

Combustibility of Charcoal for Direct Injection in Blast Furnace Ironmaking

Ka Wing Ng
CanmetENERGY
1 Haanel Drive, Ottawa, ON, Canada, K1A 1M1
Phone: (613) 996 8712
Fax: (613) 995 9728
Email: kng@nrcan.gc.ca

Louis Giroux
CanmetENERGY
1 Haanel Drive, Ottawa, ON, Canada K1A 1M1
Phone: (613) 996 7638
Fax: (613) 995 9728
Email: lgiroux@nrcan.gc.ca

Tony MacPhee
CanmetENERGY
1 Haanel Drive, Ottawa, ON, Canada, K1A 1M1
Phone: (613) 996 4440
Fax: (613) 995 9728
Email: tmacphee@nrcan.gc.ca

Ted Todoschuk
ArcelorMittal Dofasco Inc.
1390 Burlington Street East, Hamilton, ON, Canada, L8N 3J5
Phone: (905) 548 4796
Fax: (905) 548 4653
Email: ted.todoschuk@arcelormittal.com

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INTRODUCTION

Substitution of fossil fuel injection by charcoal is a feasible way to reduce GHG emission of blast furnace ironmaking. Previous modeling work showed that emissions of the process can be reduced by 25% while maintaining furnace productivity and products quality. To prepare for industrial implementation of charcoal injection, combustibility of charcoal was investigated.

TGA analysis in air at 950 °C measured char combustion rate of charcoal of 3.7mg/min whereas that of coal char was only 2.4 mg/min. Moreover, char combustion kinetics of charcoal is not affected by ash composition and pyrolysis technologies used for its production. The difference in char combustion rate was due to differences in specific surface area. BET measurement found the specific surface area of charcoal to be 155 m²/g compared to 89 m²/g for coal char. The high specific surface area of charcoal arises from preservation of the cellular structure inherent in woody biomass during its pyrolysis. It was concluded that combustion of char derived from charcoal is faster than that of coal char and is hence suitable for direct injection in blast furnace ironmaking.

Equilibrium calculation revealed that the rate of sodium accumulation in the blast furnace may increase by about 30% upon substituting coal by charcoal for injection. However, alkaline input can be controlled via careful selection of the raw biomass materials for producing charcoal.

BACKGROUND

Blast furnace ironmaking is currently the main hot metal producing technology. In 2009, blast furnaces world wide produced 898.3 Mt¹ of hot metal compared to 53.6 Mt² by direct reduced iron (DRI) pathway. Blast furnaces represent more that 94% of global hot metal production capacity. In the foreseeable future, blast furnace ironmaking will likely continue as the dominant hot metal production technology.

Operation of blast furnace ironmaking relies heavily on gasification of carbon to provide reducing gases for reduction of iron ore and the necessary energy for melting the metallic iron produced. All of the carbon gasified in the blast furnace is eventually released to the atmosphere in the form of CO₂ after retrieval of residual energy. It is therefore unavoidable that the blast furnace is a major CO₂ emission source in the integrated steel mill. Production of 1 tonne of hot metal generates about 1.5 t of CO₂. Total world-wide CO₂ emission associated with blast furnace ironmaking operation in 2009 corresponded roughly to 1347 Mt.

Global awareness of the adverse effects of atmospheric CO₂ concentration on climate change has imposed significant pressure on the steel industry to reduce CO₂ emissions associated with its manufacturing processes. In Canada, tremendous efforts have been devoted to improving the performance and energy efficiency of the blast furnace and significant advances have been achieved. Compared to 1990, energy intensity of Canadian iron and steelmaking in 2008 was reduced by 26% and absolute GHG emission by 17%. On a per tonne basis of shipped steel, GHG emissions were reduced by almost 30%³.

To further reduce GHG emission associated with blast furnace ironmaking, substitution of fossil carbon by bio-carbon is proposed to support the process. Bio-carbon refers to carbon sources originating from recent biological materials. As for fossil carbon sources, combustion of bio-carbon also releases CO₂. However, CO₂ released by combustion of biomass materials from renewable sources is balanced by the CO₂ absorbed during its growth. Since the duration of this natural carbon cycle is relatively short compared to that of fossil fuel, CO₂ originating from renewable bio-carbon sources is considered not contribute to the increase in atmospheric GHG concentration. Hence, process emission can be reduced by replacing fossil carbon with bio-carbon without affecting the furnace productivity.

