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Exergy analysis and efficiency in an industrial AC electric ARC furnace

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Abstract

In this study, the steel production process in the AC electric arc furnace (EAF) is discussed and an exergy analysis has been undertaken for the EAF with scrap preheating for an alloyed steel producer in Turkey.
Exergy analysis has been employed to obtain optimum design parameters and operation conditions. In this work; obtained results are compared with measured values and previous literature.

Keywords: Exergy; Exergy analysis; Electric arc furnace; Second law analysis

1. Introduction

The term *availability* was made popular in the USA by the M.I.T. School of Engineering in the 1940s. An equivalent term, exergy, introduced in Europe in the 1950s, is finding global acceptance partly because it can be adapted without requiring translation [1]. Exergy is equal to the maximum amount of work obtainable when the stream substance is brought from its initial state to the dead state.

Several disciplines are involved in this development and this has led to concepts such as availability, exergy, second law analysis, exergy analysis, lost work and several others. In some cases these concepts describe the same quantity and sometimes these quantities are quite different [2].

Exergy concept has gained considerable interest in thermodynamic analysis of production process since it has been seen that the first-law analysis has been insufficient from an energy performance standpoint [3].

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Nomenclature

c_p	constant pressure specific heat (kJ/kg K, kcal/kg K)
g	specific Gibbs function (kJ/kg)
g_E	gravitational acceleration (m/s^2)
h	specific enthalpy (kJ/kg)
Q, q	heat (kJ), specific heat (kJ/kg)
S_{gen}	entropy generation (kJ/K)
T	temperature (K)
V	flow rate (m/s)
W, w	work (kJ), (kJ/kg)
W_u	useful work (kJ), (kJ/kg)
Z	height of flow (m)
Ξ^{phy}	physical exergy (MJ)
Ξ^{I}	loss exergy due to irreversibilities (MJ)
$\Xi^{\text{in,ex}}$	incoming/exit exergy of the system (MJ)
μ	chemical exergy potential per kg (kJ/kg)
μ_{i0}	chemical exergy potential per kg at ambient condition (kJ/kg)
μ_{i00}	chemical exergy potential per kg at dead state in the environment (kJ/kg)
Ξ	exergy (MJ)
ψ	exergy efficiency (MJ/MJ)
ε	specific exergy (kJ/kg)
Ξ^{Q}	heat exergy (MJ)
Ξ^{W}	work exergy (MJ)

Subscripts

abs	absorption
che	chemical
cond	conduction
conv	convection
cv	control volume
cw	cooling water
dst	dust
ex	exit
gen	generation
i	for component i
in	inlet
kin	kinetic
loss	loss
ls	liquid steel
phy	physical
pot	potential
rad	radiation

rev	reversible
s	system
s1m	first scrap charging
scr	scrap
sg	stack gases
slg	slug
st-sl	steel in slug
tot	total
u	useful
0	property at environmental conditions
00	dead state in the environment
1/2	inlet/exit

Superscripts

chr	chemical reactions
elect	electric
ex	exit
in	inlet
phy	physical
s	system properties

The iron and steel industry is largest industrial energy consumer. After the employee costs, energy costs (about 30% of the total) represent the second highest cost element in integrated steel works [4].

In this study, an exergy analysis is made for the EAF of 55 tons of casting capacity shown in Fig. 1. A computer program is developed for this purpose and flowchart can be presented in Fig. 2. Obtained results of exergy analysis are compared with practical values and previously published literature. The good agreement between them is observed.

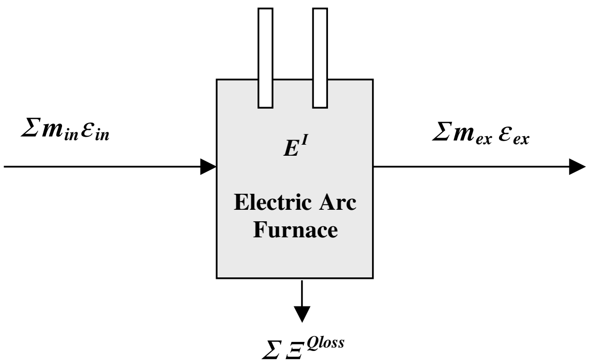

Fig. 1. Schematic display of the EAF.

