An Experimental Perspective on Praxair's Hot Oxygen Technology to Enhance Pulverized Solid Fuel Combustion for Ironmaking Blast Furnaces

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ABSTRACT

Increased tuyere injection of solid fuels such as pulverized coal in iron-making blast furnaces has been looked into over several years to reduce metallurgical coke consumption. Incomplete combustion of char in the tuyere zone and consequent disturbances in gas and burden flow in the furnace have generally limited the injection rate of such solid fuels at rates over 200 kg/tonne of hot metal in several cases. Praxair has developed an application utilizing its patented thermal nozzle technology using oxygen, which aims to improve the combustion efficiency of such injected pulverized solid fuels. This is accomplished by virtue of quicker ignition, de-volatilization of the pulverized solid fuel followed by intense mixing of the solid fuel using a high momentum, high temperature stream of oxygen generated *in situ*. An experimental investigation into the effectiveness of such an approach on pulverized fuel burnout efficiency is presented. An experimental comparison with traditional injection methods is also established. Both small scale and pilot scale experimental laboratory tests and results are discussed. Certain key factors such as hot blast enrichment level and lance location inside a blast furnace tuyere are also highlighted.

INTRODUCTION

The iron blast furnace uses carbon as a fuel to meet the energy requirements of the process as well as a reducing agent for smelting the iron ore to pig iron. The most widespread form of carbon used for this purpose is metallurgical coke. The importance of metallurgical coke in the blast furnace further rests in its ability to maintain the bed permeability and structural integrity under the reducing conditions as well as the load of the burden. Use of other forms of carbon like lump coal and lump charcoal is restricted in large capacity blast furnaces because of their tendency to disintegrate (poor compressive strength) under the load of the furnace burden and the thermo-chemical environment inside the furnace. Under such circumstances, the bed permeability is impaired, which leads to higher resistance to gas flow and increase in the pressure drop across the bed. This has a negative impact on the heat and mass transfer between the gases and the solid burden, consequently leading to furnace irregularities.

Over the past few decades, because of high coke prices and increasing pressure on the coke makers as a result of aging coke oven batteries coupled with more stringent environmental regulations, the option of injecting pulverized coal or charcoal into the blast furnaces through the tuyeres has gained prominence at several ironmaking facilities. Pulverized coal (non-coking) or charcoal fines are relatively cheaper than coking coals (used for metallurgical coke production) and lump charcoal. They are also more readily available, although the grinding and milling comes at a cost to the iron producers. Furthermore, they present a larger surface area for chemical reaction compared to metallurgical coke which is charged from

the top of the furnace. Because of their finer size distribution, they are injected through the tuyeres to avoid a negative impact on bed voidage and permeability. The goal is to maximize the combustion of the pulverized carbon in the furnace raceway to generate thermal energy and the reducing gases to chemically reduce the iron-oxide in the burden. This practice, if effectively accomplished, results in lowering of the more expensive metallurgical coke/lump charcoal consumption. On the other hand, inefficient combustion of the pulverized carbon gives rise to formation of large amounts of char, which often leads to clogging up of the coke slits (porous pathways in the cohesive zone of the furnace for the hot reducing gases to ascend) as well as the coke surrounding the furnace raceway, thereby disturbing the bed permeability and gas distribution. Furthermore, loss of unburnt carbonaceous fines may occur through the gas escaping from the top of the furnace.

In order to boost the combustion efficiency of the pulverized carbonaceous injectant, some of the popular practices followed by the blast furnace ironmakers across the globe are using an oxygen enriched air blast containing anywhere from 22-30 vol. pct. of oxygen and operating the furnace at high blast temperatures. Increasing the tuyere injection of pulverized solid fuel at a specific hot blast temperature and other tuyere injections, causes a drop in the raceway adiabatic flame temperature of the furnace. The amount of oxygen in the blast and the temperature of the hot blast are correspondingly adjusted to counter this drop due to injection of the carbonaceous solid fuel. The goal is to operate at a consistent raceway adiabatic flame temperature as well as maintain the appropriate bed permeability, which allow for a stable furnace operation.

