Trials of ULCOS-NBF at LKAB’s Experimental Blast Furnace

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Abstract

To decrease the energy consumption and the CO₂ emission in the blast furnace ironmaking process nitrogen free blast furnace processes (ULCOS-NBF), also called top gas recycling blast furnace - TGRBF were put forward in the European Ultra Low CO₂ Steelmaking (ULCOS) project. Trials of different ULCOS-NBF concepts in pilot scale at LKAB’s Experimental Blast Furnace were carried out in 2007, 2009 and 2010. Trial results indicated that a carbon saving of about 24% or higher could be reached with the ULCOS-NBF blast furnace process, and in the mean time a CO₂ mitigation of about 65% could be achieved with the combined implementation of CO₂ capture and storage.

The trials also demonstrated the feasibility of the ULCOS-NBF concepts. CO₂ capture process - VPSA of Air Liquide could work very smoothly to separate the CO₂ from the top gas; and Pebble Heater could function well for heating up the recycled top gas of high CO and H₂ contents to a temperature of about 1250°C without any safety problem. The ULCOS-NBF processes with the recycled top gas injections into both hearth and shaft tuyeres or to hearth tuyeres only were completely controllable.

Key words: ULCOS, TGRBF, LKAB EBF, blast furnace, top gas recycling, ironmaking, ULCOS-NBF

1. Introduction

ULCOS stands for Ultra–Low Carbon dioxide (CO₂) Steelmaking. It is a consortium of 48 European companies and organisations from 15 European countries that have launched a cooperative research & development initiative to enable drastic reduction in CO₂ emissions from steel production. The consortium, led by a core group including LKAB, consists of all major EU steel companies, of energy and engineering partners, research institutes and universities and is financially supported by the European Commission and core companies of the project. The target of the ULCOS programme is to reduce the CO₂ emissions of today’s best steel production routes by at least 50%[1].

Top Gas Recycled Blast Furnace (TGRBF) is one of the research sub-projects in the ULCOS programme. The concept relies on separation of the top gas of the blast furnace so that the useful components – CO+H₂ 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 (O₂) into the furnace instead of preheated air, removes nitrogen (N₂) from the gas, facilitating CO₂ 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 was

¹ Actually, many researchers and engineers from the project partners who joined the design, carrying out and evaluation of the trials at LKAB’s EBF, e.g. Dominique Sert of AcerMittal, Gerard Danloy of CRM, Jan van de Stel of Corus, Longshan Lin of Dillingen, Nicklas Eklund and Mikael Pettersson of LKAB and Alexandra Hirsch and Bernd Korthas of TKS etc. did indeed contribute much more to the project work than the author of this paper. The list of authors if listed will be too long in the paper. The author should be regarded as the contact person of this paper.
successfully tested through 3 dedicated campaigns in 2007, 2009 and 2010 respectively. This paper presents some of the trial results.

2. LKAB’s Experimental Blast Furnace

LKAB’s EBF as shown in Figure 1 was built in 1996 for the purposes of iron ore pellet development and was intended to have 5 internal campaigns for product development when designed\[^2\]. Nowadays, it is still in use for new trials after 25 campaigns thanks to its great contributions to the product development, optimization of burden structure and the new technologies of blast furnace ironmaking.

Although with a working volume of about 9 m\(^3\) the EBF is fully equipped as a commercial blast furnace, or even better. The on-line measurements of the top gas composition and the gas temperature can provide valuable information about the gas utilization and gas distributions inside the furnace. The high top pressure up to 2.5 bar makes it possible to operate the furnace at high blast volume without disturbing the process performance. The advanced top charger 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.

Figure 2 presents a schematic layout of the EBF plant. Four ferrous material bins, four slag former bins and one coke bin make it possible 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. The flexible injection system can admit multiple injections of pulverized coal together with other solid pulverized materials, e.g. BOF slag and blast furnace flue dust, simultaneously. Oil or reducing gas injection is also possible.

![Figure 1: The experimental blast furnace](image-url)
For heating up the cold blast two pebble heaters functioning as hot stove 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 [3]. The gas cleaning system with sampling function makes it very easy to take live flue dust and sludge samples for further analysis when necessary.

The 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 25 campaigns, including the three campaigns for testing the ULCOS TGRBF processes, have been carried out. The results have demonstrated that the EBF is indeed a great tool for not only product development and optimization of the operational process parameters but also for exploring new technologies of blast furnace ironmaking.

3. **The Trials of the Top Gas Recycled Blast Furnace**

To study the TGRBF process, a research group was formulated with engineers and researchers from:

- All the core companies of the ULCOS consortium – ArcelorMittal, Corus, ILVA, LKAB, Saarstahl-Dillinger Hütte, ThyssenKrupp and Voestalpine Stahl
- Two steel producers – Ruukki and SSAB
- Industrial partners – Air Liquide, Küttner, Paul Wurth, and VAI
- Research institutes – BFI, CRM, MEFOS and SGA
- One university – RWTH Aachen

In-depth theoretical studies of different blast furnace processes with top gas recycling were carried out based on mathematical modelling to select the appropriate process concept for pilot trials. Four versions of the TGRBF were proposed for further studies.