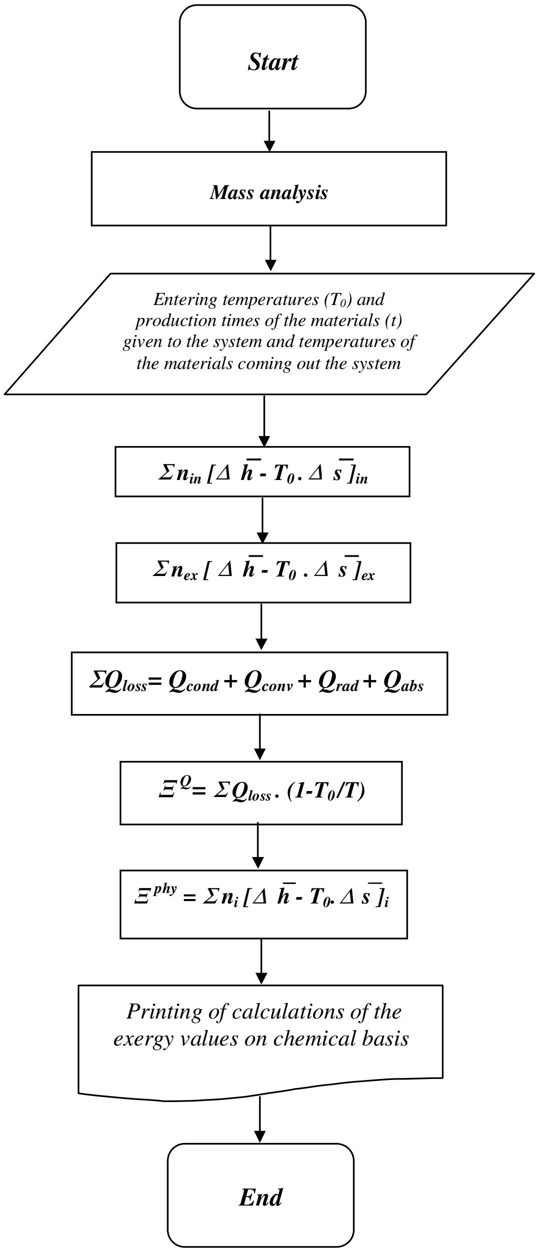

Fig. 2. Flow chart of the computer program, which performs the exergy analysis.

2. The steel production process in the EAF

In arc furnaces, electric arcs pass from the electrodes to a metal charge. It creates electric current through the metal charge resulting in generation heat due to electric resistance of the metal. This heat is supplemented by the radiation from the arcs.

The steel production can be achieved by using the necessary elements in proper amounts. Basic chemical reactions in the electric arc furnace are given as follows [5,6]:

$$2[Fe] + 3[O] \rightarrow [Fe_2O_3]$$

$$[Fe] + [O] \rightarrow [FeO]$$

$$[C] + [O] \rightarrow CO_{(g)}$$

$$[Si] + 2[O] \rightarrow [SiO_2]$$

$$[Mn] + [O] \rightarrow [MnO]$$

$$2[P] + 5[O] \rightarrow [P_2O_5]$$

$$2[Cr] + 3[O] \rightarrow [Cr_2O_3]$$

$$(CaO) + [S] \rightarrow (CaS) + [O]$$

$$(CaCO_3) \rightarrow (CaO) + CO_{2(g)}$$

$$2[Al] + 3[O] \rightarrow [Al_2O_3]$$

$$[Ca] + [O] \rightarrow (CaO)$$

$$[Zn] + [O] \rightarrow [ZnO]$$

$$CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(g)}$$

$$C_2H_{6(g)} + 7/2O_{2(g)} \rightarrow 2CO_{2(g)} + 3H_2O_{(g)}$$

$$C_3H_{8(g)} + 5O_{2(g)} \rightarrow 3CO_{2(g)} + 4H_2O_{(g)}$$

3. Exergy concepts for control volume analysis

Three types of exergy transfer across the control surface are taken into consideration in the model. These are

1. Exergy of work transfer.
2. Exergy of heat transfer.
3. Exergy associated with steady stream of matter.

3.1. Exergy of work transfer

The useful work equivalent of a given form of energy is a measure of its exergy, so it can be written that useful work is equivalent to exergy in every respect. Then, exergy of work is defined as Eq. (1).

$$\Xi^W = W_u \tag{1}$$

3.2. Exergy of heat

The exergy of a heat transfer at the control surface can be defined as follows:

$$\Xi^Q = Q_{cv}(1 - T_0/T) \tag{2}$$

where T is control surface temperature, T_0 is ambient temperature.

