Control Blast Furnace Pulverized Coal Injection to Increase PCI Rates

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Key words: Pulverized coal injection, Coal flow meter, Controlled injection, Equal distribution, Increase of PCI

INTRODUCTION

Pulverized coal injection (PCI) is a recognized method of controlling costs in iron making. The blast furnace is a complex system, so the replacement of coke with pulverized coal is not as simple as increasing the injection rates, especially when one considers iron chemistry, fuel rates and furnace campaign life. Important factors must be considered to achieve stable furnace operating conditions.

This paper reviews the benefits of real time control of the injection system through closed-loop processes. Practical examples are reviewed, showing how the furnace operating stability can be maintained while increasing injection rates and lowering overall production costs.

PRESENT SITUATION

Many blast furnaces (BF) are equipped with PCI systems, and the escalating price of coke provides increasing benefit for these producers. Most of the older coal injections operate with a static distribution design. This method is based on the assumption that the evenly designed pneumatic convey lines will provide equal coal distribution in the blast furnace hearth. Individual control of each line is not provided. Injection rates are measured by tracking the change in weight of the hopper or storage bin. This is effective as long as injection rates are at a low level, as unobserved line-to-line deviations have minimal influence on the operation.

In contrast, in the last decade, the PCI injection amounts have been increasing in the majority of furnaces worldwide, approaching values between 150 kg/thm to 220 kg/thm. These values differ from shop-to-shop because of various factors not only on the equipment side (mill capacity), but also from coke quality, which limits the amount of pulverized coal to ensure proper raceway conditions.

Under these injection rates, the static distribution method without individual flow control has largely reached its limits. Monitoring the weight change in the pulverized coal storage bin cannot account for tuyere overload. Overloading the tuyere/hearth area with unburned coal leads to clogging of the coke and reduced wind in that area. Gas flows are affected in a negative way. This can lead to the serious condition of “freezing” of certain zones inside the blast furnace, which must be avoided under all circumstances.

Show in Figure 1 is an example of a 16-tuyere BF equipped with injection line measurement. For each tuyere the set point (desired value) and the measured amount (actual value) of pulverized coal are shown. The values were measured over the course of three days, with the daily average illustrated. The PCI rates were measured using a Coal Flow Meter supplied by AMEPA GmbH.

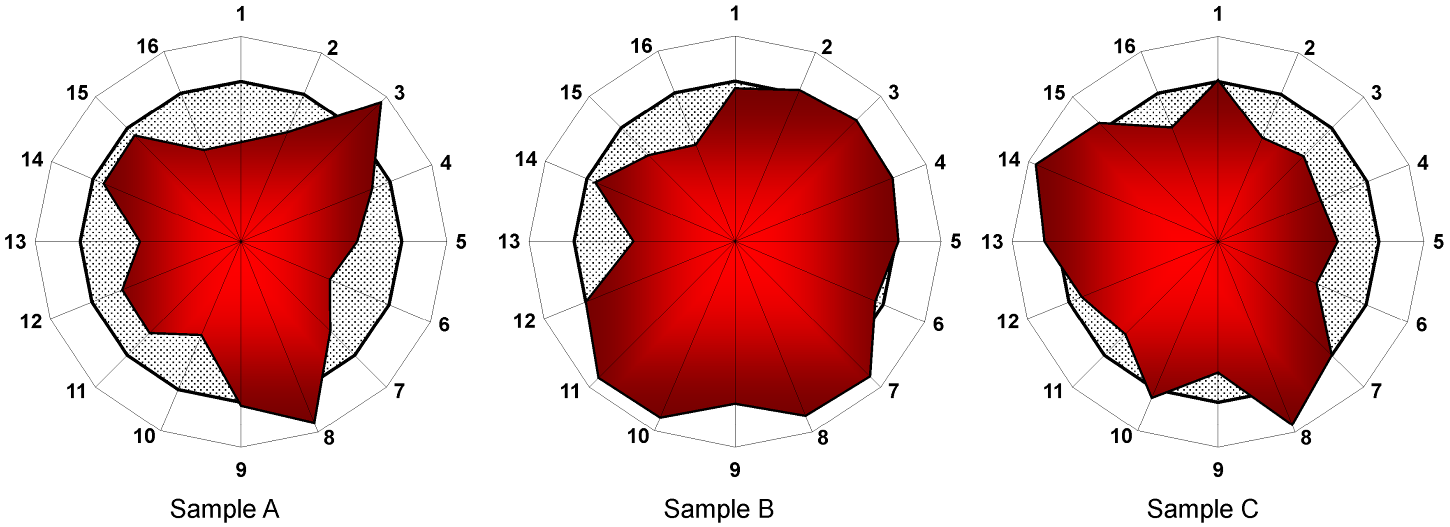


Figure 1: Measured deviation of daily injected coal amounts per tuyère (static distribution)

