Blast Furnace Ironmaking – A View on Future Developments

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Abstract

Within many industries there is a constant drive to reduce environmental impact and energy costs thereby ensuring maximum energy re-use. Within the iron and steel industry the ironmaking processes are acknowledged to be the focus area when the topic of energy saving arises. A lot of attention has been applied to the ironmaking processes with regards to environment and energy saving, with established technologies being in place to reach these goals such that the process per se, is now at or very close to theoretical limits. The following areas of the blast furnace process are currently the focus of Primetals activity with regards the target to further improve energy saving with incremental improvements:

- Flue gas recycling within blast furnace stoves
- MERIM dry gas cleaning process
- Dry slag granulation including heat recovery

This paper will present the concepts and latest status of the above technologies. The paper will review the progress to date of these development activities and thus present ideas on options for energy saving and re-use within the ironmaking system.

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1. Introduction

Within industry, there is a constant drive to reduce energy costs, reduce emissions and ensure maximum waste energy re-use. In the current economic climate of the world, optimum operation of any blast furnace installation requires the most efficient use in all applicable areas. To this end, Primetals maintains a high level of interest and support to any development opportunities that may provide assistance to our customers to reduce operating costs.

Within this paper, three technology improvements that can be added to the blast furnace process are reviewed. These improvements are at various stages of development up to and including full commercialisation. All of the technologies are supported within the Primetals organisation since they are seen as future opportunities for maintaining the strength of the company as part of a desire to be a full liner provider to the complete iron and steelmaking process.

Climate policy is an important driver for technology development within the sector however the EC’s memo ‘Ensuring a future for Steel in Europe’ acknowledges that ‘plants using best technologies are already operating close to their thermodynamic limits’ [1]. This is particularly true of the ironmaking blast furnace which the World Steel Association confirms as the predominant energy consuming process in the production of steel. These facts mean that the application of enhancements of current Best Available Technologies to individual unit operations within the process chain can only modestly reduce the carbon intensity of integrated steelmaking. Significant reductions will require the development of ‘breakthrough’ technologies facilitating carbon capture utilisation or sequestration (CCUS) of the process emissions. The ULCOS project aims to demonstrate radical new ironmaking processes, that render CCUS economically and practically viable by generating a CO₂ rich effluent stream, but they all involve radical changes to, or abandonment of, the highly efficient blast furnace process [2]. They are also high technical-risk options and even if shown to be competitive with the blast furnace they would require potentially prohibitive levels of capital investment. Alternative solutions, compatible with existing plant infrastructures and proven operating practices, should accelerate adoption of CCUS and help the industry meet its climate change obligations.

To put into context the statements above we can note that published data [3,4] show that the steel industry is responsible for 8% of the World’s anthropogenic CO₂ emissions, with a modern integrated steel plant producing about 1.8 tons of CO₂ per ton of steel [5]. The emissions are mostly associated with ironmaking, which requires carbon as a fuel and reducing agent to convert iron oxide to the metallic state. This observation belies the fact that blast furnace ironmaking is a highly developed process operating close to thermodynamic limits of efficiency as previously noted. There are no obvious enhancements that will fundamentally reduce its carbon demand or significantly improve its thermal efficiency, but, since the blast furnace is the predominant emission generator, efforts to mitigate the environmental impact of the industry have, of necessity, focused on developing revolutionary new ironmaking processes [2]. The alternative approach to these revolutionary types of changes is to propose incremental improvements that offer steps to reduce emissions or to generate more from the potential that exists within the current process.

2. Flue Gas Recycling within Blast Furnace Stoves

Primetals with Linde are developing a novel technology for the stoves plant titled Flue Gas Recycling (FGR). This will involve conversion of the stoves, from air-fuel to oxy-fuel combustion increasing the CO₂ content of the flue gas. The flame temperature generated will be moderated by waste gas recirculation to the stove burners.

Fig. 1. Development of a near transparent flame during the transition from conventional oxy-fuel combustion to ‘flameless’ combustion.
The concept entails direct recovery of waste heat from the stove waste gas, improving stove efficiency and saving enrichment fuel. Also, the increased CO₂ concentration in the flue gas arising from oxy-fuel combustion in the stoves offers the potential of reduced cost and space requirements for the later introduction of a CO₂ capture plant. The development is built on the successful implementation of so-called “Flameless” oxy-fuel combustion.

