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ORIGINAL ARTICLE

Application of a Model to Evaluate Infrared Exposure Limits in Aluminum Foundries Based on Threshold Temperature in the Range of 770-1400 nm

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ABSTRACT

High intensity optical radiation can cause damage to the eye and intense radiation in the range of 770-1400 nm can cause thermal retinal damage. In the workplaces where there are high temperature sources, the workers in front of these hot sources without bright light maybe exposed to the intense IR radiation, thus regular measurement of these radiations seems crucial. Measurement of IR radiations by radiometer in specific wavelength ranges is elusive. Moreover, when radiometers are used, the correct application of the recommended exposure limits requires knowledge of spectral radiance which seems sophisticated for hygienists. The main objective of the present study is applying a model to express retinal thermal injury in terms of temperature for molten aluminum ovens in an aluminum foundry that emit optical radiation without visible light. In the proposed model, ACGIH TLVs for retinal thermal injury in the range of 770 to 1400 nm was used where source luminance was under 0.01 cd cm^{-2}. Also, by using the output results of this proposed model it is possible to present a new chart for evaluation of exposure to IR for hot sources based on Threshold Temperature.

KEYWORDS: *IR Radiation, Model, Aluminum Foundries, Exposure Limits, Threshold Temperature*

INTRODUCTION

Following the American Conference of Governmental Industrial Hygienists Threshold Limit Values (ACGIH TLVs) measurements of exposure to Near Infrared Radiation (NIR) in the range of 770-1400 nm for retinal thermal hazard, require the calculation of weighted integrals of the incident radiation spectrum. At present there is no suitable detector available for measurements of the optical radiation from 770 to 1400 nm, though using radiometers for measuring the IR radiation is routine. Also, a serious problem is that the risk of retinal thermal damage needs to be evaluated from weighted integrals in NIR the range of 770-1400 nm [1, 2]. To solve these problems, a number of solutions have been proposed by researchers. For instance, Sisto et al. proposed a model for IR radiation exposure in traditional glass factories toevaluate the workers IR exposure, when the sourcecan be approximated as a blackbody [3]. This study has shown that without irradiance measurementsand only by using a model, it is possible to evaluate IR radiation through simple geometry. A method based on Planck's radiation law proposed by Madjidi et al[4]. In this method workers exposure was assessed to all harmful wavelength ranges of IR-A and IR-B radiation (wavelength from 770 nm to 3000 nm) and the results were compared with TLVs given by ACGIH. Also, Madjidi et al. proposed methods for a Planckian emitter to replace the acceptable effective spectral radiance to protect against retina, cornea and lens thermal injuries based on ACGIH TLVs in terms of Threshold Temperature [5-6]. By using this method the IR effective spectral radiance from a Planckian source has been replaced by temperature in the TLVs criteria already given by the ACGIH to protect against retina, cornea and lens thermal hazard from visible light and NIR radiation. Moreover, the hygienists will not need to use sophisticated units such as Watt per square meter per steradian to assess the retinal hazard by

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IR radiation. In this study, for the first time, Threshold Temperature has been used instead of effective spectral radiance for retinal thermal hazards based on recommended ACGIH TLVs for assessing retinal thermal hazard for NIR sources where a strong stimulus are absent. The Threshold Temperature was calculated by the proposed model for two Planckian sources, molten aluminum ovens, in the foundry workshops. The model description along with main results and the conclusion are presented in the following sections.

MATERIALS AND METHOD

The details of mathematical procedure and the main equations used in the proposed model have been given in Madjidi et al. [5]. Here some descriptions of the model for evaluating the retinal thermal hazards are given as follows:

Applied ACGIH TLVs for IR sources without bright light : To protect against retinal thermal injury from NIR sources, the effective spectral radiance of source based on ACGIH TLV is defined as follows:

$$L_R = \sum_{770}^{1400} L_\lambda \, R_\lambda \, \Delta\lambda \qquad (1)$$

Or in the integral form it could be rewritten:

$$L_R = \int_{770}^{1400} L_\lambda \, R_\lambda \, d\lambda \qquad (2)$$

Where L_R is the effective spectral radiance (W/m^2sr), L_λ is the spectral radiance and R_λ is the retinal thermal hazard function and λ is the wavelength. For acceptable limits of visible and near IR radiation, the exposure duration and the apparent diameter of source (α), must be considered. The ACGIH TLV expressions for sources with NIR sources without bright light where source luminance is under 0.01 cd cm^{-2} (e.g. molten aluminum) are listed in Table 1[1].