An analysis of this data provides the following observations:

1. Overload areas exist in several tuyeres (e.g. sample A: tuyère no.3 & 8)
2. Injection amounts are below optimum in many tuyeres (e.g. sample A: all tuyères except 3, 8 & 9)
3. Pattern of coal distribution changes unpredictable.
4. Average throughput as measured by changes in hopper weight is inadequate to achieve an equal distribution of pulverized coal to the BF.
5. The concept of equal distribution in a static system is not reflected in reality.

Observation 5 summarizes the weak point for all PCI installations without individual control of each tuyère. Investigating further, we see that short term flow rate changes are marked by line-to-line deviations of 50%, appear frequently and are often undetected because the overall throughput is kept constant. Below is an actual example.

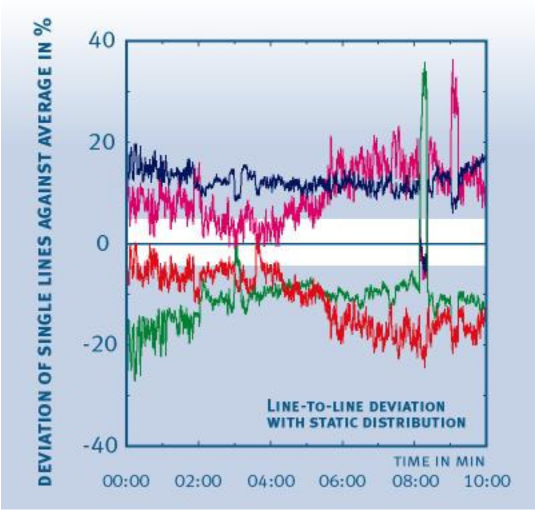


Figure 2: Example for short term flow rate deviation of selected injection lines

The measured conditions shown in figure 1 and 2 are far from optimum. To have a healthy furnace with a stable operation, guidelines are requesting deviations of less than +/- 5%. This is not reached. The real situation is unknown and problems stay unrecognized by the operator, tendencies are unpredictable.

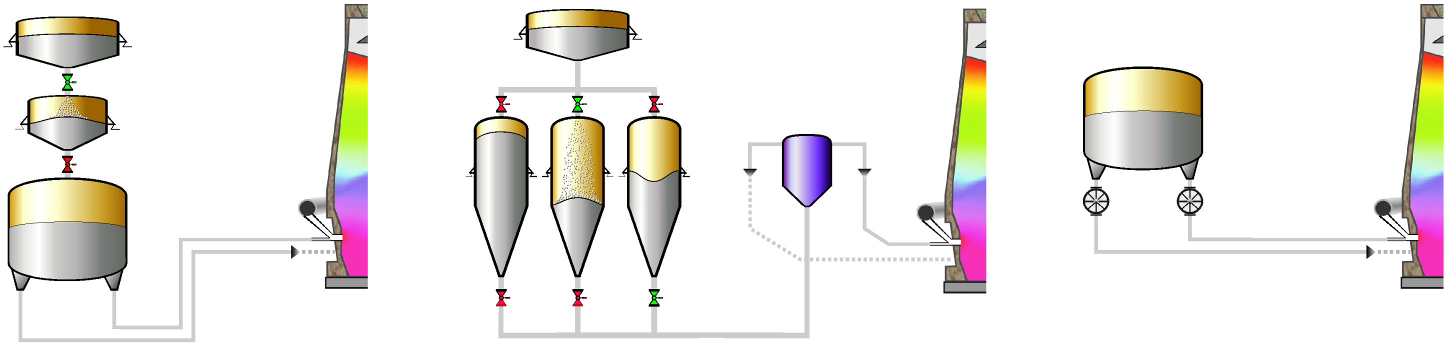
Pneumatic Conveying line designs intend to equal the line length or pneumatic resistances to provide uniform distribution. However, the deviations can not be eliminated completely as air is very compressible and even slight changes in backpressure condition in the blast furnace result in flow deviations in the individual lines.[1]