LITERATURE REVIEW

Combustion studies of pulverized solid fuels for the energy sector can be found quite extensively in the literature, especially after the emergence of this category of fuels as a popular choice following the wide fluctuations in the market prices and availability of their liquid and gaseous counterparts in various geographies. Those skilled in the art will appreciate the fact that solid fuel combustion revolves around certain key variables such as particle temperature, particle size distribution, oxygen concentration and residence time, to name a few. One can directly control the secondary variables such as heating rate of the solid fuel, mixing rate, oxygen injection rate, and thus attempt to indirectly influence the primary variables. Some of these primary variables may be relatively more difficult to control than the others under a particular set of conditions. For example, the limitation imposed by a short residence time available for the solid fuel to combust in the blast furnace raceway is circumvented by indirect methods to increase the particle temperature (higher heating rates by increasing hot blast temperature) and oxygen concentration (oxygen injection or blast enrichment), which enhance the overall kinetics of the combustion reactions. The role of oxygen towards enhancing the combustion characteristics of solid fuels has found mention in numerous works. The presentation of an exhaustive literature survey is beyond the scope of this article. A few references are discussed from the vast amount of literature available in order to help the reader appreciate the role played by oxygen in such combustion phenomena.

In a single coal particle combustion study by Timothy and co-workers [1], it was observed that the coal particle burnout time shows a general decreasing trend with a progressive increase in the oxygen partial pressure in the ambient around the coal particle. The extent of decay of the particle burnout time with increasing oxygen concentration was found to be influenced by particle size, ambient temperature and type of coal (ash content). Particle surface temperature measurements further indicated a monotonically increasing trend with oxygen concentration. The experimental determination of approximate de-volatilization times suggested that high oxygen concentrations are favorable for de-volatilization kinetics.

In yet another study on single coal particle combustion, a single particle imaging of the ignition and de-volatilization of pulverized coal during oxy-fuel combustion was looked into by Shaddix and Molina [2]. Experiments were conducted at various oxygen concentrations (12-36 vol. pct.) in N_2 and CO_2 diluent gas mixtures. Measurements indicated that the use of CO_2 as a diluent as opposed to N_2 retards the onset of ignition and increases the de-volatilization time of the coal particle. Shaddix and Molina attributed this observation to the higher molar specific heat capacity of CO_2 and its tendency to reduce the local radical concentration. An increasing oxygen concentration for a specific diluent medium, on the other hand, contributed towards improvement in the ignition time and de-volatilization kinetics of the coal particle.

This was explained on the basis of a higher mass flux of oxygen to the combustion of the volatile cloud around the coal particle, which consequently enhanced the rate of de-volatilization.

The aspect of mixing of the pulverized solid fuel with the oxygen was emphasized in a theoretical *cum* experimental investigation by Ohno and co-workers [3] on the combustion characteristics of the injected pulverized solid fuel into the blast furnace raceway. It was demonstrated that the design of the oxygen and solid fuel injection devices needs to be carefully evaluated from the standpoint of the mixing behavior of the solid fuel with oxygen. It was also shown that the level of benefit achieved as a consequence of higher oxygen concentrations in the blast can be negated if the mixing of the solid fuel with oxygen poses a limitation.

Several descriptions of experimental activity involving pilot scale test systems for studying tuyere pulverized coal injection practices for blast furnaces can be found in the literature. In one of such many publications, Mathieson et al. [4] have reported the progressive development and design of combustion test rigs to understand the combustion behavior of pulverized coal under simulated blast furnace conditions. Char samples were collected at specific locations to assess combustion efficiency under stoichiometric conditions with respect to coal and oxygen. Mathieson et al. report a general increasing trend of combustion efficiency with the volatile matter content of the coals for a specific hot blast temperature, though these increasing trends tend to become more gradual as the hot blast temperature rises.

Ariyama and co-workers [5] conducted hot model experiments on pulverized coal injection using a hot blast conduit (blowpipe) communicating with a coke packed column, with the pulverized coal injection at different axial locations along the length of the blowpipe. They reported that the lance arrangement inside the blowpipe affects the distribution of the coal particles across the blast cross section. Non-uniformities in coal distribution can arise due to less than optimal lance locations and coal feeder limitations. Ariyama and co-workers further corroborated the importance of the local oxygen availability around the coal particles during the de-volatilization stage, when the volatile cloud resulting from the coal pyrolysis combusts using the oxygen in the near vicinity, thereby causing a local depletion of oxygen in the vicinity of the coal particles, possibly negatively influencing the kinetics of the combustion reactions. Therefore, replenishment of this consumed oxygen locally around the particles is necessary to sustain the volatile combustion reactions.

