**THEMATIC SECTION: SUSTAINABLE IRON AND STEELMAKING**

# Reduced Carbon Consumption and CO$_2$ Emission at the Blast Furnace by Use of Briquettes Containing Torrefied Sawdust

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## Abstract

Lowering the carbon consumption and fossil CO$_2$ emissions is a priority in blast furnace (BF) ironmaking. Renewable biomass is one option that can play an important role in future low-carbon ironmaking particularly in the countries rich in biomass resources. In this study, full-scale trials to investigate the impact of briquettes containing torrefied sawdust on the BF efficiency and process stability have been conducted. Briquettes containing 1.8% of torrefied pelletized sawdust (TPS), 86.2% of steel mill residues, and 12% cement with sufficient mechanical strength have been produced on industrial scale. The bio-briquettes were charged at two different rates: 37% (~39 kg/tHM) and 55% (~64 kg/tHM) bio-briquettes to the SSAB BF No. 4 in Oxelösund. The gas utilization was higher during bio-briquette-charging periods without change in pressure drop up to 55% bio-briquettes, indicating sustained shaft permeability. BF dust generation or properties did not change significantly. Measurements of the top gas composition using mass spectrometry did not indicate release of hydrocarbon from TPS in connection to the charging of bio-briquettes. Evaluation of process data has been carried out using a heat and mass balance model. The evaluation of operational data in the model indicated lowering of thermal reserve zone temperature by 45 °C and reduction in carbon consumption by ~10 kg/tHM when charging 55% bio-briquettes compared to the reference case. The total CO$_2$ emission was reduced by about 33–40 kg/tHM when using 55% bio-briquettes.

**Keywords** Ironmaking · Blast furnace · Bio-briquettes · CO$_2$ emission · Torrefied sawdust

## Abbreviations

| | |
|---|---|
| B2 | $\frac{CaO}{SiO_2}$ |
| BF | Blast furnace |
| EBF | Experimental blast furnace |
| Fe$_{met}$ | Metallic iron |
| Fe$_{tot}$ | Total iron |
| EtaCO | Carbon monoxide efficiency, $EtaCO = \frac{\%CO_2}{\%CO+\%CO_2}$ |
| EtaH$_2$ | Hydrogen efficiency, $EtaH_2 = \frac{\%H_2O}{\%H_2+\%H_2O}$ |
| HM | Hot metal |

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LD          Linz Donawitz
MASMOD      Heat and mass balance model
MS          Mass spectrometry
PCI         Pulverized coal injection
RAFT        Raceway adiabatic flame temperature
TI          Tumbler index
tHM         Ton hot metal
TSD         Torrefied sawdust
TPS         Torrefied pelletized sawdust
TRZT        Thermal reserve zone temperature
VM          Volatile matter

# Introduction

The steel industry contributes, according to World Steel Association, to the global $CO_2$ emissions by 7–9% [1], mainly caused by the use of coal and coke as reductants in the blast furnace (BF). At the same time the BF is, and will in a foreseeable future be, the most energy-efficient method to produce ore-based hot metal (HM). A number of concepts to minimize the emission of $CO_2$ proposed by different R&D teams were comparatively evaluated for their relative impacts on the $CO_2$ emission as well as expected impacts on the operational conditions at the BF using a static heat and mass balance model (MASMOD) [2]. The model calculations were supported by not only experimental experience from trials in the LKAB Experimental BF (EBF) as well as in industrial BFs but also by laboratory findings. All evaluated concepts with specified assumptions, as the ULCOS top gas recycling BF, high injection of $H_2$ combined with Carbon Capture and Storage, use of bio-based reductants, charging of charcoal or carbon composite agglomerates including those involving biomass products were shown to significantly reduce the $CO_2$ emission from the BF. Estimation results from the MASMOD model using operational parameter settings-based on experience showed that the use of bio-coal (pretreated biomass) by injection or top-charging had the largest effect on the fossil $CO_2$ emission when taking the whole process system into account [3].

