

EVALUATION ON MATERIAL AND HEAT BALANCE OF EAF PROCESSES WITH INTRODUCTION OF CO₂

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Abstract

The advantages of using CO₂ for the decarburization of high alloy steels have been recognized from environmental and economic view points. The present paper presents the heat and materials balances in the decarburization process with the introduction of CO₂ as a diluting gas in Electric Arc Furnace (EAF) process for steel production. The aim is to optimize the amount of CO₂ and the materials requirements, which includes the addition of scrap, hot metal and coolant. These estimations are also important to control the bath temperature, thereby prolong the lifetime of the refractory lining of the furnace. The present calculations enable an optimization of the CO₂:O₂ ratio and materials input in the decarburization of carbon steel melts. Another important extension of the work is the possibility to enhance the addition of hot metal during steel making process. The present results show that addition of up to 20% hot metal is likely to the energy loss due to the introduction of 50% CO₂ for a 110 tons EAF resulting in the saving of electric energy.

Keywords: CO₂; Heat balance; Materials balance; Energy saving; Electric arc furnace

1. Introduction

The present authors has earlier demonstrated that the introduction of CO₂ in Electric Arc Furnace (EAF) or Argon Oxygen Decarburization (AOD) process for the production of high alloy steel grades is effective for Cr retention in the molten metal [1, 2]. CO₂ is also possible to be used in converter process to produce medium and low carbon ferrochrome in ferroalloy industry [3]. The results of former work shown that, CO₂ had a high efficiency for decarburization, especially at high initial carbon content. Previous experiments by the present authors in 1 kg scale were carried out in an induction furnace where the furnace control system maintained constant temperature in the bath, compensating automatically the endothermic effect of CO₂ introduction. In any implementation of the CO₂ decarburization concept, it is important to estimate the energy need of the process in total. Thus, the effect of CO₂ on the energy balance of the furnace unit is quite essential for the process modification.

2. Earlier work

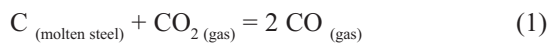
There are many researchers have put efforts in the calculation of energy and heat balance in EAF. Kirschen et al. [4] have studied the energy efficiency

and the influence of gas burners to the energy in EAF process. These authors have shown that appropriate use of natural gas burners could increase the energy intensity in EAF. Besides heat balance, materials balance and material collocation during EAF are also essential to energy consumption in the process and products' quality. It was proposed by McIntyre et al. [5] that one of the effective measures to avoid high ratio of scraps with complex chemical composition (which will lead to harmful elements to the targeted steel grade) is to increase the ratio of hot metal in EAF. Besides, increased amount of hot metal will decrease the electric energy consumption for smelting scrap. However, excessive hot metal charging may prolong the tap-to-tap time of EAF steelmaking process, since high carbon content from the excessively charged hot metal can overburden the decarburization operation during the EAF process [6, 7]. In order to effectively utilize the advantage of increasing the hot metal charging ratio and shorten the tap-to-tap time of EAF steelmaking process [8-11], many researchers have investigated the optimal hot metal charge ratio [12-18] and the selection of the refining slags. The results obtained were positive, for example, Duan et al. [18], dividing the charging process into two steps, in the first step 35-40% hot metal would be decarburized in a special equipment

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and then transferred into EAF, the left 30% hot metal would be added, in this way, could increase the hot metal ratio up to 65mass%-70 mass% in the EAF process. The tap-to-tap time of a 50 ton EAF could, at the same time, be shortened by 5-10 minutes and the electric energy consumption is decreased by 35-50 kW·h/t. A further advantage of the modification was that the content of harmful heavy metals in molten steel could be easily controlled. This emphasizes the need for a control of the decarburization time for increasing the hot metal charge in the EAF process.

Earlier studies of the present authors [1, 2] have shown that the introduction of CO₂ as the decarburizing gas increases the number of product molecules to two by means of the reaction



contributing significantly to the stirring effect of the steel bath. This would lead to an increase of hot metal charge in the EAF. A correlation between the carbon content and Cr content in the steel bath with three different decarburizers, estimated from a theoretical model developed by some of the present authors in a separate work [1] is presented in Figure 1.

