ORIGINAL ARTICLE

Occupational Exposure to Infrared Radiation in Aluminum and Cast-Iron Foundries in Zanjan, Iran

FARAMARZ MAJIDI[1], KAMALEDIN ABEDI[2*] and SEYED REZA AZIMI PIRSARAEI[1]

[1]Department of Occupational Health, Zanjan University of Medical Sciences, Zanjan, Iran; [2*]Department of Occupational Health, Faculty of Health and Paramedical Sciences, Zanjan University of Medical Sciences, Zanjan, Iran.

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ABSTRACT

The harmful effects of the long-term ocular exposure to cumulative levels of infrared radiation (IR) in glassblowing and foundries have been recognized since the late 19th century. These effects include cataracts, keratitis, and chronic dry eye problems. Therefore, infrared radiation measurements are critical and need to be assessed regularly in the industries and workplaces where there are high temperature furnaces, such as in the glass industries and foundries. However, IR measurement is not very simple, especially when the range of interest is one in which radiometers are not available, as for the IR-B and IR-C ranges, and commonly available radiometers have a limited sensitivity range. The present article deduce a calculation method for evaluating of IR irradiance based on Planck's radiation law for black body radiation and using an IR detector sensitive in the spectral range 750-1150 nm. Based on this method, workers exposure was assessed to all harmful wavelength ranges of IR radiation in three foundries (two aluminums and one cast-iron). The results suggested that IR-A and IR-B radiation (wavelength from 770 nm to 3000 nm) in the mentioned foundries were more than TLVs (threshold limit values) given by ACGIH. There were significant risks of health hazards due to IR radiation exposure. Personal protective equipment should be used in order to prevent serious damage to eyes and skin, and selection of appropriate equipment should be on an individual basis due to different radiation exposure.

Keywords: *Infrared radiation, Planck's law, Worker exposure, Foundry*

INTRODUCTION

The Radiation in wavelength range between 780 nm and 1 mm in the electromagnetic spectrum is known as infrared (IR) radiations. The infrared region is often divided into three sub – ranges:

1. IR-A, or near infrared (770 to 1400 nm)
2. IR-B, or midinfrared (1400 to 3000 nm)
3. IR-C, or far infrared (3000 to 1000000 nm)

The three infrared spectra distinguished among different penetration depth into tissues, IR-A penetrates several millimeters and IR-C does not penetrate beyond and the uppermost layer skin cells [1]. IR radiation can cause significant changes in human tissues [2]. Infrared radiation is absorbed by almost all structures of the eye. IR-A radiation is absorbed in the lens of the eye significantly and other wavelengths grater than 1400 nm (IR-B & IR-C) are absorbed by the cornea [3]. It is shown that, in accordance with Goldmann's theory when visible light or IR-A reaches the eye, the radiation is absorbed by the iris and converted into heat which is then *conducted* to the lens and causes cataracts. In addition, IR-B and IR-C in the cornea converted into heat and induces cataracts in the lens indirectly. An IR-A laser exposure, or heat conducted from the exposed pigmented iris or aqueous humor, can also cause a

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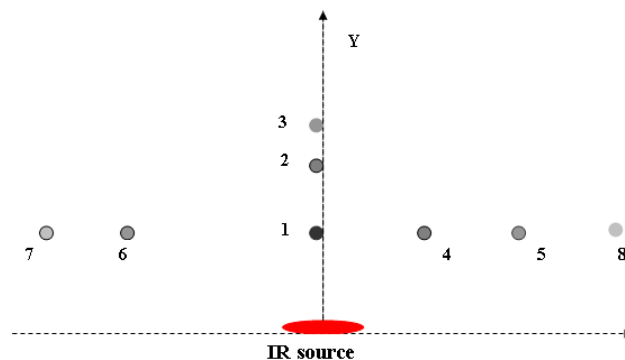*Corresponding author: Kamaledin Abedi, Email: kamal.abedi@gmail.com

Fig 1. Configuration of 8 measurement points position at eye level of workers

cataract. When human's skin exposes to high level of IR radiation, it gets warm and results in pain and burns. A considerable proportion of visible and IR-A radiation is reflected, especially from fair skin, but the proportion of which the IR-B and IR-C absorbed is greater than 90% [3].