Lowering of thermal reserve zone temperature (TRZT) in the BF to limited extent, without affecting the kinetics of the reduction reaction, improves the reduction efficiency as the reduction of FeO (wüstite) with CO shifts towards metallic iron ($Fe_{met}$), and therefore the need for direct reduction is decreased [4]. The TRZT is controlled by the sensible heat of incoming gases and materials as well as exothermic and endothermic reactions occurring in this region of the BF. TRZT can be lowered by charging of briquettes produced from in-plant fines as these contain iron oxide and carbon or by using Ferrocoke in which endothermic direct reduction of FeO with carbon will reduce the temperature [5]. Another option is charging of reactive [6–10] or activated coke that reacts readily with $CO_2$ producing CO according to the Boudouard reaction. Coke activated with slurries of magnetite and hydrated lime was charged as nut coke in the ferrous layers during operational trials in the LKAB EBF [6–8]. The tests showed that the TRZT was lowered with approximately 30–40 °C and the carbon consumption was decreased with approximately 6–8 kg/ton of hot metal (tHM) due to improved gas utilization [8]. The integrated steel plant consists of a series of interconnected units (e.g., coke plant, BF, de-sulfurization, LD, ladle furnaces, continuous caster, rolling mill, and shaping units) for iron and steel production. These units are generating different residues including dusts, sludges, mill scales and slags which are rich in iron, carbon, and lime. The traditional and most common way to recycle these residues back to the BF is via the sintering plant. Swedish BFs operate on almost 100% pellets [11], and the recycling of steel mill residues has feasibly been taken over by cement-bonded briquettes [12, 13]. The briquettes need sufficient mechanical strength for handling, transportation, and charging into the BF. Selection of residue blends, pre-treatment, and mixing of steel mill residues before the briquetting of materials are essential steps in order to achieve uniform quality over time [13–15]. Selection of residues is based on availability and their chemical, physical, and mineralogical compositions [16]. Portland cement is commonly used as binder in cold-bonded BF briquettes due to its easy availability, its ability to develop strength at room temperature, and chemical composition with lime contributing to the slag formation. The strength of cold-bonded briquettes depends on the residue blend and the cement content in the mixture. With increasing cement content, the cold compression strength of the briquettes will be increased [15, 17] as long as the acicular structure of ettringite phase is formed during hydration [18]. The ettringite needles grow with time, form a network between cement particles, and thereby contribute to the briquette strength via formation of calcium silicate hydrates (C–S–H). On heating the briquettes, the C–S–H is decomposed at 500–700 °C, and consequently, the briquettes lose their strength and may disintegrate into finer factions [19] unless there is no other phase formed that can contribute to the strength. Therefore, the use of cold-bonded briquettes as burden material in BF is still limited to about 5% of the total charged burden [20]. However, basket samples of briquettes charged into the EBF did not indicate disintegration although the weight loss was higher than could be explained by loss of crystalline water and direct reduction of iron oxide with carbon contained in the briquettes [13]. Further operational tests in the EBF up to addition of 150 kg/tHM of cold-bonded pellets were performed without disturbances of the process, but the burden descent and the gas distribution were disturbed during the periods with additions of 300 and 350 kg/tHM [21]. Taking this knowledge into account, the possible use of bio-coal in these briquettes was

studied aiming to enhance their self-reducibility and also replace part of the fossil carbon with renewable one. Besides being a feasible method for residues' recirculation in the integrated steel plant, the briquettes can be a feasible route for the introduction of biomass into the BF [22]. Due to the higher production yield compared to charcoal and higher energy density compared to raw biomass, the torrefied biomass can be used as a good alternative in some industrial applications [23, 24]. Although intensive work has been done to investigate the strength and reduction behavior of cold-bonded agglomerates containing coal [25–30] and charcoal fines [31, 32], less work is reported on the utilization of torrefied biomass in ironmaking. Research on utilization of briquettes containing torrefied sawdust in BF and its effect on carbon consumption and fossil $CO_2$ emission is limited.

In this work, the impact of briquettes containing torrefied sawdust on the BF efficiency has been comprehensively studied in technical- and full-scale trials based on laboratory studies. Produced briquettes were characterized for BF use and the operational trials evaluated using MASMOD. It is the first time that briquettes containing torrefied pelletized sawdust (TPS) are charged into an actual BF when aiming to reduce carbon consumption and fossil $CO_2$ emissions.

## Material and Methods

### Selection of Materials and Recipe Design

Bio-coals considered to be used in bio-briquettes were charcoal, torrefied forest residue, and torrefied saw dust directly or pelletized. Preliminary tests conducted at the Luleå University of Technology indicates that bio-coal with low and high volatile content in general is suitable to be added as long as the volatile release at comparably high temperature when formed reducing gases can contribute to reduction. However, the availability of charcoal is limited, and there is a disadvantage due to low yield during pretreatment. Torrefied material, on the other hand, can be produced with high yield, but the volatiles will be released at lower temperature compared to a low volatile bio-coal, especially if the bio-coal contains ash components as $K_2O$ and CaO

enhancing the volatilization. As torrefied sawdust (TSD) has only minor contents of these compounds, CO gas produced during volatilization will be formed at a temperature when CO has the ability to reduce higher iron oxides in the BF. Further, technical-scale briquetting was conducted for optimization of recipe in order to reach sufficient strength of the bio-briquettes during industrial tests. The mechanical strength was measured using tumbler index (TI) according to Swedish standard SS-ISO 3271:2007 but with screen of 6.0 mm instead of 6.3 mm. The tumbler test is conducted on 15-kg sample of briquettes that is placed in a rotating drum with a diameter of ~90 cm and rotation speed of 25 revolutions per minute. The tumbling time is fixed at 8 min to give totally 200 revolutions, and the material is removed from the drum to a receiving container equipped with a 6.0 mm sieve. The TI represents the percentage of the briquettes which are larger than 6.0 mm after tumbling. Tests were conducted with briquettes produced from in-plant residues supplied by SSAB Merox and also with addition of TSD, TPS, as well as crushed TPS provided by Bioendev AB. It was found that the addition of TSD resulted in lower TI, and higher amount of cement was needed to achieve satisfactory mechanical strength. The results showed that briquettes with TPS had higher TI compared to TSD and crushed TPS. Based on the results from laboratory and technical-scale trials, and also based on availability, price, and the need to increase the specific density and reduce volume to transport, TPS was selected to be used in full-scale production of bio-briquettes.

### Full-Scale Briquetting

The chemical compositions of integrated steel plant residue briquette mixture and TPS are given in Tables 1 and 2, respectively.

For standard briquettes, the briquetting mixture contains 92% steel mill residues and 8% cement added as binder. The mixture of steel mill residues includes different types of materials that are generated in steel plant as two types of pre-mixes, fine HM and steel scrap, pellet fines, mill scale, and LD dust. The pre-mixes consist of BF dust, filter dust, briquette fines and slags in specific proportions.

