A Real Time Non-invasive Technique for Moisture Estimation in Blast Furnace Coke

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Abstract:

In steel plants, measurement of moisture content in coke is essential to maintain the desired temperature in blast furnace. The iron making process needs the coke to iron burden ratio to be maintained as 2:1 and the moisture present in coke affects this ratio. Excessive moisture in the coke leads to chilling effect in blast furnace by decreasing raceway temperatures. For optimal blast furnace performance, the chemistry of the molten iron being produced should remain under control and the thermal balance of the furnace should remain as constant as possible. Variation in coke moisture can have an adverse effect on the thermal control of the blast furnace process and also the chemistry of the iron and slag produced. Coke fed into the Blast Furnace contains moisture, which normally varies from between 0.5% to 5%.

A Microwave-Assisted Infrared Thermography (MAIRT) based non-invasive technique has been devised for estimation of moisture in BF coke (-80 +30), Nut coke (-30 +10) and Gross coke (-10) to generate the calibration curve and corresponding software for online estimation of moisture in coke samples. The technique primarily consists of measuring the moisture in different grades of coke collected from two different coke plants and blast furnaces. Thermal images of coke samples heated in a microwave oven for an optimal time period are captured before and after heating of coke using IR camera. The correlation between the change in average temperature of coke recorded and the corresponding moisture content is obtained. With the help of this correlation, the moisture content in the coke samples, in which the percentage of moisture is not known, can now be predicted using this technique.

Key words: Blast Furnace, Coke, Moisture, Microwave heating, Thermal Imaging

1. Introduction

Modern steel industries are driven towards producing better quality products and to improve upon current practices, with the aim to reduce the cost of the end product. The measurement of coke moisture allows more precise control of the dry weight of coke being charged to the blast furnace. Coke is one of the important raw materials fed into blast furnace in terms of its effect on blast furnace operation and hot metal quality. Variation in coke moisture, which is not accounted
adjusted for, can have an adverse effect on the thermal control of the blast furnace process and also the chemistry of the iron and slag produced. Coke, iron ore pellets, lump ore and fluxing materials are the raw materials consumed by the blast furnace to make molten iron. For visualization of blast furnace operation, its schematic is shown in Fig. 1 [1,2]. For optimal blast furnace performance, the chemistry of the molten iron being produced should remain under control and the thermal balance of the furnace should remain as constant as possible [3, 4, 5]. To achieve this, the operators need to know that the addition of raw materials (coke, iron lump and pellets) is correct in terms of chemistry and weight, and this incorporates moisture being accounted for. Coke has ash, carbon and also volatile matter as its major constituents. The ash chemistry and the carbon content are taken into account in the mass balance. The moisture content is also included in the mass balance to account for its influence on the ore to coke ratio. If the operators are aware of fluctuations in the moisture of coke being produced by the coke ovens they are in a position to make adjustments to the ore mass charged to account for its influence on the thermal balance of the blast furnace [6]. An unaccounted increase or decrease in moisture affects the thermal balance of the furnace, which will alter the consistency of the molten iron chemistry.

In sintering process, coke breeze is used as a fuel. During sintering the heat input has to be controlled to get stable process conditions and improved sintering performances in terms of productivity and quality. The measurement of moisture content of coke is important as any variation in it has to be adequately compensated by decreasing or increasing the trimming fuel addition at plant [9,10]. Coke fed into the Blast Furnace contains moisture, which normally varies from between 0.5% to 5%. The content of moisture mainly depends on method of quenching adopted, i.e. dry or wet. The high moisture content in coke affects BF performance adversely in terms of C rate and production rate. Therefore moisture determination of coke is done on regular basis – thrice in a day – once per shift. This conventional method of moisture determination is time taking and fully dependent on resource and infrastructure availability. Taking into consideration all these factors, a real-time non-invasive technique is necessary for moisture estimation in blast furnace coke. Microwave-assisted IR imaging has been already used to study the alumina content in iron ores [7, 8]. Therefore, the prime objective of this paper is to develop microwave-assisted IR Thermography based non-invasive technique for estimation of
moisture in blast furnace coke of different types and size. Further, to generate a calibration curve and a software code for online estimation of moisture in coke.

