The Trial of the Top Gas Recycling Blast Furnace at LKAB's EBF and Scale-up

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The history of the LKAB's Experimental Blast Furnace is briefly reviewed and an introduction to the ULCOS new blast furnace is presented. The feasibility of the scale-up of the ULCOS New Blast Furnace- UNBF based on previous and new trials results at EBF are concisely discussed.

The historical trial results of using the EBF to simulate the conventional industrial blast furnace processes indicated that the EBF is able to imitate the commercial blast furnaces of different size and burden structure. The trial results can be directly extrapolated to the commercial furnaces. The discussions regarding the scale-up of the UNBF showed that based on the EBF as well as the trials of the UNBF concept it is completely feasible to determine the dimensions of a full scale furnace and the process parameters for an industrial scale trial of the UNBF concept.

Introduction

The Top Gas Recycling Blast Furnace (TGRBF) is one of the research sub-projects in the ULCOS programme[1]. The concept relies on the removal of the CO2 contained in the top gas of the blast furnace so that the useful components – $CO+H_2$ can be recycled back into the furnace and reused as reducing agents. This would reduce the amount of coke needed in the furnace. In addition, injecting oxygen (O_2) into the furnace instead of preheated air, removes unwanted nitrogen (N_2) from the gas, facilitating CO_2 Capture and Storage (CCS).

To experimentally test this concept, facilities were installed to operate with pure oxygen and with re-injection of preheated recycled gas on LKAB's Experimental Blast Furnace (EBF). A gas separation plant – Vacuum Pressure Swing Adsorption (VPSA) was constructed close to the EBF. Improvements on gas heater and transport system were conducted for safely preheating and injecting the CO-rich recycled top gas. The combination of the modified blast furnace and the gas separation plant were successfully tested at the LKAB's EBF in fall 2007[1].

The trial has been regarded as one of the great successes in the ULCOS programme. However, the development of breakthrough technologies into mature industrial applications involves a level of risk and requires at least one additional scale up step. This demonstration stage will take the ULCOS programme into phase II, exploring some of the technologies investigated under ULCOS I as to their potential and feasibility under large scale, industrial production conditions. This paper presents the history of the EBF, trial results of the TGRBF concept using EBF and some discussions regarding the scale-up of the TGRBF based on the results obtained.

LKAB's Experimental Blast Furnace

The Need of an EBF

In the early of 1990s, it was found at LKAB that the one-step product development from laboratory scale tests to industrial trials directly was too risky and too high cost because new pellet product of appropriate laboratory tested metallurgical properties might not behave well in an industrial furnace. The use of a pilot blast furnace for product development could provide great advantages, for instance, an actual blast furnace environment for testing the behavior of the pellets, feasibility of further in-depth studies of the samples taken during the testing and through the dissection after the test, lower cost and minimal risk, etc. However, LKAB had been an iron ore producer for many years and did not own any blast furnace, while the need of a well equipped experimental blast furnace for product development was very obvious[2].

Design and Erection of the EBF

With a commercial blast furnace of a hearth diameter of about 8.5 meters as a reference, the design of the EBF was carried out based on the earlier worldwide experiences, the experimental blast furnaces being built in 1996. The furnace profile was actually a scale-down copy of the reference furnace with a scale ratio of about 1/7, but with a relatively larger hearth volume as a buffer for hot metal. The bell top charger could function exactly like a full scale one to distribute the burden as in a commercial blast furnace. The 3 tuyeres might be too less in comparison with total tuyere numbers of the reference, but the experiences of running the experimental blast furnace showed that 3 tuyeres could work well for bosh gas distribution and reduction work in the lower region of the furnace.

LKAB's Experimental Blast Furnace

EBF as shown in **Figure 1** was built in 1996 for the purposes of customer orientated product development and the improvement of the blast furnace ironmaking technology. It was intended to have 5 campaigns for internal product development when designing. Nowadays, it is still in use for new trials after 22 campaigns due to its great contributions to the developments of pellet products, burden structure and the new technologies of blast furnace ironmaking.