Table 1 Chemical composition of steel mill residue mixture for briquettes

| | $Fe_{tot}$ | $Fe_{met}$ | Mn | CaO | MgO | $Al_2O_3$ | $SiO_2$ | $TiO_2$ | $V_2O_5$ | $P_2O_5$ | $Na_2O$ | $K_2O$ | S | C | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wt% | 56.8 | 13.5 | 0.63 | 11.5 | 1.58 | 1.31 | 5.30 | 0.54 | 0.43 | 0.06 | 0.13 | 0.22 | 0.39 | 5.07 | 0.05 |

Table 2 Chemical composition of torrefied pelletized sawdust

| Parameter | Ultimate analysis | | | | Proximate analysis | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Moisture | Ash | VM | $C_{fix}$ | C | H | O | S | N | $Na_2O$ | $K_2O$ |
| Wt% | 5.5 | 0.45 | 75.6 | 24.0 | 57.1 | 5.9 | 36.4 | 0.01 | 0.1 | 0.002 | 0.073 |

The full-scale manufacturing of bio-briquettes for the industrial campaign at the SSAB Special Steels in Oxelösund, Sweden was conducted at SSAB Merox. The briquetting blends are normally mixed in batches of ~4.4 tons, and hexagonal briquettes with a height of ~7.5 cm with an edge of 4.0 cm are produced. Some pretrials were made to ensure that the bio-briquettes produced on industrial scale could reach sufficient TI. Table 3 summarizes the recipes (R) which were produced and tested on full scale before starting industrial production of bio-briquettes for the BF trials. The cement ratio in the mixture was increased from 8% in reference mixture of standard briquette to 10–12% in TPS-containing mixture. The TPS was added at two levels: 3% and 5%. Production of briquettes based on the given recipes was in most cases repeated several times (R1–R4, R9–R10, and R11–R12) to determine the effects on strength from the amount of water added and also the reproducibility of briquetting results. After one day in a curing chamber, the briquettes were further cured and dried in ambient temperature for 14 and 35 days before conducting TI tests.

## Operational Trials at BF No. 4 at SSAB Special Steels in Oxelösund

An overview of the BF trial periods with charged materials and operational parameters are summarized in Table 4. The trial started with a reference period charging standard briquettes, i.e., briquettes with both low and high manganese (Mn) contents at a total amount of 103 kg/tHM. The mix of standard briquettes corresponding to 75% of briquettes with low Mn and 25% of such material with high Mn content was kept throughout the whole trial. Trial periods using bio-briquettes were divided into two periods during which the bio-briquettes were charged at rates of 37% (~39 kg/tHM) and 55% (~64 kg/tHM) by weight of total amount of charged briquettes. The periods were labeled 37%Bio and 55%Bio. Bio-briquettes were charged to the BF via one of two material bins used for briquettes and metallic scrap.

Stable operating periods were selected for evaluation of the BF process, and average values of operational data were used for each period of the BF trial. Periods are selected

based on similar production rate in terms of blast volume and $O_2$ enrichment to the blast; periods including stoppages or reduction of blast are excluded from the evaluated data. Further, it was carefully checked that additional coke charging due to process deviation should not influence the selected periods. Each individual period having quite similar BF operational conditions in terms of coke rate, pulverized coal injection rate (PCI), and HM quality was evaluated separately before being merged into evaluation periods, and it results in total 104 h for the reference period, 152 h for 37%Bio period, and 163 h for 55%Bio period. Almost 100% pellets, mainly olivine pellets, are used at SSAB BF No. 4 as shown in Table 4.

The total amount of briquettes charged was higher during the 55% trial period, 116 kg/tHM, compared to around 103 kg/tHM during the 37%Bio and reference periods. The coke rates are similar during the reference and 37%Bio trial periods, but lower in 55%Bio trial period. However, the amounts of coke charged and the amount consumed by the BF process can differ depending on build-up or consumption of the coke reserve. Therefore, coke consumed by the process is evaluated in MASMOD. PCI was quite stable throughout the whole trial, and the main differences between the reference periods with standard briquettes and the trials with bio-briquettes were that the injection of BF flue dust was not conducted during the bio-briquette trials, lower amounts of LD- and ladle slags were charged during the period with 55%Bio, and the scrap addition was higher during the same period. Operational parameters used in the evaluation are given in Table 4.

## Top Gas Sampling and Analyses

During BF operation, isokinetic sampling of top gas dust was conducted at the same time as samples of dry BF flue dust after the cyclone and sludge before the thickener were collected. The isokinetic dust sampling is directly correlated to the amount of dust per unit gas volumes produced and thus to the process. These samples have not been affected by subsequent gas cleaning steps. The BF top gas is sucked through a heated probe via a valve in the off-gas duct into a

**Table 3** Recipes for pretrials on full-scale production of bio-briquettes and the tumbler index, TI, after 14 and 35 days of curing in ambient temperature

| Recipe no | R1 | R2 | R3 | R4 | R5 | R6 | R7 | R8 | R9 | R10 | R11 | R12 | R13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Steel mill residue mixture, wt% | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 |
| Cement, wt% | 10 | 10 | 10 | 10 | 12 | 12 | 10 | 10 | 12 | 12 | 10 | 10 | 10 |
| TPS, wt% | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 3 | 3 | 3 | 5 | 5 | 5 |
| Moisture, % | 8.4 | 8.7 | 9.0 | 9.2 | 9.3 | 8.8 | 8.6 | 8.5 | 8.7 | 8.6 | 8.8 | 8.9 | 9.1 |
| TI, 14 days | 65 | 70 | 60 | 57 | 53 | 62 | 60 | 62 | 72 | 74 | 56 | 60 | 62 |
| TI, 35 days | 53 | 63 | 64 | 64 | 67 | 69 | 64 | 74 | 74 | 74 | 62 | 64 | 67 |

