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ESTIMATION OF FURNACE TEMPERATURE DISTRIBUTION USING DIGITAL PHOTOGRAPHIC IMAGES

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Abstract

Present work proposes a novel, low cost non-contact, temperature measurement technique using consumer grade digital still camera. The images of various visible heat sources are captured. A number of visible heat sources are used to get zones of different colours and temperature data is acquired by placing a standard miniature thermocouple in each colour zone. The colour temperature correlation is established by applying various analytical methods. The results indicate that the image-based measurements agree with the corresponding contact measurements within an error range of about 5%. The technique is successfully used for measuring the temperature distribution of different industrial applications like muffle furnace, salt bath furnace etc.

Key words: digital still camera, visible heat source imaging, non-contact temperature measurement, furnace temperature distribution

Introduction

Temperature measurement is an important requirement in many industrial processes. At present conventional devices and techniques such as contact-type sensor and pyrometers are used to measure the temperature of various sources of heat. With several visible sources of heat such as the furnaces, Bunsen burner, incandescent lamps, and oil lamps, the installation of a sensor is difficult, if not impossible. Whenever fast measurement is needed (e.g. welding), conventional sensors like resistance temperature detection (RTD) thermocouples do not meet the demand.

Large boilers, ovens, furnaces of different types and other industrial heat sources generally use thermocouples to monitor temperatures at strategic locations to identify hot spots. Thermocouples fail, and need to be replaced periodically. Replacing thermocouples inside a boiler or furnace requires shutting down the unit. As shutdown is being a laborious and time consuming process, many users wait until sizable number of thermocouples fail before shutting down the process, thus crippling efficiency and preventive maintenance programs.

Non-contact measurement techniques like pyrometers indicate temperature of the targeted location only. For getting overall temperature distribution it is required to scan the surface area using optical /radiation pyrometer but it is not advisable to keep the furnace door open for a long time. Thus, there is a need to develop a low cost system useful in giving non-contact type of temperature estimation system giving point source temperature as well as temperature distribution.

In the area of non-contact temperature measurement the techniques developed and used are based on the spectral distribution or pyrometry. One of the researches presents work on colour spectrum characterization of methane flame under various burning conditions using red, green and blue (RGB) and hue saturation value (HSV) colour models instead of resolving the real physical spectrum. The results demonstrate that each type of flame has its own characteristic distribution in both the RGB and HSV space [1]. In few more studies radiation thermometer is used. A radiation thermometer consisted of an optical system to collect the energy emitted by the target; a detector to convert this energy to an electrical signal. [2]

Other research work estimated the profile of a spectral distribution of an illuminant by shooting several known color chips illuminated by the light source under measurement. [3]

This survey reveals that area of non-contact temperature measurement using digital photography is still virgin for further research. An attempt is made to meet the demand using a consumer grade digital camera.

Digital still cameras (DSCs) have gained significant popularity in recent years. The development of digital cameras has opened up possibilities for powerful new diagnostic techniques employing two-dimensional imaging [4]. Digital photography is a fast technique and requires no other sensor, once the colour temperature correlation is established.

Most of the heat sources emit light as a function of temperature. It is possible to acquire the image to get total temperature distribution. If an image of a source could be acquired, post-processing techniques could be developed to estimate or predict the temperature. Correlated colour temperature is one of the indexes to characterize the light source [5].

