

## Firing blast furnace gas without support fuel in steel mill boilers

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### ABSTRACT

In this study, the combustion characteristics of firing blast furnace gas (BFG) individually or in combination with coke oven gas (COG) were investigated theoretically and experimentally. The theoretical results showed that at the same heat release rate under the operating conditions of stoichiometry, firing BFG individually had a greater amount of fuel gas volume flow rate, a smaller amount of air volume flow rate, and a lower adiabatic flame temperature than firing BFG with support fuel without preheating. Meanwhile, the volume flow rate of flue gas for the former was greater than the latter. The experimental results obtained from a co-firing of BFG and COG fueled-boiler in a steel company showed that whether at a higher or lower boiler load, with gradually decreasing the amount of COG supply, flame instability (lift-off and blow-out) did not occur and the rate of CO emission was very low. In addition, a decrease in the amount of COG supply brought about a great benefit to the reductions of both CO<sub>2</sub> and NO<sub>x</sub> emissions.

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### 1. Introduction

Low calorific value residual gases are generated in many industrial processes, such as in iron and steel industries [1], heavy chemistry, refining or unit of reforming [2]. For instance, the energy of residual gases issued from a blast furnace, or coke oven, is recovered in boilers for electricity production [3,4]. These by-product gases can be used as supplement of the traditional fossil fuels in thermal units [2]. For example, exhaust gases from the primary operations in the steel making process are almost exclusively utilized as supplemental fuels within the steel plant. These by-product fuels include blast furnace gas (BFG), Linz Donawitz gas (LDG, recovered from Linz Donawitz converter [5]) and coke oven gas (COG) which contain mixtures of H<sub>2</sub>, CO, CH<sub>4</sub> and trace amounts of some heavier hydrocarbons and the impurities ammonia (NH<sub>3</sub>) and hydrogen cyanide (HCN) [6]. These fuels are burned alone or in combination with natural gas (NG) to fire the coke ovens, blast furnace stoves, utility boilers and metal working furnaces. The utilization of these by-product fuels reduced the waste gas emissions at the steel mill and the requirements for external fuel sources.

Integrated steel production is a four-step process involving: coking, iron making, steel making, and metalworking. By-product fuels are generated in the coking and iron making steps, and are subsequently utilized to some extent in all stages of the steelmaking process, including the stages in which they were produced. The

coking process involves the pyrolytic heating of coal in the absence of oxygen. COG is a by-product of this process, whereby the volatile components of the coal are driven out as COG, leaving carbon-rich coke behind. COG is composed mainly of H<sub>2</sub> and methane (CH<sub>4</sub>), with some N<sub>2</sub>, CO and CO<sub>2</sub>. COG does contain slight amounts of heavier hydrocarbon fuels and can contain NH<sub>3</sub> and HCN. Typical COG has the composition (in volume) as follows: N<sub>2</sub> = 6.10%, CO<sub>2</sub> = 2.38%, CO = 7.06%, H<sub>2</sub> = 57.39%, CH<sub>4</sub> = 24.55%, C<sub>2</sub>H<sub>2</sub> = 2.42%, and O<sub>2</sub> = 0.10%. The lower heating value (also known as net calorific value, NCV, or LHV) of the COG is approximately 4131 kcal/Nm<sup>3</sup>.

BFG is a by-product of the iron making process, where iron ore, coke, and limestone are heated and melted in a blast furnace. Carbon monoxide produced from the burning of the coke reacts with the iron ore, reducing it to iron. The composition of BFG is process dependent consisting of mainly nitrogen (N<sub>2</sub>), with some carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>), and trace amounts of hydrogen (H<sub>2</sub>) [7]. Typical BFG has the following composition (in volume): N<sub>2</sub> = 55.19%, CO<sub>2</sub> = 21.27%, CO = 20.78%, and H<sub>2</sub> = 2.76%. The lower heating value of the BFG is approximately 698 kcal/Nm<sup>3</sup>, which is relatively low compared with that of COG.