*TPS* torrefied pelletized sawdust

**Table 4** BF trial overview, average amounts of materials, and operational parameters

| Periods | Unit | Ref. | 37%Bio | 55%Bio |
|---|---|---|---|---|
| Length of campaign | Days | 17 | 18 | 24 |
| Input materials and production | | | | |
| Olivine pellets | kg/tHM | 1018 | 1009 | 1001 |
| Acid pellets | kg/tHM | 243.5 | 255.0 | 254.7 |
| Coke | kg/tHM | 360.7 | 360.1 | 353.9 |
| PCI | kg/tHM | 109.1 | 109.6 | 108.9 |
| Injected BF flue dust | kg/tHM | 11.3 | 0 | 0 |
| Standard briquettes | kg/tHM | 102.7 | 64.5 | 51.5 |
| Bio-briquettes | kg/tHM | 0 | 38.7 | 64.2 |
| Total briquettes | kg/tHM | 102.7 | 103.2 | 115.8 |
| Limestone | kg/tHM | 31.9 | 31.1 | 30.4 |
| LD slag | kg/tHM | 66.9 | 69.2 | 59.8 |
| Ladle slag | kg/tHM | 6.7 | 3.5 | 0.7 |
| Scrap | kg/tHM | 15.3 | 15.4 | 17.3 |
| Hot metal, HM | tHM/h | 124.7 | 123.9 | 126.3 |
| HM temperature | °C | 1459 | 1460 | 1455 |
| Slag | kg/tHM | 186 | 180 | 174 |
| Slag basicity, B2 | – | 0.94 | 0.94 | 0.91 |
| Blast parameters | | | | |
| Hot blast flow | kNm$^3$/h | 118.1 | 118.1 | 118.1 |
| Oxygen enrichment to the blast | % | 1.6 | 1.4 | 1.5 |
| Oxygen enrichment to the PCI lance | kNm$^3$/h | 2.59 | 2.64 | 2.61 |
| Moisture in blast | g/Nm$^3$ | 9.5 | 13.9 | 8.8 |
| Blast pressure | mbar | 1125 | 1131 | 1123 |
| Blast temperature | °C | 1038 | 1033 | 1036 |
| Top gas | | | | |
| Top gas flow | kNm$^3$/h | 118.10 | 118.07 | 118.05 |
| Top gas temperature | °C | 108.9 | 100.2 | 92.8 |
| Top pressure | mbar | 70.0 | 79.6 | 78.1 |
| CO | % | 20.6 | 20.7 | 20.3 |
| CO$_2$ | % | 24.7 | 25.1 | 25.5 |
| N$_2$ | % | 51.5 | 51.1 | 51.4 |
| H$_2$ | % | 3.2 | 3.1 | 2.9 |
| Eta CO | % | 54.5 | 54.8 | 55.7 |
| Heat losses | MJ/tHM | 278.9 | 276.6 | 256.4 |
| Pressure drop, ΔP | mbar | 1090 | 1052 | 1045 |
| Raceway adiabatic flame temperature, RAFT | °C | 2176 | 2145 | 2171 |

small cyclone attached to the back of the probe where coarse particles are collected. After the cyclone, a filter holder with a paper filter inside is fitted for collecting the fine dust particles. The dry weight of the filter holder before and after the sampling is measured as well as the volume of the gas passed, its pressure and temperature. Chemical composition of the dust samples was analyzed using combustion analysis (C and S LECO) and X-ray fluorescence spectroscopy (XRF) on samples dissolved in lithium tetra-borate melts. The manually collected sludge was filtered and dried before chemical analyses were performed. Individual isokinetic samples of the very fine dust collected in the filter box had to be combined from several sampling occasions in order to have sufficient amount of material for analysis. Dried sludge and BF flue dust sampled below the cyclone were chemically analyzed. XRD was conducted with CuKα radiation for determination of mineralogical phases in the samples. The samples were finely ground, packed into a sample holder and scanned over an angular 2θ range of 10–90° using a step size 0.013 and scanning speed 0.164°/s.

Mass spectrometer (MS) measurements were performed during the trial periods. The position of the gas sampling probe was in one of the four offtakes, approximately at the same height as the charging system. SSAB BF No.4 operates

at a pressure of 50–100 mbar above the ambient pressure, and the gas had therefore to be pumped into the MS. To avoid condensation, the whole system was heated, also the pump and pipes from sampling point to the MS. Various components such as $NH_3$, HCN, $H_2S$, $SO_2$, and COS in the top gas can be measured; for this trial, the detection of possible hydrocarbons derived from the TPS in the bio-briquettes was evaluated.

## Heat and Mass Balance Model

MASMOD used for evaluation of BF trials [2, 33] is a one-dimensional static model which is accurate both in terms of material and energy balances as long as input data are consistent. The model iterates heat and mass balances within the furnace based on input and output amounts, compositions, reactions, and temperatures—all data are converted to units/tHM. The number of iterations is set to reach closing of the balances, in this case 500 was used, and it was manually checked how well the energy balance, production rate, and elemental balances are closed.