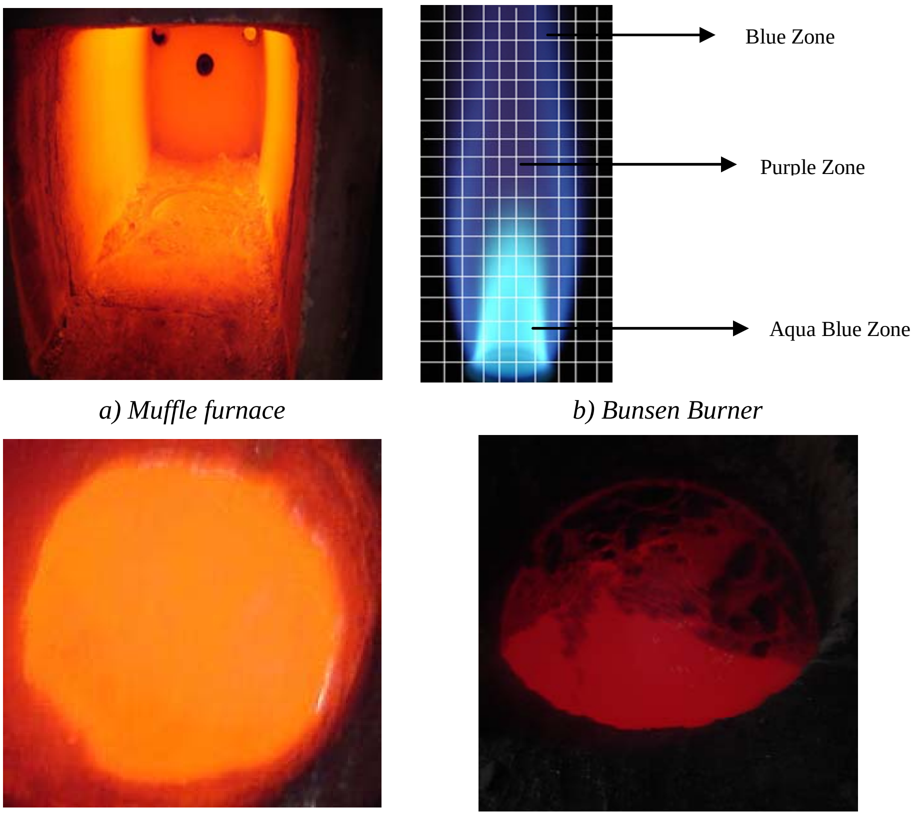
Qualitative visualization for the temperature measurement is done using digital camera [6]. By establishing colour temperature correlation a low cost, non-contact temperature measurement technique would be a viable solution for getting temperature of large visible heat sources like furnaces, ingots, molten mass etc.

In the present work, a DSC of known resolution is used to capture image of several visible sources of heat and colour temperature correlation is established.

Experimental

Source image acquisition

A consumer grade DSC (SONY, DSC-S60) is used to capture the images of various sources. It is desired that the device bandwidth should be greater than the source bandwidth. To verify if the camera is having adequate bandwidth, the camera (CCD sensor) spectral response is obtained. It is ensured that the camera has enough bandwidth to cover the visible range (400 - 700 nm). Number of images of various heat sources like muffle furnace, salt bath furnace, Bunsen burner, oil lamps, domestic stoves etc. are captured, using the camera mentioned above. Typical captured source images are shown in Fig. 1. In Fig. 1(b), a Bunsen burner is shown with the superimposed grid and various flames zones. The images are captured by varying the camera settings and modes. It is ensured the ambient light disturbance is minimal.



a) Muffle furnace *b) Bunsen Burner*

c) Molten Silver *d) Salt Bath Furnace*

Fig. 1 Photographs of Typical Visible Heat Sources

Sensor selection and temperature measurement

A typical visible source is selected, where a number of temperature zones could be identified. Zone temperature measurement is attempted using different sensors like bare and sheathed RTD, J and K type thermocouples, infrared (IR) non-contact type thermometer etc. The sensor should be suitable for point temperature measurement. Considering the zone volume, range and response time of sensor, a miniature K type thermocouple is selected for such temperature measurement. The sensor is moved in steps of 5 mm in vertical and horizontal direction in the zones of interest of a selected heat source and the temperature is measured at around 250 such points in a matrix of 20 mm x 90mm. Measurement procedure is repeated several times. It is ensured that the source is stable and stray light is minimal enough not to affect measurement. Fig. 2 depicts a photograph of temperature sensor along with the positioning system. The darkness of the background is ensured before capturing the images.

