Proceedings of the 7th World Congress on Momentum, Heat and Mass Transfer (MHMT'22)
~~Lisbon, Portugal~~ Virtual Conference – April 07 – 09, 2022
Paper No. CSP 117
DOI: 10.11159/csp22.117

Experimental Analysis Of Blast Furnace Gas Co-Firing In A Semi-Industrial Furnace Using Colour Images

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Abstract – Technologies for waste stream valorisation can be used to increase the sustainability of intensive industry processes. Within the steel industry, the waste stream of Blast Furnace Gas (BFG) could be valorised through its co-firing in subsequent steel furnaces. Nevertheless, this innovative BFG application needs additional research for its final implementation. In order to continue developing this application, this work is focused on the experimental analysis of BFG co-firing in a semi-industrial furnace, by means of a colour camera. A test campaign has been carried out with three fuel blends (100 %v Natural Gas (NG), 30 %v NG and 70 %v BFG, and 100 %v BFG), considering different air-fuel ratios. Colour images have been processed to compute quantitative characteristics related to the furnace combustion. Trends of the image features have been detected for the fuel blends and O_2 and NO_x concentrations in flue gases. This way, the proposed imaging system has been highlighted as a relevant tool for the monitoring of BFG co-firing in semi-industrial furnaces.

***Keywords*:** blast furnace gas, experimental analysis, semi-industrial furnaces, colour imaging, monitoring techniques

1. Introduction

In the current energy scenario, intensive industries need to direct their processes towards more sustainable models. These models can include innovative technologies for electrical flexibility, waste heat recovery and waste stream valorisation, for example. Within the steel industry, the processes of steelmaking generate a waste gas steam of Blas Furnace Gas (BFG). The BFG could be valorised as fuel in the subsequent steel production furnaces, reducing the use of Natural Gas (NG) and increasing the efficiency of the whole steelmaking process. Nevertheless, this innovative application needs an advanced monitoring and control of the BFG combustion, due to the low calorific value of the BFG, to meet the requirements of the steelmaking processes [1], [2].

During last years, imaging systems have been used to monitor and control combustion in furnaces. This way, images of the insides of furnaces are acquired. These images can be processed to extract specific characteristics, and furthermore, they can be used to develop models for the prediction of combustion variables [3]–[7].

Current imaging techniques of combustion monitoring and control needs to be adapted and optimised for the specific and innovative application of BFG co-firing in the steel industry. In addition, most previous literature for general combustion monitoring and control is focused on lab-scale facilities that differ from the industrial case, requiring further research to implement the studied techniques in the industry. With this context, the present work addresses the two previous challenges of the considered application of BFG co-firing for the steel industry. The methodology of the work is based on the development of an experimental campaign with a colour camera to characterise the BFG co-firing in a semi-industrial furnace. With that purpose, trends between fuel blends, flue gas emissions of O_2 and NO_x and image characteristics are analysed.

Section 2 describes the furnace and other equipment, experimental set-up, test plan and image processing methodology, whereas Section 3 includes main trends detected between combustion and image features. Finally, Section 4 gathers major conclusions of the work.

2. Methodology

Experiments were performed in a semi-industrial reheating furnace in the combustion laboratory of ArcelorMittal Global R&D (Fig. 1). A low NO_x burner of 1.2 MWt was installed, with primary and secondary air and fuel flows entering separately in the combustion chamber, where they are mixed. The furnace includes air and fuel lines of different diameter to test a wide range of fuel blends with different calorific values, balancing out fluid dynamic effects by changing the air and fuel flows. Furthermore, the furnace includes a lance that allows the feeding of oxygen.

Furnace combustion was characterised with a colour industrial camera (DFK 33GX174, supplied by The Imaging Source). The camera uses the GigE Vision interface standard and includes a CMOS sensor (Sony IMX174LQJ) of 1920 x 1200 pixels and 11.3 x 7.0 mm^2, and an electronic global shutter. Together with the camera, a lens (Fujinon HF50HA -1B) with a focal length of 50 mm was used.