All the limitations of the present system can be overcome by installing an on-belt analyzer to measure coke moisture. Thus, the online estimation of moisture of coke samples will enable operators to take quick action in case of any deviation in moisture content of coke and thus ensuring stability in BF operation.

Fig. 1. Blast furnace operation


2. Principles of Infrared Thermography in Mineral Beneficiation

Infrared thermal imaging technique converts the invisible radiation pattern of an object into visible images for feature extraction and analysis. The system consists of a thermal camera with detectors, a signal processing unit and an image acquisition system. The thermal imaging
technique is being widely used in various fields such as predictive maintenance, non-destructive evaluation, military reconnaissance, medical imaging etc. [11]

All objects that have surface temperatures above absolute zero emit electromagnetic radiation. When radiation is incident on an object, portion of it is transmitted, some portion absorbed, and some reflected. For thermal equilibrium the total flux (measured in watts) must be constant and is defined as,

\[ \Phi_{\text{Transmittal}} + \Phi_{\text{Absorbed}} + \Phi_{\text{Reflected}} = \Phi_{\text{Incident}} \] (1)

For real surfaces, during thermal equilibrium the transmissivity of solid surfaces is equal to zero, therefore (1) can be rewritten as

\[ \Phi_{\text{Absorbed}} + \Phi_{\text{Reflected}} = \Phi_{\text{Incident}} \] (2)

In case of ores and minerals in unpolished condition, the amount of heat reflected is very low; hence most of the heat incident on the ores is absorbed by them. The heat radiated by the uniformly heated coke particles is captured and displayed as thermal image through IR thermography. The coke particles with more moisture have low thermal absorptivity and are heated up less and therefore their thermal image shows lower temperature compared to dry coke particles [12].

3. Methodology for Estimation of Moisture in Various Cokes

The present investigation deals with estimation of moisture in Nut coke (-30 + 10 mm), BF coke (-80+30 mm) and Gross coke (blend of different sizes) samples. Different coke samples were collected from Coke Plants CP1 and CP2, and also from Blast furnaces IBF and HBF and oven dried such that there is no inherent moisture present in the coke. A certain quantity of oven dried coke sample is taken, its initial weight \( W_1 \) is measured (which is approximately 100g) and the sample is soaked in water for 3 to 4 days. The excess water is drained out and the final weight of the sample \( W_{f1} \) after soaking is measured. The Moisture wt.% in each sample is calculated from the difference between the initial weight \( W_1 \) and final weight of the sample \( W_{f1} \), as given below.
\[
\text{Moisture wt.} \% = \left( \frac{W_{f1} - W_i}{W_i} \right) \times 100
\] (3)

The initial average temperature \(T_i\) of the coke samples is measured from the thermal image of the coke sample captured using an IR camera. The IRBIS 3.0 professional software has been used for acquiring the temperature of coke from thermal image. The area of interest is selected i.e. circle, which gives the average temperature of the coke sample. The coke samples are then heated in microwave oven (Rating 1.25KW) for 10 seconds at 800W power which is optimum heating time and power required for nut coke and BF coke samples. The radiant heat from the heated coke specimens is captured as thermal image and analyzed using IR Thermography. The final average temperature \(T_f\) of the coke sample is obtained from the preselected area in the thermal image. The difference between initial temperature \(T_i\) and the final average temperature \(T_f\) gives the change in average temperature \((\Delta T)\). The moisture wt\% and the corresponding change in temperature \((\Delta T)\) is recorded. The heated sample is left for some time till its temperature is near room temperature. The weight of the sample \(W_{f2}\) is measured and the moisture wt\% is calculated as given below,

\[
\text{New Moisture wt.} \% = \left( \frac{W_{f2} - W_i}{W_i} \right) \times 100
\] (4)

