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EXPERIMENTAL AND THEORETICAL ANALYSIS OF HEADLIGHT SURFACE TEMPERATURE IN AN INFRARED HEATED STRESS RELIEVING OVEN

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Abstract: In this study, the IR heated stress relieve oven, was experimentally and theoretically examined. In experimental measurements, temperature was measured on headlight surface, placed in IR oven, at various conveyor speeds and various distances between IR lamps and headlight surface. In theoretical study, a mathematical model was developed for the headlights surface temperature by using heat transfer theory. The results obtained by the mathematical model and the measurement showed very good agreement with 6.5% average error. It is shown that mathematical model can be used to estimate the surface temperatures in case of different conditions were run in oven.

Keywords: IR, Stress Relieving Oven, Mathematical Model

Infrared Isıtmalı Gerilim Giderme Fırınında Far Yüzey Sıcaklığının Deneysel ve Teorik Analizi

Öz: Bu çalışmada, infrared (IR) lambalar ile çalışan bir gerilim giderme fırını deneysel ve teorik olarak incelenmiştir. Deneysel çalışmada, farklı konveyör hızları ve ısıtıcı mesafeleri için far yüzeyindeki sıcaklıklar ölçülmüştür. Teorik çalışmada ise ısı transfer ifadeleri kullanılarak bir far yüzeyindeki sıcaklıkların tahmini için bir model oluşturulmuştur. Matematik modelden elde edilen sonuçlar deneysel veriler birbirine benzerlik göstermiş ve deneysel veriler ile karşılaştırıldığında ortalama % 6.5' lik bir fark bulunmaktadır. Matematik modelin farklı çalışma şartlarında far yüzeyinin sıcaklığını tahmin etmede kullanılabileceği gösterilmiştir.

Anahtar Kelimeler: IR, Gerilim Giderme Fırını, Matematik Model

1. INTRODUCTION

IR heaters are used as heating and drying purposes in the industry. IR drying of paints, coatings, adhesives, ink, paper, board, textiles, etc. can be found in the literature (Mujumdar, 2015; ASHRAE, 2000). Sandu (1986) pointed out the advantages of IR drying in foods. It is shown that drying time can be decreased significantly compared with conventional systems (Sandu, 1986). IR heaters are also used in manufacturing processes in industry like forming or preheating applications of materials. Hasanati et. al. (1983, 1988) made experimental and theoretical studies of IR drying with opaque and semitransparent materials. Monteix et. al. (2011) examined the interaction between IR heater and semitransparent polyethylene materials by experimentally and numerically. Cosson et. al. (2011) simulated the preheating stage of PET

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bottles by using heat transfer models and ray tracing method . Bordival et. al. (2009) optimized the temperature distribution on the PET bottles to perform a uniform thickness. Heat transfer inside a commercial food drying oven was modeled and validated by Dhall et. al (2009). IR irradiation can be focused on a small area using an elliptical reflector where it is needed (Lee et. al., 2014). Cenkowski et. al. (2004) developed a mathematical model for heat and mass transfer in continuous IR micronization based on the radiation exchange principle in an enclosure. Electrical IR lambs are also important research field. In general two types of IR heaters are most widely used: medium-wavelength gas burner IR heater and short-wavelength electric IR heater (Pettersson and Strenström, 2000). Pettersson and Strenström (2000) developed a model for an electric IR heater. Schmitd et al. (2003) made an experimental set-up to compare the energy efficiency of three different emitters that used in thermoforming process of the thermoplastic sheets. Chang and Hwang (2006) developed a simulation of the infrared surface rapid heating system for injection molding and studied the heating ability of the rapid surface heating system with different reflector types.

