Flow visualization of blast furnace raceways to improve the understanding of tuyere blockages for reliable shutdown of pulverized coal injection

FLOW VISUALIZATION OF BLAST FURNACE RACEWAYS TO IMPROVE THE UNDERSTANDING OF TUYERE BLOCKAGES FOR RELIABLE SHUTDOWN OF PULVERIZED COAL INJECTION

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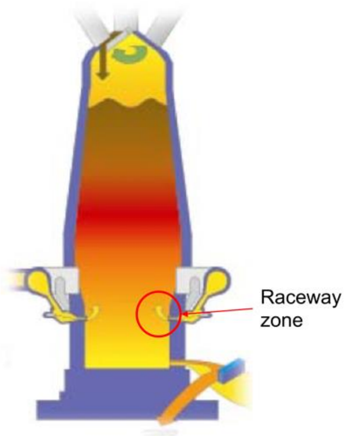
Fluid: gas-solid flows
Visualization method(s): high-speed camera
Other keywords: blast furnace, blockage detection

ABSTRACT: *The present paper discusses flow visualization in blast furnace raceways and image processing strategies for improved blockage detection via tuyere cameras. The authors conduct a systematic study on signal and image processing of blast furnace data to improve condition monitoring and obtain a reliable basis for the shutdown of additional fuel systems like pulverized coal injection (PCI) during phases with non-ideal conditions for combustion. The results presented in this paper are based on applying an edge detection algorithm on the tuyere images to distinguish the visual appearance of ordinary operating conditions from blocking structures inside the raceway.*

1. Introduction

A blast furnace for iron production in general represents a countercurrent reactor (c.f. Fig. 1). While most of the inner volume of a blast furnace is defined by a slowly downward moving bed of solid particles, the raceway areas close to the tuyeres are characterized by a much higher voidage due to the high inertia of the hot blast. This high momentum forms rather dilute areas with a highly turbulent flow of hot gas, solid particles (coke and iron ores) and liquid droplets of iron and slag (Fig. 2). As a side effect, the combination of high local temperatures and longer residence time of the particles (due to the upward acting forces of the hot wind) arc-like structures can be formed above the raceway. As a result of increasing forces from above or erratic movements of the burden these structures collapse from time to time and will block the raceway for some period (Fig. 3). These blockage events can last from several seconds up to the range of 30 minutes and result in suboptimal burning conditions for injected coke substitutes like pulverized coal. Thus, for longer lasting tuyere blockages the corresponding PCI branch must be shut down until the raceway returns to its normal operating state to avoid negative impact on overall blast furnace behavior [1].
The primary goal of this study is to obtain a better understanding of different raceway operating conditions and to test various image processing approaches for their ability to detect raceway blockages. The rapid development of camera technology allows to fully equip a blast furnace (which usually has a number of blow pipes in the range of 20 to 40) with tuyere cameras to monitor the conditions in the raceways and the proper injection of pulverized coal.
In [2] we discussed the different blockage events and their influence on hot blast flow rates on the affected tuyere. Image processing based on individual images and their grayscale histograms was discussed in [3]. The present paper discusses some new results based on edge detection algorithms.



