

Monitoring of blast furnace wall pressure profiles and their relation to process efficiency

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Abstract. The blast furnace process for ironmaking is highly optimised and very energy efficient. However, due to its dependency on coke, not only as an energy carrier but also as a chemical reductant and provider of gas permeability, it is responsible for high CO₂ emissions. Consequently, steel producers search for operation modes to minimise emissions, e.g., such as increasing the share of hydrogen-based reduction. For such new operational set points, operators have less experience in how to maintain a stable and most efficient process state. At Hüttenwerke Krupp Mannesmann, experience has shown that especially in the shaft region of the blast furnace most process instabilities arise from non-optimal gas permeability of the burden column and non-uniform burden descend. Such process disturbances can be recognised at a very early stage through careful monitoring of the gas pressures along the shaft wall. A study has been performed how different process gas pressure profiles, measured vertically along the blast furnaces wall, can indicate different process states with different efficiencies. A monitoring tool to automatically supervise the profile shape and indicate warning to blast furnace operators in case of non-optimal profiles has been developed. Data analysis has been performed to demonstrate the relevance of the findings. The results show that a better process efficiency, meaning lower CO₂ emissions, can be achieved by careful monitoring of the blast furnace wall pressures.

Keywords: blast furnace operation / wall pressure / efficiency / operation support system

1 Introduction

Despite the steel industry’s considerable efforts to decarbonise the hot metal production by switching process routes, blast furnace process efficiency is still of uppermost importance. Planning and erecting new process routes requires significant time and human resources. At the same time, it is becoming increasingly difficult to recruit new, qualified personnel. In this situation, with blast furnaces (BF) still being the main workhorses for global ironmaking, many steel producers need to rely on their stable and efficient production, to enable them to transform their plants while withstanding global competition. This includes operating BFs at new operating points, e.g., mitigating CO₂ emissions by injecting hydrogen-rich gases such as coke oven gas (COG).

Blast furnace efficiency depends on the proper interaction between the solid and gaseous phases as well as, deeper within the BF, the liquids [1]. The solids must descend evenly, while the gas passes homogeneously through the

voids in the solids packed bed. At the same time, contact between the gas and the solids must be as intense as possible to enable high reaction kinetics and energy exchange. This means operating the BF near, but under no circumstances beyond, its permeability limit.

To enable operators to maintain such an operating point at all times, careful monitoring of the permeability is required. If process instabilities arise, actions that could further hamper flow conditions, such as increasing the hot blast volume or the pulverised coal rate, must be avoided. The type of instability must also be determined, as well as proper countermeasures. BF operating companies therefore have standard operation procedures, which BF parameters need to be continuously monitored and what actions to take when defined threshold values are violated. Several methods of monitoring permeability are used; for example, the pressure drop along the packed bed’s height from blast to top is monitored, as well as the top gas temperature and the wall heat losses, which are known to provide information about gas flow stability and homogeneity [1]. Despite this, operational situations sometimes occur where all measured parameters are within the permitted thresholds, yet the BF process does not react

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fully as expected. Sometimes, even a later review of such incidents does not reveal the cause, as none of the known parameters show obvious deviations.

BF operational stability has been the subject of research for a long time due to these circumstances. Many parameters are under investigation that provide early indications, as they are connected to the gas flow (the fastest process in the BF). Process gas pressure data and its interpretation are covered in standard literature on BF operation [1–3]. Data-driven methods are already used since long time, e.g., in the Consistent BF EU project in 2013 [4], but during that time the methods could not handle the amount of variables considered nowadays, which lead to less sensitive results.

In 2018, Kamo et al. [5] developed a method at Kobe Steel evaluating the frequency of pressure fluctuations, temperature data from different process areas, and other BF data. They defined an index to predict channelling. They report having successfully integrated their method into BF operation. However, these indices are optimised for the Kobe Steel BF and a study using data of BF A at Hüttenwerke Krupp Mannesmann (HKM) in Duisburg, Germany, showed, that while pressure and temperature readings deliver comparable information, the temperature data are not as fast and more depended on the measurement location. In 2021, Ito et al. [6] used Q-statistics to detect deviation of some of the wall pressure measurement readings from the others. This approach bases on the same observation on data patterns as used in this paper but features a more advanced method for the detection. The authors of this paper use a less complex approach to enable operators to better rate how reliable the evaluation of the current situation is.

More recent work often focuses on the use of neural network-based AI methods (e.g., [7]). While they often report good results on their training and testing data sets, neural networks generally lack an explanatory component. This makes it almost impossible for operators to understand how the results were derived or how reliable they currently are. From the authors' experience, it can happen that, after several months, AI models for BF operational support have very poor accuracy, as something has changed in the operational state of the BF which is not fully reflected by the available data for the model. Instead of using neural networks, Jiang et al. [8] use value distribution analysis by box-plots and clustering algorithms for data preparation, which are similar to the methods presented in this paper for later analysis. They then train different regression models on the data. While some of these models are explainable, they are also too complex for operators to comprehend when they are under time pressure to adjust the BF operation.

A systematic research study at BF A of HKM as part of the EU-funded project 'Minimisation of CO₂ Emissions from the BF by hydrogen containing injectants and use of DRI/HBI during transition to new Ironmaking processes until 2030 (H2TransBF 2030)', revealed that the most accurate, reliable and fastest information can be obtained by monitoring of the pressure measurement taps at the BF wall. The authors of this paper therefore decided to base their work on data such as the vertical pressure profile and

fluctuations in wall pressure, with which operators are familiar with. Compared to neural network-based AI models or other state-of-the-art regression models, the indicators in this study are intentionally simple, but they are also reduced to the most important information – the change of pressure data over time. From author's experience, proper data filtering is often more important than complexity of the models applied afterwards, to create long-term applicable tools.