Table1. Acceptable effective spectral radiance, L_R, to protect Retinal thermal injury based on ACGIH TLVs used for molten aluminum where luminance is under 0.01 cd cm^{-2}.

Exposure duration(s)	Acceptable L_R($Wcm^{-2}\, sr^{-1}$)
Less than 810 s	$< 3.2/\alpha\, t^{0.25}$
Greater than 810 s	$\leq 0.6/\alpha$

The equations in table 1 are applied in the model.

Applied Equation of Retinal Irradiance Exposure Limits in the model: Retinal Irradiance Exposure Limits (RIELs) or threshold retinal irradiance can be calculated based on pupil diameter, source diameter, focal length, viewing distance and apparent diameter of the source [2]. The final equation which describes the RIELs is given by the following equation 3. The detail of retinal irradiance exposure limits are given in [7, 8]:

$$E_{R_{ACGIH}} = \gamma \, R_{ACGIH} \;\; \tau \; \left(d_p\right)^2 \qquad (3)$$

Where E_{RACGIH} is the RIELs, $\gamma = 2700\ m^{-2}$, $\tau = 0.9$, and R_{ACGIH} is weighted Integral of spectral radiance exposure limit, and d_p is the pupil diameter and is 7 mm [6]. If one of the conditions in table 1 was achieved, the calculation loop in model would stop and the final temperature, which was denoted here as Threshold Temperature, was shown in output.

RESULTS

Test of the model: At first it is necessary to test accuracy of the model for predicting the irradiance of IR radiation from molten aluminum surfaces in ovens at different distances. For this reason a study was conducted in an aluminum foundry. As depicted in Fig.1, with a Hagner Detector Model 320, which operated in the range of 750 to 1150 nm, the irradiance of three points on the normal line to the surface of the each molten aluminum oven measured. The diameters of ovens were 40 cm and the temperatures of oven1 and oven2 were 933 K and 953 K respectively.

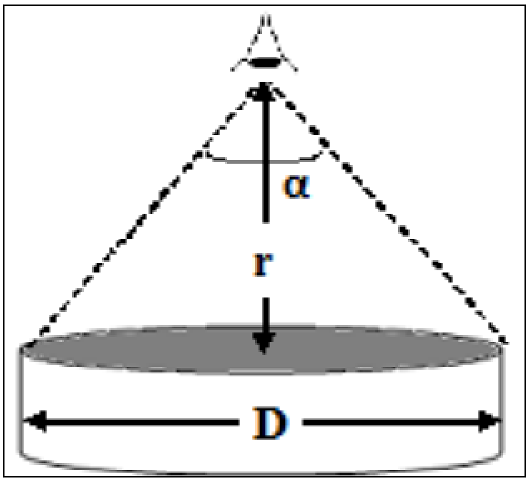

Fig.1. A schematic of the measurement point on the normal line to the surface of the molten aluminum ovens. D, r and α (= D/r) are the oven diameter, viewing distance and apparent diameter respectively.

After running the model in the range of 750 to 1150 nm, the variations of oven irradiances vs. viewing distance are shown in Figs. 2 and 3.

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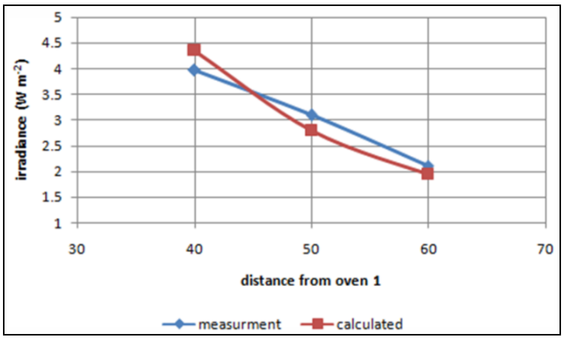

Fig 2. Irradiance of molten aluminum in oven 1 (T=933 K), plotted as a function of distance from molten surface