Data corresponding to the each of the periods previously described in Table 4 were used, and the MASMOD settings were as given in Table 5. As seen in the table, the measured heat losses and top gas composition are used. The chemical compositions of reference and bio-briquettes used are given in Table 6. The rates of dust and sludge generation were fixed as 15 kg/tHM and 5 kg/tHM, respectively, for all the evaluated periods.

The shaft efficiency was for all cases fixed at 0.98, while the TRZT was adjusted to keep the shaft efficiency constant. When the measured heat losses are fixed, the coke rate can be calculated, and the distribution of heat losses can be estimated by closing the energy balances for upper and lower parts of the BF. The heat losses are relatively constant per time unit and also per tHM if the production rate is quite constant. The amounts of coke charged, on the other hand, do not necessarily correspond to the amount of coke used by the process. The BF process is a continuous process, and if the amount of reducing agents is excessive during an operational period, part of the charged coke can contribute to the increased coke reserve. In another period, if the process conditions require more coke, part of the coke reserve can be consumed. Simultaneously, as the energy balance is closed, also the balances of oxygen, nitrogen, carbon, and hydrogen are iteratively balanced to the amounts and compositions of blast volume and top gas as well as to the production of HM and slag. The gas utilization, Eta CO ($\eta CO = \% CO_2 / (\% CO + \% CO_2)$), is fixed as deduced from measured top gas composition, while Eta $H_2$ is adjusted to give the lowest

**Table 5** Setup parameters for MASMOD evaluation of each test period

| Parameter | Conditions |
|---|---|
| Thermal reserve zone temperature, TRZT | Variable |
| Shaft efficiency | Fixed at 0.98 for all cases |
| Heat losses | Measured production data |
| Distribution of heat losses between upper and lower zones | Adjusted to close the heat balance for upper and lower zones |
| Coke rate | Calculated to close the heat and mass balance & compared to charged amount according to production data |
| Top gas temperature | Measured production data |
| Blast temperature | Measured production data |
| Blast volume | Iteratively calculated to achieve actual production rate |
| Top gas composition | Iteratively calculated to be as close as measured according to measured production data |
| Oxygen to the blast and PCI lance | Measured production data |
| Moisture in the blast | Measured production data |
| Eta CO | Measured production data |
| Eta $H_2$ | Adjusted to give the lowest difference between $H_2\%$ in measured off-gases and modelled values |
| Hot metal production rate | Measured production data |
| Hot metal temperature | Measured production data |

**Table 6** Chemical compositions of standard briquettes and bio-briquettes

| Element/oxide | CaO | MgO | SiO$_2$ | Al$_2$O$_3$ | TiO$_2$ | V$_2$O$_5$ | Na$_2$O | K$_2$O | S | Mn | Fe | C | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ref. Briquette | 9.5 | 2.1 | 5.3 | 1.3 | 0.39 | 0.45 | 0.08 | 0.13 | 0.25 | 1.7 | 54.0 | 3.9 | 0.03 |
| Bio-briquette | 9.2 | 1.4 | 4.5 | 1.2 | 0.41 | 0.32 | 0.09 | 0.12 | 0.31 | 0.40 | 57.0 | 4.1 | 0.05 |

differences between the measured and the calculated off-gas compositions.

The measured and modeled values of top gas analysis, specific blast, slag analysis, and basicity are compared in Table 7. As seen from the table, there are relatively small differences between the measured and calculated values, which illustrates that the input data are consistent and operational conditions can be explained by thermodynamic data contained in MASMOD. If MASMOD is calibrated with data from operational periods (reference and test periods), it can be used for the evaluation of other similar types of material for BF use.

## Results and Discussion

### Evaluation of Briquettes' Mechanical Strength

The TIs for bio-briquettes produced on full scale (R1–R13) measured after 14 and 35 days curing are given in Table 3. All briquettes produced with TPS had lower strength than

the accepted limit of TI = 75% for charging to the BF at SSAB in Oxelösund. Briquettes prepared by addition of 12% cement and 3% TPS (R9 and R10) showed the highest strength among all recipes. Figure 1 shows the shape of briquettes after tumbling. It can be seen that the bio-briquettes (R6 and R10) decomposed more compared to standard briquette (FR0) and larger extent of fines was generated in R6 which contains 5% TPS and 10% of cement.

The size distributions of reference and bio-briquettes after TI tests are given in Fig. 2. R5, R6, and R13 resulted in the highest ratios of fines < 8.0 mm and the lowest for the fractions > 63 mm. The middle fractions 8–63 mm were not generated in FR0, while it was high in bio-briquettes with 5% TPS and 10% cement (R5, R6, and R13).

As R9 and R10 showed the highest strength among all recipes, the production of full-scale bio-briquettes was initially started based on these recipes but a new batch of TPS was used. During mixing, the TPS was not evenly distributed in the blend and cracks propagated in the bio-briquettes during curing, which impaired the briquette strength. Therefore, the recipe for full-scale production was modified to 1.8%