“Flameless” oxy-fuel combustion is an established technology in operations such as ladle pre-heating and reheat furnaces. Fuel savings of as much as 50%, and associated reductions in CO₂ emissions, are proven benefits in these applications. “Flameless combustion” is alternatively and perhaps more meaningfully known as “volume combustion”. This is because combustion products are mixed with the developing flame, diluting the fuel and oxidant and spreading the combustion process over a larger volume than would be associated with a conventional combustion system. When applied to oxy-fuel systems, it has the effect of moderating flame temperatures down, and allows the efficiency benefits of oxy-fuel technology, linked to the elimination of nitrogen ballast, to be retained in applications that could not tolerate the high flame temperatures associated with conventional oxy-fuel flames. Figure 1 shows a flameless oxy-fuel burner in use and the transition from conventional to “flameless” combustion is evident. Combustion becomes “flameless”, when sufficient flue gas is mixed with the flame to reduce the flame temperature down to levels comparable with the walls of the combustion chamber, rendering it transparent against the radiation from the furnace walls in the background.

Introducing some of the principles of flameless oxy-fuel combustion to the gassing of blast furnace stoves is novel, and offers potential to reduce operating costs for ironmaking relative to conventional practices. This can be ascribed to efficient waste heat recovery, the replacement of “cold” combustion air with a “hot” oxygen-enriched flue-gas recycle, and enhanced heat transfer within the stove arising from the replacement of non-radiating nitrogen molecules by carbon dioxide. An important consequence of the concept is that CO₂ in the discharge stack gas is concentrated to a level of around 40-50 vol% and the mass flow of CO₂ is doubled. The technology generates conditions suited to reduced cost carbon capture and, if coupled with sequestration or CO₂ conversion technologies, it has the potential to reduce specific CO₂ emissions from the current benchmark of 1.8 tons of CO₂ per ton of steel to circa 1.1 tons per ton of steel. The principle of how blast furnace stoves could be converted from air-fuel to oxy-fuel combustion is illustrated in the schematic of Figure 2.

It can be seen that combustion air is replaced by a hot synthetic oxidant comprising a mixture of flue gas and industrial oxygen. The volume of flue gas recycled is determined by the need to moderate the oxy-fuel flame temperature to practically acceptable levels. The implications for the process heat and mass balance and flame development have been extensively modelled and illustrative results are shown in Table 1.

Fig. 2. Schematic highlighting the differences between conventional air-fuel stove operations and enhanced oxy-fuel operations employing flue gas recycle.
Table 1. Heat and mass balances for a single stove supplying hot blast air to a 2MTPA blast furnace.

<table>
<thead>
<tr>
<th></th>
<th>BFG Nm³/h</th>
<th>COG Nm³/h</th>
<th>AIR Nm³/h</th>
<th>Oxygen Nm³/h</th>
<th>Flue Gas Recycled Nm³/h</th>
<th>Heat of Combustion GJ/h</th>
<th>Flame Temp. °C</th>
<th>Stove Gas Mass Flow kg/min</th>
<th>Stove Gas Volume Nm³/h</th>
<th>Flue Gas % CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR-FUEL</td>
<td>56142</td>
<td>2998</td>
<td>52700</td>
<td>0</td>
<td>0</td>
<td>236</td>
<td>1409</td>
<td>2407</td>
<td>103,386</td>
<td>25.3</td>
</tr>
<tr>
<td>FLUE RECYCLE</td>
<td>66644</td>
<td>0</td>
<td>0</td>
<td>9372</td>
<td>27199</td>
<td>219</td>
<td>1409</td>
<td>2407</td>
<td>94,349</td>
<td>44.7</td>
</tr>
<tr>
<td>(Constant Mass Basis)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FLUE RECYCLE</td>
<td>72,951</td>
<td>0</td>
<td>0</td>
<td>10,254</td>
<td>29,786</td>
<td>240</td>
<td>1409</td>
<td>2635</td>
<td>103286</td>
<td>44.7</td>
</tr>
<tr>
<td>(Constant Vol. Basis)</td>
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<td></td>
<td></td>
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It is apparent from Table 1 that stove FGR operation can be on the basis of constant mass or constant volume flow of the combustion products. Constant mass flow ensures that convective heat transfer is unchanged relative to the conventional air-fuel operations, and the recycle of hot flue gas reduces the combustion energy requirement of the stove by 17GJ/h. Since in most applications, 2 stoves are heated simultaneously the annualised energy saving is almost 300 TJ for a single blast furnace, which is equivalent to the annual energy consumption of about 20,000 three-person households in Central Europe. The constant volume flow option arises due to the increased density of the combustion products when flue gas is recycled.

In this mode, heat recovery can be combined with increased burner gassing rates and this converts to higher hot blast temperatures and a potential for coke savings at the blast furnace.