In the lens of a car headlight (transparent part of the headlight) is produced by injection and thermal stress occurs on the surface due to production methods. Engineers designed an IR heated oven instead of previously used conventional stress relieving oven which requires natural gas as fuel. All parts of the headlight are heated in the conventional ovens, while the heat treatment is needed only on the surface of the headlight. Thus, IR heated ovens would be more proper for this applications. The distance between lamps and the headlight and the conveyor speed should be well-defined to provide a good treatment process. If the lamps are too close to headlight or conveyor speed is very slow, the surface of the headlight would get overheated and unacceptable deformations may occur on the headlight surface. On the other hand, being lamps too far from the surface or very fast conveyor speed causes poor surface quality where heat treatment cannot take place successfully. In this study the experimental and numerical analysis were made for headlight surface temperature in the electric IR heated stress relieving oven. The effect of conveyor speed, distance between heaters and headlight were investigated while the car headlight in the oven. In experimental study, the temperature change, measured from the headlight surface, was determined according to time at different conveyor speeds and different distances between IR heater lamps and headlight surface. The results were compared and discussed.

2. MATERIALS AND METHODS

2.1. Experimental study

The working drawing of the IR heated oven, used in experiments, was given in Fig. 1. IR heaters, used in oven, are IRT402XLNC brand and every heating system has four infrared lamps with gold-plated reflectors. The specifications of the IR lamps were given in Table 1.

Temperature was measured from top of the headlight surface. For continuity, two headlights were used in experiments. One is used in the oven, the other is left for cooling. During the experiments measurements were taken from the same point. Conveyor speeds in measurements were 0.65 cm/s, 0.7 cm/s, 0.75 cm/s and the distance between IR heaters and the headlight surface were 450 mm, 550 mm and 650mm. For each case at least three experiments were made and the averages of the results were taken to compare with calculations.

After measurement points have been identified, K type thermocouples have been fixed to these points by special heat-resistant adhesive tape. In temperature measurements, Easytrack model of Datapaq companies’ data logger was used. The specifications of measurement instrument were given in Table 2. The measurement instrument has a special box, not to be affected by heat while it is in the oven and it is not removed from the box during the measurements.

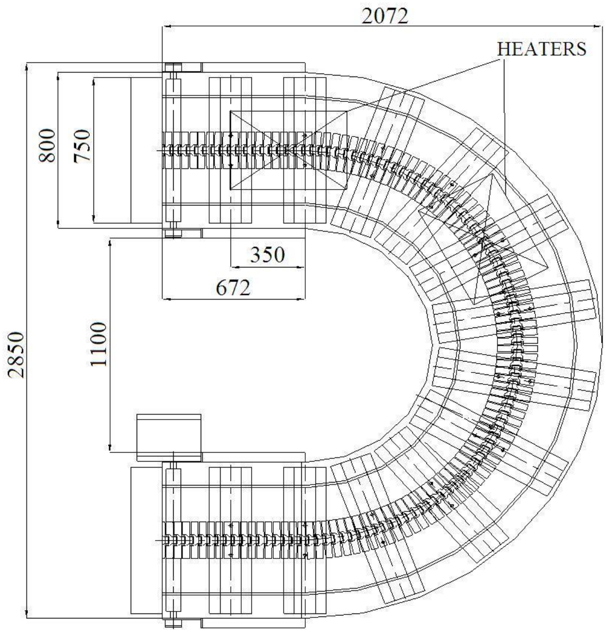


Figure 1:
Working drawing of the IR heated oven used in experiments

Table 1. Specifications of the IR lamps

Voltage (Volt)	380
Fuse (Amp)	10
Power (kW)	6
Frequency(Hz)	50 – 60
Current (A)	16
Max. Drying Temperature (°C)	170
Sound Level (dBA)	< 70

Table 2. Specifications of the thermocouples

Measurement Range (°C)	-150….500
Sensitivity (°C)	±0.5
Thermocouple Type	K

Before starting the measurements, calculation of the conveyor speed is required. For this, at the entrance section of the oven, two lines, 50 cm distance between each other, were drawn. The conveyor speed was calculated by measuring conveyor pass time between two lines. After conveyor speed was determined and the measurement instrument and the headlight were placed on the conveyor, measurements were started. During measurements the oven was not switched off and operation of the oven provided. The headlight, just came out from the oven, was left outside for cooling

The material of the lens part of headlight is polymethyl methacrylate (PMMA) that has thermoplastic and transparent plastic properties. Properties of lens material were given in Table 3.

