Flame analysis for prediction of thermocouple temperature and quality of sponge iron at TATA steel long products limited

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Abstract: The temperature profiles of the gas and charge in a coal-fired rotary sponge iron kiln affect both the iron ore reduction process and accretion formation. The temperature profile of charge is estimated from the eleven thermocouples (TC1-TC11) placed along the 80 m length of the kiln. The quality prediction models are heavily dependent upon the accuracy of the measurement of TC10. However, slowly, as the kiln’s campaign life increases TC10, and other thermocouples too, get corrupted due to deposition of material (accretions) on the thermocouples. At the beginning of the campaign, however, there is no accretion on TC10. In the present work, an attempt is made to directly correlate flame characteristics with TC10 and with quality of iron produced so that when TC10 is corrupted due to accretion or breakdown, we can still survive by using flame characteristics as a guide to control quality. The flame inside the rotary kiln has been analysed by using image analysis procedures for the first time in a sponge iron plant. The flame’s estimated average temperature and pixel intensity information are correlated with (a) the temperature measured by the thermocouple TC10 (which is installed at a distance of 20 m from the rotary kiln outlet hood) and (b) with quality of iron produced. It is found that use of average flame temperature for quality prediction has several advantages in terms of increased accuracy of prediction and quicker response time of flame to short-time changes in coal quality (particle size, moisture, ash content, etc) whereas TC10 thermocouple takes much longer to reflect these changes due to slow process of heat transfer to charge. In addition, the adverse effect of accretion formation on TC10 for quality prediction has been overcome

1. INTRODUCTION

TATA sponge has three coal-fired rotary kilns for the production of sponge iron. The rotary kiln is comprised of a rotating cylindrical shell having a length of 80 m and an internal diameter of 4 m. The feed consisting of iron ore, non-coking coal and dolomite are fed to the rotary kiln from the feed end as shown in figure 1 [1]. The rotary motion of the kiln and its slight inclination helps the feed material’s movement along the length of the kiln. The feed material passes through the preheating zone first where the coal is devolatilized and the material is heated to around 900\textdegree C [1]. It then enters the reduction zone where the majority of oxygen is removed from the iron ore [2]. Reduction and combustion reactions take place throughout the process [1]. The hot gases produced during combustion move in the counter-current direction to the feed material. The air required for combustion is supplied from blowers (Secondary Air Blowers) attached to different ports which are placed equidistantly along the length of the kiln as shown in figure 1. Combustion air is also supplied...
through a central airport on the discharge end by the Primary Air Blower.

To measure the kiln’s temperature in various sections, fixed thermocouples are permanently installed along the kiln’s length as shown in figure 2. These are numbered from 1 to 11 starting from TC1 near the feed end and TC11 near the discharge end. Quick response thermocouples (QRT) are also employed to measure the kiln temperature but are operated manually by injecting the thermocouple in the desired section. This is usually done three times a day, once in each of the three shifts. The temperature measured by the tenth thermocouple i.e. TC10 is known to be directly proportional to the quality of sponge iron. Therefore, the accuracy with which it measures the temperature becomes important to control the quality of sponge iron. However, deposition of oxide layers leads to accretion formation over the thermocouple and this causes inaccuracy in its measurement. This poses difficulties in control of rotary kiln dynamic process [3-7].

The current analysis is done on the flame produced inside the kiln in the region above the bed material as shown in figure 3 [1]. To monitor the flame produced, a small glass window (7×7 inches) is provided at the kiln outlet hood. The flame characteristics like colour, brightness, intensity and temperature are affected by the coal’s moisture, volatile matter, carbon content and its fineness [8].

The use of digital image processing for flame analysis is widely practised [9-13]. The estimated flame temperature and pixel intensity information depend on the flame characteristics. The special aspect of present work is that it focuses on correlating TC10 temperature with flame characteristics and predicting the quality of sponge iron produced using average flame temperature. Two methods are used to predict the TC10 temperature viz. intensity method and the average flame temperature method.

![Figure 1: Kiln's view along its length.](image)

2. INTENSITY METHOD

The image of the flame which is at a distance of 20m from the kiln outlet hood is acquired using a 16 MP camera through a small glass window provided at the kiln outlet hood. The position of the camera is fixed by clearly demarcating the area on the glass-shield against which the camera is placed. The acquired image is in RGB form. It is analyzed using MATLAB [14]. Every RGB image consists of pixels each having a particular intensity for red, green and blue colour. Hence, each image which is loaded to MATLAB is represented by a 3-D matrix. The RGB image is converted to red, green and blue scale image using MATLAB. A 2-D matrix is obtained for each red, green and blue scale image. This is shown pictorially in figure 4.

The 2-D matrix for the red scale image has greater intensity values as compared to the other two.
Also, red is the most contributing colour to a flame. Hence, the red scale image is considered for further analysis. Only, the flame’s bright circular portion is of interest. Hence, the image needs to be cropped to eliminate the surrounding darker region. As a measure of the intensity of each flame image acquired, the sum of intensities of each pixel in the bright circular portion of the red scale image is taken. The following steps need to be followed to get the sum of red colour intensity for the cropped image:

Step 1: At a given time instant, take 12 snapshots of the flame.
Step 2: Convert each RGB image acquired to its red(R) scale image.
Step 3: Take the sum of intensities of all the pixels only for the circular bright portion. This can be done by using a conditional statement. The pixels lying outside the circular bright portion having lesser red intensity are excluded from consideration during the summation.
Step 4: This sum of red intensities for every image acquired at a given time instant is averaged and reported as sumR (for that time instant).