2 Method for studying blast furnace process gas pressure readings

2.1 Data selection and filtering

HKM operates a data lake, providing access to synchronised data from all relevant measuring systems at their blast furnaces. From this data lake, minute interval data from more than three months of operation was used for both studies in this paper. The first study about the vertical pressure profiles is based on data from May to mid-August 2024, the second study about the influence of flow disturbances is based on data from January to mid-April 2025. In addition to the minute-interval time series, data from each available wall pressure measurement sensor (16 sensors in four vertical lines, providing 64 data series), the analysis also included BF operating point and BF efficiency-characterising data, such as hot blast and injection parameters, hot metal and slag parameters, top gas parameters, and burden feed parameters. Figure 1 shows an extract of some of the used data series for the pressure profile study (The figure illustrates the variability of the available data. The three-month period covers all types of operation, including high and low blast volumes, stable and unstable operation, and gas utilisation rates between 44% and 53%, which indicate process efficiency. The data used for the second part of the study on flow disturbances (not shown) exhibits comparable fluctuations and quality.

Prior to the data analysis, the data was filtered to remove fluctuations caused by effects that were not intended to be considered. Especially data prior and after stoppages was removed. Also, effects from stopping preparation, such as setting of extra coke, and recovery of process zones and flow stability after a stoppage were unwanted and excluded. However, data from short hot blast reduction intervals of a few minutes, which are used by operators to counter irregular stock line movement, remained in the dataset as they also reflect the investigated flow instabilities. Data removed due to stoppages is marked in Figure 1 by grey dotted lines.

Furthermore, data from wall pressure measurement sensors is very often subject to disturbances. Total sensor failure is easy to recognise and filter out, but measurements are also often temporarily disturbed by partial blockage of the measuring pipes. Such blockages can be caused, for example, by small burden particles or by aggregations, e.g., formed from condensing alkaline or zinc on the cooled BF wall. In such cases, the sensors often continue to deliver data, albeit with a systematic drift or shift. Signal

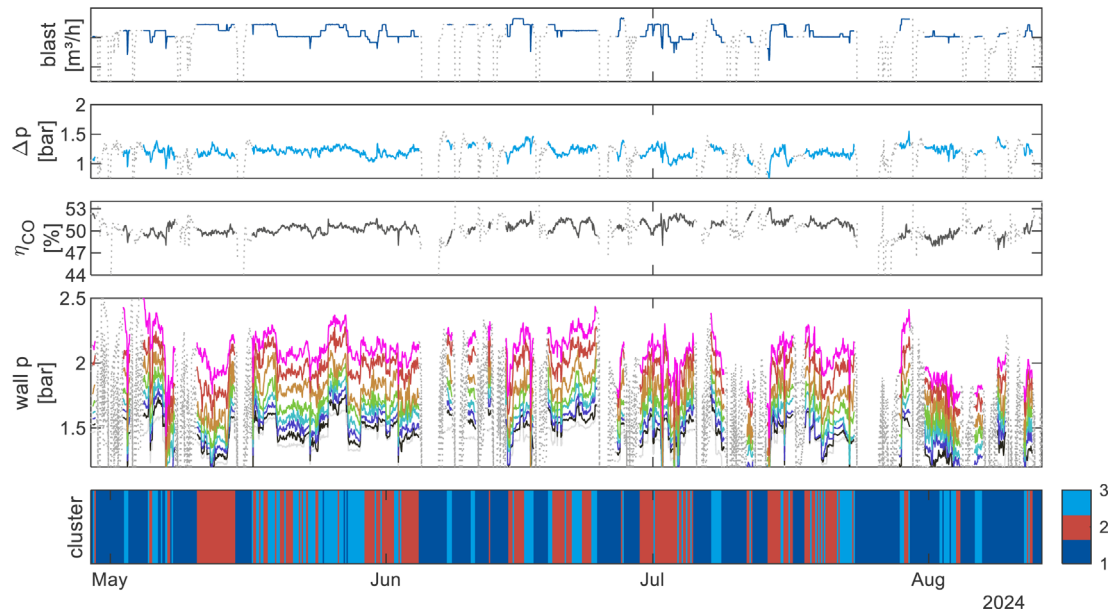


Fig. 1. Visualization of an extract of the data used for the study and assigned clusters (visualization shows hourly average values for better overview – minute data used for the study, dotted lines indicate removal of the data around blast furnace stoppages, hot blast data anonymised).

fluctuations can also often be damped compared to adjacent sensors. This corrupted data was recognised by an automated filter using two methodologies.

The first filter criterion is the correlation of one pressure data series with all the others. If a high correlation ($r \geq 0.9$) was not found with at least three other data series, the data series was discarded. This filter removes data from non-responding sensors or sensors with only damped fluctuations. The second filter criterion is shown in Figure 2. It is the deviation of individual measurements (coloured dots in Fig. 2) from the overall profile of a measurement line comprising 16 sensors. The overall profile shape was calculated using a four-data-point interval moving median filter along the sensors' readings in the measurement line (red solid line in Fig. 2). If a single measurement point deviates by more than 175 mbar from this median profile (threshold visualised as red dashed lines in Fig. 2) the data from this sensor was dumped (e.g., value from PS321 in Fig. 2). This filter removes data that show reasonable fluctuations but are too high or too low in overall, given the sensors position in the measurement line.

Data from most blast furnaces, not only those at HKM, analysed by the authors often show the above-described disturbances. It is crucial to remove such data series from the dataset prior to analysis in order to obtain accurate results. In addition, automated data filtering can be used to identify sensors requiring maintenance during the next blast furnace stoppage.