Optimization must start with the measurement of actual flow rates in each injection line to understand the real conditions of the PCI lines. The next step is consequently the control of each line to reach and guarantee healthy furnace operation. Only then the injection rates can be increased to reasonable high levels. This is an upgrade from an uncontrolled to a controlled system.

ONLINE COAL FLOW MEASUREMENT - A FIRST STEP

Blast Furnace Design

Blast Furnaces equipped with PCI injection systems have many local modifications to accommodate the on-site designs. In general, they can be described in three different categories, as shown in Figure 3.



stacked vessel design

side-by-side vessel design with distributor

high pressure rotary feeder design

Figure 3: Blast furnace equipped with PCI

PCI Injection System Design

Injection systems types can also be categorized into two types of flow ranges: dilute phase and dense phase.

The dilute phase transport is characterized by high gas velocities (more 10 m/s) and low pulverized coal concentration. The coal particles are suspended in the conveying gas and are completely separated from each other. Due to high energy consumption for providing the high amount of transport gas, this conveying method is less economical compared to a dense phase flow.

The dense phase flow on the other side is characterized by low gas velocities (2-6 m/s) and high pulverized coal concentrations (100-200 kg/m³). Figure 4 shows the different types of conveying.

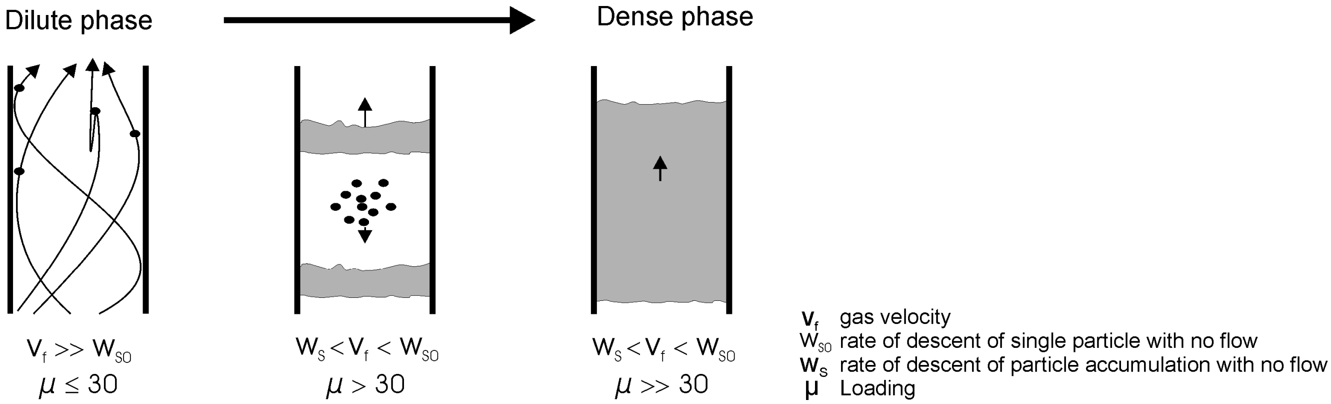


Figure 4: Different flow conditions from dilute phase to dense phase

Coal Measurement System Design

To measure the pulverized coal in each line, an accurate and reliable measurement system must be available. For this discussion, let's define what requirements the measuring system must include:

- The amount of conveying gas must not influence the measurement
- The measurement of both velocity and concentration must be independent of the type of flow
- The units must be easy to integrate in existing installations

In the past, there have been different approaches to measure the mass flow in a pneumatic conveying system:

- Microwave Doppler measurement
- Coriolis force measurement systems
- Triboelectric measurements
- Optical inspection of the plume at the tuyère
- Capacitive measurement

Since conveying pulverized coal into a blast furnace is very different from pneumatically conveying other bulk materials, the boundary conditions are important. One important factor is that the conveying gas can not be separated from the transported material. The conveying gas is also fed into the blast furnace together with the pulverized coal; naturally then that the following issues are of interest:

- Mode of conveying
- Ratio of conveying gas and pulverized coal
- Composition of the conveying gas

Comparing these criteria to the measurement approaches mentioned, the following observations can be made:

- Microwave technology is used mainly in dilute flow installations. It can be used successfully, for example, in combustion facilities where large pipe diameters provide low material concentration. However, relatively speaking, PCI installations operate at much higher material concentrations; so this technology will not provide reliable flow rates under the constantly varying flow rate velocities.
- Coriolis force meters have the advantage that they are true mass flow meters, but they also bear the inherent disadvantage that the indicated flow rate is not independent; rather it is dependent on the amount of conveying gas. Further hampering this measurement principle is the design includes inherent sharp corners in the pipe which provides a higher tendency for clogging.
- Tribo-electric measuring devices share similar disadvantages that microwave technologies do. The indicated flow rate is only correct for one fixed velocity – changes in velocity under normal operation influence the measurements.
- Trials were made with optical inspections through a watch hole at the tuyère. The fine coal particles build a dark cloud. Shapes and sizes of the clouds can also e inspected, but differences in the flow could not be detected because the movement of the plume is affected by the air flow into the blast furnace.[2] Optical inspection are only useful for the detection for complete blockage.
- Capacitive measurement technology is widely used for measuring pneumatically conveyed materials as well as coal flow applications. The technology has shown to be independent of conveying gas composition, gas flow rates and conveying modes. Therefore, it would appear as the most suitable technology for the measurement application.

Capacitive Measurement Technology Adapted for PCI Application

Flow rate can be calculated by determining the pulverized coal concentration, velocity and the cross sectional area of the conveying pipe; therefore a capacitive measuring system consists of two sensors.

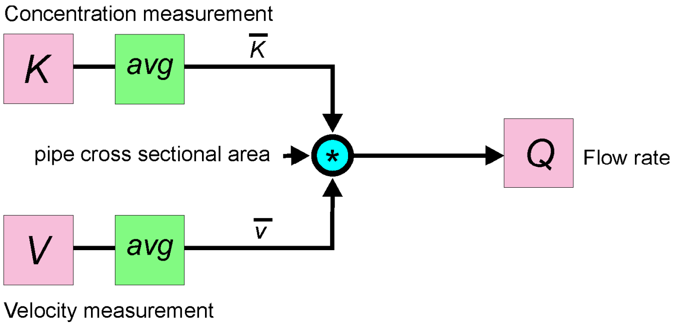


Figure 3: Principle of capacitive flow measurement

In capacitive measurements, concentration is measured by detecting the permittivity of the conveyed pulverized coal. Special attention must be paid to the size and shape of the measuring electrodes in the sensor.

Velocity is measured using a correlation function. Previous systems used the classic-style correlation function as shown in Figure 4. Two signals are acquired at distinct positions of the line and fed into an arithmetic unit that does calculate a correlation function of the two signals.

If the velocity of all coal particles passing the distance L would be the same the correlation function would have one sharp maximum indicating the exact travel time Δt.[3]

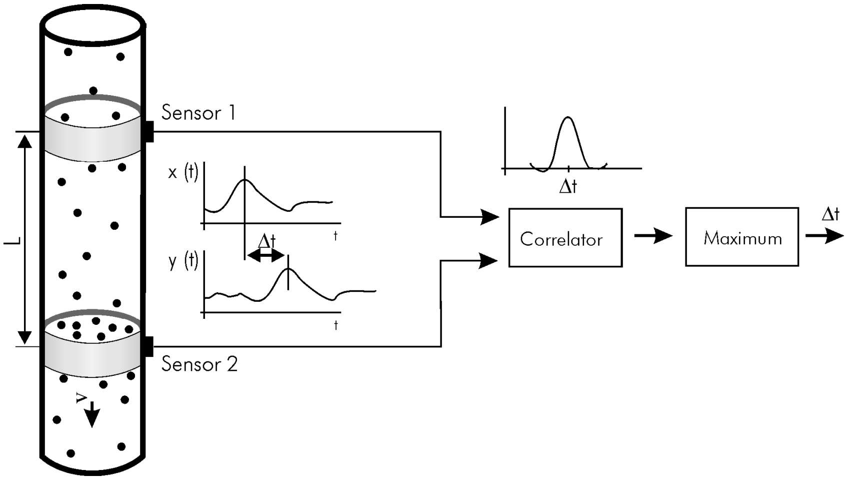


Figure 4: Signal acquisition and calculation of the correlation function

In reality not all particles have the same velocity. Apart from stochastic fluctuations there is also a distinctive distribution of the velocity over the diameter of the pipe. This distribution is dependent on various factors - e.g. the material concentration – and becomes more important especially in dense phase conveying as shown in Figure 5.