Experiments are conducted with the same sample following previous steps till moisture in the sample comes down to 1 % and a curve relating change in average temperature and moisture wt\%. is plotted. Same procedure is adopted to obtain curves relating change in average temperature and moisture wt. % for the coke samples from CP1, CP2, IBF and HBF. Finally, a single calibration curve is generated, combining the temperature and moisture data collected for coke samples from CP1, CP2 and IBF. The moisture absorbing behavior being different for coke samples from HBF, a separate calibration curve is plotted. A software program is developed in LabVIEW based on the calibration curve generated. Validation of the moisture estimation technique can be done by estimating moisture in real coke samples using the developed LabVIEW program. The steps followed for moisture estimation is given in a flowchart in Fig. 2. This procedure is followed to get separate calibration curves and corresponding LabVIEW programs for moisture estimation in nut coke, BF coke and gross coke samples.
Fig. 2: Flowchart for Moisture Estimation

1. Measure weight of coke ($W_i$)
2. Soak in water for 3-4 days till moisture % is around 10-15%
3. Measure Final Weight ($W_{fi}$) after soaking
4. Calculate Moisture wt.% in coke = $\frac{(W_{fi} - W_i)}{W_i} \times 100$
5. Measure Avg. temperature ($T_i$) of the moist coke
6. Heat the moist coke in microwave oven at optimized power for optimized time
7. Record of Moisture wt.% vs Change in Avg. temperature till moisture comes down to 1-2%
8. Cal. moisture wt.% in coke = $\frac{(W_{f2} - W_i)}{W_i} \times 100$
9. Measure weight of the coke after few hrs ($W_{f2}$)
10. Record $\Delta T$ and moisture %
11. Compute $\Delta T = [T_f - (T_i)]$
12. Measure Avg. temperature ($T_f$) of the coke

Fig. 3: Schematic for Moisture Estimation in coke

Types of coke received from plant:
1. BF Coke
2. Nut Coke
3. Gross Coke

Infrared image of heated coke samples

Moisture is added to coke by immersing sample in water

Coke samples taken out from water and heated in microwave oven for optimal time

IR Camera for thermal imaging
4. Results And Discussion

4.1 Estimation of moisture in BF coke

Oven dried BF coke samples from CP1 is taken in a petri dish and the initial weight is measured which is around 100g. A measured amount of water is added to the coke samples and soaked for 3-4 days. The moist BF coke samples are heated in a microwave oven at optimized power of 800W for 10 sec and the thermal image is captured as shown in Fig. 4. The average temperature of the BF coke samples is obtained from the thermal images captured before and after heating of samples. The change in average temperature ($\Delta T$) of the sample is recorded and the moisture content in the sample at that instant is calculated by weight difference method. The sample is allowed to cool down to room temperature and again the same procedure of heating in a microwave oven, capturing of thermal image is repeated to get a series of change in average temperature ($\Delta T$) and moisture wt. % data for coke samples from CP1. Similarly a set of $\Delta T$ and moisture wt.% data each is obtained for coke samples from CP2 and IBF. The change in average temperature ($\Delta T$) is plotted against the moisture wt. % for the coke samples from CP1, CP2 and IBF to get the final calibration curve, as shown in Fig. 5. A polynomial relationship is obtained between the change in average temperature of the coke and the coke moisture with a correlation factor ($R^2$) of 0.837. Further, it is observed that with the decrease in moisture wt. % in the sample, there is gradual increase in temperature of the heated samples.