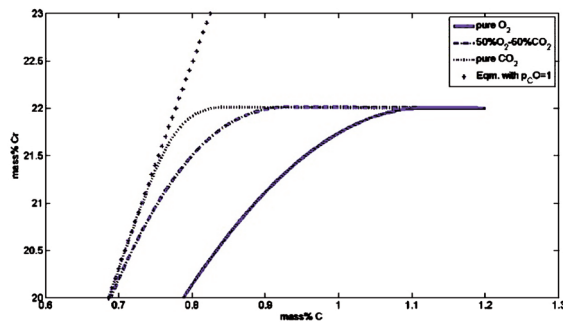


Figure 1. Carbon and chromium composition evolution in a Fe-1.20C-22Cr melt injected with three different gases, viz. 100% O₂, 50% O₂ - 50% CO₂ and 100% CO₂ [1]

It is seen that, with pure CO₂ as the decarburizer, the decarburization efficiency is closed to near-thermodynamic level, especially at high initial carbon content. Thus, the decarburization by CO₂ is promising while the loss of chromium can be kept low during the initial stages of blowing when the carbon content is high.

Asai and Szekely [19, 20] have carried out mass and heat balance calculations together with the film theory of diffusion in EAF process with oxygen-blowing and set up a mathematical model for decarburization trials based on theoretical analysis. The modeling result showed good agreement with the production data. Besides EAF, AOD is also an important process for decarburization with respect to stainless steel making. In recent years, over 75%

stainless steel is being produced through AOD process, hence extensive research has been carried out on the mass and heat balances for AOD. Models have been developed to simulate the decarburization and the oxidation of various elements during the refining process. Wei and Zhu [21, 22] had set up an AOD mathematical model to predict the decarburization process based on a few assumptions and the results such as carbon content and temperature obtained through this mathematical model are in good agreement with the real production. For the possibility to use CO₂ as a decarburizer, the feasibility has been demonstrated by earlier work carried out by the present authors [1, 2] as well as a few others, like Mannion and Fruehan, Sain and Belton [23, 24]. Jin et al. [25] have carried out research on CO₂-O₂ blowing in converter and they pointed out that, in converter the maximum introduction amount of CO₂ is 13%. If CO₂ ratio is over 13%, that will cause problem for the steel refining process since the heat is not sufficient based on heat balance calculation and analysis. And they stated that it is possible to use CO₂ in EAF since the energy needed due to CO₂ introduction could be compensated by electricity or some other fuel. No systematic study has been carried out earlier on materials and heat balance with the introduction of CO₂ during EAF or AOD process, despite the fact that it is essential for using CO₂ effectively in steelmaking processes as well as production of medium and low carbon ferroalloy process.

Based on the positive results obtained from the experiments carried out by present authors, and the lack of energy data of CO₂ introduction during EAF process, it is essential to make an estimation of heat and materials balance with introduction of CO₂, and find out the optimized CO₂ amount as well as the corresponding material input. These are presented in the present paper.

3. Calculation basis

For EAF with introduction of 100% scrap, around 60-65% of the total energy is electric energy, and 30-35% is generated from oxidation of elements, such as carbon, chromium, iron, silicon and natural gas burning through burners. Around 53% of the total energy is retained in the liquid metal while the rest is lost to slag, waste gas and cooling process, as shown in Figure 2 [26].

It is difficult to determine the total energy input in an EAF because energy supplied to the EAF is through multiple sources: Electric energy and chemical energy, the latter being released from the combustion of Natural Gas (NG), liquefied petroleum gas or oil, and the oxidation of elements in the melt during refining, like C, Si, Al, Fe, Cr, Mo and Mn. The oxidation energy contribution is not only dependent

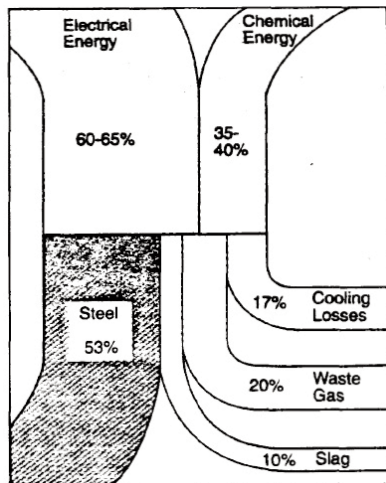


Figure 2. Energy patterns in EAF (Sankey diagram [26])

on the oxygen input but also on the chemical composition of the steel melt and slag [4].