The camera was set outside the furnace, aligned with the burner and the top viewing port. When fuel was burned, the combustion chemical reactions radiated energy, which was also reflected by the furnace inside. The received light at the top viewing port included the light radiation and reflection, which were captured by the camera, acquiring similar images to Fig. 1 (c). In this work, the CMOS sensor of the camera converts the received light (charge) to voltage of each photodiode (pixel) at the pixel location, and the global shutter samples the light received by each sensor pixel simultaneously. Image colour is obtained with a Bayer filter, which uses one colour filter per pixel to screen received light. This way, each pixel only captures the light related to one of the three colours (red, green and blue). Finally, information of the three colours is reconstructed for each pixel with a demosaicing algorithm.

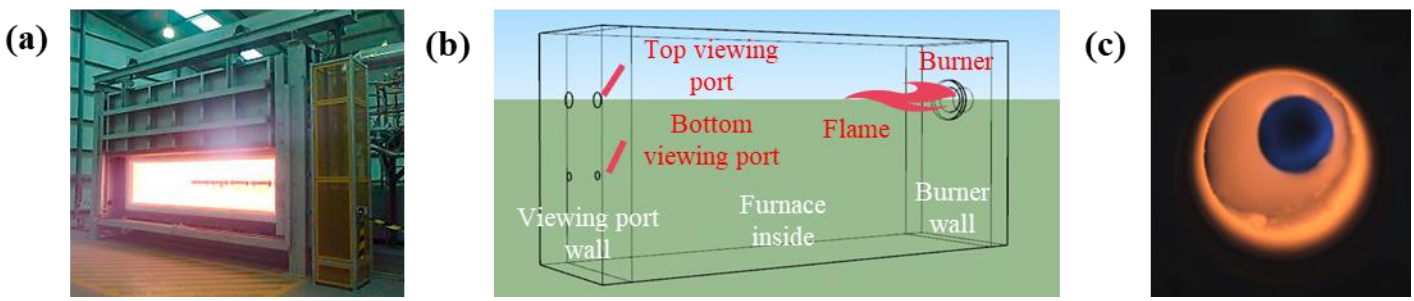

Fig. 1: Sample images of (a) the testing furnace in ArcelorMittal Asturias, (b) its scheme and (c) furnace inside and burner captured by the colour camera [2].

Tests include 3 fuel blends and 3 air-fuel ratios for each one of them. The mixture compositions are 100 %v NG, 30 %v NG and 70 %v BFG, and 100 %v BFG, referred as BFG0, BFG70, and BFG100. The tested air-fuel ratios provide flames from fuel-rich (air-lean) to fuel-lean (air-rich) conditions. Primary and secondary air were preheated to 500 ºC. This way, part of the combustion energy can be used to increase the furnace temperature, instead of heating up the air. With the fuel blend of BFG0, oxygen was fed as comburent resulting in a partial oxy-fuel combustion, in order to reduce emissions. A data acquisition and control system registered relevant operation variables of the furnace combustion, and the conditions of the combustion tests are summarised in Table 1. For the sake of comparison, the configuration of the camera was fixed for all the tests, with an exposure time of 0.5 milliseconds.

Table 1: Description of the tests.

Fuel blend	BFG0	BFG70	BFG100
[NG] (%v)	100	30	-
[BFG] (%v)	-	70	100
Partial oxy-fuel combustion	Yes	-	-

O_2 (%v) in flue gases	3.5, 1.0, 0.0	5.0, 1.5, 0.0	3.0, 1.0, 0.0

Captured images were segmented to obtain a region of interest, from which 12 features were extracted. The features were obtained computing four statistical parameters of the three colour channels that has the colour camera. The statistical parameters are the mean, standard deviation, kurtosis and skewness, which are used as combustion features in previous literature [6].

3. Results and Discussion

Under the same combustion conditions, mean and standard deviation of the three colour channels are reduced with the increase of the BFG proportion in the fuel blend (Fig. 2). On the other hand, blue channel skewness has been increased with higher proportions of O_2 and NO_X in flue gases for the three fuel blends, as seen in Fig. 3.