Praxair invented the Thermal Nozzle technology in the early nineties [6] in order to overcome injection limitations imposed by low onsite supply pressure of its products, especially oxygen, which is quite normal while producing oxygen by the VPSA (Vacuum Pressure Swing Adsorption) approach. The thermal nozzle is a device in which a gaseous reagent is heated inside a pipe *in situ* using the enthalpy of combustion of a gaseous/liquid hydrocarbon fuel and an oxidizer such as oxygen. The end of the pipe is terminated by a nozzle. The main gas along with the products of combustion expands as they flow through this nozzle to form a high velocity, high temperature, high momentum under-expanded jet downstream of the nozzle exit. The fuel is introduced into the combustion zone inside the pipe through a centrally arranged pipe with a nozzle at its end. The fuel nozzle serves as the location where the oxy-fuel flame gets attached. A schematic of the thermal nozzle for oxygen is shown in Figure 1. A thermal nozzle employed for oxygen is referred to as a Hot Oxygen Device (HOD). A photograph of a transparent HOD is shown in Figure 2. The combustion of pulverized solid fuels such as coal, charcoal, pet-coke etc. injected through the blast furnace tuyeres was identified as an area suited for the application of such a device [7].
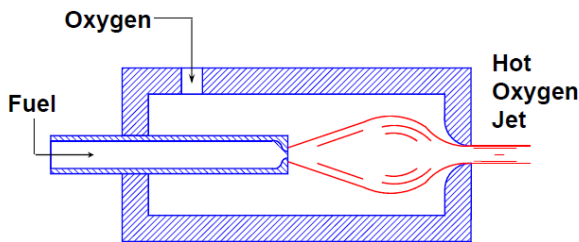

Figure 1, Schematic of a Hot Oxygen Device [6]

Figure 2, Transparent Hot Oxygen Device

The primary objective of this experimental endeavor was to look into the effect of hot oxygen injection (using a HOD) into a simulated hot blast stream in the laboratory on the combustion characteristics of a pulverized solid fuel stream injected into the hot blast in conjunction. Tests of a similar nature, but on a much lower scale were conducted in an earlier study by Riley and co-workers [8]. The present pilot scale simulations, though at a reduced scale compared to a full scale blast furnace tuyere operation, were designed to capture the major essence of the combustion related phenomena of the pulverized solid fuel. The hot blast flow rate and the chamber dimensions were selected in a manner, so as to correspond to similar tuyere velocities as commercial blast furnace tuyeres. This was important from the standpoint of simulating a short residence time of the pulverized solid fuel injectant in the combustion zone, which is typical for current tuyere injection practices.

EXPERIMENTAL APPARATUS – PROOF OF CONCEPT TESTS

Laboratory experiments to simulate this process involve generating a hot air blast using a tube apparatus that was custom designed for this purpose. The tube apparatus comprised three water cooled pipe sections that were assembled together by instrument flanges. An oxygen-natural gas diffusion flame burner was mounted on to one end of this tube assembly, while the other end was open to the atmosphere. The pressure inside the assembly was near atmospheric during operation. The purpose of this burner was to heat up the air blast to the requisite temperature. The air was introduced into the assembly just downstream of this burner. Such a method of heating the hot blast is quick and allows for the blast temperature to be flexibly controlled. It doesn't need expensive heat exchangers and is suitable for such kind of experiments. It is to be noted that the simulated hot blast will contain impurities in the form of products of combustion of natural gas with oxygen, predominantly carbon dioxide and water vapor. However, due to the presence of excess oxygen in the blast relative to what is required for the complete combustion of the solid fuel, the gasification reactions of the carbonaceous solid fuel with these impurity species will be relatively insignificant. A blast air flow rate of about 1000 Nm^3/hr was used for these experiments. Thermocouples and gas sampling ports were installed at various axial locations along the length of the assembly. The HOD and the pulverized solid fuel lance were introduced into the hot blast stream at a specific orientation through designated ports on the third pipe section of the assembly. Additional oxygen was admitted into the air blast either by direct bleeding into the air prior to its introduction into the hot tube assembly or by injection through lances just upstream of the exit of the tube apparatus. These are discussed in detail in the following paragraph. The blast was sampled for the oxygen content through a port near the exit of the hot tube assembly. A bench-top gas analyzer was used for this purpose. The temperature measured by the thermocouple near the exit of the hot tube assembly during hot blast generation was considered as the controlling blast temperature. This was just a reference temperature that was maintained at this specific location for all of the experiments. The schematic of the experimental setup is shown in Figure 3.
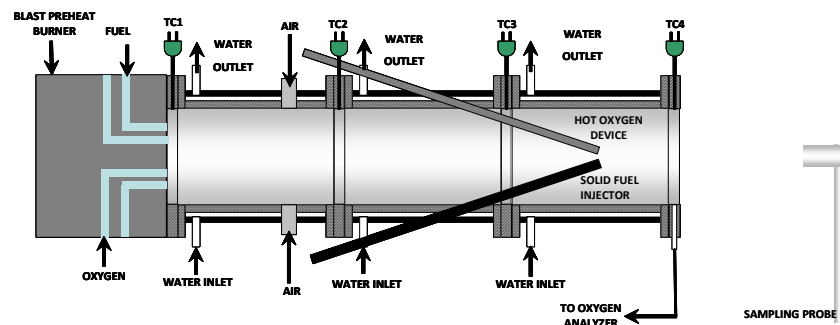