Although exposure of the skin to strong IR may lead to local thermal effects and even serious burns, especially if the exposure covers the whole body as, for example, in front of an aluminum or cast-iron forge, the most serious damage of infrared radiation is the induction of cataract in the eye lens. Cataract associated with occupational infrared exposure has been known since 1739, and the correlation between cataract and working with metals at melting temperatures have been shown in previous studies [4]. It was believed at the beginning of 20th century that IR-induced opacities were the result of the direct absorption of the radiant energy by the crystalline lens, therefore , only a small proportion of IR radiation (near infrared or IR-A:770-1400nm), which can penetrate deeply into the eye, was responsible for the cataract. Recent occupational observations led to the view that both direct absorption by the lens and indirect heating of the lens fibers through the absorption of the iris and cornea (propagation of the thermal energy to the lens by thermal conduction through the surrounding tissues) were responsible for the IR-induced opacities. Hence, both the short and long wavelength radiation in the IR ranges, through different mechanisms, can induce cataract.

In the case of aluminum and cast-iron foundries, workers exposure to IR-B and IR-C radiation is particularly important, because for the typical forge temperatures, the largest irradiance fraction is in the IR-B and IR-C ranges.

Based on the wide sources of IR radiation and its health hazards, it is necessary to measure IR irradiance in every range. Therefore, for both short- and long-term exposure, maintaining effective safety guidelines and protective IR radiation measures are important and need to be assessed regularly in any workplace.

In general, measurements in the optical region are very complex , especially when the desired range is something in which radiometers are expensive and difficult to calibrate , as for the IR-B and IR-C ranges,

and more commonly available radiometers detect only the ranges between 750-1150 nm (IR-A).

In these cases, some calculation methods have been suggested in the literature to expand the measured irradiance by the instrument to irradiance of the range of interest [5, 6].

This study presents a method for evaluating workers exposure to infrared radiation. Finally, the results of measurements and evaluations of aluminum and cast-iron foundries compare with the threshold limit values given by ACGIH [7].

MATERIALS AND METHODS

Our measurements were carried out in three different foundries (Two aluminums and one cast-iron) in Zanjan City, central Iran, during molten state of the metals. Workers exposure was measured near three ovens, indicated in the following as aluminum (No. 1 & 2) and cast-iron oven.

The ovens apertures were circular and opened during all of the working phases. The apertures diameters were 50 and 70 cm for aluminum and cast-iron ovens respectively. The all ovens are enveloped by an insulating external wall and the molten metal is located inside the oven like in a hole.

The spectral irradiance was measured using a Hagner digital radiometer (EC1 IR) sensitive in the spectral range 750-1150 nm. According to the manufacturer, this radiometer was calibrated and recalibration is necessary every two-three years under normal use of the instrument that is done by manufacturer. The measurements were performed in six points in the centerline perpendicular to the IR source and other work stations at eye level of exposed workers in different postures as Fig. 1. Points 7 and 8 were the worker`s eye level in two work stations but they were not located in the radiation zone and measurements were not performed in these points. In addition, the ovens temperature was measured with an optical pyrometer model AR922 manufactured by SMARTSENSOR Company sensitive in the range between 200-2200 °C.

Exposure evaluation in all ranges of industrial hygiene interest has been obtained by a calculation method discussed in the following section. Application

Table 1. The values of coefficient K for given wavelengths (IR-A & IR-B) based on source temperature

T (°c)	IR-A	IR-B	T (°c)	IR-A	IR-B
600	36.10	2588.5	940	12.98	174.06
640	30.82	1699.58	1000	11.45	124.73
700	24.87	963.87	1100	9.56	77.13
740	21.85	685.20	1200	8.19	50.95
800	18.32	430.59	1300	7.18	35.51
840	16.45	324.78	1400	6.40	25.86
900	14.20	220.55	1500	5.80	19.54

Table 2. IR irradiance near cast-iron foundry (molten temperature: 1480°C)

Measurement Points	r^* (cm)	IR meas† (w/cm^2)	IR-A (w/cm^2)	IR-B (w/cm^2)	$E_{IR-only}$ (w/cm^2)
1	120	501×10^{-4}	0.3	1.03	1.33
2	141	371×10^{-4}	0.22	0.76	0.98
3	170	192×10^{-4}	0.11	0.39	0.5
4	200	172×10^{-4}	0.10	0.35	0.45
5	223	36×10^{-4}	0.02	0.07	0.09
6	270	25×10^{-4}	0.01	0.05	0.06

* Direct distance of IR detector,the eye level of workers in different postures, from oven.
†IR radiation was measured with EC1-IR Hagner radiometer.

of the method as a practical tool and the field verification measurements will be provided in another paper.