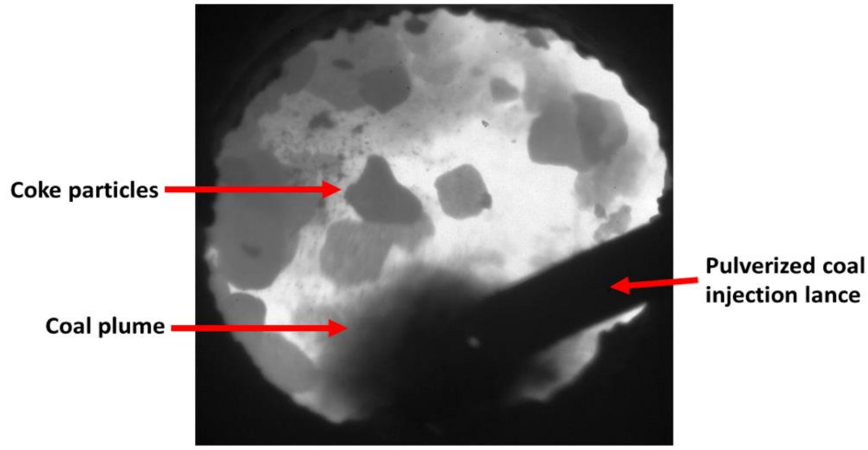


Fig. 1. Sketch of a blast furnace for iron making.

Fig. 2. Example of ordinary raceway behavior with visible coke particles and the coal plume released from the injection lance.

2. Experimental setup and image acquisition

To obtain a better understanding of raceway blockages we took approximately 100.000 images at 1 frame per second (fps) from various tuyeres during normal blast furnace operation. The images have been recorded with a CMOS camera from Photon focus. The camera was mounted directly in front of the inspection glasses, which exist at the end of every blow pipe. To block most of the heat radiation (the raceway region is the hottest section in the complete blast furnace) the glasses usually have a filter coating. The major requirement to the camera is the ability for very short exposure times around 0.5 to 1ms to freeze the fast motion of the coke particles.

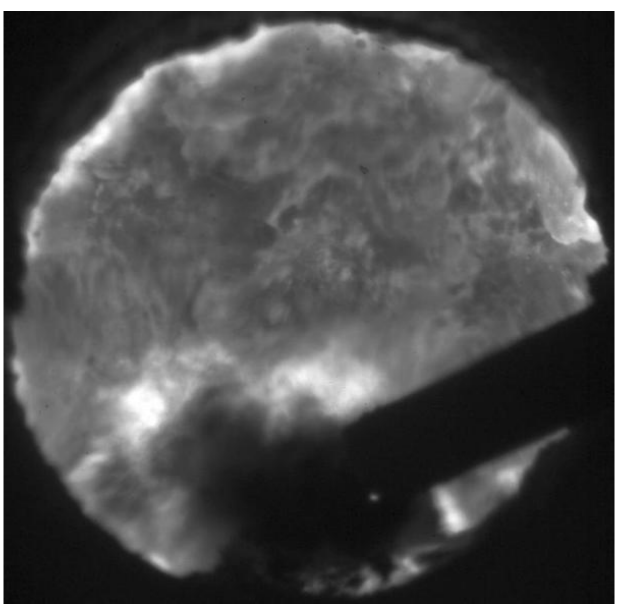


Fig. 3. Example of a complete raceway blockage.

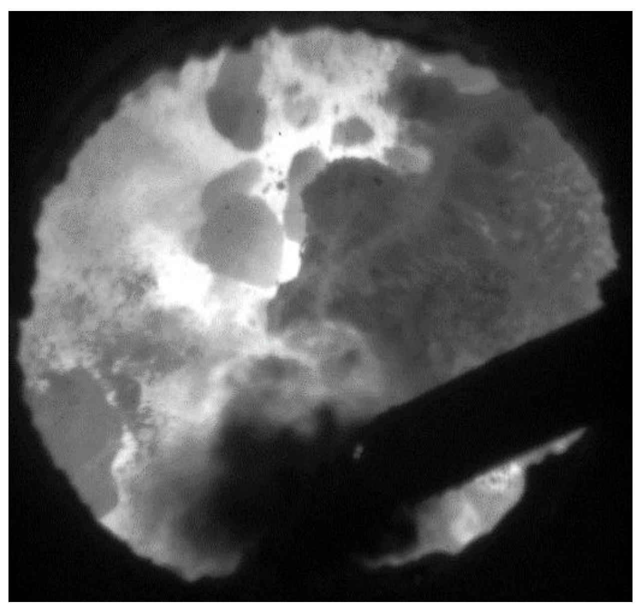


Fig. 4. Example of a partial raceway blockage.