2.2 Derivation of typical shapes of vertical pressure profiles

A vertical pressure profile is derived from the wall pressure data shown in Figure 1 (third row) by selecting a sample

time stamp (x-axes in Fig. 1) and noting the pressure value of all sensors from one vertical measurement line on the x-axes and the height of the sensor on the y-axis (see Fig. 3 as an example). Such pressure profiles are known to already carry basic information about the flow situation inside the BF. Given the pressure drop from the tuyere level to the top, there should not be an increase in pressure with height. If a profile shows this behaviour, it indicates a local flow disturbance (or a malfunctioning sensor). Often also the location of the cohesive zone can be estimated by the height where the pressure drop starts to deviate from a linear behaviour [9] e.g., between PK309 and PK307 in Figure 2. In general, the authors have found that, a strong “belly shaped”, non-linear decrease of the pressure with the height in lower BF areas is often seen in combination with a furnace operation point where the process is close to its' permeability limit.

To automatically extract such typical different shapes of the pressure profile from the data, after filtering, all minute based profiles of the more than three months of data have been calculated and k-means clustering has been applied. An Euclidean distance measure was used. The optimal cluster size depends on the operational state of the BF, particularly the variety of pressure profiles that have occurred, and must be determined on a case-by-case basis. Here, $N = 3$ clusters were found to be a good compromise, minimising the spread of the individual data points inside the cluster while avoiding clusters with too few elements and clusters with only minor differences in centroid shape. Figure 1 (second bottom row) shows the pressure values from one of the measurement lines at BF A at HKM. To improve visual clarity, only data from each second measuring point is shown in the figure, but the pressure profiles were calculated using all data after filtering. The bottom row of Figure 1 shows which data from which time

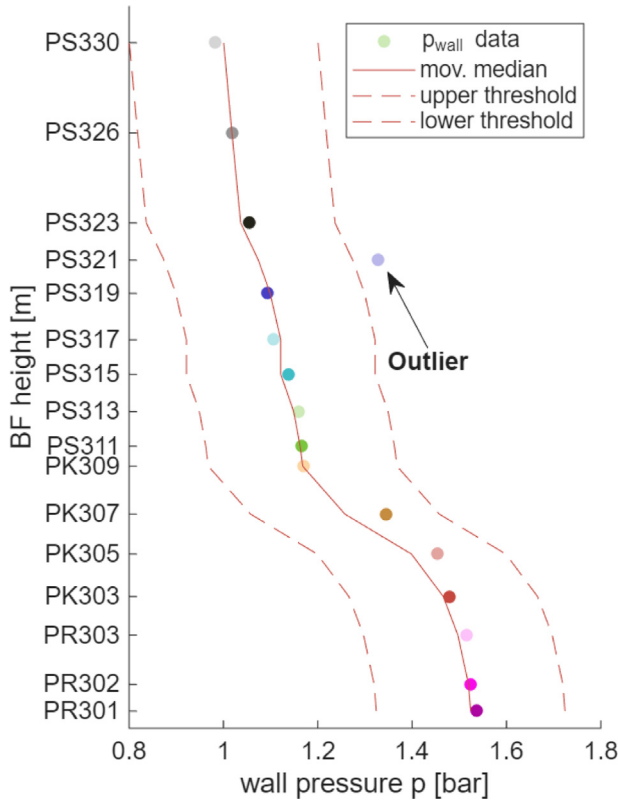


Fig. 2. Principle of 2nd filtering criteria of wall pressure profile data by moving median value (example for sector 3).

stamp was assigned to which cluster by the k-means algorithm. In the visualisation filtered out time stamps also show the colour for cluster 1 but this data has not been used in the later analysis. Figure 1 provides an initial overview that the data, assigned to all three clusters, is distributed fairly evenly across the entire dataset. There is no cluster that only occurred during an isolated period of operation. This indicates that the pressure profiles that formed the different clusters are common and typical of normal operation. As next step the data of all clusters were further analysed with regard to the operational state of the BF (see Fig. 1).

After the pressure profile data was assigned to three clusters, the centroid of each cluster was derived. The results are shown in Figure 3. The figure shows on the left side the absolute pressure values, and on the right side the same profiles but normalised to the value range [0...1]. The left side makes it easier to differentiate between the different pressure levels of the profiles, whereas the right side makes it easier to differentiate between the profiles' overall shapes.

As can be seen in Figure 3 (left), all the data assigned to cluster 3 (light blue) correspond to an operation with in total lower operational pressure than for the other clusters. Cluster 1 and 2 start (at the bottom) and end (at the top measurement location) with comparable pressure values, but exhibit different pressure drop, particularly in the height range between the measuring probes PK03 and PK07 (BF belly level). This region also shows the strongest deviation to a linear pressure drop with the height. Therefore, it can be concluded, that this is the height of the cohesive zone in the BF. This indicates that the data

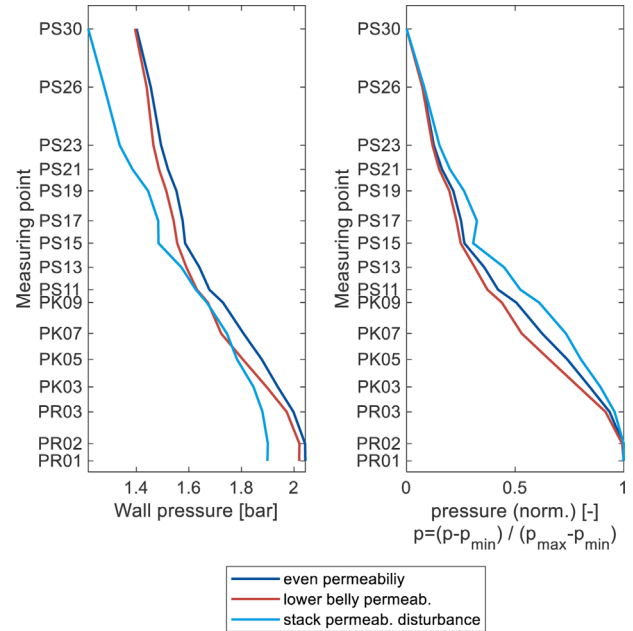


Fig. 3. Four sectors averaged vertical pressure profiles from the centroids of three clusters (left absolute pressure values, right normalised values to the interval [0...1]).