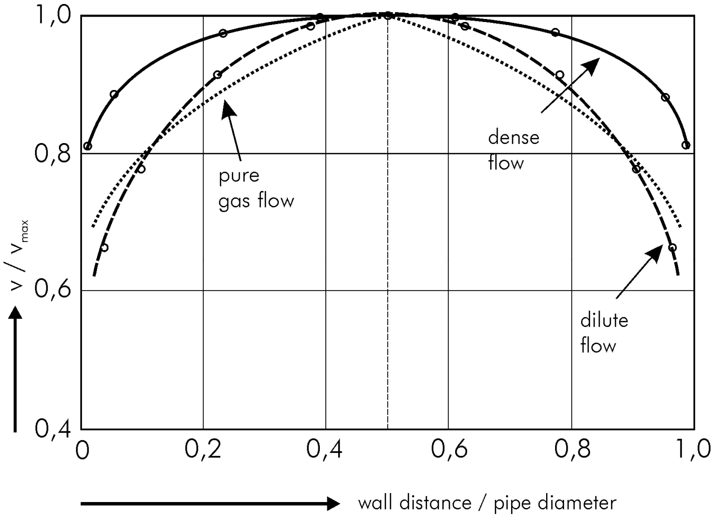


Figure 5: Normalized distribution of velocities in the pipe

Considering the real-world aspects of flow distribution, the classic-style correlation function cannot be used. The correlation function maximum position is not distinct enough to derive the average travel time. Secondary maximum peaks could exist. Therefore, to calculate an accurate value for the velocity, all particles must be taken into account. The flow rate has to be calculated as shown in Figure 6.

$$Q = \frac{\sum K_i v_i}{n} A$$

Q = flow rate
v_i = velocity of single cubicle
K_i = local solid concentration of single cubicle
A = cross sectional area of pipe
n = number of cubicles

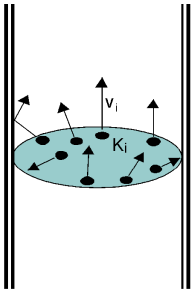


Figure 6: Calculation of flow rate

In practical aspects, it is impossible to monitor the velocity and mass of every single coal particle. Therefore a flow meter has to determine an average velocity and an average material concentration. This must be carefully done so that the resulting flow rate accurate reflects real flow rates.

To do this, AMEPA has developed an adaptive signal processing to extract as many characteristics from the two signals as possible and uses this method to calculate flow rate in its CFM product. Every characteristic measured is validated individually as to whether it contains valid information corresponding to the axial movement of particles. This adaptation that accounts for changing velocity profiles is better because of the large number of discrete values for the travel time. By using this principle of operation, the CFM has advantages compared to classical correlator designs.

IMPROVEMENTS TO EXISTING INSTALLATIONS -- CONTROLLED INJECTION

The upgrade of existing PCI installations must start with a process variable measurement tool – measuring the amount of pulverized coal in each line so as to optimize the inject rates. Naturally then, the capacitive measuring sensors are located in each injection line. An installation example is shown schematically in Figure 7.

