

The Influence of Intrinsic Drifting and Extrinsic Driving on Blast Furnace Operation

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In this study, the periodic oscillation of inner states has been observed under conditions of all coke operation with essentially no interference by operators. This oscillation also can be identified in ordinary operation conditions with fuel injection and oxygen enrichment. The dynamics of blast furnace states were analyzed in terms of the instantaneous rate of production (IRP) and the hot metal temperature (HMT) under different operating conditions. The changes due to intrinsic drifting and extrinsic driving were separated and explained by using basic physical and thermodynamic theories. The combined intrinsic and extrinsic forces which cause the inner states of a furnace to drift did not always lead to a trajectory of changes consistent with our intuition. The appreciation of this phenomena and its impact on the steering of the furnace are significant for the advance of a fundamental understanding in the field, as well as for a more effective control of the operation.

Keywords: Blast furnace, Intrinsic drifting, Extrinsic driving

1. INTRODUCTION

The blast furnace is a high temperature, multi-reaction and multi-phase reactor that includes solid raw materials, liquid iron, slag and hot blast. Until now, the blast furnace is still regarded as “black box”. The operator tries to manipulate the blast furnace by accumulated experience. Adjusting tuyere practices is the most direct and effective way to steer a blast furnace. In this study, the periodic oscillation of the inner states of a blast furnace has been observed under conditions of all coke operation with essentially no interference by operators. This oscillation can also be identified in ordinary operation conditions with fuel injection and oxygen enrichment. In addition to intrinsic force, the solution loss carbon reactions, the extrinsic forces such as wind rate and other tuyere practices also cause the inner states of the furnace to drift, the effects of extrinsic forces on furnace drift are more complicated and are not always so obviously observed, though.

Studies have rarely tried to identify the effect of intrinsic drifting and extrinsic driving. In this paper, we have tried to relate the blast furnace drift with some of the tuyere practices through analyzing a furnace at different operation conditions. We hope that this study can finally lead to some practical operation control strategies to be able to adjust the tuyere parameters to control

the furnace drifts.

2. DESCRIPTION OF DATA USED

In this work, the operating data of the blast furnace from two different operation periods were analyzed. The selection of these two particular periods was based on all coke operation with relatively stable operating conditions and normal operation with fuel injection and oxygen enrichment. The downturn in the global economy in 2008-2009 inevitably impacted steel industries and forced a lot of blast furnaces to operate in a very basic mode, such as all coke operation and minimum productivity with almost hands-off on tuyere practice for days. However, it also gave us ironmakers a rare opportunity to observe the essential operation behavior of a blast furnace. In first case, we selected the period to illustrate the furnace self-adjusting behavior and tried to explain the phenomena based on fundamentals. In the normal operation case, we selected the period that blast furnace operated under relatively stable conditions. Table 1 shows the average value and standard deviation of operation conditions at these selected periods. The variables include measured hot metal temperature (HMT), computed instantaneous production rate (IRP) and some tuyere practices, such as blast volume (BV), hot blast temperature (BT) and blast moisture (BM), oxygen enrichment (EO2) and the fuel

injections (PCI). In all coke operation, only one week period was selected. During this period, the operators only adjusted the blast volume (BV) to keep the permeability (dP/V) within a tolerable range to keep the furnace stable. It can be found from the standard deviation that the furnace operating parameters have slightly more variation in this period, except for the moisture level. In normal operation, there were a slight adjustments to tuyere practices (<10% standard deviation) during this period, except for oxygen enrichment. In general, a blast furnace operated with fuel injection is easier to keep “stable” than one operated in an all coke condition. The operator always drives the furnace towards a smooth operation by adjusting the operation conditions (BV, BT, BM, PCI and Oxygen enrichment) in order to control HMT and permeability. At this period, blast temperatures were kept relatively constant (STD less than 1%). The operators adjusted blast moisture, fuel injecting (in a normal case PCI was the only fuel injection) and oxygen enrichment to drive the furnaces stably.

3. INTRINSIC DRIFTING EFFECT : ALL COKE OPERATION

3.1 Variations in IRP and HMT

The IRP we used in this study was computed from the charging rate, i.e. the movement of the burden column. The HMT was measured in the cast-house and averaged for the cast. In the data set selected based on time some errors were identified, but all data points were kept for analysis.

The variations of IRP (dash curve) and HMT (solid curve) as functions of time during all coke operation are shown in Fig.1. Both the IRP and the HMT seemed to vary without any regular pattern but stayed around an average value; in general one would explain these variations as being due to the presence of noise in the raw data, i.e. from operations. However, when the raw data were treated by taking the moving average to attenuate the noise, the situation became more obvious.