assigned to the red profile (cluster 2) had an overall higher pressure loss in the cohesive zone area, with the cohesive zone tip being lower (red, approx. height PK07) than for the dark blue profile (cluster 1).

Figure 3 (right) suggests that the data from the third, light blue cluster had the lowest pressure drop in the cohesive zone area, but there is an anomaly between PS15 and PS21, in the region directly above the cohesive zone. From PS15 to PS17, the pressure increased. This should not be physically possible given the total pressure drop from bottom to top. This indicates that, in the vicinity of the pressure sensors, the gas flow was blocked and disturbed, rather than being homogeneous. The dark blue curve shows a profile usually observed during at stable operation with an evenly distributed pressure drop.

In summary, the k-means clustering analysis revealed systematic differences in the pressure profiles of each cluster and showed that these differences provide additional information about the BF operational state. The three clusters have therefore been characterised as “even permeability” (cluster 1, dark blue), “lower belly permeability disturbance” (cluster 2, red), and “stack permeability disturbance” (cluster 3, light blue).

2.3 Detection of flow disturbances from wall pressure measurement readings

Continuing the k-means clustering study, that derived information about flow disturbances in the different BF zones from the vertical pressure measurement lines, a more in-depth approach for detecting and characterising flow disturbance has been developed. Data from optimal steady-state operation of the BF shows in overall a parallel movement of all pressure data in a measurement line

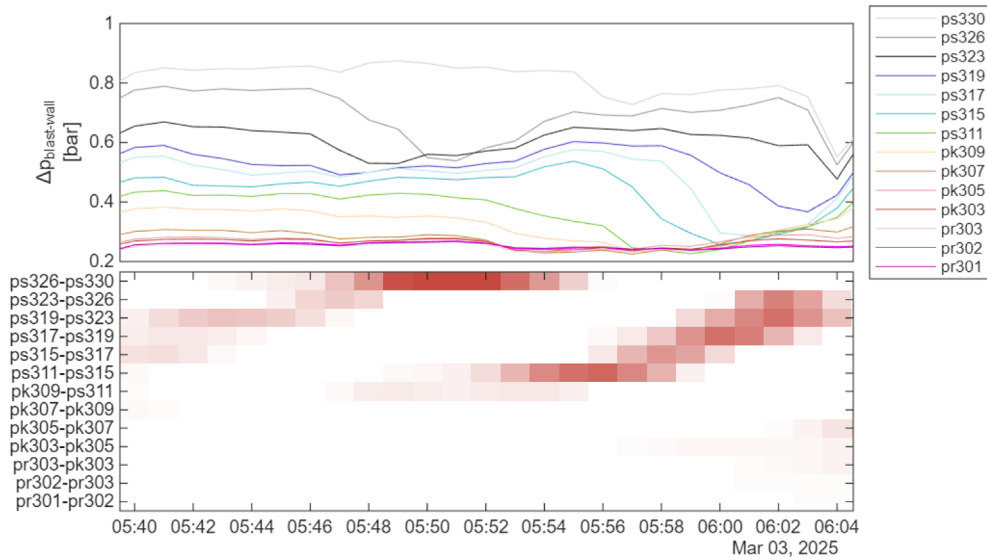


Fig. 4. Pressure drop between blast pressure and the individual wall sensor values (upper part) and change over time of the difference of the pressure between sensor locations over each other in a measurement line (lower part) (example for sector 3, therefore measurement tap names deviate from Fig. 3).

(cf. data from 05:40 to 5:46 in Fig. 4 (upper part)). Disturbances in the gas flow are visible by fast and strong deviations from this parallel behaviour (e.g., at 05:48 for PS26 and PS30 in Fig. 4 (upper part)).

In theory, in the dry area of the BF process, if the height differences of the sensors are equal, also the differences between the pressure readings (i.e. upper lines in Fig. 3) should be equal. In practise however, this is often not the case. The lines often show parallel behaviour but with heterogenous distances, possibly due to slightly blocked sensors. Therefore, attempts to work solely with the pressure difference between adjacent sensors (i.e. positioned atop each other) did not produce reliable results that could be related to other BF parameters. Consequently, it was decided to include the temporal behaviour of the pressure data in the analysis. An increase in the pressure drop between two adjacent sensors over a period of 5 min is used as an indicator of flow disturbances. If the pressure drop between two sensors exceeds 17.5 mbar/min, this is considered a ‘disturbance’. Figure 4 (lower part) shows the increase in pressure difference between adjacent sensors over time in the form of a heatmap. Dark red indicates a significant increase in pressure difference over time.