It is well known that carbon reaction with CO_2 in the steel bath as expressed by reaction (1) is endothermic, the standard enthalpy for the reaction being $\Delta H^0 = +140170 \text{ J/mol}$. The standard state for carbon dissolved in molten steel is 1wt% in the Henrian scale while, for the gases, $1.01325 \times 10^5 \text{ Pa}$.

Due to the endothermic effect, the temperature of the steel bath will decrease when CO_2 is introduced in the reaction gas system. This, in turn, will increase the consumption of electric energy in EAF for keeping the temperature constant, or lead to further loss of Cr if heat is not supplied.

In the present study, for EAF process, the materials and energy balance system boundary is defined as shown in Figure 3 and the balance calculation is based on this definition of the boundary [27].

Before carrying out the calculation, the input and output parameters in the system should be defined in the program. In the present case, all input and output parameters are defined and set according to the practical production parameters in a 65 ton EAF in Reference plant A, Sweden. Meanwhile, one should

mention that the air infiltration in EAF process is large, and it needs to be considered as input data, as shown in Figure 4 [28].

In the present study on heat and materials balance in EAF process with introducing CO_2 gas, the raw materials consumption, the electric energy need and the effect of process parameters, like gas (here CO_2 is replacing O_2), element concentration, heat loss due to cooling etc., as shown in Figure 5 on the electric energy consumption(EEC) could be evaluated.

A typical energy input and output in the present study is shown in Figure 6. From Figure 6, it is seen that in current calculation, the electric energy need (EE) takes up to 43% of the total energy input when

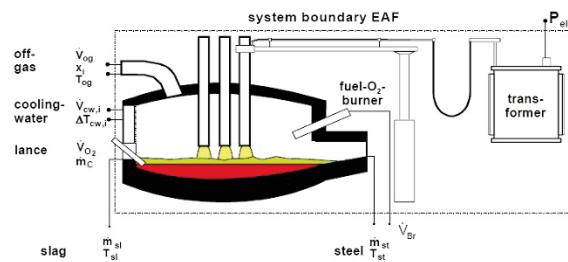


Figure 3. The materials and energy balance system boundary of EAF process [27]