In Fig.2, the solid curve shows the hot metal temperature with a 3-hour (M3hrs) moving average; the dash curve shows the instantaneous production rate with a 3-hour (M3hrs) moving average. The dash-dot curve was obtained by treating the raw data with moving average lagged for 2-hours (D2hrs). The curves of IRP and HMT seem to have periodic patterns in time, and an out-of-phase relation with respect to each other as shown in Fig.2.

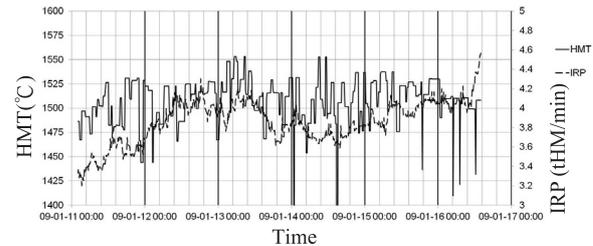


Fig.1. Curves of IRP and HMT varied with time during all coke operation.

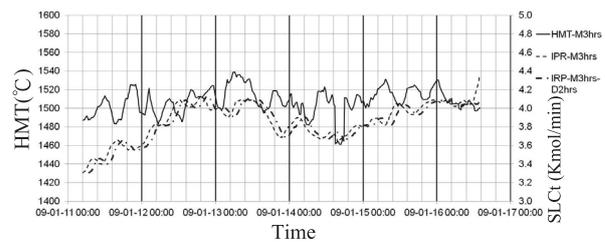


Fig.2. The smoothed curves of IRP and HMT varied with time during all coke operation.

Accepting the fact that, as shown in Figs.1 and 2, very significant performance parameters, productivity and hot metal quality, show intrinsic periodic variations on their own under very special conditions, then there are two questions which present themselves. Are there scientific explanations for such drifting-correcting phenomena, and whether this mechanism would apply under normal industrial operations? The interaction

Table 1 Average value and standard deviation of blast furnace operating parameters

| Period | BV | | BT | | BM | | PCI | |
|----------|-------------------|---------|-----------------|---------|----------------|---------|-----------|---------|
| | Average | Std Dev | Average | Std Dev | Average | Std Dev | Average | Std Dev |
| | m3/minute | % | Deg. C | % | g/m3 | % | kg/minute | % |
| All coke | 4588 | 3.37 | 1003 | 2.63 | 44 | 8.33 | - | - |
| Normal | 5266 | 0.8 | 1115 | 0.7 | 30 | 8.55 | 43 | 6.4 |
| Furnace | Oxygen Enrichment | | HM Productivity | | HM Temperature | | | |
| | Average | Std Dev | Average | Std Dev | Average | Std Dev | | |
| | % | % | t/minute | % | Deg. C | % | | |
| All coke | - | - | 3.86 | 5.78 | 1507 | 2.33 | | |
| Normal | 0.9 | 18 | 4.9 | 3.11 | 1496 | 1.46 | | |

between the two regions in the furnace (the direct and indirect reduction zones) is because the reaction product leaves one region and enters the other due to counter-current gas-solid flows. The solution loss reaction, which is strongly endothermic and intensifies the reduction at the expense of heat, is the other link between the chemical (IRP) and the thermal (HMT) states of the furnace. In the present work all computations are based on the heat and mass balance. It is important to identify under which conditions our computations would not apply. We observed that the IRP varied within a small range during the periods when the blast volume was relatively constant. This means that the IRP varied not only due to the changing blast volume caused by mechanical factors, but also due to the intrinsic driving force which continued to be operative.

3.2 Thermal Chemical Effects

Before we try to explain the relations between blast conditions, productivity and hot metal temperature, we must keep in mind the counter-current nature of gas-solid flows in a blast furnace when chemical reactions are considered. The reaction zone may be divided into two parts. In the high temperature zone where iron oxides (which have been pre-heated and pre-reduced in the low temperature zone) are reduced by CO to produce CO₂ which reacts instantaneously with coke to re-generate CO at the expense of heat. The most important link for all the quantities considered in this work was the solution loss carbon reactions taking place in the high temperature zone. The gas leaves the high temperature zone and enters the low temperature zone as the only reducing agent for iron ore pre-heating and pre-reduction.