Figure 3, Schematic of tube apparatus for small scale solid fuel combustion experiments in simulated hot air blast

Four different experimental conditions in terms of mode of oxygen injection were investigated. These different scenarios are being described as follows.

(a) **Baseline Condition:** This condition simulates normal hot air blast containing 21 volume pct. oxygen emanating from the tube assembly at a temperature of about 1073 K (~ 1470°F). There is no oxygen enrichment in this case. However, since the hot blast in the simulator is generated by heating air directly with a burner, a part of the oxygen in the air is utilized to combust the natural gas. Thus, some additional amount of oxygen is supplied externally to make up for this deficit and restore the oxygen concentration to that of normal air. The products of combustion remain in the hot blast stream.

(b) **Enriched Air Blast:** Under this situation, the blast is enriched to 25 pct. by volume of available oxygen. The additional oxygen is pre-mixed with air before it enters the tube assembly. The reference temperature of the blast near the injection point is similar to the previous condition (1073 K or 1470°F).

(c) **Ambient Oxygen Lance Injection:** This is similar to the enriched blast condition in terms of available oxygen content of the blast. However, the additional oxygen is injected at ambient temperature through the HOD into the hot blast stream without any natural gas flowing through the fuel nozzle of the HOD. The hot blast temperature at the injection location was maintained as that of the previous conditions. The oxygen flow rate through the injection device is adjusted such that the oxygen content of the simulated blast downstream of the injection point is about 25 volume pct.

(d) **Hot Oxygen Injection:** In this scenario, the oxygen is injected through the HOD at a high temperature. The flows of oxygen and natural gas to the lance are adjusted such that the oxygen content of the hot blast stream is 25 volume pct. after the injection of hot oxygen stream into the hot blast. The hot blast temperature in the vicinity of the hot oxygen injection device (1073 K or 1470°F) was adequate for auto-ignition of the HOD.

Pulverized hardwood charcoal (100 % -100 mesh size) was used for these tests. The charcoal was fed through a solids handling system using air as the carrier gas. The pulverized charcoal injection was initiated subsequently after the attainment of the desired controlling blast temperature and the admission of oxygen into the blast stream had been accomplished through the appropriate means. A charcoal feed rate of about 190-218 kg/hr (7-8 lb/min) was used for these tests. The typical proximate analysis is tabulated in Table I below. Injection of charcoal fines under a simulated hot blast ambient was looked at by Babich et al. [9]. Charcoal is a much higher reactive form of carbon than pulverized coal, and its composition is dependent upon the carbonization conditions of the wood from which it is manufactured. Babich et al. reported that the combustion efficiency of charcoal is less dependent upon the O_2/C ratio in comparison to coals.

Moisture (Mass %)	Volatile Matter (Mass %)	Ash (Mass %)	Fixed Carbon (Mass %)
3.5-5	26-30	8-9.5	57-65

Table I. Proximate analysis for hardwood charcoal used in experiments

A portion of the residual char from the combustion stream is sampled using a water-cooled suction probe and analyzed (proximate analysis) to determine the degree of fixed carbon burnout for each of the conditions as described above. A reference sample of charcoal, as received, is also sent for analysis. From the analysis results and using the principle of ash balance, the degree of fixed carbon burnout can be computed using the following simple formulation.

$$F_{carbon\ burnout} = 1 - \left(\frac{\%\,C_{final} \cdot \%\,Ash_{initial}}{\%\,C_{initial} \cdot \%\,Ash_{final}} \right) \qquad [1]$$

where **F** represents the fraction of fixed carbon burnout, 'initial' refers to the charcoal sample, as received, from the supplier and 'final' refers to the post burn condition. The ash balance principle utilizes the fact that the mass of ash in a certain amount of charcoal sample is identical before and after the combustion treatment.