Calculation method

The wavelength ranges of interest in the field of biological effects of IR radiation as mentioned by ICNIRP guidelines and ACGIH recommended exposure limits is very large and lies between 770-3000 nm, but the common available radiometers have a limited sensitivity range. In such cases, a calculation method is suggested. In this method, estimation of the IR radiation in any spectral range of interest is followed as a function of the irradiance measured in the sensitivity range of the available instrument. From this method, IR irradiance in any spectral range of interest is given by the following equation [8].

$$E(\lambda_1 - \lambda_2) = E_{det\,ector}^{750-1150} \times \frac{\int_{\lambda_1}^{\lambda_2} d_\lambda L_\lambda(T)}{\int_{750}^{1150} d_\lambda R_\lambda L_\lambda(T)}$$

(1)

Where $E(\lambda_1-\lambda_2)$ is IR irradiance in wavelength range of interest , $E_{detector}$ is the IR irradiance measured by the Hagner digital radiometer (EC1 IR) sensitive in the spectral range 750-1150 nm , $L_\lambda(T)$ is the spectral radiance which is calculated by Planck's law of radiation equation (2) and R_λ is the spectral sensitivity of Hagner digital radiometer given by manufacturer.

$$L_\lambda(T) = (\frac{2\pi c^2 h}{\lambda^5})(e^{hc/k\lambda T} - 1)^{-1}$$

(2)

Where c= 2.997925×10^8 m s^{-1} is the vacuum speed of light, h=6.6256×10^{-34} js is planck's constant, k = 1.380662×10^{-23} jk^{-1} is boltzmann's constant, T is the blackbody temperature and the wavelength λ is expressed in meters (m).

E (λ_1-λ_2) is defined as the spectral irradiance and $L_\lambda(T)$ as the spectral radiance of a given source. Also $L_\lambda(T)$ is considered for a black body source while E (λ_1-λ_2) is estimated for a real source (the ovens). By a factor N, we can establish a relationship between E (λ_1-λ_2) and $L_\lambda(T)$. This factor depends on distance from the source, the direction of observation and emissivity factor of the emitting source and is applied to both the numerator and denominator of fraction in equation (1). Thus, the ratio is independent of N and it can be removed from the equation.

For convenience, the right side of equation (1) is written as follows:

$$K = \frac{\int_{\lambda_1}^{\lambda_2} d_\lambda L_\lambda(T)}{\int_{750}^{1150} d_\lambda R_\lambda L_\lambda(T)}$$

(3)

Table 1. shows this coefficient calculations for given wavelengths (IR-A & IR-B) and source temperatures that was developed and estimated by Excell software.

By knowing the coefficient K and having the detector measurements, the spectral irradiance of the IR source between any wavelength range of interest (IR-A & IR-B & IR-C) is obtained.

RESULTS

In the case of prolonged exposures (t_{exp}>1000 sec), ACGIH recommends a limit for the irradiance at the

Table 3. IR irradiance near aluminum foundry No.1 (molten temperature: 660°C)

Measurement Points	r* (cm)	IR meas† (w/cm²)	IR-A (w/cm²)	IR-B (w/cm²)	$E_{IR-only}$ (w/cm²)
1	40	3.97×10^{-4}	23×10^{-4}	81×10^{-4}	104×10^{-4}
2	50	3.09×10^{-4}	18×10^{-4}	64×10^{-4}	82×10^{-4}
3	60	2.11×10^{-4}	12.5×10^{-4}	43×10^{-4}	55.5×10^{-4}
4	84	0.26×10^{-4}	1.5×10^{-4}	5.3×10^{-4}	6.8×10^{-4}
5	110	0.22×10^{-4}	1.3×10^{-4}	4.5×10^{-4}	5.8×10^{-4}
6	116	0.2×10^{-4}	1.1×10^{-4}	4.1×10^{-4}	5.2×10^{-4}

*Direct distance of IR detector,the eye level of workers in different postures, from oven.
†IR radiation was measured with EC1-IR Hagner radiometer.