An important concern on implementing bio-carbon application to industrial scale is the availability of renewable raw biomass. Canada is a rich in bio-resources. About 45% of the Canadian territory is covered with forests, corresponding to an area of 417.6 million hectares stretching from the Atlantic to the Pacific coasts, and to the Arctic tree line. More than half of the forested lands, about 234.5 million hectares, are productive forests. Each year, about 1 million hectares are harvested, which represents only 0.4% of productive forests⁴ in Canada. On account of the plentiful raw biomass materials available, it is logical to make use of this natural resource in Canada and to apply it to industrial processes. Other resources, such as agricultural and municipal residues and wastes, could also be considered.

Bio-carbon can be introduced into the existing blast furnace ironmaking process via two ways. It can be used to partially substitute coal in the blend for cokemaking and as auxiliary fuel by injection directly into the hearth of the furnace, Figure 1.

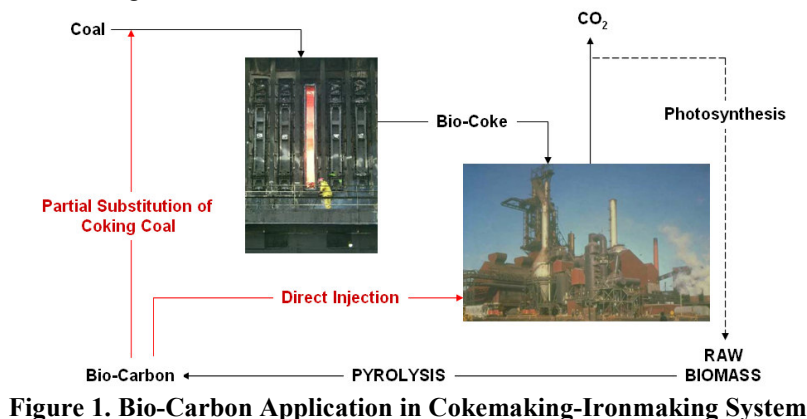


Figure 1. Bio-Carbon Application in Cokemaking-Ironmaking System

The effects of direct injection of bio-carbon from various sources on furnace behavior have been studied in detail by numerical modeling⁵⁻⁶. These investigations concluded that substitution of PCI by charcoal injection does not affect the operating conditions of the furnace and the chemistry of the hot metal produced. However, GHG emission on per tonne of metal produced basis can be reduced by as much as 25%. With such encouraging results, combustibility of charcoal was studied in this work in preparation and anticipation for industrial implementation of direct injection of charcoal in blast furnace ironmaking.

COMBUSTION DURING SOLID FUEL INJECTION

Prior to discussing combustibility of charcoal, it is worthwhile reviewing the combustion behaviour of coal during pulverized coal injection (PCI). PCI is a commonly employed practice in industrial blast furnace ironmaking. The primary goal of PCI is to reduce coke rate and operating costs. When selecting coal for direct injection, there are number of factors that need to be considered, such as ash and sulphur content, raceway cooling, coke replacement ratio, etc. Among the various factors, combustibility of coal also dictates the suitability of coal for direct injection.

Combustion of the injected coal is carried out under difficult conditions on account of the extremely short residence time in the oxygen rich environment. In fact, residence time of the injected coal in the blowpipe-tuyere of only 10-20 ms is much shorter than in other pulverized coal combustion equipment⁷. Once the injected coal enters the raceway inside the blast furnace, it has to compete with the surrounding hot coke for oxygen to complete its combustion.

Combustion of injected coal involves three major stages⁸:

1. *Blowpipe entry*: Rapid heat up of the coal upon entering the blowpipe. It causes softening and swelling of the coal particles and rapid release of volatile matter (VM) and tar.
2. *Volatile matter combustion*: Ignition and combustion of the released volatile matter causing further increase in particle temperature. Devolatilization continues until char is formed.
3. *Char combustion*: Combustion of remaining chars and formation of ash residue. In comparison, the rate of char combustion is much slower than that of VM release and combustion.

In a typical combustion test, combustibility of the tested coal is quantified by the burnout under the specific combustion environment. Burnout is defined as the ratio of mass loss of total combustibles to total combustibles in the original coal. Assuming ash in the coal is conserved during the test, burnout can be calculated by the following relationship. Burnout includes the contribution of both VM release (fast) and char combustion (slow). Hence, VM content of coal plays an important role in the measured burnout of coal.

$$\text{Burnout} = \frac{1 - \frac{A_i}{A_f}}{1 - A_i}$$

A_i = mass fraction of ash in original coal

A_f = mass fraction of ash in samples after test

When comparing burnout between charcoal and coal, the difference in VM content of these two solid fuels must be taken into consideration. Charcoal is a carbonized material produced by slow pyrolysis of biomass. Its VM content varies from as high as 40% or more down to less than 5%⁹ depending on the final carbonization temperature of the pyrolysis process. As the final temperature increases, VM content of the produced charcoal decreases and the fixed carbon content increases¹⁰. Therefore, the VM content of charcoal can be manipulated during its production. In order to have a useful comparison between the combustibility of charcoal and coal, the kinetics of char combustion of these two fuels were examined in this work.