For the same time intervals covered by the image recordings also the hot blast flow rates at the specific tuyeres have been exported from the process control system. Hence, the visual information recorded by the tuyere cameras can be correlated with the influence of blockages on the hot blast flow rates.

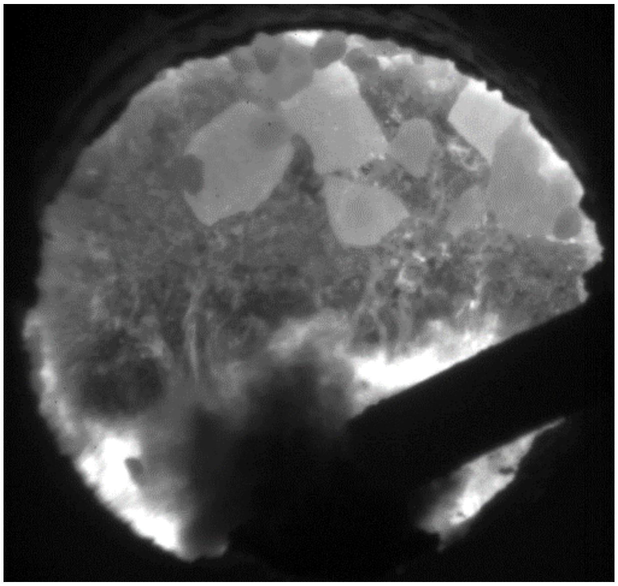


Fig. 5. Example of a blockage with coke particles.

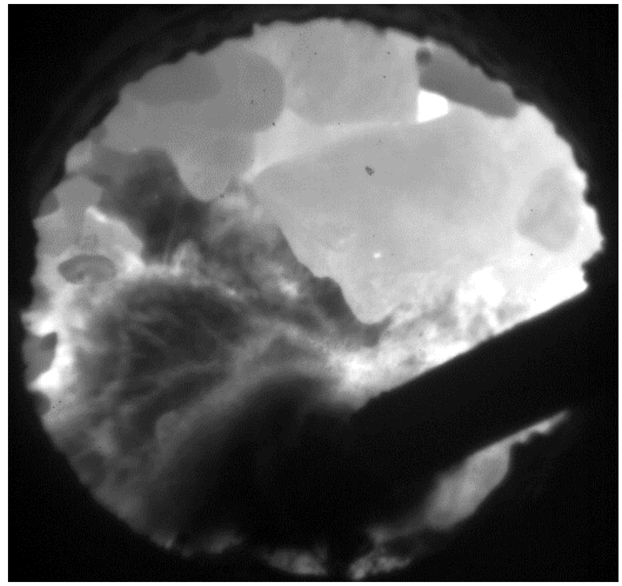


Fig. 6. Example of a massive blockage deeper inside the raceway.

3. Visual appearance of raceway blockages

Manual checking of the recorded image sequences has shown that blockage events can have very different forms of appearances as discussed in [2]. A few examples are given in Fig. 2 to 6. Figure 2 and Fig. 3 have been mentioned in the introduction. Figure 4 is an example of a partial raceway blockage. Figure 5 and Fig. 6 show more difficult cases, where the blocking structure is located deeper inside the raceway and there is still room in front of the raceway for coke particles to move around. While the blocking structure is still clearly visible in Fig. 5 there is no obvious large piece of agglomerated material in Fig. 6. However, Fig. 6. shows an instance of a massive blockage where the hot blast flow rate on that specific tuyere was reduced to below 5% of its normal value. Compared to the other figures, the coal dispersion is not as usual and leads to the assumption that a complete combustion of the coal particles is not possible at the present raceway condition. The examples demonstrate that while a human operator with some experience is able to identify raceway blockages of various kinds, it is not a trivial task for automated image processing.

