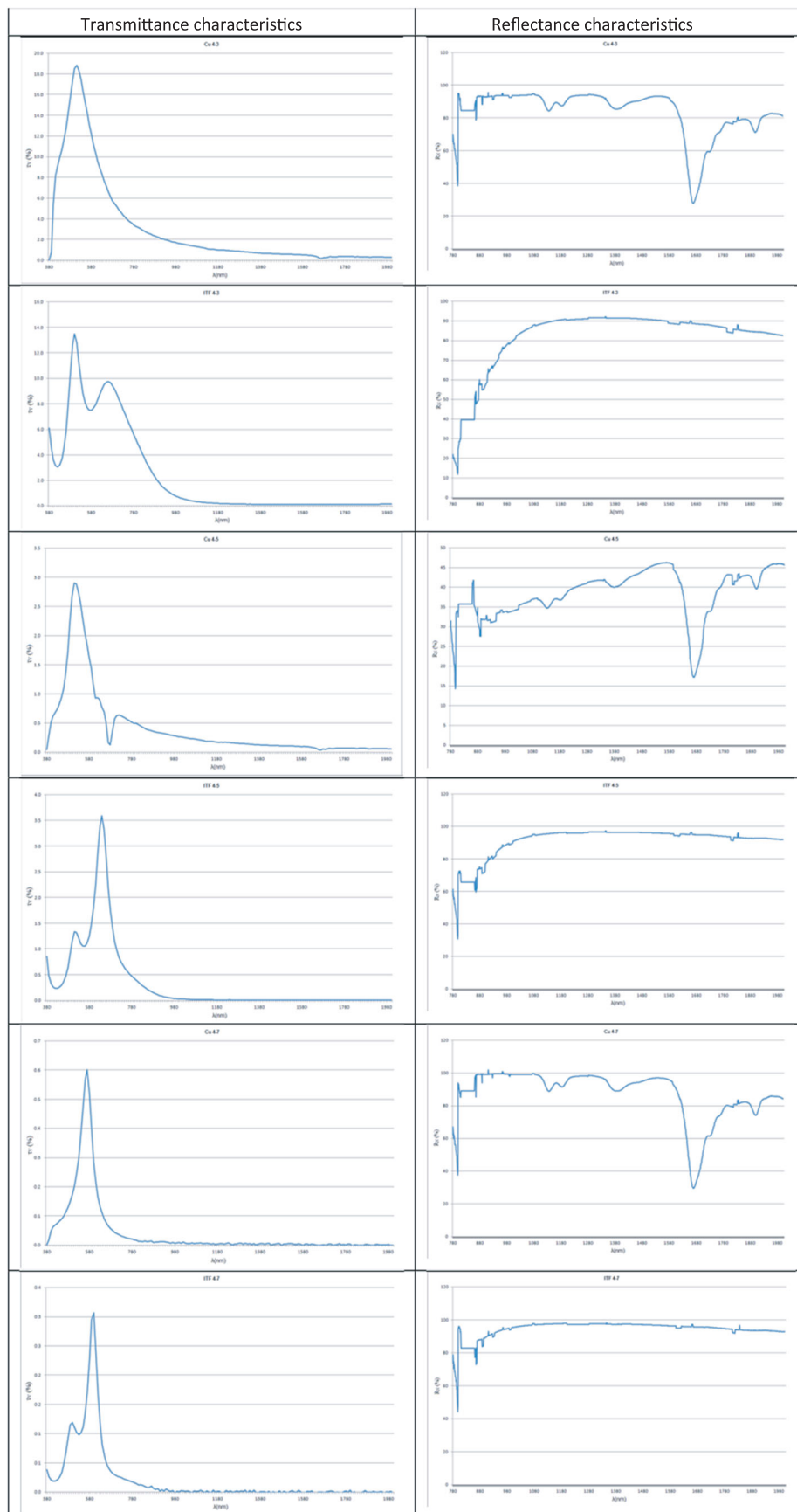


Figure 1. Transmittance and reflectance characteristics of the studied filters.
 Note: Cu 4-3 = metallic reflective filter; ITF 4-3 = interference filter; Cu 4-5 = metallic reflective filter; ITF 4-5 = interference filter;
 Cu 4-7 = metallic reflective filter; ITF 4-7 = interference filter.