The heatmap visualisation also provides a clear indication of how areas with high pressure difference increase move over time. Figure 4 (lower part) shows for example that at 05:48 between sensors PK309 and PS311 the pressure difference started to increase. Over time this area of high pressure difference moved upwards in the BF shaft. At 05:56 it was highest between sensors PS311 and PS315, at 05:58 it was highest between PS315 and PS317 and so on. As the burden and coke layers move downwards and have a lower velocity, it can be concluded that the disturbance was not caused by a locally impermeable layer of poor-quality material – the cause of the disturbance can

be more readily linked to the interaction of the gas with the movement of solids. In summary, this example demonstrates that the temporal pressure difference indicator, together with knowledge of where the disturbance occurs and basic physical knowledge of the BF process, can be used to exclude possible causes of the disturbance. This is the first step in deciding on countermeasures. Therefore, this method is superior to only monitoring the gas flow by the total pressure drop over the burden column, as is often practised.

3 Results on relation between wall pressure readings and blast furnace process state

After defining methods for clustering pressure profiles and detecting local gas flow disturbances, a holistic data analysis was performed to detect statistically significant differences in the data distributions of a multitude of other BF data series whilst different cluster were assigned or whilst different pressure increases between adjacent sensors over time where found. This allows to formulate more informed hypotheses about possible causes and demonstrate the relevance of the methods for BF operation.

To investigate whether other BF parameters show systematic differences during different identified pressure profile shapes, all relevant data series measured at a BF (cf. Sect. 2.1) were labelled with the cluster number of the assigned pressure profile shape cluster. Then for the same parameter, differences in the shape of the data distributions during occurrence of cluster one, two and three have been analysed. The shapes of the three data distributions are visualised using box-plots (see Fig. 5). The box plots show the 25th and 75th percentiles (interquartile range) of

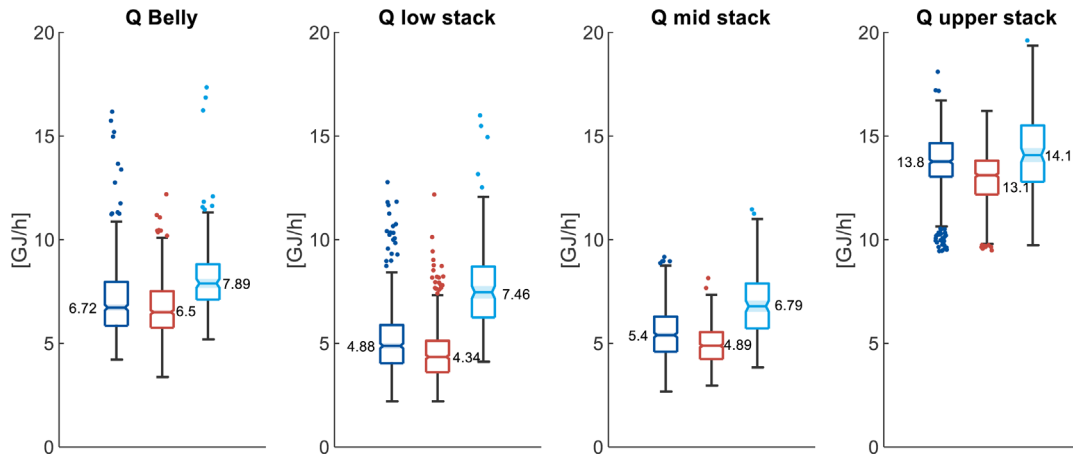


Fig. 5. Data distribution of heat losses at different BF heights during the three different clusters (explanation of box plots – see text above).

the total data distribution within a coloured box. The median value of the data distribution is indicated by a line in the box with a coloured notch amongst the median value indicating its confidence range. Data outliers are represented as individual dots, while the remaining minimum and maximum values are shown by black whiskers. The width of the interquartile box and the distance between the whiskers indicate the steepness of the distribution function, i.e. whether there is more or less 'data fluctuation'. Comparing the median values of the different columns of box plots indicates a systematic shift in the data distribution. If one median value is outside the notch area around the others, this can be understood as a 'significant' difference between the distributions.

Figure 5 shows, from left to right, the heat losses (Q) of BF A during the three-month period from bottom to top in belly, low- mid- and upper stack area. It can be seen, that the heat losses during the occurrence of pressure profiles with lower (red) and higher (dark blue) cohesive zone tip show similar data distributions of heat losses at all height levels, with the red distribution having at all levels slightly lower median values and also slightly lower distribution spread in the interquartile range and between the whiskers. The heat losses during cluster 3 (light blue) with the flow disturbance at stack height show in all heights noticeable higher heat losses, especially at low and mid stack height, with also higher data fluctuations (wider distribution spread). This difference is consistent with the differences in pressure profile shape.

Examining the top gas temperature and the gas utilisation (cf. Fig. 6), it is clear that the data distribution for these parameters differs significantly between pressure profile shape clusters 1, 2 and 3. During the disturbed flow at the stack level (cluster 3, light blue) the top gas temperature is in median 20–30 °C higher than during clusters 1 and 2. The median gas utilisation during cluster 3 is 49.4%, which is 0.9–1.3 percentage points lower than during clusters 1 and 2. This indicates that the disturbance of the stack permeability is associated with a lower process efficiency.

The same data, analysed for coherencies with the pressure profiles, were also analysed for systematic interrelations of data distributions during different values of the flow disturbance indicator (see Sect. 2.3). For the entire analysed dataset of over three months of BF operation, the maximum increase in pressure difference between two adjacent sensors over a period of 5 min was calculated. The maximum value for all sensor pairs was used to label the analysed data. Each investigated BF parameter (e.g., such as top gas temperature) value has been distributed to five bins. All top gas temperatures measured when the maximum wall pressure difference increase was between 0 and 7.5 mbar/min were stored in the first bin, all between 7.5 and 15 mbar/min to the second bin and so on. The differences in top gas temperature data values across the five bins were then visualised using box plots. The results for top gas temperature and gas utilisation are shown in Figure 7 by way of example.