TGA MEASUREMENT OF CHAR COMBUSTION KINETICS

The combustion kinetics of chars from two types of charcoals and from a high volatile coal were examined using TGA, Table I. The two charcoals employed in this work were obtained from different sources of raw

woody biomass and produced using different slow pyrolysis technologies. Charcoal A was produced from Western Canada softwood using slow pyrolysis technology. Charcoal B was produced from Eastern Canada hardwood using traditional retort technology. As shown, ash composition of these two types of charcoals is very different. It allows for a comparison on the effect of ash composition on char combustion kinetics. The PCI char sample was collected during a combustion test in the pilot scale coal injection facility at CanmetENERGY¹¹. All char samples were ground to -20 mesh (<0.85 mm) for the TGA tests.

Table I: Ash Content and Composition of Chars in TGA Test

	Charcoal A	Charcoal B	PCI Char
%Ash (db)	3.03	3.74	12.50
Composition			
(% ash)			
SiO ₂	8.02	16.75	51.15
Al ₂ O ₃	1.94	4.36	31.55
P ₂ O ₅	1.87	3.60	0.08
CaO	71.87	45.90	1.03
MgO	5.60	6.11	0.87
Na ₂ O	0.24	3.24	0.34
K ₂ O	3.02	6.08	2.14

Figure 2 illustrates the TGA experimental procedure. The sample was heated from ambient at 10 °C /min under nitrogen. Upon attaining 950 °C, sample was allowed to further devolatilize for 2 h in N₂. After this two hour soak period, all of the moisture and most of the VM in the sample had been removed and only char remained. Then, the gas atmosphere was switched to air to begin combustion of char with the temperature maintained at 950 °C. Changes in sample mass were continuously monitored until all combustibles were evolved.

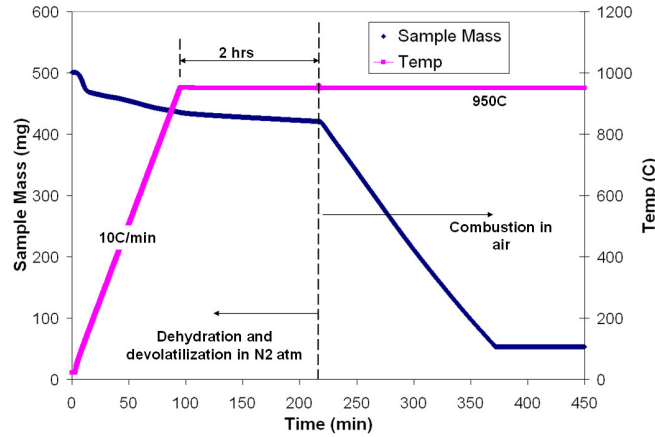


Figure 2. Illustration of TGA Char Combustibility Test Conditions and Procedures

Figure 3 shows the results obtained. To allow direct comparison, sample weights were normalized with respect to the weight attained at the time of switching the gas from N₂ to air. Combustion rate of charcoals was clearly faster than that of PCI char. Upon measuring the slopes of weight loss curves during combustion, kinetics of combustion of the char samples were obtained. As shown, weight loss rates of the two charcoal samples were almost identical despite the very different ash chemistry and production processes. This suggests that ash chemistry and method of production did not significantly contribute to the char combustion kinetics of charcoal.