Steelworks is one of energy-intensive industries, which consumes large quantities of raw materials and energy in their manufacturing process. It is well recognized that emission of CO<sub>2</sub> from fossil fuel combustion is a serious problem throughout the steel industry [8,9]. Obviously, energy efficiency improvement and CO<sub>2</sub> emission reduction in the iron- and steelmaking processes are increasing important [10]. Prior to developing new sources of

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energy, recovering and reusing waste energy to raise the energy efficiency is of great importance [11,12].

Substituting a part of a valuable fuel (e.g. NG or COG) by a less valuable fuel (e.g. BFG) is one of the most readily adaptable methods of saving fuel in industrial heat treating processes [13]. Theoretical, numerical and experimental studies of flames with multiple fuel systems, such as biomass/coal [14,15], BFG/coal [16], NG/BFG [17], or BFG/COG [18,19], are available in literatures. Recently, the waste tail gas fuel emitted from refinery plant was recovered and reused as a replacement fuel [20,21]. It was slowly added to the fuel stream of a heater furnace to replace natural gas for powering a full-scale distillation process. The results showed that recovering and reusing the waste tail gas fuel as natural gas replacement achieved tremendous savings of natural gas usage and effectively lower the emission of carbon dioxide. In the steel industry, the recovered waste blast furnace gas (BFG) was mixed with natural gas as an alternative fuel to curb the consumption of the natural gas [17]. It was found that if 50% of the waste BFG that contained 28% carbon monoxide, and 72% nitrogen was mixed with natural gas, the natural gas consumption decreased by 2%. To help understand steel gas combustion, a numerical study was conducted by Gicquel et al. [18] where the major chemical properties of steel gas flames were collected. NO production was found to be very sensitive to the temperature drop observed with vitiated air, explaining the lower levels of NO. Shieh et al. [19] developed an adaptive data-driven thermal efficiency estimator of multi-fuel boilers based on statistical identification of key variables. They found that the application of the proposed methods improved 1.94% of the thermal efficiency of a boiler burning multi-gas and 0.73% of a boiler burning coal and multi-gas in the virtual plant simulations.

As aforementioned, to utilize the residual gases as fuels in power plants is one of the effective energy-saving measures in iron and steel companies. By-product fuel combustion has been carried out by the steel industry for over one hundred years. Recycling BFG and COG for extracting their additional caloric value represents a way of reducing waste gas emissions and costs associated with using standard fuels, such as natural gas and low sulfur oil. The key combustion issue in utilizing the residual gases as fuels in the past has been to achieve heat output equivalent to that of standard fuels, so that product steel quality is not affected. Based on economical considerations, it is advantageous to develop the technology of firing BFG individually without the support fuel. However, compared with the fuel of BFG in combination with coke oven gas (COG), BFG is low in calorie because of high ratio of inert gas such as nitrogen and carbon dioxide. Owing to this special fuel property, many technical problems, such as slow burning velocity and combustion instability [18], remain to be solved in using BFG individually as the fuel for hot gas stoves and boilers. However, there is still a lack of literature regarding firing BFG alone in steel mill boilers, especially on-site experimental investigations. Therefore, in this study, we aim at investigating the combustion characteristics of firing BFG individually or in combination with COG theoretically and experimentally. On-site test of using the recovered waste fuel gas to power the boiler of a full-scale power plant was particularly emphasized in this research.

## 2. Theoretical analysis

In order to develop the technology of firing blast furnace gas without support fuel in steel mill boilers, the combustion characteristics of firing BFG individually or in combination with COG are first investigated theoretically. Considering the operating conditions of stoichiometry and without preheat at a constant heat input rate (1 MW), the effects of firing BFG individually (without

support fuel) on the amount of fuel gas volume flow rate, amount of air volume flow rate, amount of flue gas volume flow rate and adiabatic flame temperature were examined.

