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Exergy Analysis of Ceramic Production in Jordan

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Abstract

In this paper, the ceramic production in Jordan is investigated using the methodology of exergy analysis in order to use energy more efficiently. The major aim of the ceramic industry in Jordan is to minimize the energy cost in order to be a competent industry. The energy and exergy of inputs and outputs for different processes of ceramic production are evaluated. The exergy efficiency is found to be about 48.5% which is considered to be low. This fact in addition to the high cost of energy explains why the ceramic industry in Jordan can't be a strong competent to ceramics imported from other countries. One of the main suggestions to improve this industry is to reuse the waste energy from the kilns in the drying process. Another suggestion is to use the heavy fuel oil (HFO) instead of diesel and kerosene.

Keywords: Exergy; Exergy analysis; Ceramic production; Exergy efficiency; Exergy losses

1. Introduction

The ceramic production in Jordan is encountering many problems related to the waste energy, high energy cost and the environmental effects. The exergy analysis is considered as a powerful method in the performance evaluation of an engineering process. In this paper, the exergy analysis method will be used to investigate the ceramic production in Jordan in order to use energy more efficiently. This analysis will be conducted on the most exergy consuming units in the Jordan Ceramic Factory / Zarqa from which the data were taken. The exergy efficiency and losses will be calculated. These calculations give a clear view of the performance of this factory. The chemical exergy of the reactions involved in the various stages will also be calculated and examined. Based on these calculations, some suggestions will be given to improve this industry.

Many researchers investigated the exergy analysis in different engineering applications. Among them carried out the exergy investigations of the energy consumption in the industrial sector, such as Oladiran and Meyer [1]. They analyzed the energy consumption in the industrial sector in South Africa by considering only four principal sub-sectors. They calculated the average energy and exergy efficiencies for each sub-sector and then they obtained the overall values for the industrial sector based on the primary energy utilization data. Koroneos et al. [2] examined the cement production in Greece by using the method of exergy analysis in order to minimize the energy costs and environmental effects.

Camdali et al. [3] applied the energy and exergy analyses for a dry system rotary burner in a cement plant in Turkey. Utlu and Hepbasli [4] evaluated the energy and exergy efficiencies in the Turkish utility sector for a period from 1990 to 2004. They performed the energy and exergy analyses for eight power plants based on the actual data over the period studied.

The exergy analysis method has also been used in the areas of residential, transportation, environmental and trading sectors. Taufiq et al. [5] described the modeling and optimization analysis for HVAC in Malysia. They used the exergy analysis method in evaluating the overall and component efficiencies and to determine the losses. Talens et al. [6] suggested exergy analysis method to assess the environmental performance of a system like the process of biodiesel production.

Saidur et al. [7] applied the energy and exergy analyses for different modes of transport in Malaysia and they compared their results with other countries like Turkey. Jaber et al. [8] made historical investigation from 1985 to 2006 to determine the energy and exergy efficiencies of the Jordanian transportation sector.

Chen and B. Chen [9] investigated the resource inflow to the Chinese society between 1980 and 2002 based on the exergy analysis method. Tsatsaronis [10] presented the definitions of some terms and nomenclature that are used in exergy analysis.

The production of ceramic consumes a large amount of energy in any industrial sector. The energy cost of the ceramic industry has a great percentage of the total production cost. A large number of studies have been published in this area. A handy manual sponsored by United Nations Industrial Development Organization (UNIDO) investigated the ceramic production from different points of view [11]. Dincer and Rosen [12] illustrated in details how an exergy analysis could be done for industrial processes. They also showed the relation between exergy and energy with the sustainable development. Cengel and Boles [13] and Sonntag et al.

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[14] introduced and explained the fundamental of thermodynamics including exergy concept in addition to a comprehensive illustration of the concept of chemical exergy.

Based on the previous studies conducted in the literature, it is clear that no one investigated the exergy analysis of the ceramic production. In this study, exergy analysis of the processes involved in the production of ceramic in a ceramic factory in Zarqa, Jordan performed for evaluating the performance of the factory using the actual factory operational data. The exergy losses will also be calculated and the chemical exergy of the reactions will be calculated and examined.