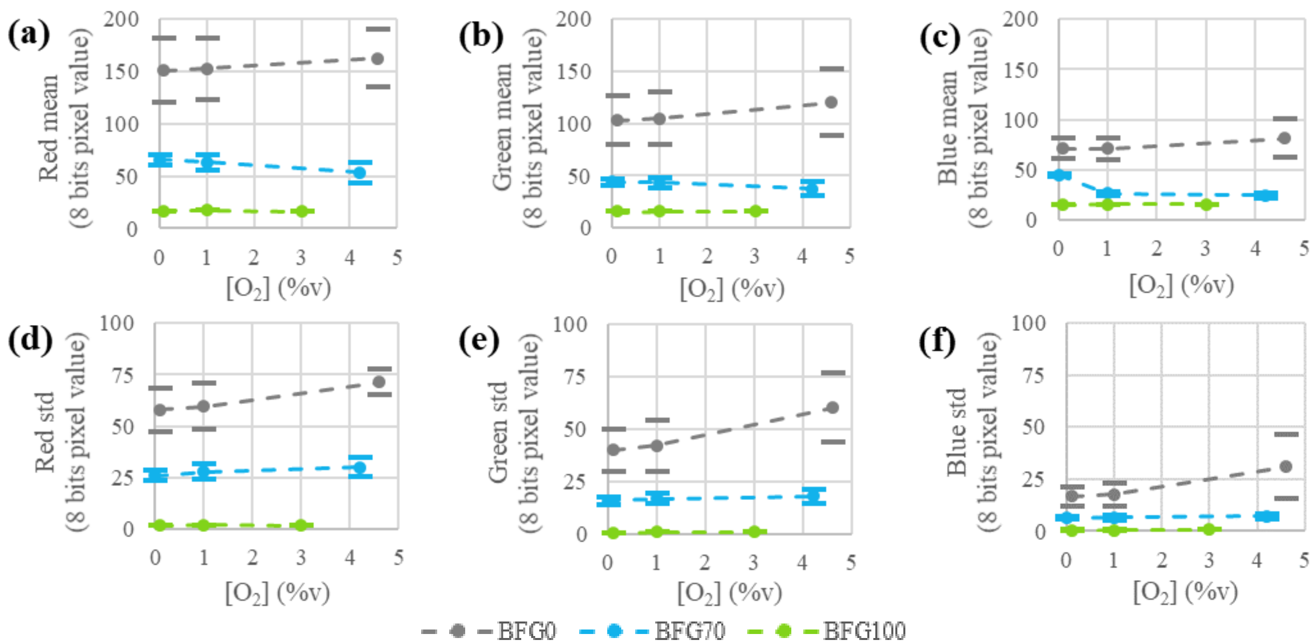

Fig. 2: Image features of (a) red mean, (b) green mean, (c) blue mean, (d) red standard deviation (std), (e) green std and (f) blue std versus O_2 concentration in flue gases. The means and standard deviations of the samples are plotted with points and horizontal lines, respectively.

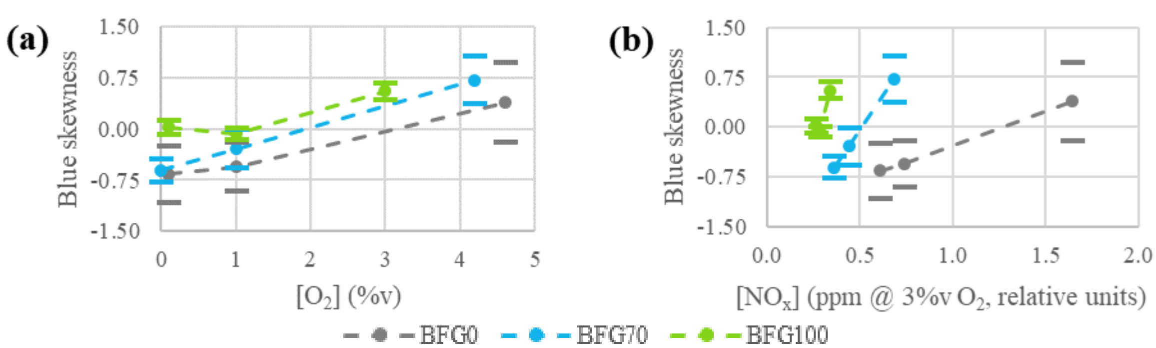

Fig. 3: Image feature of blue skewness versus (a) O_2 and (b) NO_x concentration in flue gases. The means and standard deviations of the samples are plotted with points and horizontal lines, respectively.