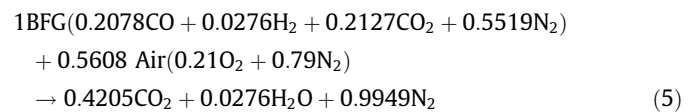
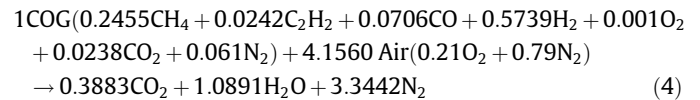
The total inlet gas supply rate included the sum of COG, BFG and combustion air supply rates. For a fixed total heat input rate (heat release rate), the fuel gas supply increased with the decrease of its heating value. Eq. (1) illustrates the total heat input rate was the sum of both COG and BFG heat input rate. Meanwhile, Eqs. (2) and (3) were used to calculate the total inlet fuel supply volume flow rate and mass flow rate, respectively.

$$\dot{q}_{in} = \sum \dot{q}_{in,i} \quad (1)$$

$$\dot{Q}_{in} = \sum \dot{q}_{in,i}/HV_i \quad (2)$$

$$\dot{m}_{in,F} = \sum \frac{\dot{Q}_{in,F,i} \cdot M_i}{22.4 \text{ m}^3/\text{kmole}} \quad (3)$$

where  $\dot{q}_{in}$  (kcal/s) is the total heat input rate;  $\dot{q}_{in,i}$  (kcal/s) the heat release rate of fuel gas  $i$ ;  $\dot{Q}_{in,F}$  ( $\text{m}^3/\text{s}$ ) the total fuel supply volume flow rate;  $\dot{m}_{in,F}$  (kg/s) the total fuel supply mass flow rate;  $HV_i$  (kcal/ $\text{m}^3$ ) the heating value of fuel gas  $i$ ;  $\dot{q}_{in}$  ( $\text{m}^3/\text{s}$ ) the supply volume flow rate of fuel gas  $i$ ;  $M_i$  molecular weight of fuel gas  $i$ . Subscript “ $i$ ” denotes COG and BFG respectively in this study. Inlet flow rate of theoretical air required was calculated according to theoretical combustion reactions of COG and BFG in Eqs. (4) and (5), respectively. Then the total inlet flow rate of theoretical air ( $\dot{Q}_{in,A}$ ) was the summation of the theoretical air required for firing COG and the BFG, as shown in Eq. (6). The total gas supply volume flow rate ( $\dot{Q}_{in}$ ) is the summation of total inlet fuel ( $\dot{Q}_{in,F}$ ) and theoretical air ( $\dot{Q}_{in,A}$ ) supply volume flow rates, as illustrated in Eq. (7).



$$\dot{Q}_{in,A} = \sum \dot{Q}_{in,F,i} * N_i \quad (6)$$

where  $N_i$  is the molar coefficient of air in Eqs. (4) or (5)

$$\dot{Q}_{in} = \dot{Q}_{in,A} + \dot{Q}_{in,F} \quad (7)$$

When the combustion was complete without any heat loss or changes in kinetic or potential energy, the maximum temperature of the products was known as the adiabatic flame temperature ( $T_{ad}$ ). The adiabatic flame temperature of a steady-flow combustion process for various COG/BFG mixtures was calculated by equating the enthalpy of the fully reacted combustion products of a flame with the total heat input to the flame, including both the chemical and sensible heat entering the furnace through the burner [22]. In the calculations, the combustion process was assumed to be under a constant pressure. The effect of dissociation of combustion products was neglected.

$$T_{ad} = \dot{q} / \sum C_p(T_{ad})\dot{m}_{ad} \quad (8)$$

where  $T_{ad}$  ( $^{\circ}\text{C}$ ) is the adiabatic flame temperature;  $C_p(T_{ad})$  is the specific heat of the products between the ambient and  $T_{ad}$  (in unit of  $\text{kJ}/\text{kg}^{\circ}\text{C}$ ), which is function of temperature;  $\dot{m}_{ad}$  (kg/s) is the mass flow rate of combustion products;  $\dot{q}$  (kJ/s) is total heat input, including the total chemical and sensible heat input.

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