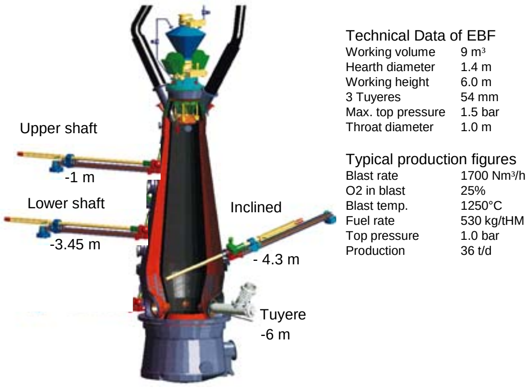

Figure 1. The experimental blast furnace

Although the EBF is not as large as a commercial blast furnace in size, it is fully equipped as a commercial one, or even better. The on-line measurements of the top gas composition of high accuracy as well as the gas temperature measurements in two crossed diametrical directions can provide valuable information about the gas utilization and distribution inside the furnace. The high pressure top up to 1.5 bar (gauge) makes it possible to operate the furnace at high blast volume without deteriorating process performance. The advanced bell-less top charging system in use since the year 2000 gives great flexibility for adjusting the burden distribution. 'Live sampling' during the operation through upper and lower shaft gas and burden probes, as well as the inclined burden probe can provide more detailed 'inside information' for improved analysis of the furnace process. Tuyere optical cameras can help the operator to enhance the thermal state control to some extent.

Fig. 2 shows a schematic layout of the EBF plant. Four ferrous burden bins, four slag former bins and one coke bin give the great flexibility to test different burden structure during a campaign. The charging system with skip car can serve the furnace well up to a production rate of about 1.85 t/h. Advanced flexible injection system can admit multiple injections of pulverized coal together with other pulverized materials, e.g. BOF slag, simultaneously. Oil or reducing gas injection is also possible.

Figure 2. Schematic diagram of the LKAB's Experimental Blast Furnace

For heating up the cold blast two pebble heaters, functioning as hot stoves, are used and are able to heat up the air from room temperature to a temperature of about 1250°C. High oxygen enrichment ratio of up to 40% to blast was tested without any problem during one campaign. Gas cleaning system with sampling function makes it very easy to take flue dust and sludge samples during operation for further analysis when necessary.

Tapping system consists of a drilling machine for opening the tap hole and a mud gun for closing the tap hole. Sampling of hot metal and slag as well as the measurement of the hot metal temperature during tapping are manually conducted. Chemical analyses of hot metal and slag are performed on-site, providing quick thermal information of the furnace to process engineers for controlling.

So far 22 campaigns, including the campaign for testing the ULCOS New Blast Furnace process, have been carried out. The results have demonstrated that the EBF is really a great tool for product development as well as for exploring new technologies of blast furnace ironmaking.

Comparisons of the EBF Trial to Commercial BF Performance

The most important factor to be considered when comparing EBF trial to a commercial BF performance is how to make the comparisons. In general the reductant rate and hot metal quality should be the first parameters to be taken into account. With similar burden structure and blast parameters, if the reductant rate and the hot metal quality of the EBF trial are in line with those of the commercial BF, it can be concluded empirically that the EBF is able to simulate the commercial blast furnace process.

Table 1 [3] shows some comparisons between the EBF trials and the industrial operations. Generally, the reductant rate of the EBF was about 50~70 kg/tHM higher than that of the industrial blast furnace operations. This is due to the higher heat losses and the higher silicon content in the hot metal at the EBF compared to industrial furnaces. Assuming the silicon content in the hot metal and the heat losses of the EBF were at the same level as at the industrial furnaces, the total consumption of the reductant could be revised to roughly the same level.