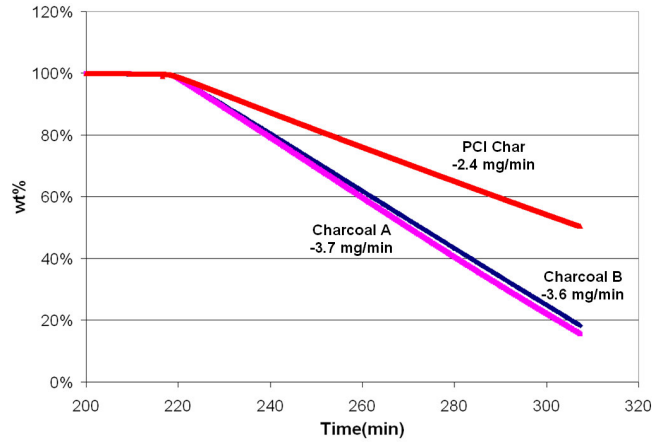


Figure 3. Combustion Kinetics of Charcoals and PCI Char

EFFECT OF PARTICLE MORPHOLOGY

To further elaborate on the causes of the observed difference in char combustion kinetics between charcoal and coal, SEM analysis was performed. SEM images of the char samples used in the TGA experiments are shown in Figure 4, and it is clear that morphologies of the particles are very different.

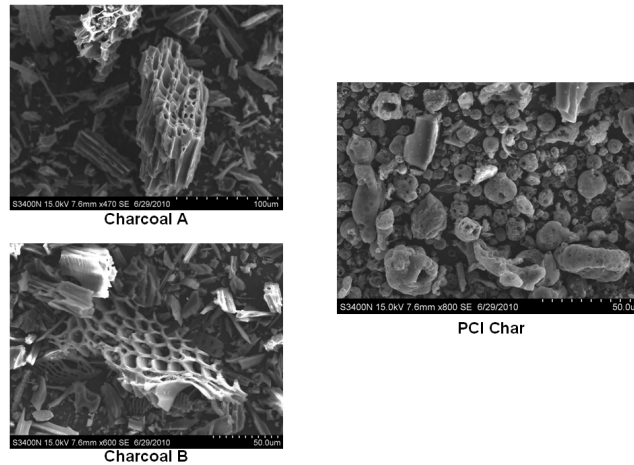


Figure 4. SEM Images of Charcoals and PCI Char

PCI char particles are porous and quasi-spherical. PCI char was obtained by quenching the coal particles which had previously undergone very rapid heating. This led to softening and swelling of the coal particle with simultaneous rapid release of volatile matter. As a consequence, spherical particles with high porosity were produced, Figure 4.

For charcoal samples, which originate from woody biomass, the cellular structure of wood can be clearly seen. Unlike coal, biomass does not plastify during carbonization as wood is converted into charcoal. Therefore, the cellular structure of the original wood is preserved in the resultant charcoal.

The inherited cellular structure of wood in charcoal has resulted in a higher specific surface area compared to the PCI char. BET measurements revealed that the specific surface area of Charcoal A was $155 \text{ m}^2/\text{g}$, whereas that of the PCI char was only $89 \text{ m}^2/\text{g}$. Comparing the ratio of specific surface area of Charcoal A and PCI char ($155 \text{ m}^2/\text{g} : 89 \text{ m}^2/\text{g}$) to that of the combustion kinetics measured via TGA ($-3.6 \text{ mg}/\text{min} : -2.4 \text{ mg}/\text{min}$), found these to be similar (1.74 and 1.50). It appears the specific surface of a particle appears to be an important factor that contributes to its combustibility.

ALKALINE INPUT WITH CHARCOAL INJECTION

Control of alkaline loading, in particular sodium and potassium, is an important consideration in the operating the blast furnace in view of the fact that the hearth of the blast furnace is sufficiently hot to vaporize these two elements. As the Na and K vapours ascend in the furnace, temperature decreases, which results in their condensation and recycling back into the hearth by the burden descend. As a consequence of vaporization and condensation of Na and K in different region of the blast furnace, these elements may accumulate and lead to furnace wall erosion.

With reference to Table I, ash chemistry of charcoal is significantly different from that of coal. When substituting PCI by charcoal injection, the alkaline input needs to be addressed. However, a direct comparison of the ash composition of charcoal and coal is not sufficient. This is because the coke and fluxing rates are both affected when PCI is substituted by charcoal injection to maintain material balance of the process and composition of the hot metal produced. Hence, the alkaline input from other sources needs to be taken into consideration as well.

Using the numerical model developed at CanmetENERGY⁶, the total input of Na and K from all sources (iron ore, flux, coke and injectant) to the blast furnace was calculated. Injection of the coal that produced the PCI char used in the TGA experiment and Charcoal B were compared. In the calculation, it was assumed the injection rate was maintained at 140 kg/tHM in both cases. Fluxing rates were adjusted to maintain the slag and hot metal compositions comparable in both cases. Table II compares the total Na and K input from all sources to the blast furnace. The Na input is slightly increased and the K input is slightly decreased on per tonne of hot metal produced basis when coal injection was substituted by charcoal injection.