The reduction of iron ore in blast furnace follows two mechanisms, namely, the indirect reduction in the upper shaft (where carbon is chemically inert due to lower temperatures, therefore leading to a gaseous phase of decreasing reducing potential) and the direct reduction which takes place in higher temperature regions where the gas is essentially in equilibrium with the always present "reactive" carbon. The furnace is divided by an isotherm in range of 950 to 1000°C across which solid carbon changes from being absolutely inert to extremely reactive chemically. It should be pointed out that the blast furnace is truly a continuous reactor in terms of gas flow, but not for flows of solids and liquids. The charging and discharging operations are carried out intermittently (10 minutes per charge). Particularly, tapping practice is less frequent and causes the burden descending rate to change over a short period (2~4 hours per tapping). Therefore, there is no shortage of fluctuations in a blast furnace to initiate the interactions to result in cyclic changes in the internal states and furnace performance (1-2 cycles per

day). If the operational fluctuations lead to an increase in "direct reduction" more CO will be produced to intensify the "indirect reduction" above (through the larger amount of reductant available and an increase of CO concentration in the gas) where the iron ore is pre-reduced. Through a time of one half of the period of oscillation, the burden with a higher degree of pre-reduction earlier leads to a corresponding decrease in "direct reduction" because the total reduction is constant. The consequence would lead to a change in the opposite direction, (a decrease in direct reduction) which would induce the same self-correcting mechanism and subsequent changes (an increase in direct reduction some time later), thus, to complete the whole cycle of the periodic variation.

If the internal chemical and thermal states of a blast furnace and its performance parameters, such as productivity and hot metal temperature, are plotted over time, these curves would look like waves. Since bosh gas is the most important link for these interactions mentioned above and the engine to drive the furnace operations, a change in bosh gas properties would twist the shape of the curve, not the nature of a wave. The influence of the change of any tuyere variable on the inner states and furnace performance would be indirectly through the change of bosh gas properties.

The mechanism also causes the variations in the descending rate of the raw material. Furthermore, the material descending rate more or less represents the IRP.

Figure 3 shows the trend of the moving average values of IRP and the solution loss of carbon per minute (SLCt) as functions of time during all coke operation. As mentioned above, the self-correcting mechanism between direct reduction, i.e. solution loss reactions, and indirect reduction leads to the periodic variations of IRP. We can find a similar pattern between IRP and SLCt in Fig.3, i.e. as the IRP increases, the SLCt increases, too. As we know, a solution loss of carbon is an endothermic reaction. Assuming that the heat input through the tuyeres is essentially constant over time, when more heat is consumed by chemical reactions, such as solution loss reaction, less heat will be used for the physical heating of the burden materials. Therefore, colder slag/metal mass entering the hearth will lead to colder hot metal. As it takes time for the solid/liquid mass in front of the tuyeres to be tapped out as hot metal and slag, there should in principle be a time delay for the same batch of material to give us the signal of intensity of solution loss reactions and later the temperature of hot metal, as shown in Fig.4. The out-of-phase relation between HMT (solid curve) and SLCt (dash curve) are shown in this figure with a time delay of two hours (dash-dot curve). Combining Figs.3 and 4 will lead to Fig.2. The HMT varied inversely with

IRP and a time-delay effect was observed between these two parameters.

a blast furnace is not “constant in time”, but in a dynamically steady state that oscillates within a range.

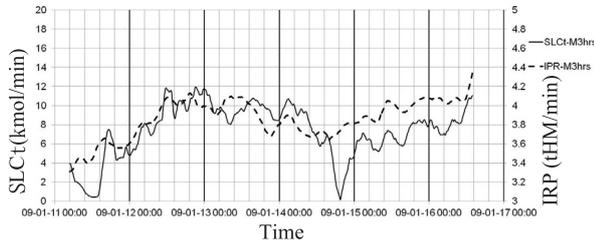


Fig.3. Trend of IRP and SLCT as functions of time during all coke operation.

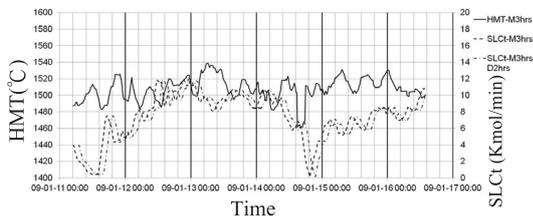


Fig.4. Trend of HMT and SLCT as functions of time during all coke operation.