Table 1. EBF trials vs industrial BF operation

	Case I		Case II		Case III	
	EBF	No3, SSAB	EBF	No 2, Brmen	EBF	No. 6, Duferco
Pellet /Sinter /Lumpy	100 /0 /0	100 /0 /0	46 /54 /0	49 /44 /7	73 /0 /27	80 /0 /20
Injection	PC	PC	Oil	Oil/ plastic	PC	PC
Coke	439	326	474	406	477	391
Inj. rate kg/tHM	100	139	54	48/21	100	118
Fuel rate kg/tHM	539	464	528	475	577	509

When comparing the hot metal quality, besides the hot metal temperature and the silicon content in the hot metal, sulfur content in the slag should also be considered. Although the hot metal temperature of EBF is lower than that of the industrial furnaces, the sulfur content in hot metal is similar in both cases. This might indicate that the thermal state of the EBF is still in appropriate status, the hot metal temperature of the EBF can not represent the thermal state of the furnace in the same way as it does for the industrial furnaces.

Furthermore, considering alkali removal, the slag behavior of EBF is quite similar to commercial furnaces. Therefore, it can be concluded empirically that the trial results from EBF can be used to predict the behaviors of the commercial furnaces, at least for the conventional blast furnace ironmaking process.

The Trials of the Top Gas Recycling Blast Furnace

The Top Gas Recycling Blast Furnace [4]

Four versions of the Top Gas recycling blast furnace concepts were put forward. The common features of the different TGRBF processes are the use of the oxygen instead of pre-heated air, the CO_2 removal and the re-injection of the recycled CO-rich top gas into the BF. The main differences between different versions are the recycled gas temperature for injection and injecting position on BF. The recycled top gas can be injected into conventional tuyere only, e.g. version 3, or shaft/stack tuyere only or both, e.g. version 4. Recycled gas temperature can vary too, from room temperature to a temperature of about 1250°C. **Figure 3** shows the flow-sheet of the version 3 and 4 of the proposed TGRBF process[4], which were tested at LKAB's EBF in 2007.

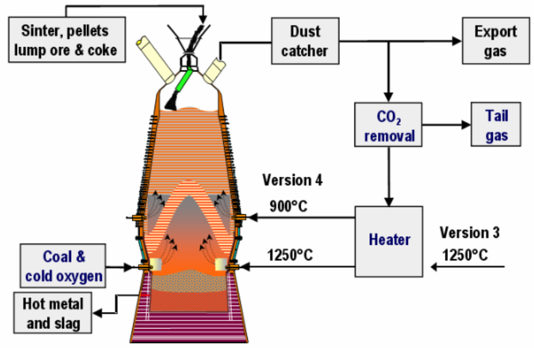

Figure 3. Process flow of the two versions of the TGRBF

Improvement of the EBF

To guarantee the safety of heating and transporting the recycled CO-rich reducing gas as well as a smooth running of the trial, a series of improvements on the EBF and its auxiliary facilities were accomplished before the trials [5].

- New hearth tuyeres for TGRBF process were designed and manufactured
- Shaft gas injection system with 3 shaft tuyeres and gas distributors was developed and mounted on the EBF for testing version 4 of TGRBF concept
- Pulverized coal injection system was adapted for using much higher amount of coal
- Measures for enhancing the process safety and reliability were taken
- VPSA plant for removing CO_2 of the top gas was constructed by Air Liquide and tested through some campaigns before the TGRBF campaign

After the modifications and the reconstructions of the EBF, the pilot plant is able to simulate both conventional and ULCOS blast furnace process. **Figure 4** shows the schematic view of the TGRBF process with CO_2 removal unit – VPSA plant [6].

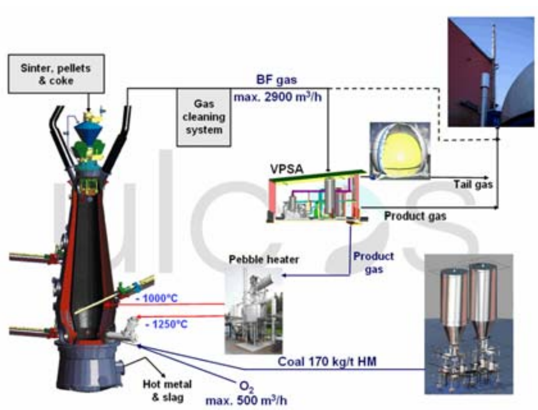

Figure 4. ULCOS blast furnace at LKAB's EBF plant

Trial Results of the TGRBF [4][6]

Seven weeks trials were successfully carried out at the EBF in the fall 2007. After the start-up phase in conventional BF process the operations were gradually shifted to the top gas recycling mode. Version 3 of the new concept was tested, and then version 4 with different coal injection levels was studied to try to optimize the process parameters.