**Table 7** Measured and calculated top gas compositions, blast volumes, slag compositions, and basicities

| | Unit | Trial data | | | | | | MASMOD data | | | | | |
| | | Ref. | | 37Bio | | 55Bio | | Model result | | | % deviation | | |
| | | Ave. | SD | Ave. | SD | Ave. | SD | Ref. | 37Bio | 55Bio | Ref. | 37Bio | 55Bio |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Top gas composition | | | | | | | | | | | | | |
| $H_2$ | % | 3.16 | 0.01 | 3.06 | 0.01 | 2.89 | 0.01 | 3.10 | 3.05 | 2.82 | − 1.94 | − 0.20 | − 2.66 |
| CO | % | 20.6 | 0.31 | 20.7 | 0.27 | 20.3 | 0.25 | 20.8 | 20.8 | 20.4 | 0.96 | 0.58 | 0.73 |
| CO | % | 24.7 | 0.26 | 25.1 | 0.27 | 25.5 | 0.25 | 24.9 | 25.3 | 25.7 | 0.80 | 0.59 | 0.74 |
| $N_2$ | % | 51.5 | 0.46 | 51.1 | 0.44 | 51.4 | 0.42 | 51.3 | 50.8 | 51.1 | − 0.47 | − 0.51 | − 0.51 |
| Specific blast | $Nm^3/tHM$ | 947 | 10.4 | 953 | 9.79 | 935 | 9.81 | 941 | 936 | 917 | − 0.69 | − 1.79 | − 1.92 |
| Slag composition | | | | | | | | | | | | | |
| CaO | % | 33.4 | 0.56 | 33.4 | 0.67 | 33.6 | 0.49 | 32.5 | 32.8 | 31.8 | − 3.08 | − 1.79 | − 5.57 |
| MgO | % | 12.8 | 0.18 | 12.4 | 0.20 | 12.2 | 0.25 | 13.0 | 12.5 | 12.4 | 1.71 | 0.32 | 1.32 |
| $SiO_2$ | % | 35.7 | 0.79 | 35.5 | 0.58 | 37.1 | 0.38 | 34.6 | 35.1 | 36.0 | − 3.20 | − 1.25 | − 2.89 |
| $Al_2O_3$ | % | 12.0 | 0.37 | 11.8 | 0.29 | 11.5 | 0.26 | 12.5 | 12.0 | 12.3 | 3.88 | 1.87 | 6.15 |
| S | % | 1.33 | 0.09 | 1.34 | 0.08 | 1.37 | 0.09 | 1.36 | 1.35 | 1.37 | 1.87 | 0.56 | 5.18 |
| $K_2O$ | % | 0.76 | 0.13 | 0.82 | 0.12 | 0.91 | 0.14 | 0.76 | 0.77 | 0.79 | − 0.33 | − 6.36 | − 15.3 |
| B2 | – | 0.93 | 0.03 | 0.94 | 0.03 | 0.91 | 0.02 | 0.94 | 0.93 | 0.88 | 0.54 | − 0.98 | − 2.86 |

Standard deviation of measured data is shown as well as %deviation of model result compared to measured data

**Fig. 1** Photograph of briquettes after tumbling: **a** FR0; **b** R6; **c** R10. FR0: standard briquette
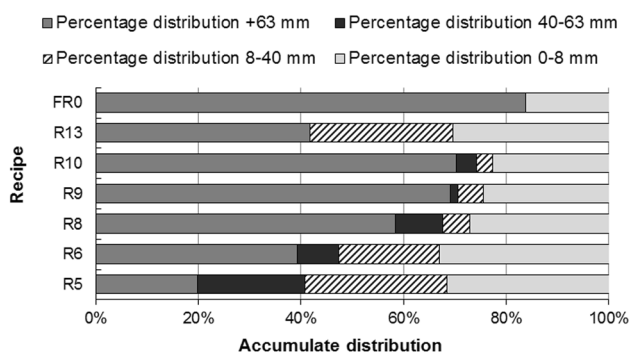
**Fig. 2** Percentage size distributions in sieved bio-briquettes and reference briquette after TI tests. FR0: standard briquette

TPS, 12% cement, and 86.2% of steel mill residues. The produced bio-briquettes demonstrated an adequate TI and about 6000 tons were produced for the BF trial.

## Operational Conditions and BF Stability

The HM temperature and Si contents were stable at around 1460 °C and 0.60 wt%, respectively, for reference and 37%Bio periods and slightly lower during 55%Bio period, 1455 °C and 0.55 wt%. Table 4 shows average process data and as can be seen the Eta CO was higher during the periods with bio-briquette charging. The reference period shows highest top gas temperature and gas flow. Both 37%Bio and 55%Bio periods have similar top gas flow, but the top gas temperature is lower for 55%Bio charging. The pressure drop is higher during the reference period compared to 37% and 55%Bio periods; this indicates that charged briquettes are not affecting the shaft permeability. It is mainly differences in blast pressure that indicates differences in resistance in the BF and they show similar trends as the pressure drops.

## Top Gas Sampling and Analyses

Isokinetic collected top gas dust samples were performed during the 37%Bio period (7 samples) and during the 55%Bio period (1 sample). Around 93–95% of the total samples consist of coarse dust and around 5–7% of fine dust. The chemical composition of manually collected BF flue dust

and dried sludge samples in the gas cleaning system and the isokinetic collected samples before the gas cleaning at approximately the same time is given in Table 8.

Results show that the Fe and CaO contents were lower while C, SiO₂, and Al₂O₃ contents were higher during the 37%Bio period compared to 55%Bio period in both BF flue dust and isokinetic samples indicating less coke leaving the BF during 55%Bio period. In the case of sludge samples, the Fe and C contents were higher during 37%Bio than in 55% Bio.

XRD analysis of manually sampled BF flue dust and sludge showed no significant differences between the charging of 37% and 55% bio-briquettes, as shown in Fig. 3. Detected phases are hematite, calcium carbonate, quartz, and magnetite, and the results are in line with previous studies [34].