3.3. Exergy associated with a steady stream of matter (flow exergy)

Exergy of stream of matter is equal to the maximum amount of work obtainable when the stream is brought from its initial state to the dead state by processes. Exergy of a stream of matter ε (specific form) can be divided into distinct components. These components are written in four forms:

1. Kinetic exergy (ε_{kin}).
2. Potential exergy (ε_{pot}).
3. Physical exergy (ε_{phy}).
4. Chemical exergy (ε_{che}).

The kinetic and potential energies of a stream of substance are ordered forms of energy. So, these are fully convertible to work. Because of the disordered, and, entropy dependent nature of the physical and chemical exergies components can only be determined by considering a composite, two part system, the stream under consideration and the environment [7]. Total specific exergy for the stream flow can be written as

$$\varepsilon_{tot} = \varepsilon_{kin} + \varepsilon_{pot} + \varepsilon_{phy} + \varepsilon_{che} \tag{3}$$

The kinetic, potential, physical and chemical exergies evaluated at the temperature and the pressure of the environment T_0, P_0 can be defined as follows:

$$\varepsilon_{kin} = V_i^2/2 \tag{4}$$

$$\varepsilon_{pot} = g_E Z_i \tag{5}$$

3.3.1. Physical energy

Physical energy can be obtained using module given in Fig. 3. The state of the stream under consideration at the entrance to the module is defined by P_1 and T_1. The exit state corresponds to the environmental state (P_0, T_0). The only interaction associated with the processes in the module is reversible heat transfer with the environment, which is:

$$q_{rev} = T_0(s_0 - s_1) \tag{6}$$

The steady flow energy can be defined by the following equation:

$$q_{rev} - w_{rev} = h_0 - h_1 \tag{7}$$

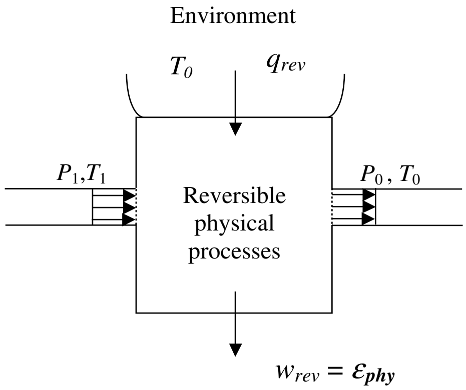

Fig. 3. A reversible module.

The reversible work delivered by the module is equal to the specific physical exergy of the stream. Thus, based on Eqs. (6) and (7) [7]:

$$\varepsilon_{\text{phy}} = (h_1 - T_0 s_1) - (h_0 - T_0 s_0) \tag{8}$$

Physical exergy for species i can be defined by the following equation:

$$\varepsilon_{\text{phy}} = (h_{i1} - h_{i0}) - T_0(s_{i1} - s_{i0}) \tag{8a}$$

3.3.2. Chemical exergy

Chemical exergy equation can be defined by the following equation:

$$\varepsilon_{\text{che}} = \sum_i (\mu_{i0} - \mu_{i00}) \tag{9}$$

μ_{i0} and μ_{i00} in Eq. (9) can be written for ideal gases as follows:

$$\mu_{i0} = g_i(P_0, T_0) + RT_0 \ln(P_{i0}/P_0) \tag{9a}$$

$$\mu_{i00} = g_i(P_0, T_0) + RT_0 \ln(P_{i00}/P_0) \tag{9b}$$

where

$$g_i(P_0, T_0) = h_{i0} - T_0 s_{i0} \tag{9c}$$

In Eqs. (9a) and (9b):

P_{i0}: partial pressure of ith component at T_0 and P_0 conditions;
P_{i00}: partial pressure of ith component at dead state.

If some of the species i of system or of streams do not exist in environment, μ_{i00} will be determined by one of the known methods such that $\mu_{i0} - \mu_{i00}$ will be equal to the chemical exergy of these species at T_0, P_0 [8].