Considering the potential for carbon capture, the CO₂ content of the flue gas is essentially doubled by comparison to conventional operating practices. In mass terms the flue gas contains 0.8 tons of CO₂/ton of hot metal, more than one third of current specific emission levels for steel making. Generation of the oxygen required to facilitate this will erode the CCUS benefits marginally by virtue of the power consumed to operate an Air Separation Unit. This will reduce the net emission reduction potential by circa 0.05 tons of CO₂ per ton of hot metal or by approximately 6%.

It is worth noting that flue gas recycle eliminates the use of both air and coke oven gas in the combustion process. Production of Sulphur and nitrous oxides will therefore be substantially reduced.

Accordingly specific objectives of the current development project will be:

- Confirmation of a CO₂ content of 40 to 50% in the modified flue gas.
- Verification of waste heat recovery and enhanced thermal efficiency of the stoves.
- Confirmation that the new operating conditions maintain or increase the temperature of the hot blast delivered to the blast furnace and hence avoids negative impacts on the ironmaking process.

At this time, the technology is being discussed in detail with a number of operators with a view to obtain a nomination for a lead customer project.

3. MERIM – Dry Gas Cleaning Process

Primetals has developed its own dry gas cleaning bag filter technology called MERIM which stands for Maximised Emission Reduction & Energy Recovery for Ironmaking. It offers the opportunity to treat top gases coming from ironmaking facilities like blast furnaces as well as direct reduction plants (e.g. COREX®, FINEX®) on a dry basis. It is important to stress that the development of this technology is seen as a cross ironmaking process application and this is clearly a useful business strategy to maximise return on the development investment. It also clearly demonstrates the will and desire for the individual units within the parts of the Primetals organisation to work together for the better benefit of the whole.

The MERIM gas cleaning process comprises two important steps, the coarse cleaning in a cyclone and the fine cleaning in a bag filter system. The highly efficient coarse cleaning takes place in the Primetals cyclone where a minimum of 85% of the dust is removed. This generated dust can be easily reused in the sinter plant.
Fig. 3. Top gas temperature behavior during extraordinary process situations: (left: high temperature case e.g. slips; right: low temperature case e.g. start up).

Fine cleaning will be carried out in the newly developed high pressure bag filter system. Therefore, the fine dust laden gas enters a certain number of pressure resistant filter vessels. Inside this system the dust is collected on high performing filter media which allow a dust concentration in the clean gas of less than 5 mg/Nm³. The removed dust is collected on the bottom of the filter and transported via pneumatic conveying into a storage silo system. This high pressure filter operation is based on the successful development of the use of bag filters in other parts of the iron and steel flowsheet and is a logical step forward.

The cleaned top gas from the filter vessels is collected and directed into a top gas recovery turbine (TRT), where the high energy content of the gas is converted into electricity. It is well accepted that the use of a TRT is well known in the industry but the combination of MERIM and TRT is novel. With the lower pressure drop required for cleaning purposes (pressure drop of bag is less than pressure drop of wet scrubber annular gap unit), then there is more pressure energy available to the TRT. Furthermore, the gas at the TRT is hotter since there is equally less temperature loss in the filter compared to the wet scrubber and as a result again more electrical energy can be realised.

Beside the benefits, restrictions also need to be considered. Handling of the varying top gas temperatures is a major challenge, because filter bags only work properly in a temperature window of 80°C up to 250°C. Primetals developed a top gas conditioning concept which moderates the temperature of top gas being fed to the gas cleaning system to maintain this required window. Figure 3 illustrates typical variation in operating conditions.

This temperature moderation concept comprises a burden burner and an advanced burden spray system.

**Burden burner:**

- Prevent condensation at the filter cloth and avoids clogging
- Corrosion protection of gas ducts and gas cleaning equipment
- Increase blast furnace efficiency and decrease coke consumption
- High velocity units to achieve an optimised temperature distribution in the top gas

The burden burner can be operated either with natural gas or with coke oven gas. Primetals would recommend the use of natural gas for the following reasons:

- Volumetric consumption figures for coke oven gas are twice as much due to the lower calorific value
- Lower investment costs for burner (no compressor needed)
- Lower maintenance effort and easier for operation
- No trace heating and steam for cleaning required
Burden spray:

- Fast temperature control due to fine water droplet distribution
- Prevent gas ducts and gas cleaning equipment against high temperature impact during slips
- Fewer water amount required compared to common burden sprays
- No wetting of the burden due to fast and effective evaporation of the water droplets

This technology is now in operation at Kardemir Number 5 blast furnace in Turkey. Performance is completely in line with expectations and the technology is to be further promoted to other customers.