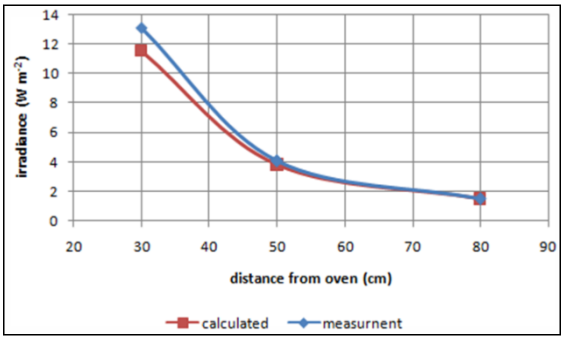

Fig 3. Irradiance of molten aluminum in oven 2 (T=953 K), plotted as a function of distance from molten surface

In Table 2 the details of measured and calculated data and Relative Error (%) between measurements and calculations for each point are shown.

Table 2. Comparison between measured and model results of IR irradiance emitted in the wavelength ranges 770 to 1400 nm, by two molten surfaces at different distances.

Oven (Temperature)	r (cm)	α = D/r (rad)	Irradiance Measured	(Wm^{-2}) Model	RE%
1 (953 K)	80	0.5	1.48	1.48	0
	50	0.8	3.79	4.06	6
	30	1.23	11.53	13.10	11.98
2 (933 K)	60	0.66	1.94	2.11	14.2
	50	0.80	2.79	3.09	7.7
	40	1.00	4.36	3.97	5.7

Replacement of effective spectral radiance recommended by ACGIH TLVs with Threshold Temperature for near IR radiations: The main objective of this proposed model is to replace the effective spectral radiance (Wm^{-2} sr^{-1}) with the term Threshold Temperature (^{o}C), recommended by ACGIH TLVs for near IR radiations for the workers in front of molten aluminum ovens. To this end the spectral radiance, source apparent diameter and viewing duration recommended by ACGIH for prevention of retinal thermal injury from near IR radiation have been applied in the proposed model. After running the model for different positions of eye levels to the hot sources (ovens), the calculated Threshold Temperatures for each oven are shown in Table 3.

Table 3. Calculated Spectral radiance, Retinal Irradiance and Threshold Temperature of aluminum molten surfaces by model for exposure duration of t = 1s.

Oven (Molten Temperature)	r (cm)	Spectral radiance ($Wm^{-2}sr^{-1}$)	RIEL (Wm^{-2})	Calculated threshold temperature by Model (K)	Acceptable exposure	Non acceptable exposure
1 (T=953 K)	80	1.48	7595	1118	√	
	50	3.79	4754	884		×
	30	11.53	2844	684		×
2 (T=933 K)	60	2.41	5694	968	√	
	50	2.39	4757	884		×
	40	3.74	3792	790		×

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In Fig. 4, the boundaries between acceptable and non-acceptable IR exposure for two molten ovens, in terms of Threshold Temperature, are shown.

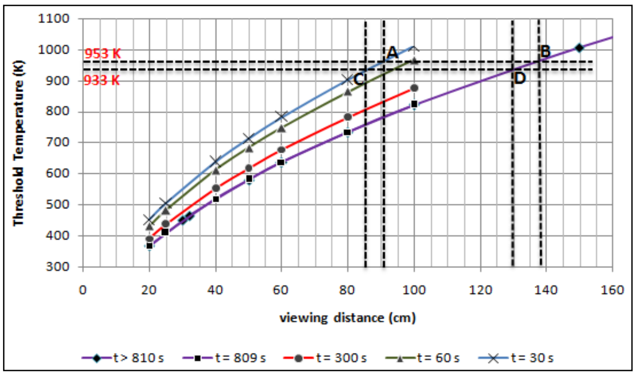

Fig 4. Estimated Threshold Temperature based on ACGIH TLV, plotted as a function of viewing distance for two molten aluminum ovens ($T_{oven\ 1}$= 933 K and T_{oven2}= 953 K) and for the exposure duration $t \geq 1.0$ s. The right and left hand of points A (953 K, 91 cm), B (953 K, 138 cm), C (933 K, 85 cm) and D (933 K, 130 cm) which located on curves, show acceptable and non-acceptable exposures respectively. Due to the curve related to exposure time of 300s completely located in the left hand of lines 953 K and 933 K, it shows non-acceptable exposure.