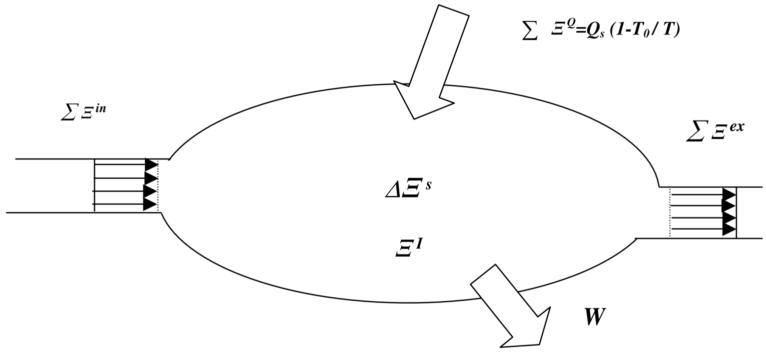

Fig. 4. Exergy balance of an open system.

4. Modeling of exergy balance

Exergy balance for the system shown in Fig. 4 can be written by the following equation.

$$\Delta\Xi^{s} = \sum \Xi^{in} - \sum \Xi^{ex} - W + \sum Q_{s}(1 - T_{0}/T) - \Xi^{I} \quad (10)$$

This equation shows that exergy decrease due to the irreversibilities.

4.1. The electric arc furnace application

The energies and exergies going in and going out of an EAF and obtained results from this study are compared with the values presented in Table 1 [9].

4.1.1. For the example arc furnace

The schematic diagram of the EAF is shown in Fig. 1 and the exergy balance for this system can be obtained using Eqs. (11)–(11c). Following assumptions have been made during exergy analysis.

- *The furnace is a steady state process.*
- *The changes of potential and kinetic energy of materials going into the EAF and coming out of the EAF are neglected.*
- *Stack gases are assumed as ideal gases.*

Table 1
Values of energies and exergies of the EAF with scrap preheating, which are given in literature [9]

Inlet energies and exergies			Outlet energies and exergies		
Source	Energy (%)	Exergy (%)	Product	Energy (%)	Exergy (%)
Electrical energy	60	60	Liquid steel	57	41.9
Scrap	7	2.16	Waste gas	21	15.3
Oxy-fuel burner	3	3	Slag	10	7.6
Liquid reaction chemical energy	30	30	Refrigeration water and various	12	0.3
			Exergy destruction in the furnace		30.06

The exergy balance for the EAF can be written as follows:

$$\sum_{\text{in}} m_{\text{in}}\varepsilon_{\text{in}} = \sum_{\text{ex}} m_{\text{ex}}\varepsilon_{\text{ex}} + \sum \Xi^{\cos s} + \Xi^{\text{I}} \tag{11}$$

Therefore

$$\sum_{\text{in}} \text{m}_{\text{in}}\varepsilon_{\text{in}} = \text{m}_{\text{scr}}\varepsilon_{\text{scr}} + \text{m}_{\text{cw}}\varepsilon_{\text{cw}} + \Xi^{\text{elect}} + \Xi^{\text{chr}} \tag{11a}$$

where

$$\begin{aligned}\Xi^{\text{chr}} = \{ & m_{\text{Fe}_2\text{O}_3}\varepsilon_{\text{Fe}_2\text{O}_3} + m_{\text{FeO}}\varepsilon_{\text{FeO}} + m_{\text{CO}}\varepsilon_{\text{CO}} + m_{\text{SiO}_2}\varepsilon_{\text{SiO}_2} + m_{\text{MnO}}\varepsilon_{\text{MnO}} + m_{\text{P}_2\text{O}_5}\varepsilon_{\text{P}_2\text{O}_5} \\ & + m_{\text{Cr}_2\text{O}_3}\varepsilon_{\text{Cr}_2\text{O}_3} + m_{\text{CaS}}\varepsilon_{\text{CaS}} + m_{\text{O}}\varepsilon_{\text{O}} + m_{\text{CaO}}\varepsilon_{\text{CaO}} + m_{\text{CO}_2}\varepsilon_{\text{CO}_2} + m_{\text{Al}_2\text{O}_3}\varepsilon_{\text{Al}_2\text{O}_3} \\ & + m_{\text{ZnO}}\varepsilon_{\text{ZnO}} + m_{\text{H}_2\text{O}}\varepsilon_{\text{H}_2\text{O}}\} - \{m_{\text{Fe}}\varepsilon_{\text{Fe}} + m_{\text{O}}\varepsilon_{\text{O}} + m_{\text{C}}\varepsilon_{\text{C}} + m_{\text{Si}}\varepsilon_{\text{Si}} + m_{\text{Mn}}\varepsilon_{\text{Mn}} + m_{\text{P}}\varepsilon_{\text{P}} \\ & + m_{\text{Cr}}\varepsilon_{\text{Cr}} + m_{\text{CaO}}\varepsilon_{\text{CaO}} + m_{\text{S}}\varepsilon_{\text{S}} + m_{\text{CaCO}_3}\varepsilon_{\text{CaCO}_3} + m_{\text{Al}}\varepsilon_{\text{Al}} + m_{\text{Ca}}\varepsilon_{\text{Ca}} + m_{\text{Zn}}\varepsilon_{\text{Zn}} + m_{\text{CH}_4}\varepsilon_{\text{CH}_4} \\ & + m_{\text{C}_2\text{H}_6}\varepsilon_{\text{C}_2\text{H}_6} + m_{\text{C}_3\text{H}_8}\varepsilon_{\text{C}_3\text{H}_8}\}\end{aligned} \tag{11b}$$