In a nutshell bag filter systems will find the way into the ironmaking top gas cleaning as state-of-the-art technology. The mentioned significant benefits and the access to high sophisticated bag filter materials support this development. Primetals has picked up this technology to increase its environmental technology portfolio with another dry-based gas cleaning process.

4. Dry Granulation Including Heat Recovery

Each year approximately 400 million tons of blast furnace slag are produced worldwide. The slag, which has a tapping temperature of around 1,500°C, is normally used as a substitute for cement clinker or as an aggregate material in road construction. The current state-of-the-art practice is to granulate molten blast furnace slag in wet-granulation plants using large volumes of water. However, up until now it has not been possible to utilise the remnant heat energy of the molten slag, which amounts to approximately 1.8 GJ of energy per ton of slag.

In an R&D project currently underway by a group of companies led by Primetals and comprising “Voestalpine Stahl GmbH”, FEhS Building Materials Institute and the University of Leoben, a new technology based on dry slag granulation is being investigated to use air to cool molten slag and to recover the remnant heat energy for heating applications or for the generation of electrical energy. At the same time, the slag product should also fulfill the same criteria as wet-granulated slag for use in the cement industry.

The project was officially launched on September 1, 2011. A technical plant was set up at the University of Leoben in Austria where in the summer of 2012 through 2013, a series of dry slag granulation campaigns were carried out using re-melted blast furnace slag. The quality of the granulated slag produced and the elevated off-gas temperatures made during the trials were highly promising and helped determine the process boundaries and provide the basis for a larger site based plant.

The results from the campaigns were used to calibrate calculation models of the granulator (e.g. a 3-D CFD model), as the basis for the upscaling of the technical plant design to an industrial scale pilot plant. The pilot plant is to be erected on the site of our industrial partner to investigate the dry slag granulation process in an industrial scale iron and steelmaking environment.

The wet process for granulation of slag is quite accepting to fluctuations in the quantity and properties of the slag, however, it has the following drawbacks:

- Despite mechanical dewatering in drums, silos or heaps, a residual moisture of about 10 - 12 % moisture remains in the slag sand. For the manufacturing of cement, the product therefore, first has to be re-dried, with high energy expenditure. Assuming 10 % residual moisture, the required drying energy amounts to around 132 kWh/t.
- For granulation with open water circuits, vapour containing Sulphur can be released, and a correspondingly large amount of fresh water (about 1 m³/t) has to be fed into the system. Granulation plants with closed water circuits and condensation systems can prevent the emission of water vapour containing Sulphur.
- When slag is quenched with water, the high energy potential of liquid slag is wasted to heat and evaporate water. For granulation purposes, the circulated water has to be re-cooled in cooling towers or with other cooling methods. Finally the heat is released to the environment at a low temperature level without being used.

Huge amounts of water and of drying energy can be avoided by dry dispersion and quick cooling of the liquid slag. The essential prerequisite for the introduction of an alternative dry technique is that the obtained product needs identical or even better properties compared to the slag sand produced conventionally using wet granulation. This
applies in particular to the glass content (target > 95%), which is a key parameter for the reactivity and hence the quality of the slag sand.

The glass content has a direct impact on the strength of the cements and concretes. However, the required glass content can only be achieved by sudden cooling below the transformation temperature of approximately 900°C. Due to the less efficient cooling mechanism of water-free quenching, the dry process is technically more challenging than conventional water based granulation.

Obviously “dry” granulation requires no subsequent drying of the product. This leads to a CO₂ reduction of roughly 30 kg/t in comparison with wet process. Given global production of approximately 210 million t of slag sand (2007), this is equivalent to a potential CO₂ reduction of over 6.3 million t per year.

Dry slag granulation is based on molten slag atomisation using a variable speed rotating cup or dish (see Figure.4). The slag is delivered onto the centre of the cup from a slag runner via a vertical refractory lined pipe. The rotation of the cup forces the slag outwards to the cup lip where it is atomised (see Figure. 5). Simulation and calculation of the rotating cup gives as a result a suitable cup design with its main design parameters, the diameter of the cup and required rotational speed. The speed of the cup will be varied according to the current slag flow for a consistently product quality (including grain size distribution) and process stability.

The atomised particles, mainly in a grain size of 1 to 6 mm, impact on an inclined water cooled wall, bounce off the wall and fall into a bed of granules. A large part of the heat transfer takes place in this flight phase of the particles. A first particle cooling effect is caused by the convection heat transfer to the cooling air and the radiation heat transfer mainly to the cool surface of the water cooled wall. But also during the impact phase of the particles at the water cooled wall a considerable part of heat loss of the particles takes places by heat conductance.