![Fig. 4: Thermal image of BF coke samples (size: -80+30)](image-url)
Based on the calibration curve obtained, a program has been developed in LabVIEW for estimating moisture in real coke samples. The program displays the moisture % in BF coke, when "Change in Average Temperature" of coke is entered. The front page of the "Moisture Estimation program" is shown in Fig. 6. This technique is validated by estimating moisture in BF coke samples with unknown moisture content and this validation has been done for atleast 78 samples from CP1, CP2 and IBF. The moisture estimated by IR imaging technique is plotted against the moisture wt% obtained through weight difference method and the validation plot thus obtained is given in Fig. 7. The validation curve in Fig. 7 with a slope of 1.008 and 0 intercept, shows a good correlation ($R^2$=0.795) between the estimated moisture and actual moisture in coke samples. The error in moisture measurement is primarily due to the following reasons. (i) Error in measurement of average temperature of coke, as the circular area selected for temperature measurement not only covers coke surface but also gap between the coke particles, including the temperature of the petridish in which sample is kept. (ii) Through IR imaging only the surface temperature of the coke can be measured and the effect on temperature due to moisture present inside the coke cannot be accounted for. These errors can be minimized by using coke samples crushed to smaller size.

**Fig. 5: Average temperature vs. moisture wt % plot for BF coke samples**

\[
y = 0.025x^2 - 1.857x + 35.32 \\
R^2 = 0.837
\]
Fig. 6: LabVIEW Program for Estimation of Moisture in BF Coke

Fig. 7: Validation of Estimated Moisture in BF Coke

\[ y = 1.008x \]

\[ R^2 = 0.795 \]
4.2 Estimation of moisture in Nut coke

A similar procedure as in case of BF coke has been adopted to get the calibration curve for Nut coke samples from CP1, CP2 and IBF, the thermal image for which has been shown in Fig. 8. The calibration curve for Nut coke samples is shown in Fig. 9, from which it can be observed that the curve has a $R^2$ value of 0.932, which is quite improved than 0.795 obtained in case of BF coke.

Fig. 8: Thermal image of Nut coke samples (size: -30 +10)

![Thermal image of Nut coke samples](image1)

Fig. 9: Average temperature vs. moisture wt % plot for Nut coke samples

![Graph showing the relationship between moisture content and temperature change](image2)

\[ y = 0.013x^2 - 1.383x + 37.63 \]

\[ R^2 = 0.932 \]
This calibration curve is used to get the moisture percent in coke samples with unknown moisture. The moisture estimated by IR imaging technique is plotted against the moisture wt% in the nut coke samples and the validation plot thus obtained is given in Fig. 10. The validation curve in Fig. 10 with a slope of 0.947 at 0 intercept, shows a good correlation ($R^2=0.899$) between the estimated moisture and actual moisture in coke samples. It can be clearly observed that there is slight variation in moisture values from the expected moisture wt%. The improvement in results in case of nut coke is mainly due to smaller size samples considered than in case of BF coke. Due to smaller size samples, the gap between the coke particles is less than in case of BF coke and the average temperature measurement is thus more accurate, resulting in precise moisture estimation.

![Validation of Estimated Moisture in Nut Coke](image)

**Fig. 10: Validation of Estimated Moisture in Nut Coke**

### 4.3 Estimation of moisture in Gross coke

Moisture estimation results for BF coke and nut coke indicate that better accuracy can be achieved with smaller size coke samples. Therefore Gross coke samples which were mainly in the size range of (-80+30) to (-30+10) were crushed to +10 size and dried in an oven. A fixed
quantity of dried Gross coke samples from CP1, crushed to 10mm size, is taken in a petri dish. Moisture is added to the coke samples by soaking approximately 100g of gross coke samples in water for 3-4 days. The moist gross coke samples are heated in a microwave oven for 30 sec and the thermal image is captured as shown in Fig. 11.