and

$$\sum_{\text{ex}} m_{\text{ex}}\varepsilon_{\text{ex}} = m_{\text{ls}}\varepsilon_{\text{ls}} + m_{\text{dst}}\varepsilon_{\text{dst}} + m_{\text{slg}}\varepsilon_{\text{slg}} + m_{\text{st-sl}}\varepsilon_{\text{st-sl}} + m_{\text{sg}}\varepsilon_{\text{sg}} + m_{\text{cw}}\varepsilon_{\text{cw}} \tag{11c}$$

Only physical exergy is taken into account in the above equations given for the EAF. So, ε can be written as Eq. (12).

$$\varepsilon_i = (h_i - h_{i0}) - T_0(s_i - s_{i0}) \tag{12}$$

$$h_i - h_{i0} = \int_{T_0=298}^{T} c_p \,\mathrm{d}T \tag{13}$$

$$s_i - s_{i0} = \int_{T_0=298}^{T} (c_p/T)\,\mathrm{d}T \tag{14}$$

$$\bar{c}_p = a + bT + cT^{-2} \tag{15}$$

$$\sum \Xi^{Q} = \sum Q_{\text{loss}}(1 - T_0/T) \tag{16}$$

$$\Xi^{\text{I}} = \int_1^2 T_0 \mathrm{d}S_{\text{gen}} \tag{17}$$

The *a*, *b* and *c* coefficients of constant pressure specific heat of some substances used in Eq. (15) are given in Table 2 [10].

4.2. Exergy efficiency

Exergy efficiency can be expressed as the ratio of the exergies going out the EAF to the exergies going in the EAF. So, Exergy efficiency is written as follow:

$$\psi = \Sigma m_{\text{ex}}\varepsilon_{\text{ex}}/\Sigma m_{\text{in}}\varepsilon_{\text{in}} \tag{18}$$

Table 2
Constant pressure specific heat and its coefficients of some substances used in the EAF [10]

Substance	a	b	c	$\overline{c_p} = a + bT + cT^{-2}$ (kcal/kmol K)
Fe	4.18	5.92×10^{-3}	0	$4.18 + 5.92\times10^{-3}T$
C	4.1	1.02×10^{-3}	-2.1×10^{5}	$4.1 + 1.02\times10^{-3}T - 2.1\times10^{5}T^{-2}$
$\langle Si \rangle$	5.72	0.59×10^{-3}	-0.99×10^{5}	$5.72 + 0.59\times10^{-3}T - 0.99\times10^{5}T^{-2}$ ($298 < T <$ MP)
$\{Si\}$	6.12	–		6.12 (MP $< T < 1873$); MP:1685 K
FeO	12.38	1.62×10^{-3}	-0.38×10^{5}	$12.38 + 1.62\times10^{-3}T - 0.38\times10^{5}T^{-2}$
$\langle Fe_2O_3 \rangle_\alpha$	23.5	18.6×10^{-3}	-3.55×10^{5}	$23.5 + 18.6\times10^{-3}T - 3.55\times10^{5}T^{-2}$ ($298 < T < 950$)
$\langle Fe_2O_3 \rangle_\beta$	36	–	–	36 ($950 < T < 1050$)
$\langle Fe_2O_3 \rangle_\delta$	31.7	1.76×10^{-3}	–	$31.7 + 1.76\times10^{-3}T$ ($1050 < T < 1873$)

$T = T(K)$; $\langle\rangle$: solid-phase; $\{\}$: liquid-phase; $\langle\rangle_\alpha$: α-phase; $\langle\rangle_\beta$: β-phase; $\langle\rangle_\delta$: δ-phase; MP: melting point.