In comparison with the conventional blast furnace process a carbon saving ratio of about 24% could be achieved, corresponding to a reduction of the CO_2 emission of up to 76% when assuming the underground storage of the corresponding captured CO2.

In terms of top gas recycling, the operation of the VPSA – the CO_2 removal unit was smooth and reliable. The top gas recycling ratio could be up to 90% with CO recovery of about 88%. No safety issue has been recorded during the 7-week operation of the new blast furnace processes.

Scale-up of the ULCOS New Blast Furnace

Scientifically scale-up of the TGRBF process to a full scale industrial plant based on the EBF trial results is quite complex and difficult. A rational approach called dimensional analysis which has been used in the physical sciences for quite some time is a proven method of developing functional relationships that describe any given process in a dimensionless form to facilitate modeling and scale-up or scale-down. The analysis can be applied even when the equations governing the process are not known. The end result of dimensional analysis is a complete set of dimensionless numbers that describe a physical process, and that outline the conditions under which this process behaves “similarly” in the model and its full-sized counterpart. Dimensional analysis is the basis of scale-up methods.

A complete blast furnace process consists of five sub-processes as the blast system including the hot stove, the charging system, the injection system, gas cleaning and the blast furnace itself. For the new ULCOS blast furnace, VPSA is a new component. The gas cleaning, the charging system and the injection system are rather the same as they are in the conventional process. The needs for scale-up are the blast furnace itself, blast system and the VPSA. In this paper only the scale-up of the blast furnace is discussed.

Fundamentals for Scale-up

Based on the dimensional analysis, an industrial process can be described using a complete set of dimensionless numbers and this dimensionless space in which the measurements are presented or measured will make the process scale invariant. According to the modeling theory, two processes are considered similar if there is a geometrical, kinematic, and dynamic similarity[7]. Geometric similarity means both systems must have the same shape, and linear dimensions in model must be related to the corresponding dimensions in the full scale facility by a constant factor. For a blast furnace, this means that the ratio of the diameter to height should be the same for the EBF and a full scale furnace, i.e.

$$\left(\frac{D}{H}\right)_M = \left(\frac{D}{H}\right)_F \qquad (1)$$

where M stands for model for experiment and F represents the full scale

Kinematic similarity requires similar flow patterns in both vessels; and the velocities at the corresponding points must have a constant ratio. Dynamic similarity is that all corresponding forces at corresponding points in two geometrically similar systems have a constant ratio.

However, for an actual complex industrial process like the blast furnace ironmaking, to achieve a complete similarity between the pilot model and a full scale process is very difficult and probably unrealistic. In practice, the approach for scale-up is based on partial similarity, empirical knowledge and more experiments.

Scale-up of the UNBF based on the EBF Trial

The works of the scale-up of a blast furnace are to determine the geometric profile of the full-scale furnace, the total number and the dimension of tuyeres, and maybe the position of the shaft tuyere as well as the corresponding process parameters for operation, mainly oxygen and recycled gas flow into both hearth and shaft tuyeres. Determination of the geometric profile of the furnace can follow the principle of ‘partial geometric similarity’ and easy to accomplish, while the determination of the process parameters needs to follow both the ‘kinematic and dynamic similarity’.

Geometric Profile of the Full Scale Blast Furnace

According to the principle of the Geometric Similarity, the geometric profile of a full scale blast furnace for the UNBF concept should be an enlarged copy of the EBF, and the burden size also should be proportional to that of the EBF. However, the burden used in the EBF had the same size (pellet) or slightly less in the characteristic diameter (sinter and slag formers), which is against the rule of geometric similarity. As well known from the operation experiences and the trial results of the EBF, as long as the geometric profile of a pilot furnace is similar to that of a full scale one, the furnace still can simulate the blast furnace process of full scale. Therefore, this violation will not affect the scale-up of the furnace profile. The diameters and the heights of the full scale furnace can be determined based on the ratio as shown in equation (1).