Multiple samples were taken for each condition in order to nullify the effects caused due to inhomogeneities resulting from non-uniform distribution of particles and gas temperature across the cross section of the combustion stream. The sample was collected about 0.91 m (~ 3 feet) from the exit of the tube apparatus. The choice of such a distance stems from the fact of similar raceway dimensions in commercial blast furnaces [10]. It is to be noted that the degree of burnout of the samples collected in this manner will be lower than similar measurements using the same material and injection practices on a commercial furnace. This can be attributed to the fact that the combustion stream vents into the open ambient in the present experimental conditions. Therefore, the likelihood of the combustion reactions getting quenched as a result of entrainment of cold ambient air is very high. However, such effects resulting from quenching of the combustion reactions will manifest themselves within all the different conditions under consideration in this study.

The photographs showing the flame patterns observed for the different conditions are given in Figure 4. A visual comparison of the flame patterns for the different conditions reflects that the brightness of the flame in the hot oxygen injection mode is representative of the high temperatures that the charcoal particles are heated up to as a result of the energy release rate from the combustion, which in turn causes them to radiate. The flame patterns for the other modes are relatively less bright than the hot oxygen injection mode. The degree of fixed carbon burnout for the multiple char samples collected for each condition was averaged over the number of samples and normalized against the degree of carbon burnout determined for the baseline condition. These normalized values have been plotted in the form of a histogram in Figure 5. With the exception of the baseline condition, the O_2/C mass ratio in the combustion stream for the other three conditions was maintained the same. It may be noted that the 'O_2' refers to the free oxygen available in the blast to react with the solid fuel. The 'C' refers to the carbon present in the solid fuel in the form of fixed carbon. For the given geometry of the experimental apparatus and the stated experimental conditions, the degree of fixed carbon burnout for the condition in which the oxygen is injected at a high temperature through the HOD was found to be approximately 25-35 mass pct. higher than the enriched hot blast and cold (ambient) oxygen injection conditions. It is imperative to note that the actual numbers for the degree of carbon burnout for various experimental works of this kind will be a strong function of the geometry of the experimental apparatus, experimental conditions and the physicochemical characteristics of the solid fuel. Therefore, of more significance to the reader are the trends that the experimental data convey.
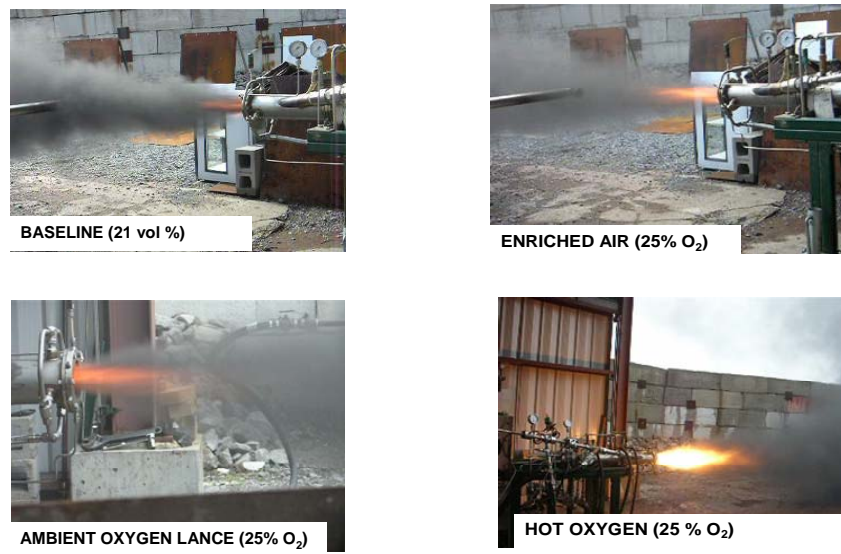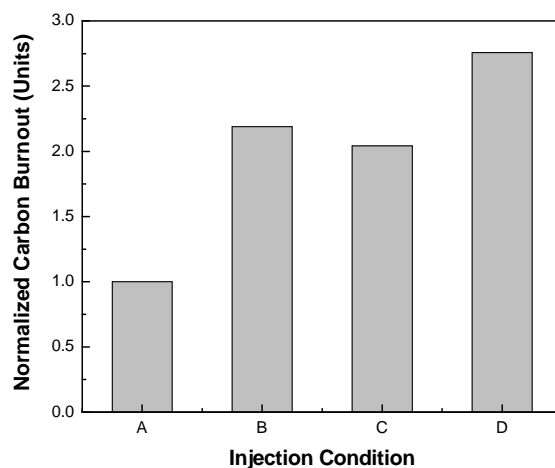