4. EXTRINSIC DRIVING EFFECT : NORMAL OPERATION

4.1 Variation in IRP, HMT and SLC

Theoretically, a higher wind rate corresponds to a higher production rate. As mentioned earlier, the wind rate was only adjusted slightly during the normal operation period. Moreover the IRP and blast volume did not have a high co-relation (the Pearson correlation coefficient, $r=0.3$). This leads to the conclusion that a blast volume change is a contributing factor, but not the major cause for IRP variations. In order to find out the effect of blasting operation conditions on IRP, a shorter period, one day, was selected for analysis. Figure 5 shows the trend of the tuyere parameters as functions of time during the selected period. There are no obvious patterns between IRP and tuyere practices in this short period. However, the curve of IRP seems to have a periodic variation in time. We have already revealed and explained the self-correcting mechanism during all coke operation. In this section, interactions between regions linked by counter-current flows where direct and indirect reduction prevails are discussed. Furthermore, interdependence between the chemical state and the thermal state in the high temperature region due to solution loss carbon reactions are fundamental and operative in a blast furnace. These interactions represent the intrinsic nature of a blast furnace (a continuous reactor) and lead to the conclusion that a steady state in

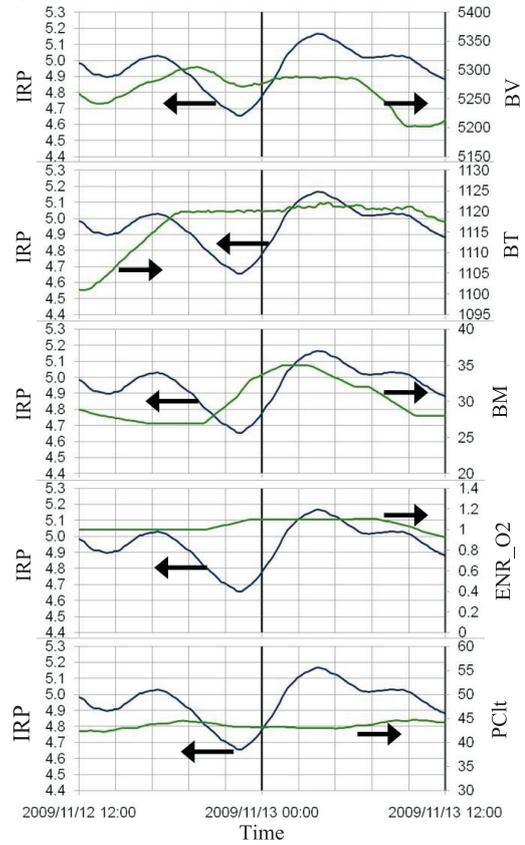


Fig.5. Curves of IRP and tuyere practices varied over time during normal operation.

According to the analysis of the all coke operation, an in-phase relation between IRP and SLCT can be found. A similar correlation can be also found in the normal operation shown in Fig.6. It indicated that the self-correcting mechanism was also observed in the cases operated with fuel injection and oxygen enrichment.

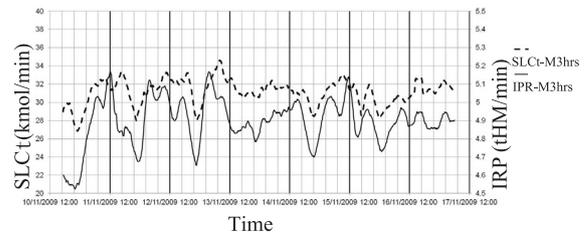


Fig.6. Trend of IRP and SLCT as functions of time during normal operation.

In Fig.4, we have found that HMT and SLCt have a higher degree of co-relation during all coke operation. Figure 7 shows the curves of HMT and SLCt as functions of time during normal operation. An out-of-phase relation between HMT and SLCt was also observed, as shown in Fig.7.

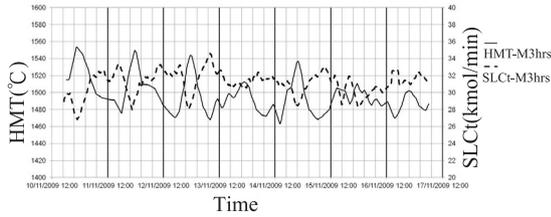


Fig.7. Trend of HMT and SLCt as functions of time during normal operation.