4. Image processing strategies

As there are endless possibilities in the field of image processing we tried to classify the methods under test into two major families. The simpler approaches are based on processing individual images. As an example, an adaptive thresholding method based on Otsu's method was outlined in [3] and delivered good results. The second family of algorithms is history based and uses sequences of two or more images for processing. This, on one hand, has the big advantage of having more information available. On the other hand, this inevitably also increases computation times. For example, full 2D correlation of two consecutive images is out of scope if the goal is to process a complete blast furnace at 1 fps on standard industrial computing hardware. The further discussion in this paper focuses on the results of an edge

detection algorithm tested on the presented images and a test-case consisting of 10000 consecutive images covering a time span of 2h 45min of real blast furnace operation.
Ordinary raceway behavior is characterized by the presence of coke particles (c.f. Fig. 2). Hence, an edge detection algorithm should be able to find the edges of the coke particles and the number of pixels identified as an "edge" must be related to the number of coke particles and would give a proper measure of the current raceway state. Thus, we tested an edge detection approach based on the following processing steps:

1. Set all pixels with grey levels below 0.2 (on a normalized scale between 0 and 1) to 0.
2. Create a binary mask with a threshold level of 0.65 to eliminate bright areas which are dominated by heat radiation.
3. Calculate the image gradient by applying a Sobel filter [5].
4. Mask the gradient image by applying the mask from step 2.
5. Convert the result from step 4 to a binary image by applying a threshold of 0.3.
6. Sum all pixels which are set to '1'.

The result provides a measure for the number of structures found in the image as illustrated in Fig. 7 and Fig. 8. While for ordinary raceway operation the number of active pixels is mainly limited to the boundaries of the coke particles (Fig. 7) a blocking structure delivers smaller gradient values but in total much more active pixels due to the texture of the blocking structure. Table 1 gives the corresponding numbers for Fig. 2 - 6.

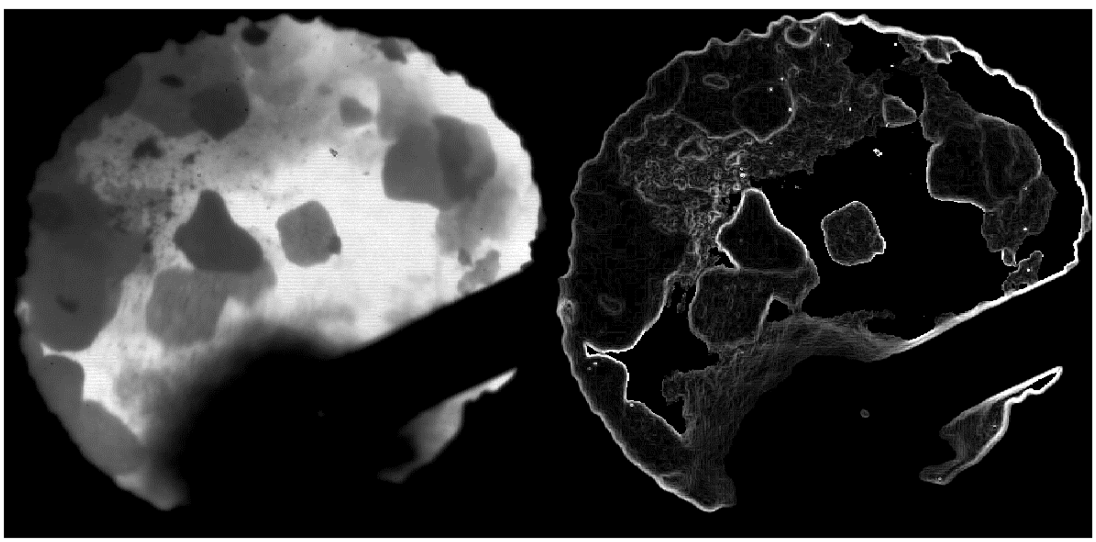


Fig. 7. Example of ordinary raceway behavior with visible coke particles and the coal plume released from the injection lance.