Figure 4, Combustion streams for various oxygen injection conditions

Normalized Average Carbon Burnout under Various Injection Conditions

A: Baseline Condition (21 Volume Pct. O_2)
B: Enriched Hot Blast (25 Volume Pct. O_2)
C: Ambient (Cold) Oxygen Injection (25 Volume Pct. O_2)
D: Hot Oxygen Injection (25 Volume Pct. O_2)

Figure 5, Fixed carbon burnout under various oxygen injection conditions

EXPERIMENTAL APPARATUS – LARGE SCALE TESTS

Following the proof-of-concept tests using the previously described tube apparatus, the transition was made to a full scale commercial blast furnace blowpipe and tuyere arrangement as the apparatus to conduct similar tests. One of the objectives was to conduct the tests at a larger scale, almost twice as much as the scale described in the preceding section. Another purpose was to determine the ideal location of the HOD and the solid fuel injection lance inside the tuyere that would not cause any impingement of the solid fuel in the combustion stream against the walls of the tuyere.

This blowpipe had two side ports for the introduction of the injection devices and a water cooled copper tuyere at its end. A refractory lined hot blast generating chamber was designed to pre-heat the air to the desired temperature. This section mated with the end of the blowpipe using a custom designed flange to form a continuous passageway for the hot blast to flow through. The blast pre-heating section comprised air inlets for the blast located downstream of an oxygen-natural gas diffusion flame blast preheating burner, along similar lines as the smaller scale tube apparatus as described earlier. Oxygen was directly injected into the air prior to its ingress into the preheating chamber to attain the desired level of enrichment. Openings were drilled through the refractory lining near the tip of the blowpipe for insertion of thermocouples for blast temperature measurements and for gas sampling in order to ascertain the oxygen concentration. Figure 6 shows a cartoon and a photograph of this experimental arrangement. These experiments were conducted in open air with near atmospheric pressure conditions prevailing inside the blowpipe and tuyere during hot blast flow. The blast velocity at the tuyere exit was within the operating range of commercial blast furnace tuyeres.

The hot blast flow rate was in the range of 1800-1900 Nm^3/hr at a temperature of about 1090 K (~ 1500°F) near the blowpipe-tuyere mating location. The HOD was operated using about 215 Nm^3/hr of oxygen. The pulverized charcoal feed rate was maintained in the range of 380-410 kg/hr (14-15 lb/min). Char samples were collected from the combustion stream about 0.91 m (~ 3 feet) from the exit of the tuyere, similar to the sampling exercise during the tests using the tube apparatus.