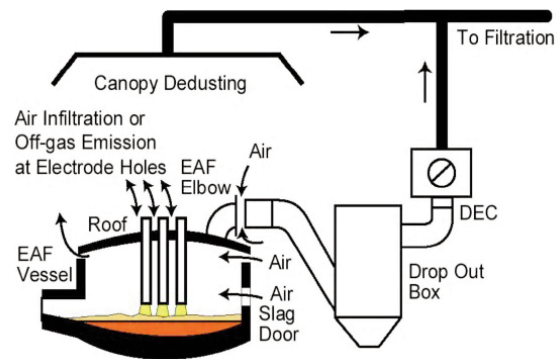


Figure 4. The schematic diagram of exhausting at EAF process

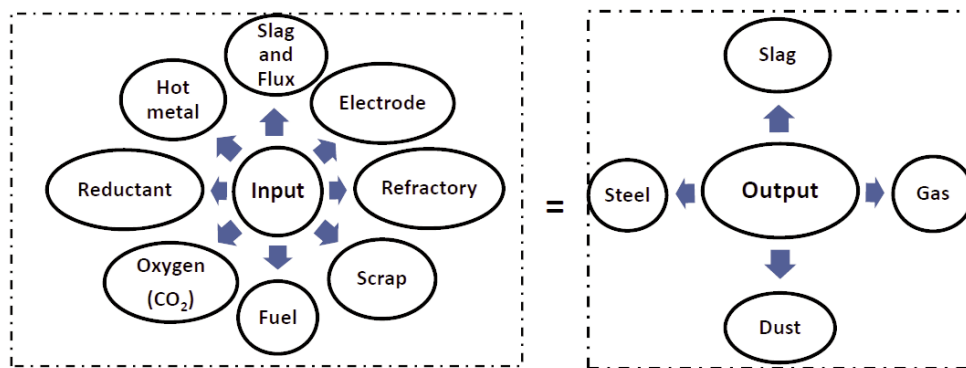


Figure 5. Parameters set on materials balance calculation

hot metal is introduced for energy consumption, while 63% of the energy is output into steel. The electric energy need in current cases is different from the one shown in Figure 2, because the authors introduced hot metal as well as CO₂ in the EAF process, which will be discussed in details in the following paragraphs.

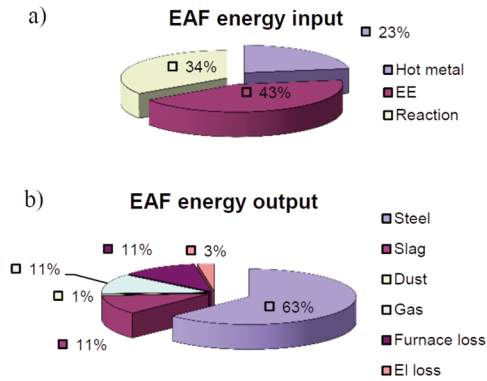


Figure 6. Typical energy input (a) and output (b) in current energy balance calculation

4. Results and Discussion

As discussed in chapter 3, CO₂ introduction is an endothermic reaction, which indicates that, it needs electric energy compensation in order to keep the temperature constant. Heat and materials balances with introduction of CO₂ were calculated with different amounts of CO₂. At the same time, the proportion of materials, like hot metal and scrap amount were also estimated. The results obtained are discussed in this chapter.

4.1 The verification of the calculation basis

The heat and material balances were tested in the case of the Swedish reference EAF plant A of 65 ton capacity, producing high alloy steel, and the difference between the results of the theoretical calculation and the real production were evaluated.

For heat no. 61143 in the reference plant, the electric energy need is 586 kW·h/t obtained from the present calculation by adjusting the infiltrated air amount in the program, and the real electricity consumption was 586 kW·h/t in the plant, which would indicate that the assumption and the parameters selected in the current calculation are reasonable.

4.2 Energy variation with introduction of CO₂ in EAF process

The amount of CO₂ introduced into O₂ at 1943K was ranging from 0% to 40% for electric energy consumption calculation in the present work. The

calculation results are presented in Figure 7.

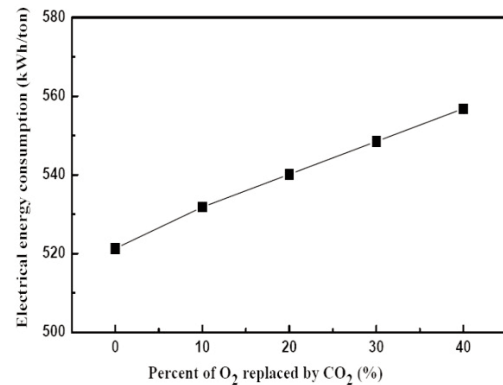


Figure 7. The energy consumption with different gas mixtures at 1943K

From Figure 7, it can be seen that, with the increase of CO₂ in the oxidant gas mixture, the electric energy consumption is increasing. By adding 20% CO₂ in the system, the electric energy will increase by 17kW·h/tls (“tls” is per ton liquid steel). However, if one can retain 0.3 mass% Cr in the melt, the cost saving will then be more than the energy consumption according to the calculation shown in Table 1 based on the industrial data obtained from reference plant A.