Figure 7 (left) shows that there is a nearly linear relationship between the median value of the top gas temperature distribution and the flow disturbance indicator. The higher the pressure difference between two adjacent sensors at one vertical wall line increases over time, the higher the median value of the top gas temperature also becomes. Along with the median value, the spread of the top gas temperature data also increases, as can be seen from the larger differences between the interquartile ranges (boxes in Fig. 7). A similar effect is visible for the gas utilisation. As long as the flow disturbance indicator is below 22.5 mbar/min the median gas utilisation value does not change (although the minimum values decrease). For higher flow disturbance indicator values, the median gas utilisation also starts to decrease. At flow disturbance indicator values of > 37.5 mbar/min the median gas utilisation is approximately one percentage point lower than without flow disturbances.

To make the flow disturbance indicator available to BF operators, a Python-based online dashboard system was set up. This system constantly reads the wall pressure

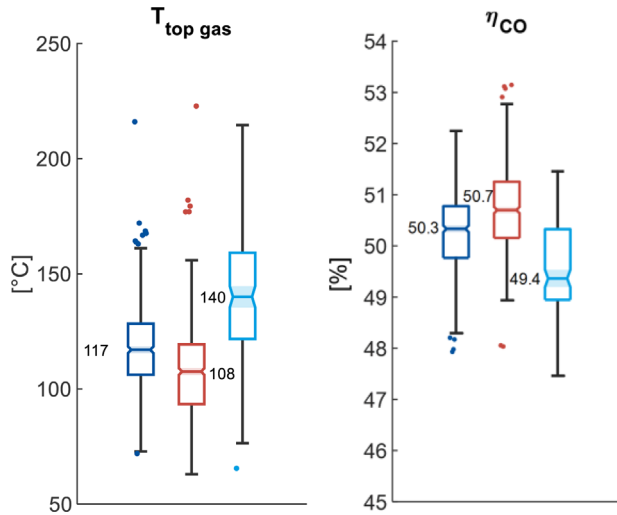


Fig. 6. Data distribution of top gas temperature (left) and gas utilization (right) during the three different clusters (general explanation of box plots – see text above Fig. 5).

measurement data from the HKM data lake, performs the automated data filtering (see Sect. 2.1) and visualises data from the last 3 h of the four pressure measurement lines, alongside heat loss data. It also computes pressure profiles for each measurement line (see the right-hand side of the screenshot in Fig. 8). For each adjacent wall pressure sensor pair in each of the four measurement lines the flow disturbance indicator value is computed and visualised with its radial position around the BF and its height in a flat projection. Beside the flat projection, a profile of the BF shape with annotation of the sensor positions is given (see left part of the screenshot in Fig. 8). The flat projection can be switched to a 3D visualisation with the values projected onto the shape of the BF's shell. Next to the flat projection on the right side the readings for the wall pressure and the current wall pressure profile are visualised for all three sectors to enable the operators to monitor the source data for the flow disturbance detection. Below the wall pressure timeseries, also the heat losses are visualised to enable comparison. The colours of the heat loss readings match the colours of the pressure data at same height. A view similar to the lower part of Figure 3 for the last seven days of data is also available (not shown in Fig. 8) by choosing the “Historie” (engl. history) tap instead the “aktuell” (engl. actual) tap. In the top left corner of the dashboard a notification light with traffic light colours indicates the overall flow state. If the flow disturbance value for at least one sensor pair is above 17.5 mbar/min, the light is red; if it is below 50% of this threshold value, the light is yellow. The online dashboard can be accessed via a browser on the entire HKM intranet.

4 Discussion

In addition to the relationship between the shape of the pressure profile and the flow disturbance indicator with the other BF parameters, as explained in Section 3, a multitude of other BF data series were investigated using the same

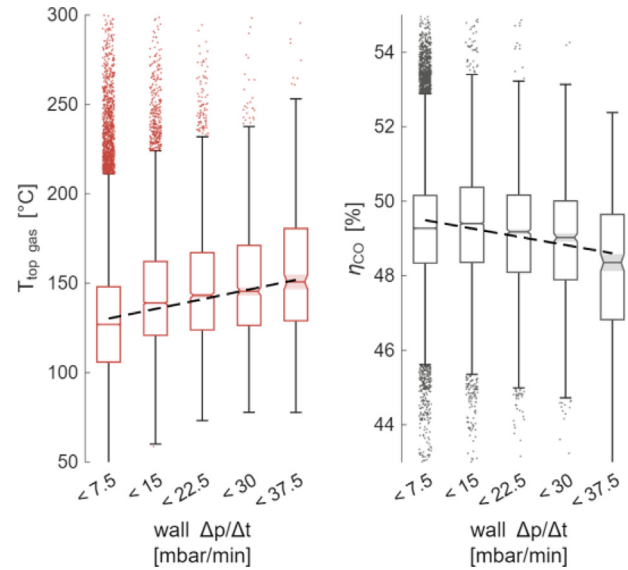


Fig. 7. Change of data distribution shape of top gas temperature (left) and gas utilisation (right) at increasing values of the flow disturbance indicator (general explanation of box plots – see text above Fig. 5).

methodology. Data on the investigated parameters from the three-month period has been divided into data-bins. In the first study the data bins were built from the pressure profile cluster (see Sect. 2.2), and in the second study, the bins represent different values of the flow disturbance indicator (see Sect. 2.3). It was found that parameters also reflecting the gas flow, e.g., as the total pressure drop from tuyere to top, or other top parameters showed changes in the data distributions in the bins, that were similar to the effects like discussed in Section 3. These investigations also revealed that the presented approach enables the formulation of hypotheses regarding the cause of the monitored effect. In the case of the vertical pressure profile from cluster 3, which indicates a disturbance in permeability shortly above the cohesive zone, the proportion of charging materials in the burden was examined. Figure 9 shows the specific (kg of charge per ton of produced hot metal) amount of pellets in the burden.