Table 4. IR irradiance near aluminum foundry No.2 (molten temperature: 680°C)

Measurement Points	r* (cm)	IR meas† (w/cm²)	IR-A (w/cm²)	IR-B (w/cm²)	$E_{IR-only}$ (w/cm²)
1	30	13.09×10^{-4}	77×10^{-4}	270×10^{-4}	347×10^{-4}
2	50	4.06×10^{-4}	24×10^{-4}	84×10^{-4}	108×10^{-4}
3	80	1.48×10^{-4}	9×10^{-4}	31×10^{-4}	40×10^{-4}
4	85	0.48×10^{-4}	2.8×10^{-4}	9.9×10^{-4}	12.7×10^{-4}
5	114	0.45×10^{-4}	2.7×10^{-4}	9.3×10^{-4}	12×10^{-4}
6	140	0.17×10^{-4}	1×10^{-4}	3.5×10^{-4}	4.5×10^{-4}

* Direct distance of IR detector,the eye level of workers in different postures, from oven.
†IR radiation was measured with EC1-IR Hagner radiometer.

cornea level of 10 mW/cm² for radiation in the IR range 770-3000 nm (IR-ACGIH range).

For exposure durations greater than 10^3 sec (17 mins), an acceptable exposure is present when:

$$E_{IR-only}\left[W/cm^2\right] \leq 0.01$$

(4)

As regards the exposure duration of workers with infrared radiation was more than 17 mins, thus the equation (4) used for evaluating exposure levels of the workers to IR radiation.

The results of measurements and calculations were compared with the TLVs (threshold limit values) given by the (ACGIH).

Table 2, 3 and 4 respectively show the results of measurements with the calculation method previously described for exposure to IR-A and IR-B radiation of workers dedicated to one cast-iron and two aluminum foundries.

From Table 2, it is evident that the minimum of $E_{IR-only}$ was 0.06 w/cm² that is more than TLVs recommended by ACGIH (0.01w/m²). This result showed that the IR radiation (IR-A and IR-B) could be hazardous for cornea and lens of eyes.

The results of IR measurements in two aluminum foundries were shown in tables 3 and 4. From these tables, it is evident that the minimum of $E_{IR-only}$ is 4.5×10^{-4} w/cm². It does not exceed the threshold exposure values recommended by ACGIH (0.01 w/m²). In the case of aluminum foundries, only the measurement points that located on the vertical line perpendicular to the ovens had radiation values more than TLVs.

The results suggested that IR-A and IR-B radiation (wavelength from 770 nm to 3000 nm) in these foundries were more than TLVs given by the (ACGIH)

[4] thus, IR radiation may have harmful effects on the cornea and lens in these foundries.

DISCUSSION

The aim of this study was the evaluation of workers exposure to IR radiation in aluminum and cast-iron foundries and comparison its results with the threshold limit values given by ACGIH.

As it has been shown in IR wavelength range 770-3000 nm the workers exposure to IR radiation in all foundries (aluminum and cast-iron) exceed the TLVs given by ACGIH [4].

Sisto *et* al [8] reported a general method of evaluating exposure to infrared radiation (IR-A, IR-B, IR-C). The results of measurements and evaluations in two traditional Italian glass factories are reported and compared with the TLVs given by ACGIH. Intense exposures in the IR-B and IR-C ranges have been found for some workers, exceeding the limit by a large factor. Also Okuno [9] reported that exposure to intense optical radiation leads to the development of infrared cataracts in the workplace. It is suggested that IR cataracts are induced by IR-B or IR-C in the workplace. Olanrewaju *et al* [10] investigated the levels of optical radiation exposure in glassblowing and to determine type(s) of protective eyewear commonly used. In craft glassblowing, which employs furnace systems, irradiance levels exceeding the TLVs for near infrared (760-1100 nm) were obtained.

Since IR radiation in the 770-3000 nm range (IR-A, IR-B) has the highest heat effect on eye (cornea and lens), according to the results of our study, the workers exposure to IR radiation due to molten furnace should be avoided unless the workers wear the eye protectors and/or increasing the distance from it. The durations of workers exposure naer molten furnace agree with the exposure durations recommended by ACGIH that is

limited to lower than 17 minutes. This study showed that variation exists in aluminum and iron-cast foundries ocular radiation exposure due to different molten metals and heating systems, therefore selection of appropriate eye protector should be on an individual basis.

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