As the exposure limit values show in Table 1, the variations of acceptable IR irradiances in the range of 770-1400 nm are dependent on source apparent diameter. Obviously, due to oven diameters and viewing distances in this research, it was impossible to see more variations between viewing distances and Threshold Temperatures in Fig. 4 for $\alpha < 0.1$ rad.

DISCUSSION

As previously described, the main aim of this research was replacing ACGIH TLVs for retinal thermal hazard for workers that are exposed to near IR radiation in front of molten aluminum ovens, with Threshold Temperature by a model. Therefore, the test of proposed model is necessary. As the Fig. 2 and 3 show, it seems obvious that the proportions of irradiance variations vs. distance from molten surfaces by the model calculation are more promising than those of measurements. In addition, the results in Fig. 2 and 3 and Table 2, show that with the increase of distance from sources (decrease of source apparent diameter), the irradiance decreases, but not proportional to inverse square distance, because the IR sources under these conditions are non-point sources.

It seems that the increase of relative error between measurements and the model for different viewing distances in Table 2 could be from additional IR radiations, except ovens, that come from other hot surfaces in the workshop. Table 3 shows to decide whether the IR is permissible or not, instead of comparison between measured/calculated spectral radiance and current TLVs, the comparisons were made between source temperature and calculated temperature namely Threshold Temperature. The comparisons between temperature of molten sources and calculated Threshold Temperature by model showed that the IR exposure for different situations in the range of 770 to 1400 nm in front of aluminum oven 1 and aluminum oven 2, were acceptable/not acceptable. Besides, Table 3 shows that the value of effective spectral radiance limits and Retinal Irradiance Exposure Limits (RIELs) are dependent on the apparent diameter of IR sources based on recommended ACGIH TLVs formula in Table 1. For example, the effective spectral radiance and RIEL values increase where source apparent diameter increases, but Threshold Temperature decreases. In other words, the Threshold Temperature is higher when the RIELs is lower and vice versa. This means that when the eye level is closer to the oven for acceptable exposure to IR radiation, the Threshold Temperature value must decrease.

The method for accessing whether an observer has an acceptable/ non-acceptable IR exposure, only by using source temperature and Threshold Temperature, has been described by Madjidi et al. [5], but here it is necessary to introduce a new chart for applied using of this proposed method. By using this chart, it is possible to determine easily whether the acceptable/non-acceptable exposures for workers have occurred or not. As depicted in Fig. 4, the Threshold Temperatures against viewing distances and exposure durations are plotted. By intersection of these plotted curves with source molten temperature line, these curves are divided into two parts, left and right hand side of the intersection points. The left part of curves that have lower temperatures than source temperature, demonstrates non-acceptable exposure and the right hand of curves demonstrates acceptable exposure. Likewise for the molten aluminum ovens, e.g. for the molten aluminum oven 1 with temperature of 953 K and exposure duration t=30 s, as depicted in Fig. 4, the viewing distances 100 and 80 cm are located in right and left hand side of intersection point A respectively. Thus the IR exposure for exposure duration t=30 s, is acceptable for viewing distance of 100 cm and not acceptable for viewing distance of 80 cm.

In general, the calculated Threshold Temperature by this model could replace the unit of W m^{-2} sr^{-1} with ^{o}C or ^{o}F. However, at present due to the lack of previous related studies, it may be necessary to conduct other experiments to estimate Threshold Temperatures with more accuracy based on ACGIH TLVs or INCIRP guidelines for retinal thermal injury.

CONCLUSION

The present model expresses the Threshold Temperature for retinal thermal injury based on recommended ACGIH TLV for two molten ovens in the aluminum foundries. The input data for this model are the ACGIH TLV formulas for retinal thermal injury, viewing distance, ovens diameter and prolonged exposure duration for receptors. The model output data are effective spectral radiance, retinal irradiance exposure limit and Threshold Temperature for each receptor position. By comparing the calculated Threshold Temperatures and molten aluminum temperatures, without using IR meter, it was easily determined by a chart, whether for each receptor position, the exposure of near IR in the range of 770-1400 nm emitted from ovens is acceptable or non-acceptable.

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