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# Medium oxygen enriched blast furnace with top gas recycling strategy

Wei Zhang[1,2,*], Zheng-liang Xue[2], Ju-hua Zhang[2], Wei Wang[2], Chang-gui Cheng[2], Zong-shu Zou[3]

[1] The State Key Laboratory of Refractories and Metallurgy, Wuhan University of Science and Technology, Wuhan 430081, Hubei, China

[2] Key Laboratory for Ferrous Metallurgy and Resources Utilization of Ministry of Education, Wuhan University of Science and Technology, Wuhan 430081, Hubei, China

[3] School of Metallurgy, Northeastern University, Shenyang 110004, Liaoning, China

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ABSTRACT

Top gas recycling oxygen blast furnace (TGR-OBF) process is a promising ironmaking process. The biggest challenge of the TGR-OBF in operation is the dramatic decrease of top gas volume (per ton hot metal), which once led to hanging-up and shutdowns in practice of the Toulachermet. In order to avoid this weakness, the strategy of medium oxygen blast furnace was presented. The maneuverable zone of the TGR-OBF was determined by the top gas volume, which should not be far from the data of the traditional blast furnace. The deviation of ±12.5% was used, and then the maneuverable blast oxygen content is from 0.30 to 0.47 according to the calculation. The flame temperature and the top gas volume have no much difference compared to those of the traditional blast furnace. The minimum carbon consumption of 357 kg per ton hot metal in the maneuverable zone occurs at the oxygen content of 0.30 (fuel saving of 14%). In the unsteady evolution, the $N_2$ accumulation could approach nearly zero after the recycling reached 6 times. Thus far, some TGR-OBF industrial trials have been carried out in different countries, but the method of medium oxygen enriched TGR-OBF has not been implemented, because the accumulation of $N_2$ was worried about. The presented strategy of medium oxygen enriched TGR-OBF is applicable and the strategy with good operational performance is strongly suggested as a forerunner of the full oxygen blast furnace.

**Symbol List**

$c_P$—Heat capacity, kJ/kg;
$er$—Error;
$K$—Coke rate, kg/t;
$m$—Mass of material per ton hot metal, kg;
$N$—Volume of $N_2$, $m^3$;
$Q$—Input or output item in thermal balance calculation;
$r_d$—Direct reduction degree;
$r_i$—Indirect reduction degree;
$Ra$—Distribution ratio of recycling gas;
$t$—Temperature, °C;
$V$—Volume of gas produced for every ton hot metal, $m^3$;
$x$—Volume fraction of gas;
$\eta$—Utilization ratio of CO or $H_2$ in blast furnace;
$\omega$—Weight fraction of solid material;
$\phi$—Volume fraction of gaseous material;
Subscript
accu—Accumulation of quantities;
b—Blast;
bosh—Bosh gas;
de—Status of top gas flows after $CO_2$ stripping;
de_$CO_2$—$CO_2$ stripped from vacuum pressure swing absorption;
de_$H_2O$—$H_2O$ removed from top gas;
de_$N_2$—$N_2$ in top gas flows after $CO_2$ stripping;
ex—Exported top gas;
fb—Top gas flows after $CO_2$ stripping and partly used as fuel to heat both blast and hearth recycling gas;
fg—Fuel gas exported after $CO_2$ stripping;
fh—Top gas flows after $CO_2$ stripping and partly used as fuel to heat hearth recycling gas;
ft—Flame temperature;
he—Hearth;
$H_2O$_b—$H_2O$ in blast;
hm—Hot metal;
in—Input;
in_$i$—Input item $i$;
$O_2$_b—$O_2$ in blast;
out—Output;
out_$i$—Output item $i$;
sh—Shaft;

* Corresponding author. Ph.D.; Tel.: +86 27 68862529.
*E-mail address*: *wei_zhang@wust.edu.cn* (*W. Zhang*).

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sh_$O_2$—Industrial oxygen used in combustion process with shaft recycling gas;

top—Top gas;

top_sh—Partial top gas flowing towards combustor in shaft.

## 1. Introduction

The oxygen blast furnace ironmaking process uses highly oxygen-enriched blast instead of air blast compared to the traditional blast furnace, and in some special cases, it may refer to full oxygen blast furnace (OBF) or nitrogen free blast furnace (NF-BF). It is often combined with top gas recycling technology and called top gas recycling oxygen blast furnace (TGR-OBF). Characterized by high productivity, high PCR (pulverized coal rate), low fuel rate, and low $CO_2$ emission, the TGR-OBF process is considered to be one of the promising ironmaking processes[1-10].