MS data for shorter time frames were analyzed relative to charges of pellets and briquettes (data from dumps). This was done to determine if volatile matter from the bio-briquettes could be detected. The results showed no effects regarding measured hydrocarbons after charging of pellets and bio-briquettes, and no significant differences could be noted between the charge of 37%Bio and 55%Bio.

## Data Evaluation Using Heat and Mass Balance Model

MASMOD has been used to evaluate the BF process efficiency according to the set-up parameters previously described in Table 5. For each period, the measured heat losses were used, while the carbon consumption was calculated using the model. The raceway adiabatic flame temperature (RAFT) calculated in the model using the corresponding measured data showed quite similar values for all evaluated periods. The RAFT was slightly lower during 37%Bio period due to higher moisture content and lower O₂ enrichment to the blast compared to those during the other periods as shown in Table 4.
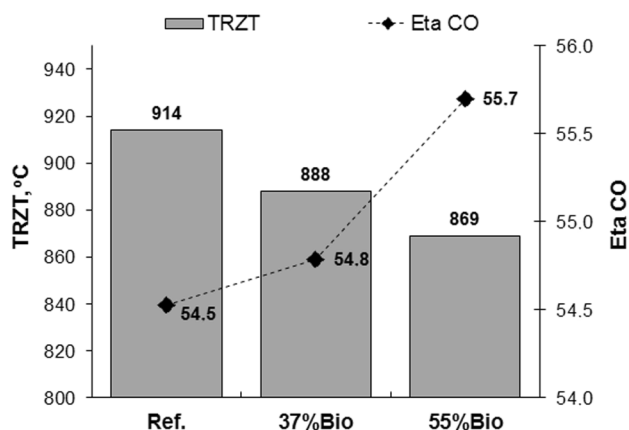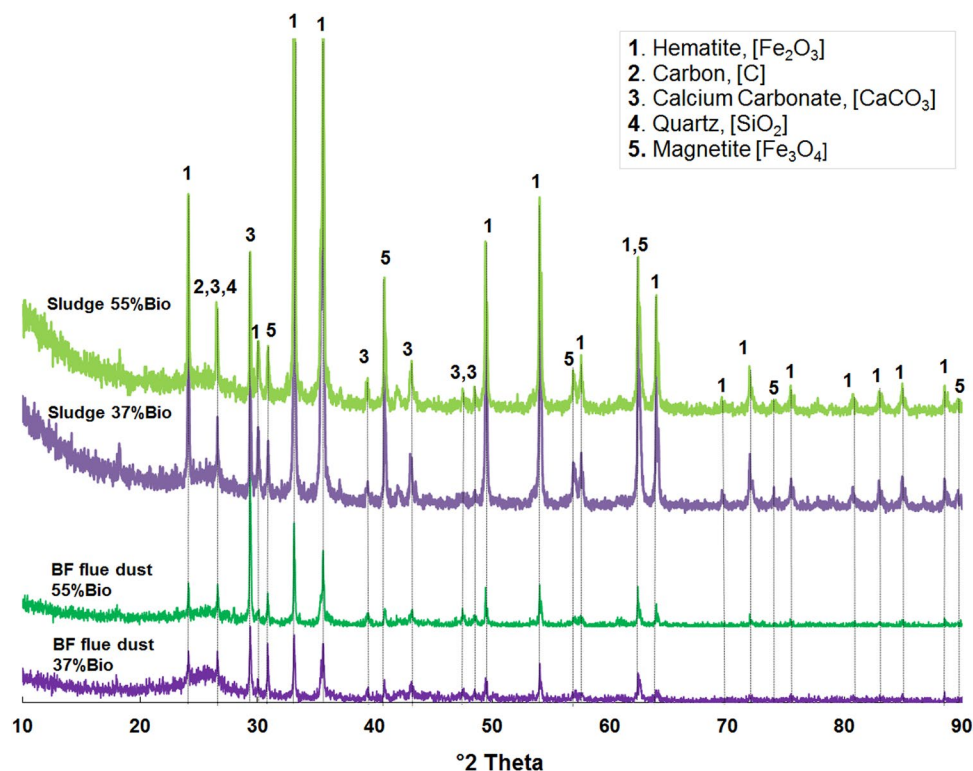
The difference of TRZTs in the evaluated periods is calculated by assuming that the shaft efficiency in all cases is 0.98, and at the same time, checking that the calculated top gas composition is close to the measured one, and the results are shown in Fig. 4. It can be seen that the estimated TRZT is decreased by 45 °C in 55%Bio period compared to

**Table 8** Chemical compositions of BF flue dust, sludge, and isokinetic collected dust

| Sample type | Period | Fe | CaO | SiO₂ | MnO | P₂O₅ | Al₂O₃ | MgO | Na₂O | K₂O | C | S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flue dust | 37%Bio | 21.0 | 7.3 | 6.1 | 0.33 | 0.07 | 2.1 | 1.2 | 0.06 | 0.14 | 47.7 | 0.43 |
| | 55%Bio | 22.8 | 8.1 | 5.8 | 0.38 | 0.08 | 1.8 | 1.2 | 0.06 | 0.13 | 44.5 | 0.42 |
| Sludge | 37%Bio | 55.5 | 4.0 | 6.3 | 0.14 | 0.12 | 2.8 | 1.8 | 0.11 | 0.11 | 16.4 | 0.15 |
| | 55%Bio | 47.1 | 5.4 | 7.1 | 0.21 | 0.11 | 2.6 | 1.4 | 0.08 | 0.15 | 13.8 | 0.15 |
| Isokinetic | 37%Bio | 26.3 | 7.6 | 6.4 | 0.38 | 0.07 | 2.3 | 1.5 | 0.05 | 0.06 | 38.0 | 0.36 |
| | 55%Bio | 32.3 | 8.3 | 5.8 | 0.38 | 0.08 | 1.7 | 1.4 | 0.04 | 0.04 | 30.1 | 0.33 |