Table II: Total Alkaline Input with Coal and Charcoal Injection

Element	Coal injection	Charcoal Injection
Na	526 g/tHM	583 g/tHM
K	1029 g/tHM	946 g/tHM

Equilibrium distributions of Na and K between different phases in the hearth of the blast furnace were calculated using FactSage¹². Calculation revealed that neither of these two element report to the hot metal phase. All Na and K input to the furnace is found in either the slag or the gas phase. The amount reported to the slag will be tapped out of the furnace. However, the amount of Na and K reported to the gas phase will re-condense in the upper part of the furnace and potentially accumulate in the furnace. Therefore, it is important to know the distribution of the alkaline input between different phases.

Figures 5 and 6 compare the model prediction of the distribution of Na and K in slag and gas phases of coal injection with charcoal injection. The amount of Na reported to the gas phase when substituting PCI with charcoal injection was increased from 193 g/tHM to 254 g/tHM, corresponding to a 31% increase. For K, the amount reported to the gas phase was slightly reduced by about 5%. Therefore, when charcoal injection is considered, one should anticipate that the accumulation of Na in the blast furnace is likely to be increased compared to coal injection.

It should be emphasized that the potential increase in Na accumulation depends on the choice of charcoal to substitute coal injection. The ash content and composition of charcoal is determined by the original biomass. It varies between different biomass materials and different parts/sections of the same biomass. Therefore, the alkaline content in charcoal can be controlled via careful selection of raw biomass material feed for production of charcoal.

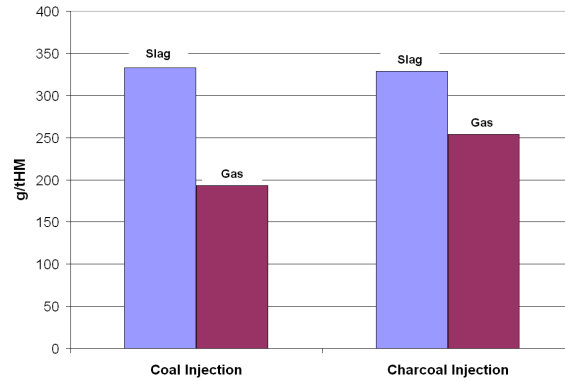


Figure 5. Equilibrium Distribution of Sodium

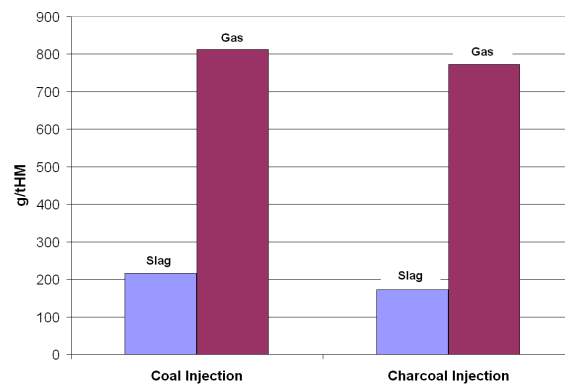


Figure 5. Equilibrium Distribution of Potassium

CONCLUSIONS

Substitution of fossil fuel injection by charcoal is a feasible way of reducing GHG emissions of blast furnace ironmaking. It was shown in the previous modeling work that emissions from the process can be reduced by 25% while maintaining the furnace productivity and product quality. In preparation for industrial implementation of charcoal injection, combustibility of charcoal was studied.

TGA experiments were conducted to compare combustion kinetics of char from charcoal to that of char from coal. It was concluded that char from charcoal combusts faster than that of char from coal and is suitable for direct injection in blast furnace ironmaking. The measured combustion rate in air at 950 °C of charcoal was 3.7 mg/min, whereas that of coal char was only 2.4 mg/min (difference of 35%). Moreover, char combustion kinetics of charcoal are not affected by the ash composition and pyrolysis technologies employed for its production.

The high char combustion kinetics of charcoal are related to the fact that specific surface area of charcoal is much greater than that of coal char. BET measurement revealed that specific surface area of charcoal was 155 m²/g compared to 89 m²/g for coal char. The high specific surface area of charcoal originates from the preservation of the cellular structure of woody biomass during pyrolysis.

Equilibrium calculation found the rate of Na accumulation in the blast furnace to potentially increase by about 30% when coal injection is substituted by charcoal injection. The alkaline input can be controlled via careful selection of raw biomass materials for producing charcoal for direct injection in blast furnace ironmaking.

ACKNOWLEDGEMENTS

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