As can be seen in Figure 9, the proportion of pellets in the burden is significantly higher during pressure profiles similar to the centroid of cluster 3. This is counterintuitive, as it is usually assumed that pellets increase the permeability of the burden column. However, during the investigated time period, HKM BF A also injected coke oven gas. A laboratory study performed by University of Oulu as part of the EU project H2TransBF 2030 (see funding section) brought indications, that the pellets charged by HKM might exhibit higher low-temperature disintegration in the presence of higher hydrogen content in the reduction gas. Therefore, it can be hypothesised that the low-temperature disintegration of the burden influences the monitored gas flow behaviour. Other parameters, e.g., such as pulverised coal rate, also known to influence permeability have not shown strong differences amongst the clusters.

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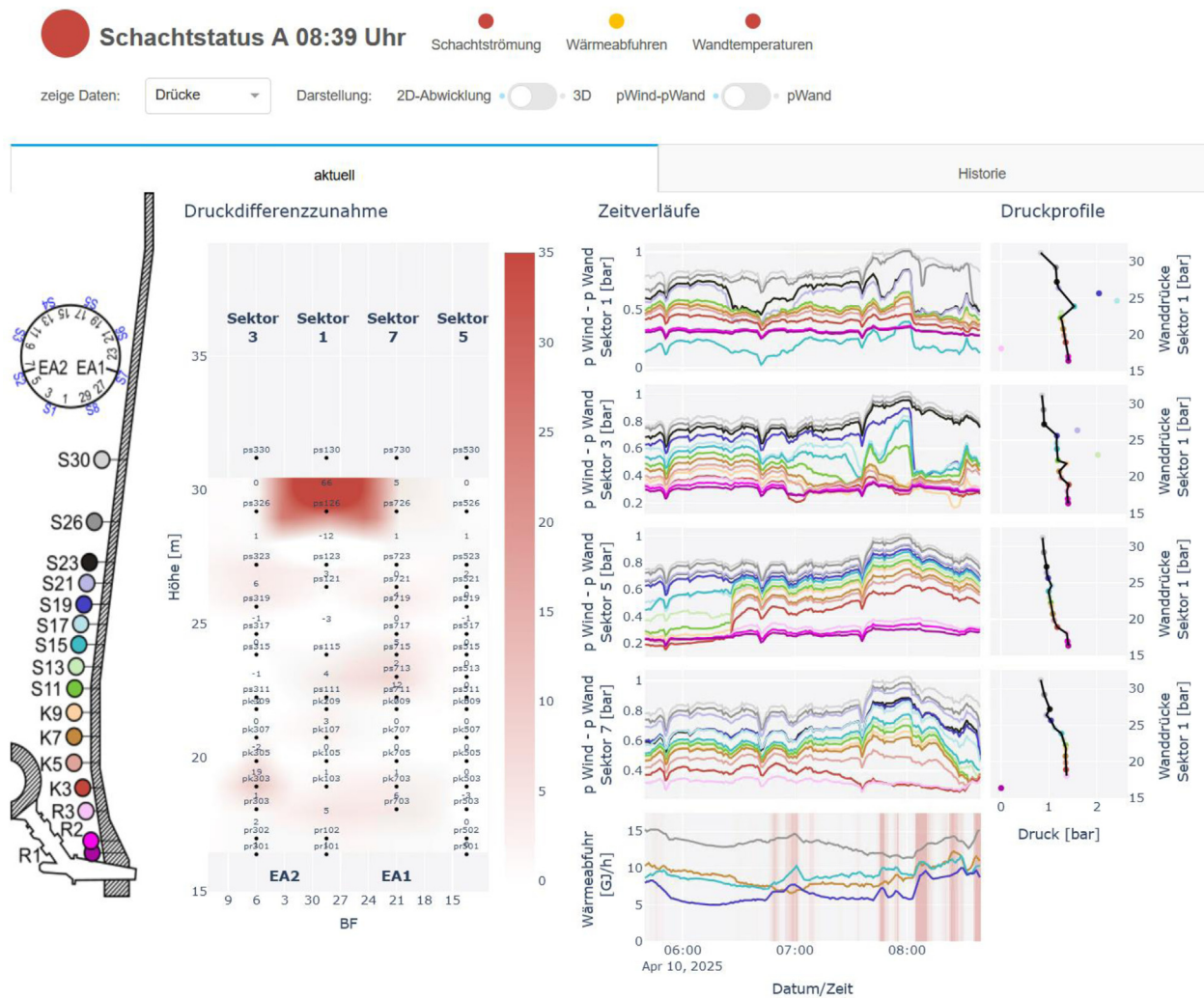


Fig. 8. Screenshot of a dashboard solution for constant BF flow state monitoring.

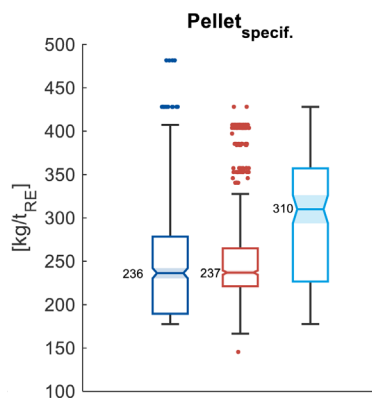


Fig. 9. Data distribution of pellet charge during the three different clusters (general explanation of box plots – see text above Fig. 5).