The exact process was presented by Wenzel et al. in an American patent[1]; thereafter, fundamental studies such as static balance models and mathematical models were performed by different researchers[2-10]. Wang et al.[3] simulated the blast furnace operation with coke oven gas injection in combination with top gas recycling, and oxygen enrichments of their cases were 3.0%, 19.2%, and 71.1%, respectively. Jin et al.[4] investigated the energy consumption and carbon emission for the TGR-OBF process (with 100% oxygen enriched) by modeling the stack, the bosh, the combustion zone, and the gas recycling system. Helle et al.[9] carried out the simulation and optimization of recycling $CO_2$ stripping top gas in the blast furnace under massive oxygen enrichment, and its impact on the production economy and emissions of the steel plant, and oxygen enrichments of their cases were 80% and 100%. Zhang et al.[10] calculated optimum process parameters of nitrogen free blast furnaces (100% oxygen enriched) by using a mathematical model, and found that the emissions of $CO_2$ would be reduced by 45.91% and 49.02% for a single row of tuyeres and two rows of tuyeres in the NF-BFs, respectively. Until now, the investigated TGR-OBF processes are all enriched with full oxygen blast or highly oxygen-enriched blast, but a strategy of TGR-OBF with medium oxygen enrichment (40%−60%) has not entered researchers′ view.

Meanwhile, industrial trials have been successfully implemented in different countries to reduce carbon consumption and $CO_2$ emissions[11-15]. In the late 1980s, a series of industrial experiments of TGR-OBF were launched on blast furnace No. 2 (1033 $m^3$) of RPA Toulachermet in the Soviet Union and about 250 kt of hot metal was produced[13]. Almost in the same period, a trial of TGR-OBF of 8 $m^3$ was conducted by NKK in Japan[12]. In the test plant, a coal rate of 407 kg/t, a coke rate of 258 kg/t and a productivity of 7.35 t/(d · $m^{-3}$) were achieved. In order to reduce $CO_2$ emissions, a group of ULCOS (ultra low $CO_2$ steelmaking) programs were presented by 48 European companies and organizations, and among them, the TGR-OBF process is one of the most important programs[16]. In 2007, a pilot test of the TGR-OBF process was carried out on the EBF (experimental blast furnace) of Luleå[14]. The $CO_2$ savings in the experimental blast furnace was up to 1270 kg/t which represents 76% of the reference without any safety issues recorded. In 2009, the Central Iron and Steel Research Institute of China successfully carried out an industrial trial in an oxygen blast furnace with injection of coke oven gas in Ying Steel, Yingkou, China[17]. In April 2013, the COURSE50 ($CO_2$ ultimate reduction in steelmaking process by innovative technology for Cool Earth 50) carried out COG (coke oven gas) and reformed COG (RCOG) injection operation trials at LKAB′s EBF in Luleå, and it was concluded that the roles of coke and coal were partially substituted by COG or RCOG and the total input of carbon decreased[15]. However, the production status of blast furnace usually deteriorates in practice after adopting full oxygen blast. As pointed out in the RPA Toulachermet, the hearth drainage ability would deteriorate if the furnace ran for a long period with low consumption and outflow rates of oxygen blast[13]. As a blast furnace model was simulated and experimentally conducted, the flow rate of gas dramatically influenced the solid flow pattern in a blast furnace[18,19]. Thus, the shortage of bosh gas or top gas compared to that in a normal blast furnace led to hanging-up and shutdowns of the blast furnace[13]. Even recycling and injecting with top gas in tuyeres, the TGR-OBF is still insufficient in the volume of bosh gas and top gas[2-15].

In this paper a strategy of medium oxygen enriched blast furnace with top gas recycling was proposed to solve the problem of the shortage of the bosh gas volume and top gas volume, and to make the TGR-OBF process more practicable. Furthermore, a high flame temperature would result in a high content of Si in pig iron, which would influence the steelmaking process[20]; thus, control of the flame temperature should be considered. Simultaneously, the unsteady accumulation of $N_2$ in the process should also be taken into account[14].

## 2. Mathematical Model

### 2.1. Description

The description of the investigated TGR-OBF process