Table 1. The estimation of cost saving by introducing CO₂

Items	Cost
20%CO ₂	-17 kW·h/t* 0.5 SEK/kW·h = -8.5 SEK/t
Cr retention	+0.3 mass%* 6900 SEK/t/0.6 = +34.5 SEK/t
Net saving	26.0 SEK/t

The figures in Table 1 were assuming the price of electricity as 0.5 SEK/kW·h and the price of ferrochrome as 6900 SEK/t (Cr content is 60%). From the calculation of the production cost, one could see that, the cost increase due to electricity consumption, caused by 20% CO₂ introduction, will be less than that saved from Cr retention. The Cr retention is around 1.0 mass% with the introduction of pure CO₂ obtained in the earlier experimental studies [1]. However, it is admitted that further confirmatory experimentation would be needed in order to determine the amount of Cr retention with different gas ratios more precisely.

4.3 The way to increase the hot-metal charge by introducing CO₂

As pointed by the previous researchers [29-31], one way to save energy consumption is by enhancing

the amount of hot metal added in the EAF process, which is applied widely in China nowadays. However, the increase of hot metal amount will increase the initial carbon content in EAF significantly. Hence

1) It will prolong the duration time of decarburization, which increase the tap-to-tap time, decrease the productivity;

2) Decarburization with O₂ will increase the temperature in EAF resulting in the “boiling” of slag in the furnace, leading to problems for the downstream refining processes. High initial carbon amount would lead to intensive slag foaming during decarburization with oxygen. And too high temperature will cause serious damage to the refractory lining of the furnace.

If a part of oxygen is replaced by CO₂ in the beginning, this may

1) Reduce the temperature increase during decarburization. In this case, the slag “boiling” during decarburization would be minimized. Control the bath temperature, prolonging the lifetime of the furnace lining can be achieved.

2) Increase the efficiency of decarburization using CO₂ has been demonstrated in earlier experiments [1]. The tap-to-tap time will be shortened to some extent at high initial carbon content. In this case, energy consumptions due to the addition of hot metal in case of CO₂-O₂ blowing could also be evaluated.

The parameters for current calculations were taken as following: EAF for carbon steel refining; steel amount is 110t; aim carbon is 0.06 mass%. The compositions of charge mix including hot metal and scrap are shown in Table 2. And the compositions of steel product are shown in Table 3.

Table 2. Compositions of Hot Metal (HM, 1400 °C) and scrap (25 °C) in mass percentage

	C	Si	Mn	S	P	Al	Fe
HM	4.5	0.56	0.24	0.03	0.085	-	94.585
Scrap	0.4	0.4	0.6	0.02	0.02	0.02	98.54

Table 3. The compositions of steel product in mass percentage

C	Si	Mn	S	P	O	Fe
0.06	0.02	0.09	0.015	0.009	0.05	-

During heat and materials calculations, it is essential to consider PCR ($PCR = \frac{CO_2}{CO_2 + CO} \times 100\%$) value when introducing CO₂ to get more accurate energy requirement. When the composition of CO₂ changed, the PCR will be recalculated. Normally, PCR is in the range of 20-30%. For current calculation, PCR is selected as 15-20%, because more CO will generated

when decarburize the melt with CO₂.

The energy balances for different gas mixtures with different materials ratios were calculated and the results are listed in Table 4.

Table 4. Energy balance calculation for different materials and gas mixtures

HM mass%	Scrap mass%	Gas volume ratio	PCR	Total Heat, kW·h	Heat kW·h/ts
0	100	100%O ₂	18.4	41939	381.3
0	100	100%O ₂	18.4	42137	383.1
10	90	95%O ₂ +5% CO ₂	17.87	42650	387.7
10	90	95%O ₂ +5% CO ₂	18.4	42572	387
20	80	95%O ₂ +5% CO ₂	18.4	37012	336.5
30	70	95%O ₂ +5% CO ₂	18.4	31436	285.8
40	60	100%O ₂	17.14	24957	226.9
40	60	95%O ₂ +5% CO ₂	16.54	25875	235.2
40	60	95%O ₂ +5% CO ₂	18.4	25422	231.1
50	50	95%O ₂ +5% CO ₂	18.4	20332	184.8
40	60	75%O ₂ +25% CO ₂	18.99	28299	257.3
40	60	50%O ₂ +50% CO ₂	17.88	32422	294.7
40	60	25%O ₂ +75% CO ₂	18.12	36155	328.7
40	60	0%O ₂ +100% CO ₂	18.4	42817	389.2
60	40	100% O ₂	17.5	15838	144
60	40	95%O ₂ +5% CO ₂	13.4	16755	152.3
60	40	95%O ₂ +5% CO ₂	18.4	15241	138.6
60	40	75%O ₂ +25% CO ₂	17.4	20428	185.7
60	40	50%O ₂ +50% CO ₂	17.4	25019	227.4
70	30	95%O ₂ +5% CO ₂	16.5	9836	89.4
70	30	95%O ₂ +5% CO ₂	18.4	9204	83.7