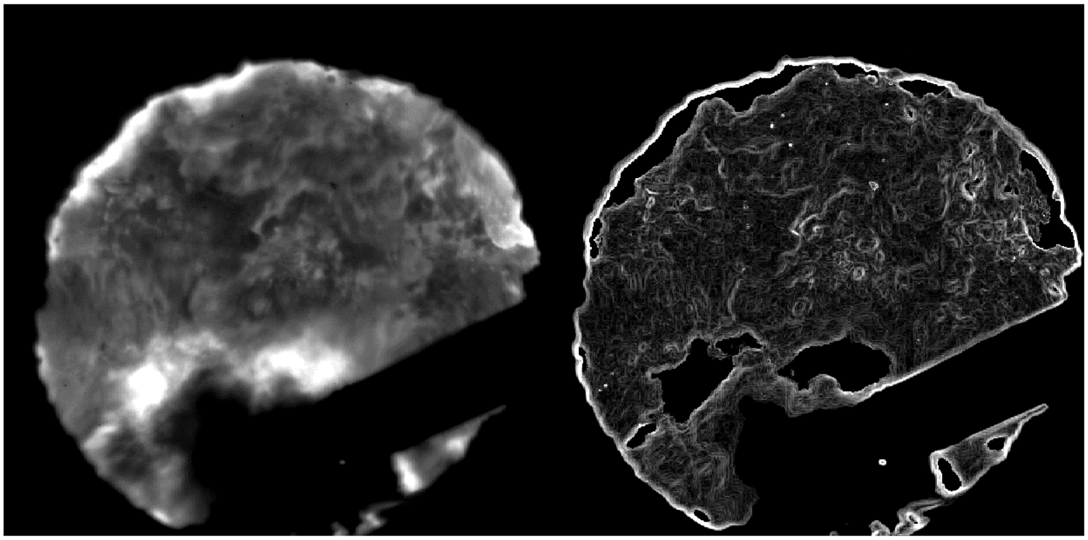


Fig. 8. Example of ordinary raceway behavior with visible coke particles and the coal plume released from the injection lance.

Table 1. Resulting values of the edge detection algorithm for the examples in Fig. 2 – 6.

Figure	*Average gradient*	*Standard dev. of gradient levels*	*Sum of active pixels after binary conversion*
2	14.58	27.20	46191
3	14.84	25.26	82873
4	14.28	23.43	75515
5	16.46	30.52	61348
6	13.49	26.65	49373

As can be seen from Table 1 the average gradient levels and the standard deviation of the gradient values do not deliver a significant measure for blockage detection, but the sum of active pixels after binary conversion of the masked gradient images provides useful values. Only the case shown in Fig. 6 is difficult to detect and its result does not differ very much from the result for Fig. 2.
The processing procedure was then tested on a set of 10000 images and compared with a manually defined reference signal marking all time intervals with non-ideal raceway behaviour. The reference signal was defined very strict on purpose, and every suspect time interval was set to ‘1’. Figure 9 shows the resulting signals. In addition to the original signal of the edge detection algorithm (blue line) a moving average filter with a window size of 25 samples was applied and plotted in red.
The comparison with the reference signal shows that most of the blockage events are captured by the image processing method and the positive peaks of the resulting signal can be used to finally derive a yes/no decision if an individual PCI branch needs to be shut down for some time. A systematic quality assessment of signal and image processing results for blockage detection will be presented in [6].

The average processing time per image was 0.13 s on an ordinary desktop PC. This would allow a complete processing of the present blast furnace with 20 tuyeres in three second intervals which should be sufficient for raceway monitoring.