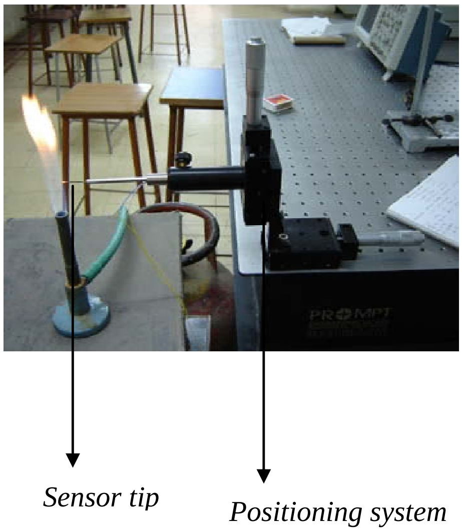


Fig. 2. Temperature sensor and positioning system for an open flame with controlled air fuel ratio

Colour temperature correlation

For the captured digital frames Individual pixels are separated using region growing technique. Pixel location and its Red, Green and Blue colour properties are obtained for individual pixel. A colour histogram can be used to represent the color compositions of an image [5]. The temperature and its distribution in a frame can be calculated from the ratio between the grey-levels of corresponding pixels within two images captured at selected wavelengths [7].

Image data analysis

To differentiate various zones in the source and to observe the dominance of the colour in zones, histograms of the Red (R), Green (G) and Blue (B) components of the source are found out. Threshold values are set from these histograms and using region grow algorithm heat zones are differentiated [7]. The exercise is carried out on a naked flame for various air/fuel settings.

The pixel colour values and the corresponding temperature values are tabulated using spreadsheet.

To find out the correlation between colour values (R, G, B) the independent variables and temperature, the dependent variable, various techniques such as least square method, polynomial fit, linear and non-linear regression are used. The appropriate method should fit the data well with minimum standard deviation.

The analysis is done using commercially available standard statistical software. Difference between actual temperature and predicted temperature by each method was worked out. standard deviation (SD) of the difference for every method was calculated. The method, giving minimum standard deviation, is selected. Temperature colour correlation must be solved with nonlinear regression techniques. It is hard to find the solution to such nonlinear equations if there are many parameters [9]. In the present work, there are three independent variables (colour components) and one dependent variable (temperature). Detailed statistical analysis using appropriate software is carried out and the colour temperature correlation is formulated.

The sample colour components, actual and predicted temperature values are listed in Table1.

Table 1: Actual and predicted temperature values

RED	GREEN	BLUE	Measured Temperature, °C	Predicted Temperature, °C	% Temperature Difference
8	9	29	900	915	1.66
14	10	21	950	980	3.15
14	12	34	950	985	3.68
14	44	98	650	680	4.61
15	16	46	1000	1030	3
16	49	100	650	680	3.68
19	18	58	1050	1040	-1
20	22	61	1000	1005	0.5
20	34	97	1050	1025	-2.38

Statistical analysis

For authentication of the analysis certain tests are to be carried out. These tests help in deciding whether to accept or reject the hypothesis. As suggested in the analysis the parameters P, R^2 and t- value are computed by regression analysis. In this analysis, P is the probability value, R^2 is the residual of predicted and actual values and t-value indicates the significance of independent variables.

Significance of statistical term p-value used in hypothesis tests to help you decide whether to reject or fail to reject a null hypothesis. A commonly used cut-off value for the p-value is 0.05.

The residual plots are plotted and the p-value and t- value obtained for the predictors Red, Green, Blue and constant are computed. The residual plots for a typical image are shown in Fig. 3.

The graph indicate that the residuals (difference between predicted value and actual observed value) are randomly distributed and do not show any trend. This indicates that the predictive model does not either over-estimate or under-estimate the predicted value.