For heat and materials balance calculation, different gases and different charge mixtures were selected, from using 100% scrap to add 70% hot metal in the EAF, and gas ranging from pure O₂ to pure CO₂. For the same materials' proportion and gas mixture, different PCR values were selected for calculation.

Through Table 4, it is found that, under the same input parameters, higher PCR gives lower energy requirement, which is because higher PCR indicates more CO₂ generation and more energy generated from carbon oxidized into CO₂ instead of CO. The energy variation with CO₂ ratio is illustrated in Figure 8 while the energy consumption with different hot metal ratio and PCR is shown in Figure 9.

It is easy to obtain from Figure 8 that, with the increase of CO₂ addition, for the same melt, the energy consumption is increased. For blowing pure

CO₂, the energy requirement would be significant. If one compares the energy needed for 40% hot metal + 60% scrap oxidized by different gases, for pure O₂ introduction, it needs 24957 kW·h energy for the whole system, while blowing pure CO₂, the energy need is 42817 kW·h, which is around 160 kW·h/lts electricity more needed in the case of a 110 ton EAF. It is may not be economical to use pure CO₂ in this case. Hence, the optimized amount CO₂ needs to be further investigated together with experiment in order to obtain the pattern of Cr retention with CO₂ introduction. There is an energy drop at 5% of CO₂ for 60% hot metal + 40% scrap. This is attributed to the fact that, at 5% CO₂, PCR is larger than that used for energy calculations with blowing pure O₂. At this composition of hot metal, the energy decrease with increase of PCR is larger than the energy increase caused by CO₂ introduction. It is also found by present authors that, with the increase of hot metal addition, the energy consumption decreased with larger PCR values, as shown in Figure 9, the lines have an obvious minus slope at 60% hot metal and 70% hot metal as compared to

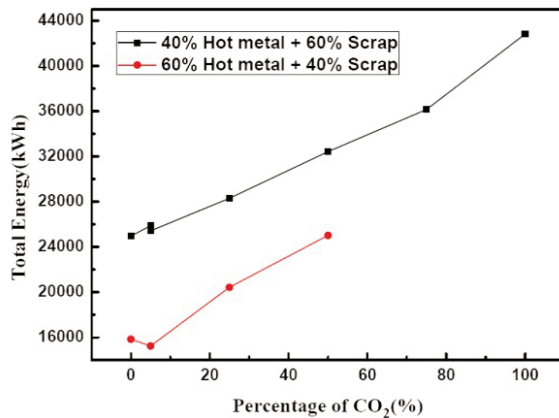


Figure 8. The energy consumption with increase of CO₂ for different charge proportioning

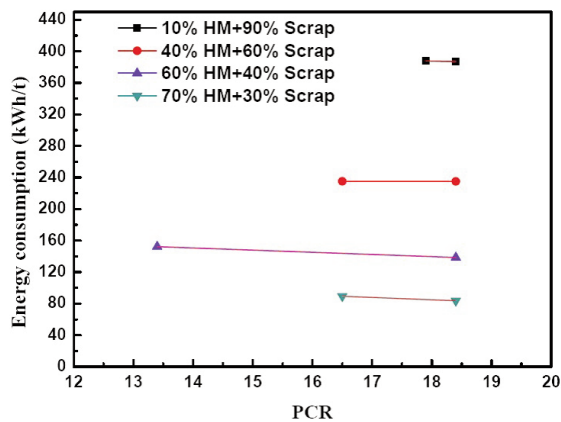


Figure 9. The energy change with PCR at 95% O₂ + 5% CO₂

those corresponding to 10% hot metal and 40% hot metal. This indicates that the energy increase with the introduction of CO₂ may compensate with increase a small amount of PCR at high hot metal charge.