The calculated sumR is compared with TC10 temperature for the same time instant when the image is acquired. The plot is shown in figure 5. The correlation indicates that it is possible to estimate TC10 temperature using sumR. However, the r-squared (R²) value is very small and a better method needs to be employed to estimate TC10 temperature. Thus, the average flame temperature is used to estimate TC10 in further discussion.

![Figure 2. An overview of fixed thermocouples arrangement along the rotary kiln.](image)

![Figure 3. The cross-sectional view of the rotary kiln.](image)

![Figure 4. Flame’s original RGB image converted to red, green and blue scale image.](image)
3. AVERAGE FLAME TEMPERATURE METHOD

The flame temperature is an effective parameter to look at in order to monitor the kiln’s flame. A method has been established to measure flame temperature by using a two-colour method technique [12]. The flame’s temperature can be measured from the flame’s acquired image. The method used to calculate the average flame temperature is as follows:

The formula used to calculate the temperature of each pixel is given by

\[ T(i, j) = \frac{C_2\left(\frac{1}{\lambda_G} - \frac{1}{\lambda_R}\right)}{\ln\left(\frac{P_R(i, j)}{P_G(i, j)}\right) + C_A' - 5\ln\left(\frac{\lambda_R}{\lambda_G}\right)} \]  

(1)

where \( T(i, j) \) is the temperature (in Kelvin) for the pixel at position \((i, j)\) i.e. \(i^{th}\) row and \(j^{th}\) column. \( C_2 \) is second Planck’s constant, \( \lambda_R \) is constant of red channel’s radiation wavelength, \( \lambda_G \) is constant of green channel’s radiation wavelength, \( P_R(i, j) \) is the image’s pixel intensity of red channel at position \((i, j)\), \( P_G(i, j) \) is the image’s pixel intensity of green channel at position \((i, j)\) and \( C_A' \) is the Comprehensive Correction Coefficient.

We equate the relatively lesser red intensities of the background pixels (the darker region) surrounding the circular bright portion of the red scale image to 0 i.e. \( P_R(i, j) = 0 \) using conditional statement in MATLAB. If \( I_{ij} \) is the unit measure for a pixel at location \((i, j)\), then \( I_{ij} = 0 \) if \( P_R(i, j) = 0 \) and \( I_{ij} = 1 \) if \( P_R(i, j) > 0 \).

The formula to find out the average temperature of the flame is given by

\[ \mu_T = \frac{1}{A} \sum_{i=0}^{w-1} \sum_{j=0}^{h-1} T(i, j) \times I_{ij} \]  

(2)

where \( \mu_T \) is the average temperature of the flame region (bright circular portion), \( T(i, j) \) is the
temperature for the pixel at position \((i, j)\), \(I_{ij}\) is the unit measure for a pixel at location \((i, j)\). \(A\) is the flame area (only the bright circular portion), ‘\(h\)’ is the image’s height and ‘\(w\)’ is its width.

Flame area, \(A\) is calculated using the following formula:

\[
A = \sum_{i=0}^{w-1} \sum_{j=0}^{h-1} I_{ij}
\]  

(3)

4. PROCEDURE FOR ESTIMATING TC10 TEMPERATURE FROM AVERAGE FLAME TEMPERATURE (AVGT)

The plot in figure 6 shows that TC10 can be back estimated from the average flame temperature \((R^2 = 0.37)\) in the event when TC10 becomes corrupted. As mentioned earlier, TC10 is an important thermocouple because the temperature measured by it is directly proportional to the quality of sponge iron. An increase in TC10 temperature is followed by an increase in the quality of sponge iron. The \(r\)-squared\((R^2)\) value for the plot of quality against TC10 on five different days is shown in table 1.

![Figure 6. A plot of TC10 against calculated average flame temperature.](image)

**Table 1.** \(R^2\) for the plots of Quality versus TC10 and Quality versus \(\text{avgT}\) obtained on 5 different days.

| Day | \(R^2\) for quality versus TC10 | \(R^2\) for quality versus \(\text{avgT}\) |
|-----|---------------------------------|-----------------------------------|
| 1   | 0.3871                          | 0.4038                            |
| 2   | 0.5479                          | 0.2291                            |
| 3   | 0.8199                          | 0.3456                            |
| 4   | 0.5189                          | 0.7563                            |
| 5   | 0.4162                          | 0.6706                            |

5. QUALITY PREDICTION FROM AVERAGE FLAME TEMPERATURE

The average flame temperature is also indicative of the quality of sponge iron. The quality of sponge iron produced increases as the flame’s average temperature increases. The \(r\)-squared\((R^2)\) value of the plots of average flame temperature against the quality of sponge iron produced on 5 different days is also given in table 1. It shows that quality can be predicted from the average flame temperature. Thus, when TC10 measures the temperature inaccurately, the average flame temperature can be used to predict the quality of sponge iron produced. Since the flame image can be acquired on a continuous basis, this method proves reliable to predict the quality of sponge iron on a continuous basis.
6. CONCLUSION

Flame image analysis can be used to estimate TC10 temperature when TC10 develops accretion and gives an inaccurate measurement. As TC10 temperature is directly proportional to the quality of sponge iron produced, its accurate measurement is important for quality control. Two methods can be employed to measure TC10 temperature viz. Intensity method and Average flame temperature method. However, the average flame temperature method gives a better prediction of TC10 temperature than intensity method. When TC10 gives inaccurate reading due to accretion formation, the average flame temperature can be used to predict the quality of sponge iron produced.

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