Table 3. Properties of lens material

Density (kg/m³)	940-1210
Specific heat (J/kg)	1460-2050

2.2. Theoretical study

Headlight surface temperature change according to time is considered to be under influence of natural convection and radiation heat transfer and following equation can be written [1].

$$mc_p \frac{dT_s}{dt} = h_g A_s (T_g - T_{s1}) + Q_r \tag{1}$$

The rate of surface temperature change according to time $\frac{dT_s}{dt}$, can be calculated as in Eq. 2.

$$\frac{dT_s}{dt} = \frac{T_{s2} - T_{s1}}{t_2 - t_1} \tag{2}$$

T_{s2} can be estimated using Eq. 1 and 2.

$$T_{s2} = \frac{h_g A_s (T_g - T_{s1})(t_2 - t_1)}{mc_p} + \frac{(t_2 - t_1) Q_r}{mc_p} + T_{s1} \tag{3}$$

In these equations m is mass of heated part of the headlight surface, c_p is specific heat of headlight surface, T_s is surface temperature of the headlight, h_g is heat transfer coefficient, A_s is headlights surface area, T_g is ambient air temperature, Q_r is radiation heat transfer.

In this study two different heat transfer coefficients (h_g) were calculated. While the headlights surface is cooler than the ambient air at the initial time that it entered into the oven, Nusselt number was calculated using formula for surface of a cold horizontal plate (Ra≈$1x10^7$) (Eq. 4) (Çengel, 2003). After the surface temperature reached the ambient air temperature, Nusselt number was calculated using formula for upper surface of a hot plate (Ra≈ $3.5x10^7$) (Eq. 5) (Çengel, 2003). Average calculated h_g was 5.41 W/m^{2}K.

$$Nu_L = 0.27 Ra_L^{1/4} \tag{4}$$

$$Nu_L = 0.15 Ra_L^{1/3} \tag{5}$$

The oven conveyor was divided into 15 virtual parts and the surface temperature was calculated by Eq. 1. in every parts. Radiation heat transfer Q_r was calculated by Eq. 6.

$$Q_r = Q_{es} + Q_{sw} \tag{6}$$

Q_{es} shows the radiation heat transfer between the IR heater and the headlight surface and Q_{sw} shows the radiation heat transfer from the headlight surface to oven walls. The Stefan-Boltzman law can be used to estimate infrared output capability if the values are known (Çengel, 2003). Q_{es} and Q_{sw} were calculated by expression of radiation heat transfer between two surfaces (Eq. 7-8) (Çengel, 2003). In these equations σ is the Stefan-Boltzmann constant 5.67x10^{-8} W/m^{2}K^4, T_e is the temperature of IR heater, ε_e is 0.26 the emissivity of the IR lamps (Pettersson and Strenström, 2000), A_e is the IR heater surface area, F_{es} is view factor between

IR heater and the headlight surface, ε_s is the emissivity of the headlight surface, A_s is the headlight surface area, T_w is the temperature of the oven walls, F_{sw} is view factor between headlight surface and oven walls, A_w is the oven walls area, ε_w is the emissivity of the oven walls.

$$Q_{es} = \frac{\sigma(T_e^{\,4} - T_s^{\,4})}{\dfrac{1-\varepsilon_e}{A_e - \varepsilon_e} + \dfrac{1}{A_e F_{es}} + \dfrac{1-\varepsilon_s}{A_s \varepsilon_s}} \tag{7}$$

$$Q_{sw} = \frac{\sigma(T_s^{\,4} - T_w^{\,4})}{\dfrac{1-\varepsilon_s}{A_s - \varepsilon_s} + \dfrac{1}{A_s F_{sw}} + \dfrac{1-\varepsilon_w}{A_w \varepsilon_w}} \tag{8}$$