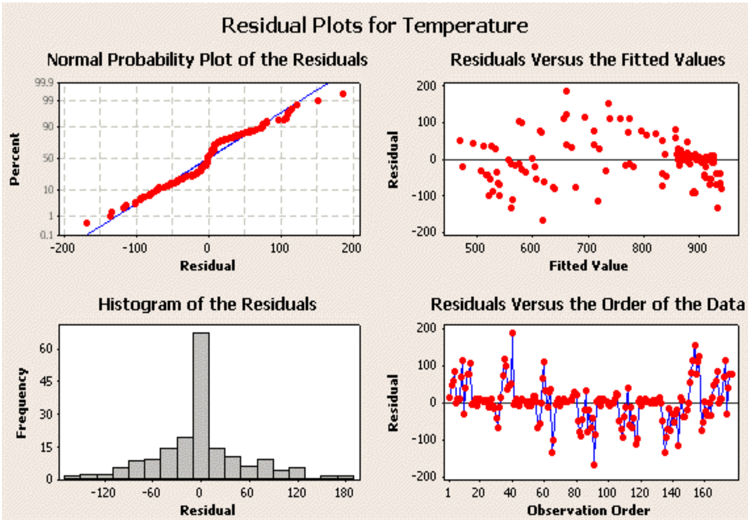


Fig. 3. Residual plots for predictors

This is clear from residual graph of residuals verses fitted values. The p-values obtained for RED, GREEN and BLUE are 0.000, indicating that they are significantly related to temperature with more than 95% confidence level [10].

- The R^2, adjusted R^2 and predicted R^2 value are very high (more than 90%). It indicates that the coefficient of determination is excellent. All these values indicate that the model fits the data well and has greater predictive ability.
- The residuals (difference between predicted value and actual observed value) are normally distributed. The graph (histogram of residuals) shows that the maximum residuals are concentrated near zero.
- The higher the absolute value of the t-value, the more likely the predictor is significant [11].

The results indicate that the GREEN predictor is least impacting.

Temperature measurement application

Colour temperature correlation is formulated. This correlation is validated for various industrial applications. The furnace is one such heat source used in the metallurgical applications**.** By varying the temperature from 600-1000 °C the photographs of the laboratory muffle furnace are taken. The temperature is varied in steps of 50°C using available controls n panel. The photographs at different temperatures are shown in Fig. 4. The images taken are processed and the pixel-colour information is obtained. Selecting the appropriate equation the temperature values are calculated. The measured and the predicted temperature values for the muffle furnace are tabulated. Table 2 gives the result of such measurement.

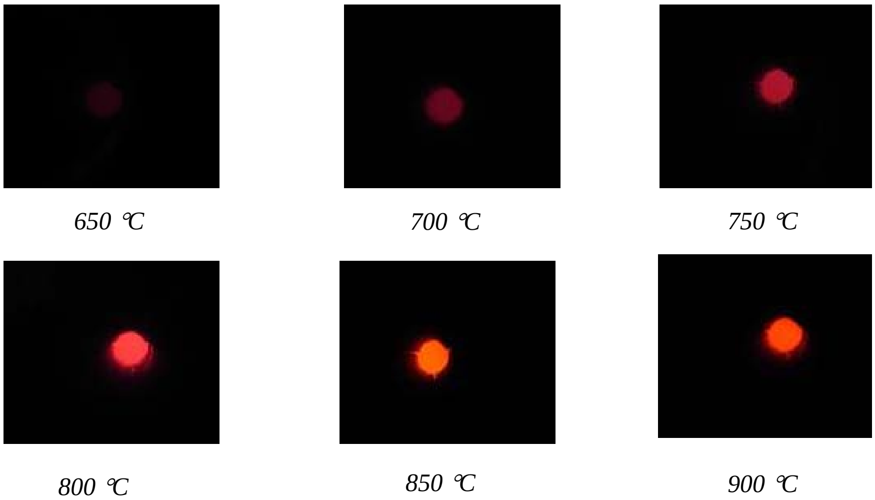


Fig. 4. Muffle furnace photographs at different temperatures

Table 2. Measured and predicted temperature values for muffle furnace.

R	G	B	Measured Temperature, °C	Predicted Temperature, °C	% Temperature Difference
35	4	15	650	667	3%
144	1	48	700	746	7%
161	18	38	750	797	6%
214	48	47	800	830	4%
215	56	31	850	897	6%
216	68	13	900	927	3%
222	76	5	950	987	4%
226	72	3	970	954	-2%

Temperature distribution on any wall of the furnace can be obtained. On the similar lines the temperature of the salt bath furnace is also predicted. The same procedure could be used for ingots or samples kept in furnaces. Using this technique temperature of the molten silver is estimated. Figure 5 shows the photographs of the molten silver in a crucible at different temperatures.