Additionally, the distributions of BF parameter data were compared for periods with different flow disturbance indicator values distinguishing periods with/without flow disturbance with disturbance indicator higher or lower than 17.5 mbar/min. Figure 10 shows a series of half-violin plots. The data distribution with no disturbance / disturbance are noted at the y-axis, the x-axis shows in both directions the probability value of the distribution function. This enables direct comparison of the shapes of the two data distributions. The median values of the distributions are marked by a solid line in the same colour as the distribution, the interquartile range is marked by dashed lines. Outliers are marked by crosses.

Figure 10 shows the data distributions of several BF parameters (from left to right): blast volume, raceway adiabatic flame temperature, hot metal temperature, and

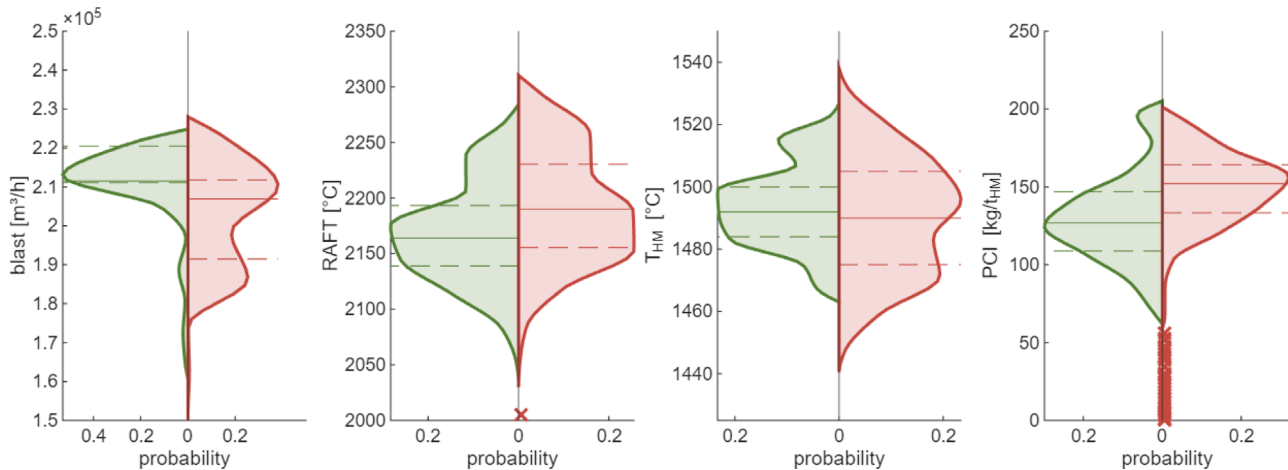


Fig. 10. Value distribution of (left to right) blast volume, Raceway adiabatic flame temperature, hot metal temperature and pulverised coal injection during no indication of flow disturbances (green distribution plot left) and indication of flow disturbance (right, red distribution plot).

pulverised coal injection. Data during ‘no indication of flow disturbances’ is represented by the green distribution plot to the left of the zero probability value, and data during ‘indication of flow disturbance’ is represented by the red distribution plot to the right.

For the blast volume it can be stated, that in general a higher blast volume of approx. $2.1 \times 10^5 \text{ m}^3/\text{h}$ was applied in median during normal operation within the 3 investigated months of data. During flow disturbances also lower values frequently occurred. This is to be expected, as withdrawal of hot blast is a common and desired action by operators during flow disturbances. Same time the raceway adiabatic flame temperature (RAFT) shows a wider spread value distribution and a higher median value during flow problems. The hot metal temperature also shows a wider distribution spread, with a higher probability of the temperature being far from the target temperature. Finally, the injection rate of pulverised coal (PCI) is systematically significantly higher during flow instabilities. PCI is usually used in BF operation to control the hot metal temperature. The deviation in the distribution of these parameters suggests that a higher proportion of flow disturbances occurred when the hot metal temperature fluctuated more than expected, prompting operators to introduce countermeasures to increase the heat in the process. A stronger change in the heat supply could also affect the stability of the melting zone location, which is known to be a bottleneck for gas flow in the BF process.

5 Conclusion

Following the analysis of the relation between the data from wall pressure measurements at an industrial scale BF and other BF operational parameters, it can be concluded that indicators derived from the pressure measurement data, such as the shape of the vertical pressure profile or a significant short-term increase in pressure difference between two sensors positioned above each other in a vertical wall measurement line, can detect flow

disturbances associated with lower BF efficiency, as indicated by gas utilisation:

- A significantly lower gas utilisation was found during the occurrence of a vertical pressure profile shape indicating permeability problems above the cohesive zone.
- A significantly lower gas utilisation was found when the pressure difference between sensors above each other increased by more than 17.5 mbar/min.
- Further data analysis enabled the formulation of hypotheses that at least partly explain the causes for the identified flow disturbances.

Based on these findings, an automated dashboard system was developed to support BF operators in supervising wall pressure readings. The system has been in test operation under the monitoring of HKM BF engineers for approximately six months and has reliably detected flow disturbances since then, sometimes even before one of the KPIs traditionally used at HKM has indicated a problem. Currently, the system’s parameters, such as the threshold values for recognising flow disturbances and for filtering data are being optimised to ensure that warnings are only issued when operator intervention is required to avoid overwhelming operators.

The system’s acceptance and usefulness are increased by basing it on comprehensible physical effects and easy-to-verify indicators. A key factor in the system’s reliability thus far is the automated and well-founded filtering of the 64 data series received from the wall pressure measurements.

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Conflicts of interest

The authors have nothing to disclose.

Data availability statement

Data associated with this article cannot be disclosed due to cartel law restrictions and business secrets.

Author contribution statement

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