Table 4. View factors between IR heater and the headlight surface

Distance between IR heaters and headlight surface (mm)	450		550		650	
Conveyor No	F_{e1s}	F_{e2s}	F_{e1s}	F_{e2s}	F_{e1s}	F_{e2s}
1	0.0016	0.0000	0.0026	0.0000	0.0043	0.0000
2	0.0030	0.0000	0.0063	0.0003	0.0061	0.0000
3	0.0088	0.0060	0.0098	0.0003	0.0130	0.0002
4	0.0232	0.0021	0.0259	0.0012	0.0246	0.0019
5	0.0650	0.0028	0.0622	0.0044	0.0536	0.0060
6	0.2291	0.0127	0.1821	0.0160	0.1284	0.0149
7	0.2153	0.0564	0.1748	0.0593	0.1418	0.0401
8	0.0512	0.2064	0.0537	0.1670	0.0652	0.0917
9	0.0115	0.1875	0.0143	0.1478	0.0277	0.1469
10	0.0046	0.1050	0.0070	0.0936	0.0124	0.1166
11	0.0027	0.0329	0.0020	0.0363	0.0035	0.0388
12	0.0003	0.0083	0.0003	0.0126	0.0004	0.0193
13	0.0000	0.0018	0.0000	0.0014	0.0000	0.0026
14	0.0000	0.0014	0.0000	0.0008	0.0000	0.0013
15	0.0000	0.0004	0.0000	0.0007	0.0000	0.0003

The view factors between the IR heater surface and headlight surface and between headlight surface and oven walls have been realized using Fluent software (Table 4-5). Surface-to-surface (S2S) radiation model was used to determine the view factors. The S2S radiation model is good for modeling the enclosure radiative transfer without participating media (Ansys Fluent, 2012; Sevilgen and Kılıç, 2011).

Table 5. View factors between headlight surface and the oven walls

Distance between IR heaters and headlight surface (mm)	450			550			650		
Conveyor No	F_{sw1}	F_{sw2}	F_{sw3}	F_{sw1}	F_{sw2}	F_{sw3}	F_{sw1}	F_{sw2}	F_{sw3}
1	0.2534	0.2063	0.1859	0.2548	0.2063	0.1838	0.2451	0.1994	01766
2	0.3152	0.2513	0.2279	0.3169	0.2513	0.2236	0.3112	0.249	0.214
3	0.3496	0.2589	0.258	0.3545	0.2589	0.2525	0.3588	0.2578	0.2442
4	0.407	0.225	0.2765	0.4142	0.225	0.268	0.4169	0.2261	0.2618
5	0.4361	0.2082	0.2723	0.4442	0.2085	0.2644	0.4437	0.2126	0.2616
6	0.4557	0.1902	0.2296	0.4655	0.194	0.234	0.4726	0.1948	0.2427
7	0.4782	0.179	0.2322	0.4896	0.1824	0.2314	0.4937	0.1829	0.2337
8	0.4821	0.1806	0.2335	0.4936	0.1839	0.2329	0.4967	0.1881	0.2397
9	0.4663	0.1902	0.2287	0.4766	0.1947	0.235	0.4906	0.1928	0.2357
10	0.4657	0.1921	0.2783	0.474	0.1928	0.2726	0.478	0.1962	0.2643
11	0.4553	0.1982	0.3028	0.4619	0.1982	0.2947	0.4718	0.1944	0.2884
12	0.4266	0.2159	0.288	0.4291	0.2159	0.284	0.4407	0.2114	0.281
13	0.3584	0.2582	0.257	0.3599	0.2583	0.2569	0.3605	0.2572	0.2558
14	0.3216	0.2483	0.2229	0.3228	0.2484	0.2223	0.3241	0.2482	0.2222
15	0.2507	0.2056	0.1815	0.2506	0.2057	0.1805	0.2515	0.2064	0.1801