Determination of Recycled Gas Flows

Both theoretical studies and the blast furnace practices have demonstrated that the gas flow in the lower region or the so-called bosh gas volume, which is mainly dependent on the oxygen and the recycled gas flows, is one of the key factors for a successful operation of the blast furnace process. When scaling-up from the EBF to a full scale industrial furnace, the oxygen and recycled gas flows can be decided based on the bosh gas volume obtained during the EBF trials.

Considering the shaft region of the furnace as a chemical reactor with counter-current gas-solid flows, as the burden descent rate is much lower than the gas flow, this region may be regarded as one packed bed reactor with gas flow of high speed. The EBF trials and the industrial operation also indicate that the shaft efficiency of a blast furnace is not very much furnace-size dependent, which may imply that the reduction rate of the iron oxides in the shaft region are rather fast and is not affected by the gas flow and furnace size. The retention time of the gas in the region is not important either for the scale-up. As a result the reduction rate may be seen as a trivial factor for the scale-up of the furnace and can be ignored.

Therefore, for this 'chemical reactor' above with gas flow, to achieve the good result of the scale-up, besides the geometric similarity discussed in section above, the equal Reynolds numbers and the Euler numbers are also required [7][8], i.e.

$$\mathrm{Re}_M = \mathrm{Re}_F \quad \text{and} \quad \mathrm{Eu}_M = \mathrm{Eu}_F \qquad (2)$$

For packed bed, Reynolds number is defined as

$$\mathrm{Re} = \frac{\rho V D}{\mu(1-\varepsilon)}$$

Eulers number is defined as $Eu = \frac{\Delta P}{\rho V^2}$

where: ρ is he density of the fluid (kg/m³); V is the mean fluid velocity (m/s); D is the diameter (m), μ is the dynamic viscosity of the fluid; ΔP is the pressure drop, ε is the voidage of the bed.

Based on the process parameters obtained from the EBF trials, the gas velocity can be found out for EBF and used to extrapolate to a full scale blast furnace. Accordingly, the total tuyere number and the tuyere diameter can be calculated on the basis of the geometric similarity as $\left(\frac{nD_t}{D_h}\right)_M = \left(\frac{nD_t}{D_h}\right)_F$, as well as the oxygen and recycled gas flows can be determined too; where Dt and Dh represent the tuyere and hearth diameter respectively, and n is the total hearth or shaft tuyeres number.

Discussions

The scale-up method discussed in the section above is based on some assumptions and 'partial similarity' between the EBF and an industrial furnace. When performing the actual scale-up of the UNBF based on the EBF and trial results to a full scale industrial furnace, more detailed works have to be conducted, and more experiments in both pilot scale and industrial scale might be necessary to optimize the furnace geometric dimensions of the UNBF and the corresponding process parameters.

Actually trials using the EBF to simulate the conventional blast furnace process have already indicated great feasibility of extrapolating the EBF results to the commercial furnaces, although the 'complete similarity' between the EBF and the industrial furnaces was not satisfied. Therefore it may be concluded that it is completely feasible to conduct the scale-up of the UNBF process based on the EBF trial results.

Conclusions

Trials of using the EBF to simulate the conventional blast furnace process indicated that the trial results at the EBF can be extrapolated to the industrial furnaces. The differences in terms of reducing agents consumption between the EBF and the industrial furnaces are mainly due to the higher heat losses and silicon content in the hot metal. It is possible to build an industrial blast furnace ironmaking process based on the EBF for the conventional blast furnace.

The concepts of UNBF were put into trials at the EBF and great successes were achieved. The theoretical analysis for scaling UNBF concept based on the EBF trial results and the experiences gained from the EBF trials for conventional blast furnace ironmaking indicate great feasibility of building the full scale ULCOS New Blast Furnace Process.

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[1] Priority 3 of the 6th Framework Programme in the area of "Very low CO_2 Steel Processes", in co-ordination with the 2003 and 2004 calls of the Research Fund for Coal and Steel

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