Table 2. Infrared transmittance within the 780–1400 and 780–2000 nm range, infrared reflectance within the 780–2000 nm range and infrared absorptance within the 780–2000 nm range.

Symbol	Infrared transmittance τ_A and τ_N (%)		Infrared reflectance R_N (%)	Infrared absorptance A_N (%)
	τ_A 780–1400 (nm)	τ_N 780–2000 (nm)	R_N 780–2000 (nm)	A_N 780–2000 (nm)
Cu 4-3	1.486	0.942	83.516	15.542
ITF 4-3	1.003	0.563	82.084	17.353
Cu 4-5	0.216	0.134	87.319	12.547
ITF 4-5	0.038	0.006	91.037	8.957
Cu 4-7	0.004	0.023	88.308	11.669
ITF 4-7	0.004	0.039	94.312	5.649

- IR transmittance within the 780–2000 nm range

$$\tau_N = \frac{1}{123} \int_{780\text{nm}}^{2000\text{nm}} \tau(\lambda) \cdot d\lambda, \quad (4)$$

where $\tau(\lambda)$ = spectral transmittance;

- IR reflectance within the 780–2000 nm range

$$R_N = \frac{1}{1221} \int_{780\text{nm}}^{2000\text{nm}} \zeta(\lambda) \cdot d\lambda, \quad (5)$$

where $\zeta(\lambda)$ = spectral reflectance;

- IR absorptance within the 780–2000 nm range

$$A_N = 1 - (R_N + \tau_N), \quad (6)$$

where R_N = IR reflectance within the 780–2000 nm range, τ_N = IR transmittance within the 780–2000 nm range.

The factor before integrals corresponding to the value of the measurement step at the measurement of spectral characteristics.

4. Results

Figure 1 presents the transmittance and reflectance characteristics of the studied filters.

Table 2 presents the values of coefficients determined on the basis of equations (3)–(6).

5. Discussion

Optical radiation within the 780–1400 nm spectrum range passes through the anterior compartment of the eye, the lens and reaches the retina. Exposure to an excessive amount of radiation from this range can result in burns of the retina and, in extreme cases, its permanent damage. Radiation above 1400 nm can cause burns and damage to the sclera. Consequently, chronic long-term exposure may lead to the development of cataracts, referred to as IR or glass worker's cataracts. In view of the above, the spectral transmittance for the 780–1400 and 780–2000 nm ranges was compared. The results presented on the graphs

in Figure 1 and the determined transmittance values (see Table 2) indicate unequivocally more effective blocking of IR radiation provided by interference filters. The values of τ_A and τ_N for interference filters are lower even by an order of magnitude than those obtained for the metallic reflective filters. For instance, the mean value of IR transmittance within the 780–2000 nm range for interference filters with protection level 4-5 (one of the most common protection levels used in the metallurgic industry) equals 0.006% and is significantly lower than the maximum acceptable value specified in [12], which is 10.6%.

For all the investigated filters, the values of R_N exceed 60%, which classifies them in the group of filters with increased IR reflectance.

The levels of the IR absorptance for metallic reflective filters and interference filters of 4-3 and 4-5 protection class are similar. For the highest of the investigated protection levels – 4-7 – the value of that coefficient is twice lower for interference filters. The above findings are important for selection of a filter appropriate for the radiation source. The selection of filter protection level is dependent on the temperature of the radiation source. The 4-7 level is used for radiation sources whose temperature exceeds 1600 K (e.g., occurs in the metallurgic industry). With such high temperatures, reduction of filter heating as a result of exposure to IR radiation is important.

As it follows from comparative analysis of the optic properties of filters taking advantage of the interference technology and filters coated with a single metallic layer reflecting IR radiation, the interference filters provide a more effective blocking of IR radiation in comparison with the currently used protective filters.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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