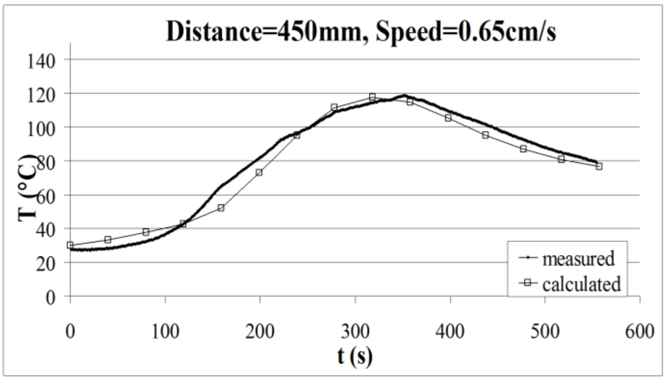
3. RESULTS AND DISCUSSION

At the initial time that headlight entered in the oven, the natural convection is effective. While the temperature of the ambient air inside the oven is higher than that of headlight surface temperature at steady conditions, heat is transferred from the ambient air to headlight by natural convection. Headlight surface was rapidly heated by radiation when the headlight entering the view field of the heater, depend on distance between heater and headlight surface. After the headlight surface exceeds the ambient temperature, heat transfer occurs from headlight surface to environment by natural convection. This case happens approximately 200 s, after the headlight is put in to the oven. The headlight continues to warm up under influence of IR heater and reaches the maximum temperature approximately in 300 s. Due to increasing headlight surface temperature and the headlight exiting form the view field of the IR heaters, natural convection, from headlight surface to environment, increases and the headlight enters to the cooling zone.

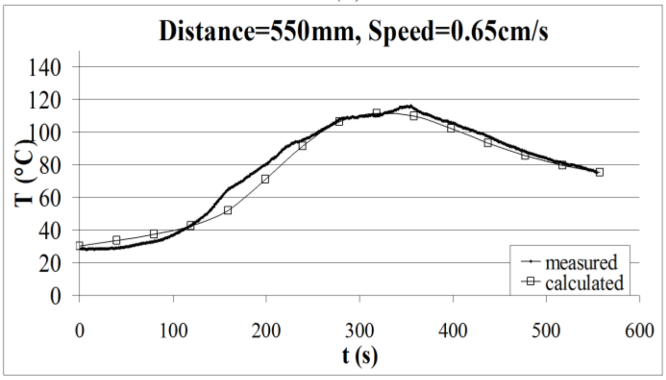
The most important parameters affecting the headlight surface temperature are conveyor speeds and distances between the headlight surface and IR heater. Headlight surface temperature is increasing at lower distances between surface and IR heaters and by reducing the conveyor speeds. The distance between the IR heaters and headlight surface is a more effective parameter than conveyor speed.

By using the model, calculations show very good agreement with the measured temperature from the headlight surface. Calculated and measured values are compatible with each other and the average error is about 6.5% as seen in Figures 2, 3 and 4.