5. The computer solution of the exergy analysis

Exergy analysis in the EAF is conducted using the computer program, which was developed in Q-Basic language. The flow chart of the program is given in Fig. 2. The obtained numerical results are tabulated in Tables 3–7.

5.1. Exergy efficiency

Numerical value of exergy efficiency can be obtained as follows:

$$\psi = \Sigma m_{ex}\varepsilon_{ex}/\Sigma m_{in}\varepsilon_{in} = (1 - 53366.4/119884) = 0.55$$

6. Discussions and conclusions

- The values of incoming and outgoing energies and exergies are compared in the Table 1. Constant pressure specific heat and its coefficients of some substances are shown in Table 2. Exergy values of substances on a chemical component basis going into the EAF, are shown in Table 3. Exergies of chemical reactions in dust, slag, stack gases and exergy for the endothermic reactions are calculated and presented in Tables 4 and 5 respectively.
- Exergy values of liquid steel, dust, slug, steel in slug, stack gases and cooling water on a chemical component basis going out of the EAF, are shown in Table 6.
- Exergy going into the EAF and exergy going out of the EAF values are presented in the Table 7 and overall exergy loss in the system is found to be 44.5%. The exergy losses in the EAF are caused by chemical reactions, heat transfer and other reasons.
- Importance of controlling of outlet temperature of liquid steel must be realized because the liquid steel has a significant exergy value of 54491.6 MJ as can be seen from Table 7.

Table 3
Exergy values of substances going into the EAF on a chemical component basis

Chemical component	Exergy (Ξ) (MJ)	Chemical component	Exergy (Ξ) (MJ)
First scrap charging (500 K)		*Third scrap charging (500 K)*	
Fe	776*	Fe	298.4
C	14.6**	C	5.6
Si	5***	Si	1.9
Mn	5.5****	Mn	2.1
P	0.5	P	0.2
S	0.8	S	0.3
Cr	3.4	Cr	1.3
Ni	1	Ni	0.4
Mo	0.4	Mo	0.1
Cu	1.3	Cu	0.5
Total	808.5	Total	310.8
Cooling water (303 K)			
H_2O	106.5		
Total	106.5		

Note: The exergy calculations of some components are given as follows:
$^{*}\Xi^{Fe} = n_{Fes1m}[\Delta\bar{h}_{Fe} - T_0\Delta\bar{s}_{Fe}]$.
$^{**}\Xi^{C} = n_{Cs1m}[\Delta\bar{h}_{C} - T_0\Delta\bar{s}_{C}]$.
$^{***}\Xi^{Si} = n_{Sis1m}[\Delta\bar{h}_{Si} - T_0\Delta\bar{s}_{Si}]$.
$^{****}\Xi^{Mn} = n_{Mns1m}[\Delta\bar{h}_{Mn} - T_0\Delta\bar{s}_{Mn}]$.
$T_0 = 298$ K, where n_{Fes1m}: mol numbers of Fe in first scrap charging, n_{Cs1m}: mol numbers of C in first scrap charging, n_{Sis1m}: mol numbers of Si in first scrap charging, n_{Mns1m}: mol numbers of Mn in first scrap charging.

Table 4
The exergies of chemical reactions

Chemical component	Exergy (Ξ) (MJ)	Chemical component	Exergy (Ξ) (MJ)	Chemical component	Exergy (Ξ) (MJ)
Exergy of chemical reactions occurring in dust		*Exergy of chemical reactions occurring in slag*		*Exergy of chemical reactions occurring in stack gases*	
Fe_2O_3	2612.6[a]	CaO	3.5	CO	13507.4
CaO	0.1	SiO_2	7946.8	CO_2	4895.2
MnO	274.1	FeO	3185.3	CH_4	487.2
Cr_2O_3	22.4	MnO	2466.6	C_2H_6	1.2
ZnO	3.2	Fe_2O_3	1441.4	C_3H_8	0.3
Total	2912.4	P_2O_5	424.3	Total	18891.3
		Al_2O_3	2309.8		
		Cr_2O_3	149.8		
		Total	17927.5		

$\varepsilon = \int_{T_0=298}^{T} c_p \mathrm{d}T - T_0 \int_{T_0=298}^{T} (c_p/T)\mathrm{d}T$.