Laboratory tests regarding the reduction and melting behaviours of the ferrous burden as well as burden structure under the TGRBF process conditions were conducted to obtain the suitable burden structure for the ULCOS blast furnace. Feasibility and safety studies of preheating the CO-rich recycled gas were performed to ensure the safety for gas recycling. Coal gasification trials with pure oxygen were accomplished in both laboratory and pilot scale to provide information for designing tuyere.

To verify the feasibility of the proposed TGRBF concepts, it was decided to carry out the pilot scale trials at the LKAB’s EBF. Version 1, 3 and 4 of the proposed TGRBF were put into trials through three separate EBF campaigns of 7-week for each.

### 3.1. The Top Gas Recycled Blast Furnace

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 BF. The main differences between different versions are the recycled gas temperature for injection and injecting position on BF. The preheated recycled top gas can be injected through conventional tuyeres only, e.g. version 3; or through both shaft and hearth tuyeres e.g. version 4; or correspondingly with the same recycled gas flow as version 4 but recycled gas of room temperature is injected into hearth tuyeres, e.g. version 1. The temperature of the preheated recycled gas as well as the recycled gas flows to shaft and hearth tuyeres could vary too, which would be determined and optimized through the EBF trials achieving the maximal carbon saving. Figure 3 shows the flow-sheet of the version 1, 3 and 4 of the proposed TGRBF process\(^4\).

![Figure 3: Process flow of the three versions of the TGRBF](image-url)
3.2. **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 trials, a series of improvements on the EBF and its auxiliary facilities were accomplished before trials.

- New hearth tuyeres for TGRBF, especially the hearth tuyeres for trial of version 1, were designed and manufactured.
- Shaft gas injection system - Figure 4 consists of 3 shaft tuyeres and gas distributors were developed and mounted on the EBF for testing version1 and 4\(^5\).
- Pulverized coal injection system was adapted for using much higher amount of oxygen.
- Gas transport system was reconstructed for being able to simultaneously inject recycled.

![Figure 4: Gas injection system of TGRBF](image)

![Figure 5: ULCOS blast furnace at LKAB's EBF plant.](image)
gas of room temperature to hearth tuyeres, and pre-heated one to shaft tuyeres

- Measures for enhancing the process safety and reliability were taken
- VPSA plant for removing CO₂ of the top gas was constructed by Air Liquide and tested through some campaigns before the TGRBF campaigns

After the modifications and the reconstructions of the EBF, the pilot plant is able to simulate both conventional and ULCOS blast furnace processes. Figure 5 shows the schematic view of the TGRBF process with CO₂ removal unit – VPSA plant[6].

3.3. The Trials

Three campaigns for testing TGRBF concepts at LKAB’s EBF were carried out in the autumns of 2007, 2009 and 2010 respectively. The first campaign was dedicated to version 3 and 4, while the second one was assigned to version 1 and 3. Based on the evaluations of the first two campaigns the third campaign was once again given to version 4 for testing different temperatures and flows of the recycled gas. The main objective of the third campaign was to try to find out the suitable or even optimal operational process parameters, e.g. suitable ratio of recycled gas flows between the shaft and hearth, the temperature of the recycled gas to shaft tuyeres, etc.

The ferrous materials for all three campaigns consisted of 30% LKAB’s acid pellet - KPBA and 70% sinter of Ruukki but with one exception during the first campaign for 5-day 100% LKAB olivine pellet operation, which was financially supported by LKAB. Coke, pulverized coal and slag formers were provided by SSAB, Luleå Works.

To facilitate the evaluation of the trial results a relative constant production rate of about 1.5 t/h was targeted throughout all the campaigns. Three levels of PCI rates of about 130, 150 and 170 kg/tHM were tested to optimize the coal injection in the proposed TGRBF processes. When testing the version 1 and 4, efforts also were paid to the optimal use of the recycled gas in both hearth and shaft tuyeres. Table 1 presents a brief view of the trial progress during the first campaign.

During the trials gas temperature and composition profiles across diametrical direction of two levels were measured using two shaft probes everyday. Burden samples in connection with the gas profiles above were taken too.

Before the blow-down of the first and the third campaign baskets containing different sinter and pellet samples of project partners were charged into the furnace for studying the behaviours of ferrous materials under the TGRBF conditions. During the shut-down the EBF was quenched by blowing nitrogen from the top through burden column to the hearth tuyeres. After the quenching the EBF was dissected independently by LKAB and samples were taken according to a predetermined plan during the excavation for further study. Internal state of the burden column, shape and position of the cohesive zone as well as the raceway status were observed and recorded.