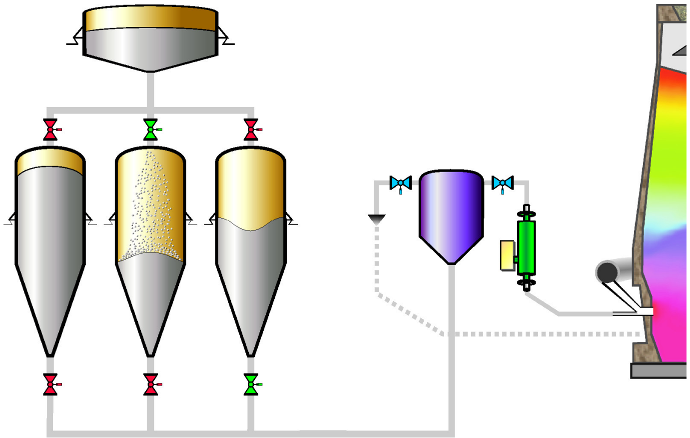


Figure 7: Side-by-side-vessel design with controlled injection

The measured signal output is fed directly into the PLC where a PID controller compares the input signals with the set points and controls the valves in the injection lines. As illustrated in Figure 8, the control loop is now closed.

Whether altering the line flow by a valve or by adjusting the transport gas, the measurement system can be used in various PCI installation layouts such as a side-by-side-vessel design, a stacked-vessel design with locking chamber or high pressure rotary feeders.

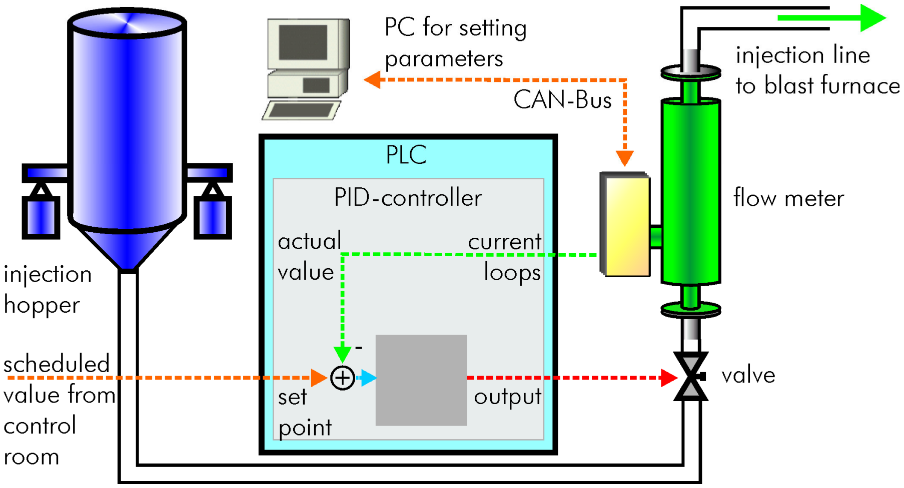


Figure 8: Principle of a closed loop control injection

By the controlled injection for each individual line and maintaining an equal distribution among the lines, a stable injection is reached and the healthy operation of the furnace is achieved. Figure 9 shows the performance of line-to-line deviations in a controlled injection environment.

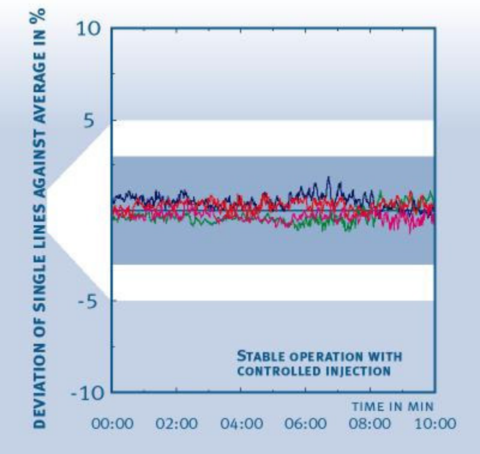


Figure 9: Stable injection for each line

With stable and uniform PCI distribution, overloading areas of the hearth can be avoided. With overloads optimized, the PCI rate can then be optimally increased for the individual blast furnace installation.

Operational Aspects to Increasing PCI Injection Rates

There are limiting factors on PCI rates inherent to the process that cannot be influenced by a control system. For example, coke quality and burden distribution are examples for these factors. From these boundary conditions the highest possible PCI rate must be determined individually for each blast furnace.

Again referencing the installation in Figure 1, we see that the operator calculated an optimum injection rate of 22.5 tons/hr. As a result of monitoring the blast furnace condition, the set point for the PCI was reduced to 20 tons/hr. In sample A the total injection rate was further decreased to 16.5 tons/hr, because a lower quality of pig iron was introduced. These efforts are shown in Figure 10. We see that even with the reduced injection rates, two tuyeres were still overloaded (no. 3 and 8).