[a] $\Xi^{Fe_2O_3} = m_{Fe_2O_3}\varepsilon_{Fe_2O_3} - m_{Fe}\varepsilon_{Fe} - m_O\varepsilon_O$.

- The energy efficiency was found to be 96% according to the first law although the exergy efficiency is found to be 55% according to the second law.

Table 5
Exergy for the endothermic reactions

Chemical component	Exergy (Ξ) (MJ)
$CaCO_3$	1325.1
CaS	29.6
Total	1354.7

Table 6
Exergy values of the substances going out the EAF on a chemical component basis

Chemical component	Exergy (Ξ) (MJ)	Chemical component	Exergy (Ξ) (kJ)
Liquid steel (1873 K)		*Dust (1673 K)*	
Fe	53862	Fe_2O_3	420
C	101.7	CaO	42.7
Si	68.1	MnO	33.6
Mn	205.7	Al_2O_3	72.6
P	9.7	Cr_2O_3	21.7
S	36.4	SiO_2	26.5
Cr	59.4	C	35.5
Ni	60.4	ZnO	0.4
Mo	13.6	Total	653
Cu	74.6		
Total	54491.6		
			Exergy (Ξ) (MJ)
Slug (1873 K)		*Steel in slag (1873 K)*	
CaO	1421	Fe	290
SiO_2	762.6	C	0.5
FeO	742.3	Si	0.4
MnO	367.7	Mn	1
Fe_2O_3	263.4	P	0.05
P_2O_5	78.7	S	0.2
Al_2O_3	285	Cr	0.3
Cr_2O_3	175.3	Ni	0.3
CaS	10.5	Mo	0.07
MgO	0.1	Cu	0.4
Total	4106.6	Total	293.2
			Exergy (Ξ) (kJ)
Stack gases (1673 K)		*Cooling water (311 K)*	
CO	2787.8	H_2O	707.7
CO_2	1344.9	Total	707.7
H_2O	775.8		
N_2	2.1		
Total	4910.6		

- The exergy losses obtained in this study are 14.5% more than those in the literature. This discrepancy comes from the fact that the modeled furnace is assumed to work less efficiently than those in the literature. It is possible to decrease the production costs of the system by taking necessary precautions.

Table 7
Exergy balance of the system

Material	Exergy (Ξ) (MJ)	Material	Exergy (Ξ) (MJ)
Exergy going into the EAF		*Exergy going out the EAF*	
First scrap charging	808.5 (0.67%)	Liquid steel	54491.6 (45.5%)
Second scrap charging	0 (0%)	Dust	653 (0.5%)
Third scrap charging	310.8 (0.25%)	Slug	4106.6 (3.4%)
Coke	0 (0%)	Steel in slug	293.2 (0.2%)
Fluxes	0 (0%)	Stack gases	4910.6 (4.1%)
Deoxidization materials	0 (0%)	Cooling water	707.7 (0.6%)
Electrode	0 (0%)	Endothermic reactions	1354.7 (1.1%)
Natural gas	0 (0%)	Exergy losses	53366.4 (44.5%)
Oxygen	0 (0%)	Total	119884 (100%)
Cooling water	106.5 (0.08%)		
Electric energy	78927 (66%)		
Chemical reactions	39731.2 (33%)		
Total	119884 (100%)		

- The cooling water of 600 tons is used per casting, leaves the furnace with a temperature difference of 8 °C as between 30 and 38 °C. From the standpoint of first law of thermodynamics, one can see that the cooling water carries a significant amount of energy out of the system [11,12]. However, from standpoint of the exergy analysis, it carries only 0.6% of the total exergy out of the system. Therefore, it can be seen that the cooling water exergy is rather low.
- It is clearly seen that the chemical reactions, which play an important role in the production of the steel of desired composition, have a significant proportion of exergy (33% in modeled EAF).

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