![Thermal image of Gross coke samples](image)

**Fig. 11: Thermal image of Gross coke samples**

The average temperature of the gross coke samples is obtained from the thermal images captured before and after heating of samples. The change in average temperature (ΔT) of the sample is recorded and the moisture content in the sample at that instant is calculated by weight difference method. The sample is allowed to cool down to room temperature and again the same procedure of heating in a microwave oven, capturing of thermal image is repeated to get a series of 'change in average temperature (ΔT)' and 'moisture wt.\%' data for coke samples from CP1. Similarly a set of ΔT and moisture wt.% data is obtained for coke samples from CP2, IBF and HBF. The change in average temperature (ΔT) is plotted against the moisture wt. % for the gross coke samples to get the final calibration curve, as shown in Fig. 12. A polynomial relationship is obtained between the change in average temperature of the coke and the coke moisture with a correlation factor (R²) of 0.924. Further, it is observed that with the decrease in moisture wt. % in the sample, there is gradual increase in temperature of the heated samples when moisture is between 0.5% to 16% and for moisture wt. % below 0.5, the temperature remains nearly constant. Therefore with this calibration curve, moisture wt. % in coke breeze, between 0.5% to 16% can be easily estimated.
Based on the calibration curve obtained, the software code developed in LabVIEW has been used for estimating moisture in real coke samples. The program displays the moisture % in Gross coke, when "Change in Average Temperature" of coke is entered. Validation has been done onsite at Tata Steel for 12 days for atleast 64 gross coke samples collected from CP1, CP2, IBF and HBF at different shifts. The moisture estimated by IR imaging technique is plotted against the moisture wt% obtained by conventional technique from CRMT Lab in Tata Steel and the validation plot thus obtained is given in Fig. 13. The validation curve in Fig. 13 with a slope of 1.0 and 0 intercept, shows a good correlation ($R^2=0.925$) between the estimated moisture and actual moisture in coke samples. It can be clearly observed that in case of gross coke samples there is very little variation in moisture values from the expected moisture wt%. The results in the case of gross coke is much improved than that of nut coke and BF coke as the causes for error as mentioned in Section 4.1 have been minimized by selecting smaller size coke samples.
5. Observations:

1. Moisture estimation in coke depends on the size and type of coke under consideration. Correlation of estimated with calculated wt% of moisture was found to be better ($R^2 \geq 0.9$) for the coke size range of +10 and -10. This is because gap between coke samples is less, hence temperature reading corresponds to the sample only. This is obvious from the average temperature calculation shown in Fig. 14. The temperature calculated by selecting a circular area C1 covering all the coke pieces is 3.46°C more than the average temperature calculated by separately selecting area of each coke piece. This error in temperature measurement can be eliminated if coke pieces are crushed to smaller size as the gap between the coke particles is reduced and more coke surface is exposed during thermal imaging giving accurate temperature corresponding and hence more precise
moisture wt. % present in coke. The variation in correlation factor $R^2$ for moisture estimation in coke of different sizes is shown in Fig 15.

![Figure 15: Moisture Estimation in Coke of Different Sizes](image)

Average Temperature of all samples from circular selection $C1 = 48.66^\circ C$

Average Temperature of all samples considered individually = $(X1+X2+X3+X4+X5+X6)/6 = 52.12^\circ C$

Difference in Average Temperature = $3.46^\circ C$

**Fig: 14: Calculation of Average Temperature of Coke through Area Selection**

2. Overall moisture wt% estimation using microwave assisted IR thermography based technique has been found to be quite encouraging. Thus can be considered as a non-invasive, fast tool for moisture detection in coke.

6. **Conclusions:**

Microwave assisted IR thermography based technique has been found to be suitable for estimation of moisture in various types of cokes like BF coke, Nut coke, Gross coke and Coke breeze. However, in this laboratory based study, the technique is found to give more accurate moisture values in case of Gross coke and coke breeze which were crushed to smaller size of the order of +10 and -10 respectively. This is because smaller size coke particles are distributed more uniformly in the petri dish and as a result give more accurate value of temperature change.
whereas for bigger coke pieces glass area is exposed in the gap region between the cokes. Since glass is microwave inert and average temperature change includes the change in temperature of coke as well as glass, accuracy in the average temperature due to the moisture in coke is less accurate. This problem will not exist for estimating moisture in bulk amount of coke. The microwave assisted IR thermography based technique can be considered as a useful non-contact tool for real-time prediction of moisture in Blast furnace coke.

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References