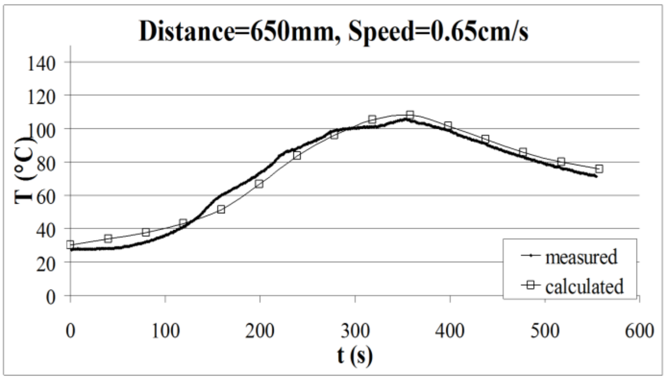
As seen in Figures 2, 3 and 4 the largest deviation between measured and calculated values varies according to conveyor speeds and occurs between 160-240 s for 0.65 cm/s, between 150-230 s for 0.7 cm/s and 140-210 s for 0.75 cm/s conveyor speeds. The maximum error emerged for the case of 450 mm distance between IR heater and headlight surface and 0.7 cm/s conveyor speed in 150th second. The calculated values are closer to the measured values where the distance between IR heaters and the headlight surface is 500 mm. In case of 450 mm distance between headlight surface and IR heaters, calculated temperatures are lower than measured temperatures with the error 7.1%. For 650 mm distance between headlight surface and the IR heaters, calculated values are higher than measured values with the error 6.81%.



(a)



(b)



(c)

Figure 2:

Headlight surface temperature change according to time for 0.65 cm/s conveyor speed; Distance between headlight surface and IR heaters: a) 450 mm b) 550 mm c) 650 mm

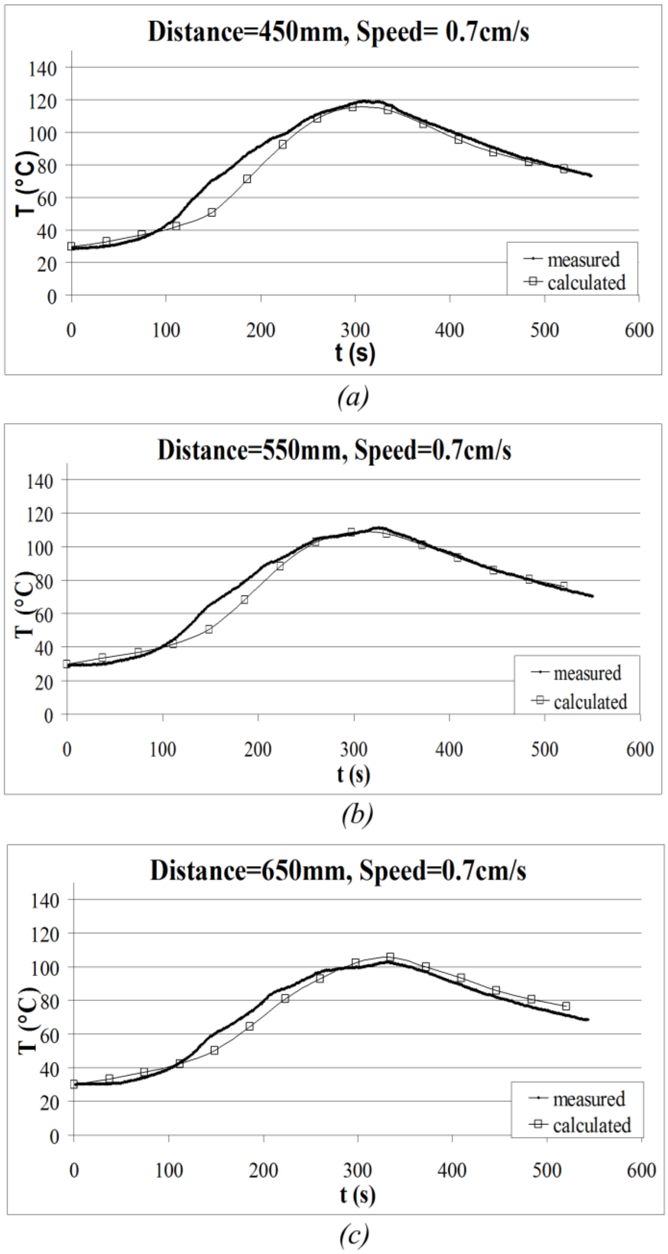
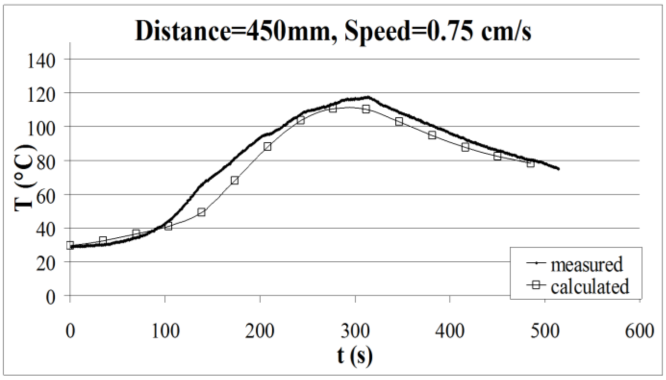
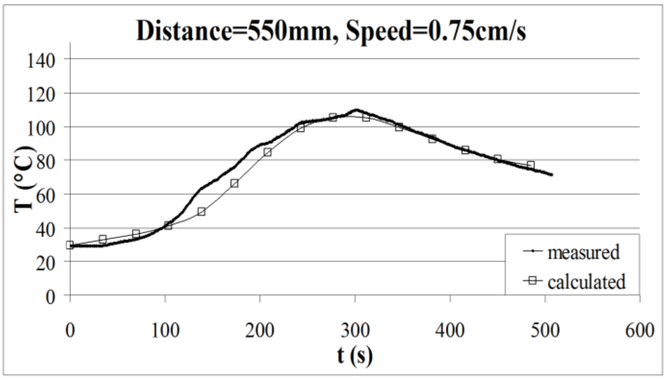