I. EFFECT OF BLAST ENRICHMENT

In addition to the oxygen injection through the HOD, the oxygen content of the enriched hot blast could be important in sustaining the combustion of the pulverized solid fuel downstream of the HOD in the blast furnace raceway. In order to ascertain this hypothesis, a few tests were conducted in which the oxygen concentration of the hot blast (by virtue of enrichment) was varied. The oxygen injection rate through the HOD into the blast under these test conditions remained identical. This was one approach by which the O_2/C ratio in the combustion stream could be varied. All the other conditions remained the same such as location of the injection devices, blast temperature, solid fuel feed rate etc. The pulverized charcoal was injected at the same rate as mentioned before. Char samples collected from the combustion stream were analyzed to determine the degree of carbon burnout. Figure 7 shows the comparison of the degree of carbon burnout (using ash as a tracer) as a function of the O_2/C mass ratio in the bulk combustion stream representing the different enrichment levels. It is to be noted that the O_2/C mass ratio considers the oxygen contributions from the blast air, enrichment, as well as the HOD. The fixed carbon contribution is assumed to be strictly from the pulverized solid fuel (charcoal in this case).
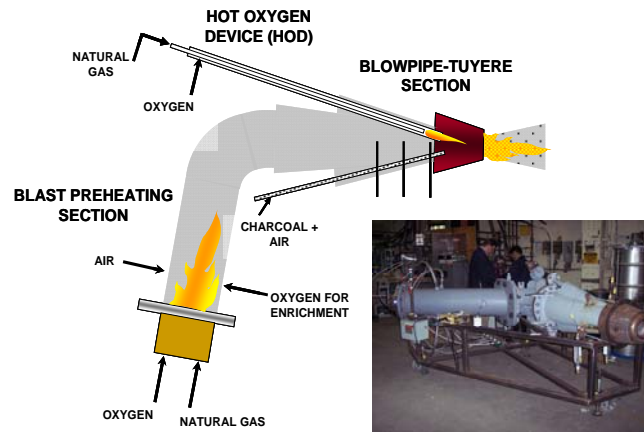

Figure 6, Schematic and photograph of the blowpipe-tuyere experimental assembly

It is only the contribution from the enrichment oxygen that is varying for each of these cases shown. The values of fixed carbon burnout indicated have been averaged over multiple experiments for each condition. The error bars have also been shown. Conditions A, B and C pertain to the hot blast oxygen contents of 22 vol. pct., 25 vol. pct. and 30 vol. pct. respectively.

Figure 7 suggests that the increase in the O_2/C mass ratio in the combustion stream by virtue of higher blast enrichment levels has a favorable influence over the carbon burnout efficiency. It is to be noted that the intent of the HOD is to initiate the pyrolysis of the pulverized solid fuel earlier relative to the traditional oxygen injection methods on a microscopic scale. The pulverized solid fuel is typically injected at ambient temperature using a conveying gas into the tuyeres. As a result, external heat transfer from the gas phase to the particles becomes significant prior to the onset of pyrolysis. The HOD is effective in this regard by realization of higher particle heating rates as a consequence of the high local temperature of the jet. This, subsequently, leads to faster de-volatilization kinetics and rapid combustion of the evolving volatile matter with the locally available oxygen, which is further boosted as a result of the strong mixing characteristics of the jet. The combustion of the volatile cloud around the particles raises the temperature of the particles abruptly resulting in further pyrolysis. This sequence of processes at the microscopic scale translates into a larger volatile matter to char formation ratio during the pyrolysis process (using the HOD) compared to the pyrolysis step under the other oxygen injection conditions. The oxygen delivered through the HOD is not adequate for the combustion reactions of the injected solid fuel to go to completion. Therefore, the partial combustion of the volatile matter and the char particles resulting due to the action of the HOD undergoes completion by the interaction with the additional oxygen present in the hot blast. In other words, the

oxygen in the hot blast aids in the combustion reactions, which are initiated by the HOD to sustain further downstream, and is, therefore, equally important in maximizing the burnout of the solid fuel. The role of the oxygen content of the hot blast towards realizing very large pulverized solid fuel injection rates has been emphasized in several works [3, 11]. Other solid fuel-specific characteristics such as the hydrogen concentration and particle size could potentially impact the degree of burnout, but have not been considered in the present study.

The combustion efficiency of the pulverized solid fuel injected into the furnace raceway is likely to be dependent upon the rate controlling mechanisms that govern the kinetics of the char combustion reactions. The improvement in the solid fuel injection rate as a result of utilizing approaches such as the HOD and hot blast enrichment has to be examined in the light of several other factors. Some of these include burden distribution practices, reducibility of the ferrous burden, physicochemical properties of the metallurgical coke, composition and rank of the pulverized solid fuel etc.
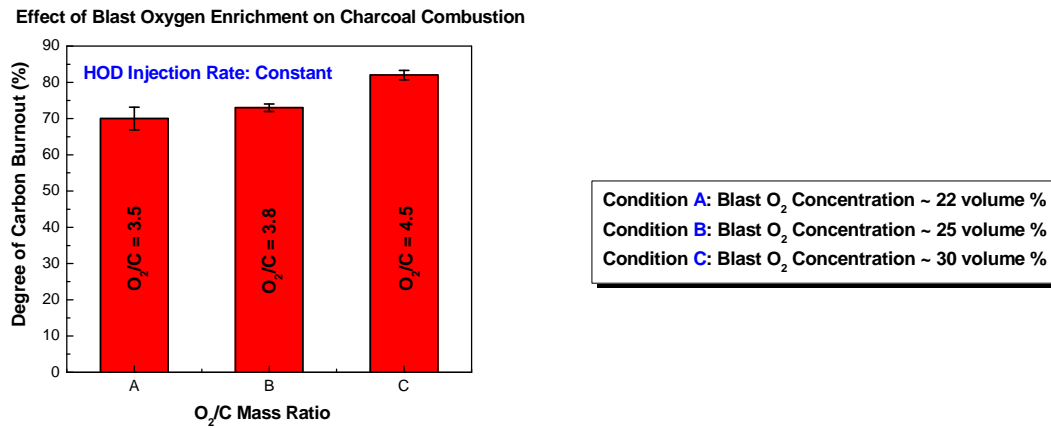