4.2 Combined effect on BF performance

Furthermore, we summarized all the effects of tuyere practices in terms of the heat content of the raceway gas. Each tuyere parameter contributes to the heat input to the furnace; some are positive, some are negative. As the wind rate, hot blast temperature and oxygen enrichment increase, the heat input also increases. The first two parameters provide more heat injecting into furnace from the tuyere. The last one will lead to burning more coke and generating more heat in the raceways. On the contrary, as the moisture and fuel injection increase, the furnace needs to provide more heat to dissociate these two items and causing less heat being available to heat the furnace. Figure 8 shows the relationship between HMT, SLCt and tuyere practices as functions of time over a shorter period. In Fig.8(a), operators try to increase the hot metal temperature by increasing the blast temperature. The solution loss carbon also decreases at the same period and it will lead hot metal temperature increase, too. It indicates that the effect of intrinsic drift and extrinsic driving is reinforced. On the contrary, the case in Fig.8(b) shows the cancelling effect between intrinsic drift and extrinsic driving. The operator decreased the blast moisture to increase hot metal temperature. However, the hot metal temperature should decrease due to the steep rise of solution loss carbon during the same period. The combined effect led the hot metal temperature to slightly decrease. This indicates that operator can adjust the blasting operation conditions to control the hot metal temperature under the condition that the heat required of solution loss of carbon reaction does not vary much. When heat re quired of solution loss of carbon varied steeply as shown in Fig.8(b), the hot metal temperature varied according to the variation of solution loss of

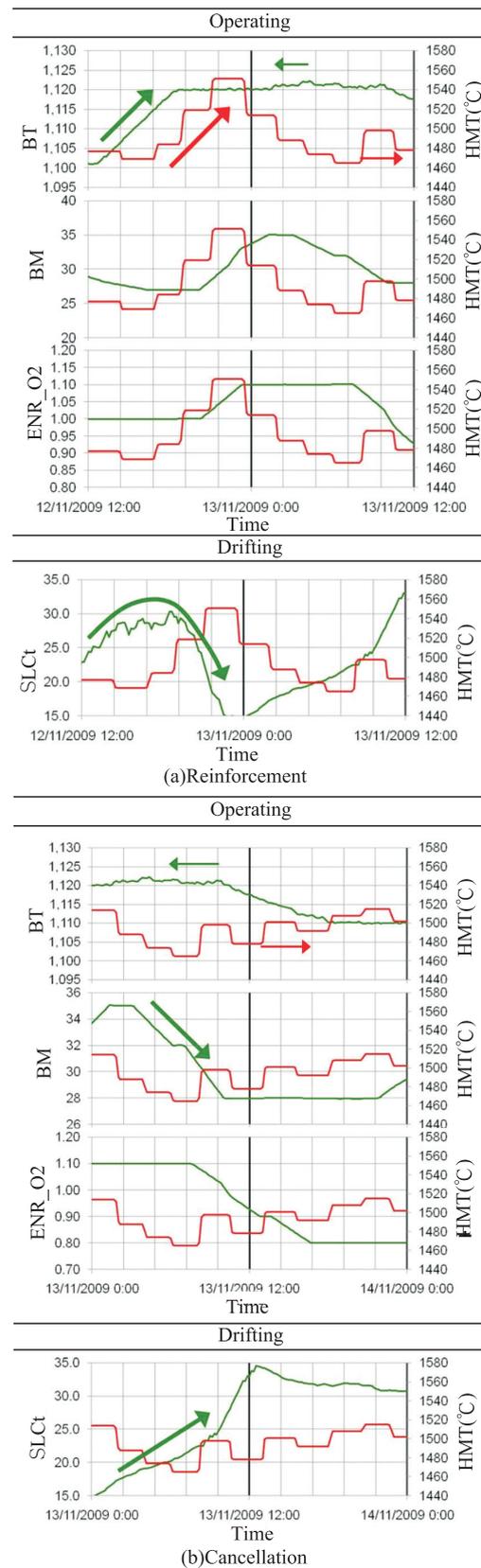


Fig.8. The curves of HMT and tuyere practices varied over time during normal operation.

carbon. The intrinsic drift as the result of the interacting mechanism presented earlier seems to be the dominant factor causing the variations of hot metal temperature. The intrinsic variations of blast furnace performance should be taken into consideration pro-actively in the control of a blast furnace.

5. CONCLUSIONS

From the above investigation, the following conclusions are obtained:

- (1) The instantaneous production rate (IRP) and hot metal temperature (HMT) have periodic variation during all coke operation with minor adjustment in tuyere conditions and normal operation with fuel injection and oxygen enrichment.
- (2) The variations of instantaneous production rate and solution loss of carbon in time were found to be in phase. An out-of phase relation between solution loss of carbon and hot metal temperature was also established.
- (3) A time-delay effect was found between IRP and HMT, and the delay time depended on descent rate of burden materials.

- (4) The observed drifting and self-correcting of blast furnace operating conditions may be explained based on the nature of counter-current flows and solution loss of carbon reactions, and is fundamental and common in all types of operations. The length of period of oscillations and the magnitude of changes depend on raceway (bosh) gas properties, then, indirectly on tuyere practice.
- (5) The dominant influence of intrinsic variations on furnace productivity and hot metal quality should be taken into consideration pro-actively in the control of a blast furnace.

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