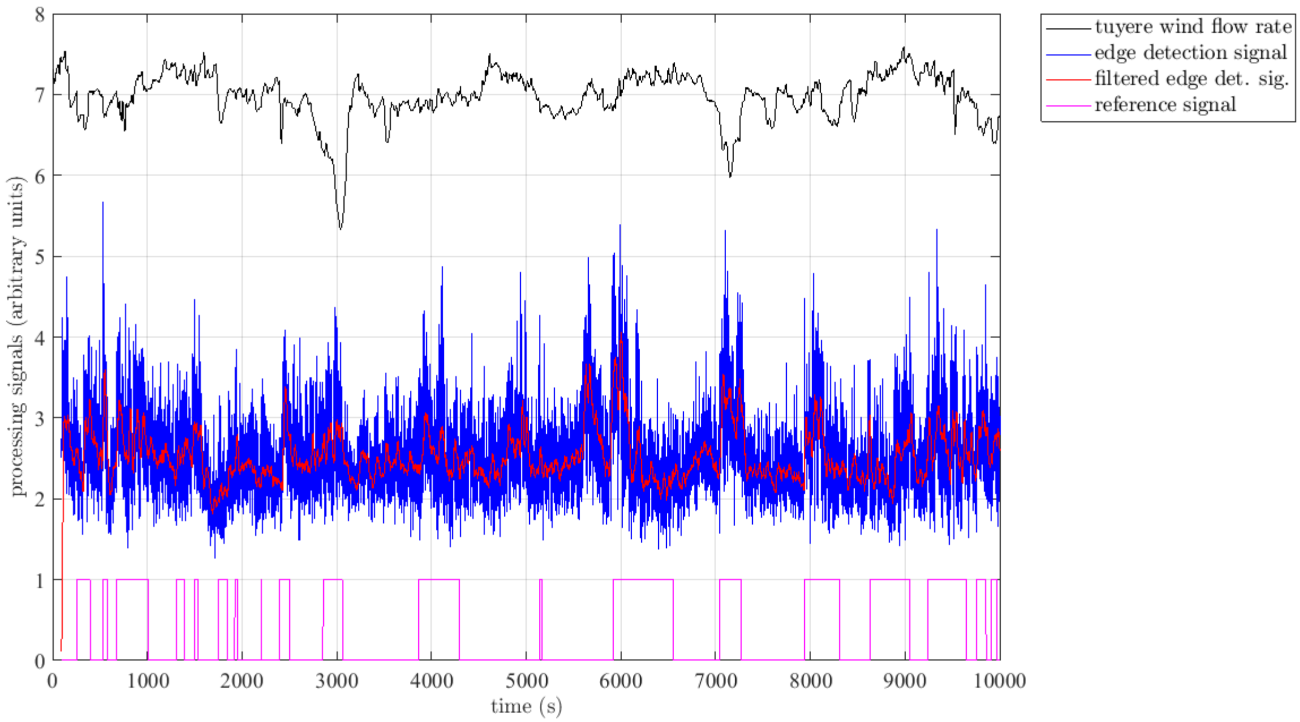


Fig. 9. Resulting signal of edge detection processing compared with the flow rate signal of the tuyere and a manually defined reference signal.

5. Conclusions

The present paper summarizes some results of a systematic study on raceway blockage detection in blast furnaces. As the primary goal is to implement an online system which is capable of processing a typical blast furnace with 20 to 40 tuyeres online at a reasonable frame rate (which should be in the range of 1 to 5 fps). The discussed edge detection algorithm is able to provide useful results at a reasonable processing time. However, some blockage events remain difficult to detect on a visual basis, especially when the blocking structures are located deeper inside the raceway and are not clearly visible on the tuyere camera images.

One possible approach for the next project phase could be to wrap the most promising algorithms which are currently under test in a machine learning framework for faster fine tuning of parameters and adaption to each individual tuyere.

Although there is still lots of room for improvements, the systematic screening of thousands of tuyere camera images has improved the understanding of raceway behavior at different operating conditions.

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