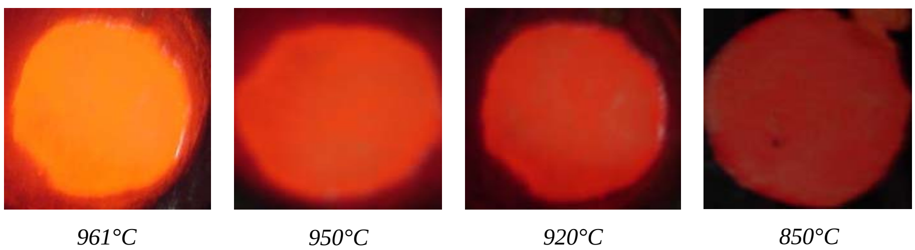


Fig. 5. Molten silver photographs at different temperatures

The Measured and predicted values of molten metals are indicated in Table 3.

Table 3. Measured and predicted temperature values for molten silver.

Measured Temperature (°C)	Predicted Temperature (°C)
961	958
950	941
920	917
850	813

Results and discussion

Colour temperature correlation is formulated. This correlation is successfully used for temperature measurement of various heat sources in industrial applications. The temperature difference between actual and predicted value is calculated for each source.

The temperature difference between actual and predicted value for a typical source is plotted in a Bar chart shown in Fig. 5. From the computations, 41% readings indicate variation within+/- 2 %. 34% readings indicate variation between ± 2 % to ± 5 %. 15% readings indicate variation between ± 5 % to ± 10 %. The temperature difference more than ± 10 % is found only in 9 % cases.

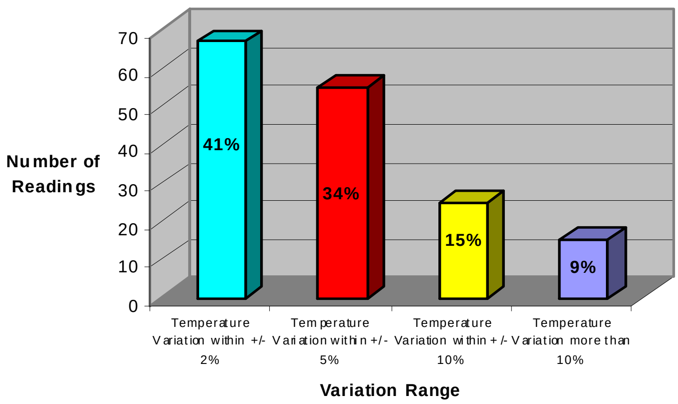


Fig. 5. Bar chart showing difference in actual and predicted values for a typical source.

This study reveals that this temperature measurement method offers huge benefits over conventional system of temperature measurement using contact and non-contact type sensors. Currently, it is observed that many problems are faced during temperature measurement by thermocouple sensors. Different sensor material is required for different temperature range, which means no single thermocouple sensor, can be used for wide range of temperature measurement. This leads to additional cost. Moreover, contaminated thermocouple can lead to inaccurate temperature measurement and there is a need to clean thermocouple sensors frequently. Repeated use of sensors leads to burnout and also frequent wear and tear of sensors. The sensors need to be changed periodically. Localized heating of sensor leads to inaccurate temperature measurement. There are certain issues with regard to accuracy also. Each material has self-resistance to heating. Hence it takes some time to stabilize the thermocouple sensor in muffle furnace.

The above-mentioned, newly developed technique would need no operating cost. It is just required to photograph the heat source and temperature would arrive instantaneously using developed software. There will not be any need of replacement or wear and tear of parts. This system offers good accuracy with minor variation with respect to actual temperature. Also, it is possible to obtain temperature at various locations.

Conclusions

Colour temperature correlation formulated using linear regression gives minimum standard deviation as compared to other techniques. Point source temperature prediction and temperature distribution prediction using the same technique is the significant contribution of the work presented using easily available consumer grade digital still camera. Digital photography technique for visible heat sources has a good potential for non-contact temperature measurement. In metallurgical applications the method seems to be superior to prevailing contact and non- contact temperature measurement methods like thermocouples, radiation and optical pyrometers.

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