Small sized particles have already created a solid surface before impacting the water cooled wall and bounce directly off the water cooled wall without deformation. Larger sized particles cannot create a stable solid crust on the particle furnaces during their first flight phase. They deform by impacting the wall to a flat form, but they create again a spherical shape during bouncing off the wall because of the physical properties of blast furnace slag. The correct angle, quality of the impact surface and the cold surface temperature of the water cooled wall prevent sticking effects of the slag particles at the wall.

![Fig. 4. Dry granulation concept.](image-url)
The solidifying granules fall into a bed of granules that is designed to ensure that there is no agglomeration. The bed is kept in motion by the design of the cooling air distributor. Several air distribution lines feed cooling air into the granule bed, creating a high heat exchange rate between the granulate and the cooling air to discharge cold slag granulate from the granulator whilst harvesting the energy by producing hot air.

The discharging system at the bottom is designed for independent discharge at several different sections of the granulator to a conveyor system. This creates the possibility to even the granulate bed surface for a homogenised bed thickness with the discharging system in the granulator. Also cooling air can pass the discharging modules to have a direct bottom up flow of the cooling air in the granulate bed (counter flow principal).

With environmental and energy saving considerations becoming ever more important and even becoming enshrined in legislation, there is clearly a need for a major improvement in slag handling.

Our past experience of the dry granulation process is being further enhanced with heat recovery technology to satisfy this requirement and the topic is now a major R&D project at Primetals Technologies in conjunction with industrial partners.

A site has been chosen to build a new industrial size dry slag granulation pilot plant which will be capable of handling full slag flow from a single taphole in STEP 1. This STEP will assess and improve process performance and evaluate detailed off gas parameter information for a subsequent heat recovery plant installation. It is the intention to upgrade the facility in a STEP 2 development to include slag flow and full heat recovery from multiple tapholes on the furnace. A view at the development of the STEP 1 granulation plant is shown in Figure 6.

The process of atomising slag using a spinning cup has been suitably proven by Primetals (to be clear, the initial development steps were started by Davy and Kvaerner in the 1990s), over the years and it is known the granulate produced by this method at over 95% glassy is suitable for use in the cement industry. The challenge and focus for us now is to produce the same granulate at air temperatures which are high enough to make the process suitable for waste heat recovery.
One of the main goals for the current dry slag granulation technology development was the recovery of the large thermal energy potential of the slag. By cooling the granulator with air the off gas can be used for driving different heat recovery applications. Several systems capable of utilising the energy in hot air delivered from the granulator have been considered. The major challenge is the intermittent availability of molten slag.

For efficient heat recovery systems high temperatures of the off gas are required, so the aim is to produce off gas temperatures at \(~600^\circ C\) at the industrial sized plants (previous research results already show promising temperatures). By tuning the cooling air distribution this could be increased significantly, perhaps to \(650^\circ C\). With the control of the cooling air amount in dependency on current slag flow the off gas temperature can be kept at a constant level for almost every load condition.

Depending on the plant setup the energy can be used directly for preheating or heating purposes in the core process, or for the production of process steam and/or electricity. Generally the most common application for heat recovery is the production of process steam that can be used within the steelworks – feeding of steam in existing steelwork steam grid or replacement of fired steam boilers at steam consumers. The granulator off gas will be guided into waste heat boiler(s) for steam production. Because of the high granulator off gas temperatures superheated steam of a high quality can be produced together with good thermal efficiency of the boiler. The boiler off gas can be partly recirculated to the granulator to create an even higher total process energy efficiency.

In Figure 7 and 8 the process flow diagram of a granulator and heat recovery system for superheated steam production is shown. The process parameters shown in these figures are exemplary for a slag flow of \(1\) t/min which gives an output of approx. \(29\) t/h superheated steam. Converting this amount of produced steam in a steam turbine and generator means an electricity output potential of approximately \(6.5\) MWel (for \(1\) t/min slag flow).

Dry slag granulation with heat recovery stands as one of our very top research and development programs to deliver a customer focused, value added solution.

Fig. 7. Process flow diagram of a dry slag granulation system for steam generation.
5. Conclusion

Within the content of this paper, we have hopefully taken the opportunity to highlight the status of the blast furnace as an advanced process that takes seriously its impact on the world. In addition, we have then explained how Primetals are making development of the necessary technologies to ensure that the safe handling of the environment is of paramount importance in future thinking.

References