**Fig. 3** XRD diagrams for BF flue dust (bottom) and sludge (top) for 37%Bio and 55%Bio periods



1. Hematite, [$Fe_2O_3$]
2. Carbon, [C]
3. Calcium Carbonate, [$CaCO_3$]
4. Quartz, [$SiO_2$]
5. Magnetite [$Fe_3O_4$]



**Fig. 4** Thermal reserve zone temperature (TRZT) and Eta CO for evaluated periods

the value estimated for the reference period. In addition, the measured gas utilization (Eta CO) is higher during 55%Bio period compared to that at the reference period.

This trial was accompanied by saving amounts of 3.3 and 10.9 kg/tHM of carbon in the periods of 37%Bio and 55%Bio, respectively. The higher gas utilization is likely linked to lower TRZT. At lower TRZT, the indirect reduction equilibrium shifts towards higher reduction of FeO to $Fe_{met}$ in the shaft. It was reported in the literature that a decrease of TRZT by 100 °C is able to save 19 kg/tHM of

reducing agents [28], which is in a good agreement with the measured and calculated values of reducing agents during the bio-briquette trials.

To ensure that the achievements in terms of lower carbon consumption and $CO_2$ emission were not related to differences in operational conditions between the reference period and test periods, the effects from the different settings in blast moisture as well as injected BF flue dust, LD slag, scrap, and briquette rates during the reference period were analyzed, see Table 4. TRZT, shaft efficiency, Eta $H_2$, and $N_2$ concentration in top gas already determined for each evaluation period were kept unchanged, while the mentioned reference data for differing parameters were used. The coke rate, top gas temperature, and Eta CO were calculated for the test periods, and Fig. 5 summarizes the collective effects on coke, carbon, and $CO_2$ emission when inserting the reference period settings. As seen obviously, this resulted in lower carbon consumption and $CO_2$ emission compared to those when using the original operational data for 37%Bio (~ − 0.8 kg carbon/tHM). For 55%Bio period, the carbon consumption differed by ~ − 1.8 kg/tHM. The $CO_2$ emissions were reduced by 33–40 kg/tHM when charging 55% bio-briquettes. Further tests, preferably with higher bio-coal content of briquettes and higher charging rate, are required to confirm the positive results on lowering of carbon consumption and $CO_2$ emission achieved in this study.
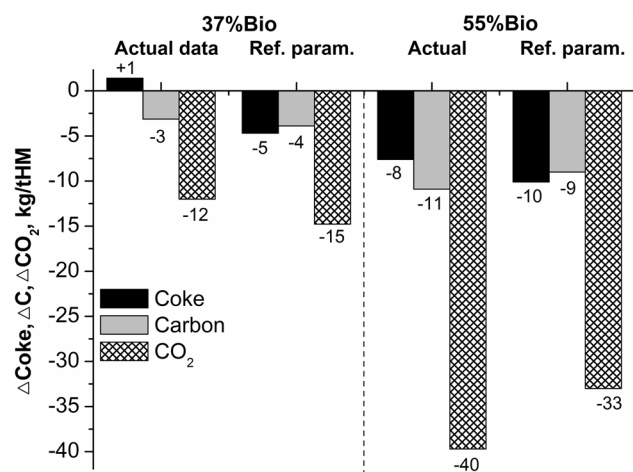
**Fig. 5** Differences (kg/tHM) in calculated coke, carbon, consumption, and $CO_2$ emission between the reference period and test periods based on actual operational data as well as when using reference period parameter settings for blast moisture, BF flue dust injection rate, LD-slag addition for test periods

and test periods showed that the calculated results were valid also taking these differences into account.

## Conclusions

The present paper discussed the effects of charging briquettes containing torrefied pelletized sawdust (TPS) on the blast furnace (BF) efficiency and process stability. Full-scale briquettes with sufficient mechanical strength were produced by mixing 1.8% of TPS and 12% cement with 86.2% of steel mill residues. The bio-briquettes were charged at two different rates to BF No. 4 at SSAB in Oxelösund: 37%Bio (38.7 kg/tHM) and 55%Bio (64.2 kg/tHM), and the results have been compared with a reference period without charging bio-briquettes.

Bio-briquette charging resulted in an estimated lower shaft temperature and improved gas utilization. Lowering of shaft temperature will, according to thermodynamic data for the reduction of FeO with CO, shift the equilibrium toward metallic Fe and $CO_2$.

Measurements with mass spectrometry on BF top gas showed no signs of hydrocarbons being released when charging bio-briquettes containing TPS with high volatile content.

Heat and mass balance calculations based on operational data for reference period and test periods with 55% bio-briquettes indicated lowering of thermal reserve zone temperature by 45 °C compared to the reference case, which results are in accordance with the extent of higher gas utilization measured.

With 55% bio-briquettes charged, the carbon consumption was reduced with ∼9–11 kg/tHM, due to the improved gas efficiency. Analyzing operational differences in terms of input materials and blast moisture between the reference

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