Figure 3:

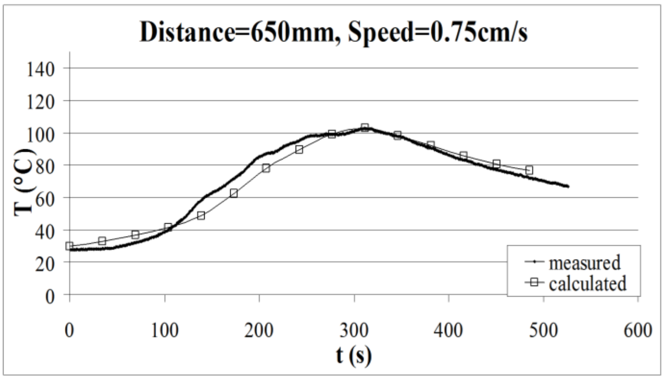
Headlight surface temperature change according to time for 0.7 cm/s conveyor speed; Distance between headlight surface and IR heaters:
a) 450 mm b) 550 mm c) 650 mm



(a)



(b)



(c)

Figure 4:

Headlight surface temperature change according to time for 0.75 cm/s conveyor speed; Distance between headlight surface and IR heaters:
a) 450 mm b) 550 mm c) 650 mm

4. CONCLUSIONS

In this study, the IR heated stress relieving oven was analyzed theoretically and experimentally. Developed theoretical model shown compliance with experiments and the error, between theoretical calculations and experimental results, is lower than 6.5%. In theoretical model, the change of temperature according to time on the headlight surface can be obtained by entering the values of conveyor speed and the distance between headlight surface and IR heaters. Therefore the conveyor speed and the distance between headlight surface and IR heaters that obtain the most appropriate stress relieving temperature can be found by using the model.

The measurements and the calculation were made for the top of the headlight surface. In case of lack of flat geometry of the headlight surface, different temperatures can be occurred in different regions. Searching these temperatures and applicability of the above model will be useful to investigate. Especially by researching the radiation properties of the headlights at different wavelengths, IR oven can be made more efficient and gas burning IR heated systems can be also investigated. The study on economic benefits of using the IR power adjustable lambs may also be helpful in future studies.

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