Figure 7, Variation of fixed carbon burnout as a function of blast oxygen concentration

II. LOCATION OF INJECTION DEVICES

The aspect of the appropriate location of the oxygen and solid fuel injection devices inside the tuyere is to be highlighted for a few reasons. Recessing the solid fuel injection device excessively into the tuyere or blowpipe is favorable from the combustion point of view, but doing so also elevates the risk of impingement of the solid stream against the inner walls of the tuyere and possible restriction in blast flow as a result of higher degree of combustion occurring inside the tuyere-blowpipe arrangement. The possibility of ash build-up on the inner walls of the tuyere is augmented as well under such circumstances. In order to find out the suitable location for the injection devices inside the tuyere, a trial and error exercise was conducted, in which the radiating particle stream was looked at visually for a specific location of the injection devices. Figure 8 shows the combustion stream emerging from the tuyere exit at one of the acceptable recess distances for the injection devices. The recess distance with respect to the tuyere exit was approximately 0.125 m (~ 5") in this case. It is to be appreciated that the choice of the appropriate position of the injection devices inside the tuyere will have a dependence upon the tuyere design, design of the injection devices themselves and the hot blast momentum.
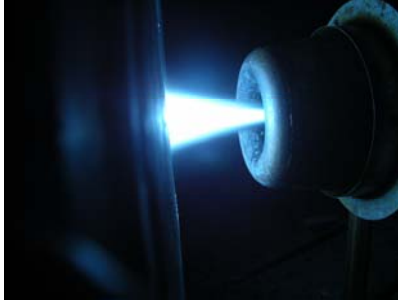
Figure 8, Solid fuel combustion stream emanating from tuyere exit (Filtered Image)

III. EFFECT OF HOT AND COLD OXYGEN INJECTION

In an experiment to visually observe the differences in combustion behavior of the injected solid fuel between hot and cold oxygen injection through an injection device, the flame patterns were visually compared under the hot oxygen injection mode and cold oxygen injection mode. The only difference between the two scenarios was the absence of the fuel flowing through the HOD to heat up the oxygen in the cold oxygen injection. Other parameters such as the blast flow rate, oxygen concentration of the blast, blast temperature and solid fuel injection rate remained invariant. Figure 9 and Figure 10 show the photographs of the flame pattern ensuing from the tuyere exit for both conditions. The plume color further downstream of the combustion zone is also much darker (not shown in photographs) for the cold oxygen injection condition as opposed to the case when the oxygen is injected at a high temperature.

Figure 9, Combustion zone in hot oxygen mode

Figure 10, Combustion zone in cold oxygen mode

SUMMARY

Combustion of a pulverized solid fuel (charcoal) in a simulated hot air blast ambient, typical of blast furnace tuyere injection, was studied for several conditions, each representative of a different mode for introducing the oxygen into the combustion stream. Experiments were conducted on a small scale as well as a pilot scale using a custom designed tube apparatus as well as a commercial blast furnace blowpipe-tuyere arrangement respectively. The degree of fixed carbon burnout using hot oxygen was observed to be about 25-35 mass pct. higher than the conventional oxygen injection methods such as enrichment and cold oxygen injection for the current experimental set-up and conditions. The importance of the oxygen content of the hot blast in association with the HOD to further improve the fixed carbon burnout of the pulverized solid fuel has also been demonstrated. The location of the injection devices in relation to the tuyere for minimizing tuyere erosion has also been addressed using a trial and error approach.

ACKNOWLEDGEMENTS

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