<table>
<thead>
<tr>
<th>Trial period</th>
<th>day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional start-up</td>
<td>7</td>
</tr>
<tr>
<td>Version 3</td>
<td>14</td>
</tr>
<tr>
<td>Version 4</td>
<td>12</td>
</tr>
<tr>
<td>Optimising the coal rate, version 4</td>
<td>4</td>
</tr>
<tr>
<td>100% LKAB pellet, version 4</td>
<td>5</td>
</tr>
<tr>
<td>Higher coal rate, version 4</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 1: Timeline of the EBF trial.
4. The Trial Results

4.1. Blast Furnace Process

In general, the blast furnace operation with all three versions of TGRBF was very stable and easy to control. Various adaptations in operation conditions through the campaigns were carried out for achieving the objectives of the different trial sub-periods. Responses of the process state to the adjustments in operation conditions were sensitive and quick.

Burden descent for all three versions was quite stable and smooth. Permeability of the burden column did not deteriorate seriously with the decrease in coke rate. A good hot metal quality and suitable thermal stability of the process were achieved, especially for version 1 despite a low [%Si] down to about 0.25% compared to a normal level of about 1.5%. Shifting of the recycled gas between the shaft and hearth tuyeres was easy to accomplish. Measurements given by both two shaft probes and the above burden probes indicated that the gas distributions through the trial phases were reasonable and the gas efficiency in shaft region as well as in the top was stable and satisfactory.

The operation with 100% LKAB’s olivine pellet also was stable as that of the other sub-periods even with slightly higher top gas utilisation.

4.2. Top Gas Recycling

VPSA plant could process up to 97% of the BF off gas and generate quality reducing gas with a CO₂ slip of lower than 3%. The CO recovery could be up to a level of 88% [7]. No equipment failure for separating the CO₂ from the top gas occurred.

The recycling ratio of the recycled gas in the TGRBF process could be up to 90% during the trial. The pebble heaters worked smoothly for heating up the CO₂-rich recycled reducing gas. Gas injection system for transporting and injecting the high temperature reducing gas was very reliable. No safety issue in terms of heating-up, transporting and injecting recycled top gas during the 3 campaigns was recorded.

4.3. Carbon Saving

It was found that the carbon saving, in comparison with the reference period (start-up), was affected significantly by the injection of the recycled reducing gas. When injecting the recycled reducing gas into the hearth tuyeres only – version 3 of TGRBF, with a coal injection rate of about 130 kg/tHM a carbon saving ratio of about 15% during the first campaign was achieved, while up to 23% was realized during the second campaign. When injecting preheated recycled gas into both shaft and hearth tuyeres – version 4, with a coal rate of about 170 kg/tHM carbon saving ratios of about 24% during the first campaign and of about 27% or even higher during the third campaign were obtained respectively. The difference in carbon saving ratio of version 4 above could mainly result from the differences in the temperatures and CO content of the recycled gas injected. With version 1 and a PCI rate of about 170 kg/tHM a carbon saving ratio of about 23% was reached during the second campaign. When using 100% LKAB’s pellet as ferrous burden and with a coal injection rate of about 155 kg/tHM, also 24% carbon saving was achieved with the version 4.

Based on the data obtained through three campaigns it could be preliminarily concluded that a volume of 100 Nm³/tHM recycled gas injection could result in a decrease in fuel rate of about 10 kg/tHM, which was in good agreement with modelling calculations [7].

4.4. Reduction in CO₂ Emission

The trial carried out at the LKAB’s EBF did not cover the CO₂ storage. Therefore the decrease in CO₂ emission during the trial by using the TGRBF technology was only direct from the decreased consumption of reducing agents. Careful evaluation of the campaign data indicated that about 27%
reduction in CO2 emission could be achieved by applying the top gas recycling technology to the BF ironmaking.

When taking the CO2 storage into consideration the CO2 captured by the VPSA plant could be further treated and stored. Assuming the VPSA plant processes top gas needed for the TGRBF operation the total reduction of more than 1270 kg/tHM in CO2 emission could be reachable in the case of version 4 in comparison with the reference period[7], which is accounted for 76% CO2 generated. Considering an integrated steel plant of BF-BOF processes and with the hot rolled coil as the final product, the potential of reducing the CO2 emission could be up to about 65% by the use of the TGRBF process and CCS technology.

Comprehensive evaluation of the third ULCOS TGRBF campaign has been undergoing, and even better results could be achieved according to the preliminary results.

5. Conclusions

Trials of the ULCOS TGRBF processes were successfully carried out. The test results clearly demonstrated the technical feasibility of the ULCOS new blast furnace concept for hot metal production. It has been possible to operate the EBF with pure oxygen and pre-heated recycled top gas instead of the pre-heated air. The blast furnace operation was smooth and the process state was stable. The VPSA plant for removing the CO2 in the top gas worked efficiently and reliably and provided high quality reducing gas. No safety issue was found in heating and injecting the CO-rich recycled gas.

A carbon saving ratio of more than 27%, in comparison with the reference period of the trial, could be obtained by using the TGRBF at EBF plant. A total reduction in the CO2 emission by about 76% would be reached in the blast furnace ironmaking process through the adoption of TGRBF with CCS in the near future.

Considering an integrated steel plant with hot rolled coil as the final product, a net cut in the CO2 emission by about 65% could be accomplished by the combined use of the TGRBF with CCS.

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References