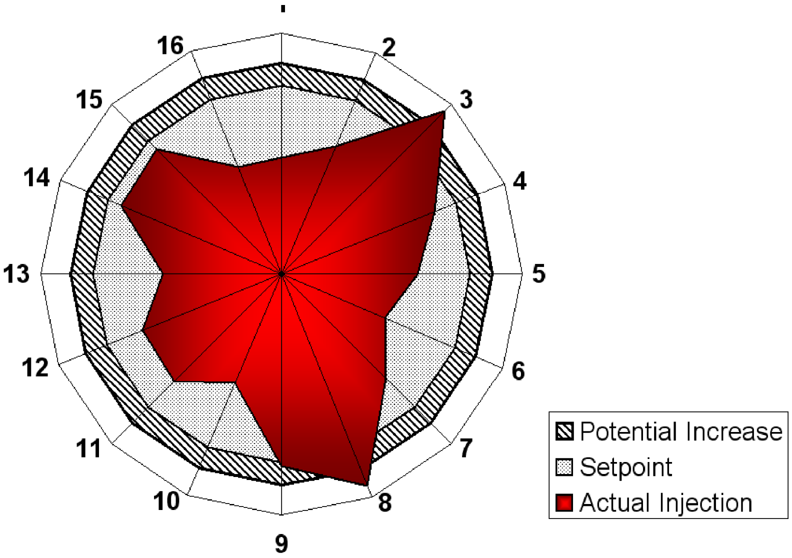


Figure 10: Deviations and potential increase of PCI (sample A)

By maintaining an equal distribution, the risk of overloading can be minimized and the set point can be increased to the initially aimed 22.5 tons/hr without a loss in quality of the pig iron. A potential increase of the PCI rate of 36% is possible. The numbers for the other samples are shown in Table I.

Table I: Overview of potential increase of PCI

	A	B	C
Optimum PCI	22.5 t/h	22.5 t/h	22.5 t/h
Limit by BF condition	20 t/h	20 t/h	20 t/h
Actual total injection	16.5 t/h	19.75 t/h	18.2 t/h
Avg. deviation (%) from limit	-17.5 %	-1.25 %	-9 %
Standard deviation (line to line)	24.5 %	21.5 %	22.8 %
Potential increase of PCI	**36.4 %**	**13.9 %**	**23.6 %**

CONCLUSION

Economic benefits of increasing PCI injection rates are overwhelming when one considers the continually rising cost of coke. Optimizing the injection rates cannot be done by simply pushing more pulverized coal through the feeding bin, as this can lead to tuyere overload and significant operating issues. The solution for injection optimization is through closed-loop real time control of the coal injection system. Historical application experiences along with underlying physics illustrates to us that the optimal sensor to measure coal flow rates is with the capacitive method, as it best accomplishes real world flow rate indication. Whether upgrading existing facilities or accounting for closed loop control in new PCI systems, optimizing the system design affords the ability to:

1. **Optimize PCI rates by minimizing line-to-line deviations**

   We have seen that deviations can be minimized using a controlled injection system. To achieve closed-loop control, a flow meter is needed. With an equal distribution of the injected pulverized coal, the set point for the PCI can be increased. Nevertheless the same level of quality of the pig iron can be maintained. Further on the level of quality and the blast furnace condition can be improved by strictly avoiding undetected PCI overload to parts of the blast furnace.

2. **Efficient operation of the PCI installation**

   Online measurement is a critical tool in dense phase transport of material. Dense phase conveying has economic advantages by injecting with lower energy consumption and less pipe wear. Operational issues including clogging can be mastered with an online flow tool.

3. **Stabilization of the blast furnace**

   With uniform and balanced PCI injection, variables that once affected the blast furnace can be reduced and the process will run more stabilize.

Increasing coal injection rates are a reality driven by raw material costs and environmental concerns that are altering the pricing structure of coke. Improved injection rates offer a direct opportunity for significant savings. To achieve higher rates without harming the current operation, line-to-line deviations must be controlled. Measurement technology is available to accomplish this task, and thus afford today's Blast Furnace operations another step in continuous improvement.

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