Trends detected allow the development of predictive models to estimate the fuel blend burned and O_2 and NO_X concentrations in flue gases, by correlating them with statistical features of the furnace images. To adjust these correlations, different models can be considered, including Machine Learning algorithms. The effectiveness of the models to estimate O_2 and NO_X concentration in flue gases could be increased by developing specific models with different exposure times for each fuel blend. Furthermore, the methodology used in this work could be applied to estimate other operation variables and analyse additional flow effects.

4. Summary of results and conclusions

In this work, BFG co-firing in a semi-industrial furnace has been analysed using a colour camera, carrying out an experimental campaign with three fuel blends and three air-fuel fuel ratios. From the images of the furnace inside, 12 features have been extracted, computing statistical parameters of the three colour channels. The relationships between the image features and the fuel blends, O_2 and NO_x concentrations in flue gases have been studied. Means and standard deviations of the three colour channels have been highlighted as descriptors of the fuel blend, while the skewness of the blue channel has been highlighted as descriptor of the O_2 and NO_X concentrations in flue gases. This study has provided a first step towards the development of combustion diagnosis models for BFG co-firing at industrial scale.

Acknowledgements

This work has been supported by the European Union's Horizon 2020 Research and Innovation Programme under the Grant Agreement No. 820771 (BAMBOO project).

References

[1] X. Wang, C. Li, C. H. Lam, K. Subramanian, Z. Qin, J. Mou, M. Jin, S. S. Chopra, V. Singh, Y. S. Ok, J. Yan, H. Li and C. S. K. Lin, "Emerging waste valorisation techniques to moderate the hazardous impacts, and their path towards sustainability," *Journal of Hazardous Materials*, vol. 423, Feb. 2022, doi: 10.1016/j.jhazmat.2021.127023.

[2] V. Cuervo-Piñera, D. Cifrián-Riesgo, P. Nguyen, V. Battaglia, M. Fantuzzi, A. D. Rocca, M. Ageno, A. Rensgard, C. Wang, J. Niska, T. Ekman, C. Rein and W. Adler, "Blast Furnace Gas Based Combustion Systems in Steel Reheating Furnaces," in *Energy Procedia*, 2017, vol. 120, pp. 357–364. doi: 10.1016/j.egypro.2017.07.215.

[3] Z. Han, J. Li, B. Zhang, M. M. Hossain, and C. Xu, "Prediction of combustion state through a semi-supervised learning model and flame imaging," *Fuel*, vol. 289, Apr. 2021, doi: 10.1016/j.fuel.2020.119745.

[4] A. González-Espinosa, A. Gil, L. Royo-Pascual, A. Nueno, and C. Herce, "Effects of hydrogen and primary air in a commercial partially-premixed atmospheric gas burner by means of optical and supervised machine learning techniques," *International Journal of Hydrogen Energy*, vol. 45, no. 55, pp. 31130–31150, Nov. 2020, doi: 10.1016/j.ijhydene.2020.08.045.

[5] A. P. Mathew, A. Asokan, K. Batri, and D. Sivakumar, "Comparative analysis of flame image features for combustion analysis," *Indian Journal of Science and Technology*, vol. 9, no. 6, 2016, doi: 10.17485/ijst/2016/v9i6/79904.

[6] A. González-Cencerrado, B. Peña, and A. Gil, "Experimental analysis of biomass co-firing flames in a pulverized fuel swirl burner using a CCD based visualization system," *Fuel Processing Technology*, vol. 130, no. C, pp. 299–310, Feb. 2015, doi: 10.1016/j.fuproc.2014.10.041.

[7] G. Giakos, Annual IEEE Computer Conference, IEEE International Conference on Imaging Systems and Techniques 10 2013.10.22-23 Beijing, and IST 10 2013.10.22-23 Beijing, *2013 IEEE International Conference on Imaging Systems and Techniques (IST)* 22-23 Oct. 2013, Vision Hotel Beijing, Beijing, China.