One interesting phenomenon is, for introducing 25% CO₂ in 40% hot metal + 60% scrap, the energy requirement is 30kW·h/tls higher than that with pure oxygen blowing for a 110t EAF, with carbon from 1.2 mass% down to 0.06 mass%. However, this energy consumption can be compensated by introducing more hot metal. As shown in Table 4 and Figure 8, for pure O₂ injected to 40% hot metal + 60% scrap, the energy consumption is the same as that for 60% hot metal + 40% scrap with blowing of 50% O₂ + 50% CO₂, which indicates that enhanced hot metal amount will compensate the energy loss by introducing CO₂. This also shows the possibility of using high initial carbon at EAF process. Hence, one can add high carbon ferrochrome to EAF to save the cost, since the price of low carbon ferrochrome is 1.5-2 times of that of high carbon ferrochrome.

The energy consumption change with hot metal amount varying is shown in Figure 10.

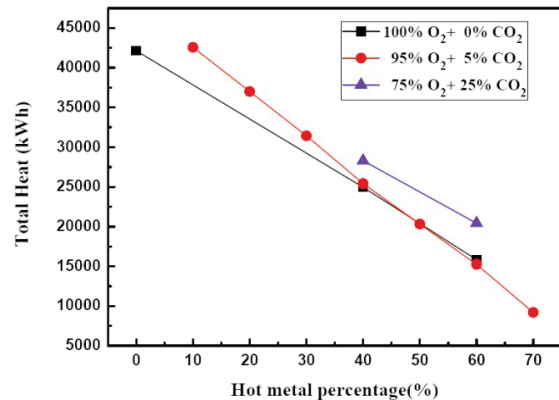


Figure 10. The energy needed with hot metal increase in EAF

It is shown in Figure 10 that, with the increase of hot metal charge, for the same gas composition, the energy need is decreased, which indicates that hot metal charge will decrease energy supply. For 95% O₂ + 5% CO₂, the energy change with hot metal amount is most obvious, shown by the sharper slope of the line. For pure O₂ and 25% CO₂ introduction, the energy slopes are similar and smaller than that with 5% CO₂ introduction. That may indicate that, hot metal charging with the aim to save energy is more effective in 5% CO₂ introduction. This, however, needs further confirmation by experiments. But the tap-to-tap time could be shortened by introducing CO₂ as indicated by the experimental result [1] as

this would compensate the decarburization time increase caused by high carbon content due to the addition of hot metal.

5. Conclusions

Through the present calculation and analysis, one could conclude that:

The introduction of CO₂ will increase electric energy consumption if one wants to keep the constant temperature and this would be proportional to the amount of CO₂ introduced. The producer can profit if 0.3 mass% Cr is saved when blowing 25% CO₂ which would increase the electric energy needed.

Energy consumption because of introducing CO₂ can be compensated by introducing more hot metal. For pure O₂ injected to 40% hot metal + 60% scrap, the energy consumption is the same as that for 60% hot metal + 40% scrap blowing 50% O₂ + 50% CO₂.

The energy consumption decreases with hot metal ratio increase in EAF. It is shown that the best effect due to CO₂ introduction is 5% in O₂-CO₂ gas mixtures. The tap-to-tap time could be shortened by introducing CO₂ to enhance the decarburization effect. This estimate does not take into account the cost savings by Cr retention in the metal.

In order to decrease electric energy consumption, hot-metal charge ratio could be increased, and with the aim to avoid the overheating of bath, CO₂ could be introduced properly.

6. Future work

CO₂ introduction during EAF is a complicated physico-chemical process, which requires the consideration of both thermodynamic and kinetics aspects. Hence, it is necessary to divide the decarburization into different steps and change gas ratio to see the energy change and to find out the economical way for the gas blowing. And the aim to use CO₂ is not only for enhancing decarburization effect, but also for Cr retention. One needs to consider Cr saving during the whole process and find the economical way to use CO₂. Besides, heat balance calculations need to be supported by experimental work, which is planned in future studies.

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