2. Manufacturing Processes of Ceramic

The main stages of ceramic production in the factory under consideration are illustrated in Figure 1. These stages are:

1. Raw materials: The raw materials are all from Jordan. They contain:

   - Kaolin (Al2O3.SiO2.2H2O): this comes from two main areas in Jordan, Batn AlGhol and Mahis.
   - Calcium Carbonate (limestone) (CaCo3): it comes from the Jordan Carbonate Company in Amman. Both Kaolin and Calcium Carbonate are used to increase the thermal expansion of the ceramic block in order to make it straight.
   - Sand: it is brought from AlDisi area. The sand is used to increase the absorption of the mixture.
   - Water (H2O): it is used as a solvent media.

2. Grinding: In this process, the raw materials are mixed with water in a proper proportion and are grinded in a ball mill to make a homogeneous mixture. Ball mills and blungers are used for grinding. This process continues until we get slurry of the required density.

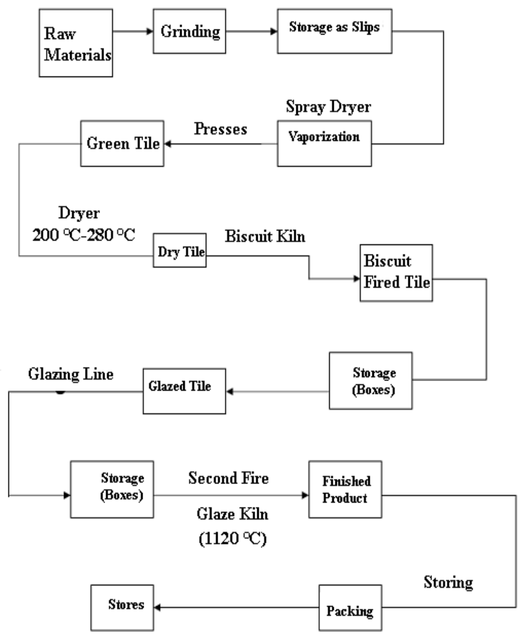

Figure 1: Ceramic production stages.

3. Storing: After preparation of the slurry of required density, it is stored in as slips. Slurry is then pumped at the ambient temperature through a hydraulic pump into the spray dryer where the slurry is sprayed through nozzles.
4. Vaporization in the spray dryer: Material is dried in spray dryer, so the moisture added during grinding process is removed in the spray dryer.The solution is vaporized in the spray dryer at a temperature range of 300°C to 550°C. The maximum temperature may reach 560°C. Hot flue gases are used as a heating source. Hot gases are generated by combustion of fuels such as diesel and kerosene. Input moisture to spray dryer is 35 to 40%, which is dried to 5 to 6 %. This process produces the powder which is then stored in silos and left to cool naturally. Storing: After preparation of the slurry of required density, it is stored in as slips. Slurry is then pumped at the ambient temperature through a hydraulic pump into the spray dryer where the slurry is sprayed through nozzles.
5. Pressing or Forming: The powder in silos is then sent to the hydraulic press where the required sizes of biscuit tiles are formed and sent to dryer through conveyer. This process occurs at a temperature range of 40°C to 50°C in order to prevent the coherence of the pressed powder with the press itself. The pressing process produces the green tile. Metal molds patterns are used for ceramics forming in the factory under consideration. The shape of these molds should consider the shrink of the ceramics when fired.
6. Drying: After press, biscuits containing about 5% to 6% moisture are sent to dryer and dried to about 2% to 3% moisture level. The green tile produced in the previous stage is dried at a temperature range of 200°C-280°C to produce the dry tile. After that, the dry tile is entered to the biscuit kiln with a maximum temperature of 1150°C. The result is a biscuit fired tile. This tile is stored in boxes and moved using kiln cars to the glaze line.
7. Glazing: The biscuit fired tile is entered to the glazing line to produce the glazed tile which is also stored in boxes. The glazed tile is entered to a second fire which is the glaze kiln where the glaze is melted on a maximum temperature of 1100°C without any reaction to produce the finished product.
8. Sorting and packing: The finished product is sorted to different classes then packed and stored.

3. Exergy Analysis

3.1. Equations of Exergy Analysis on Ceramic Production:

The exergy balance (as shown in Figure 2) for the considered process is given by the following equation [2]:

$$E_{input} = E_{product} + E_{losses} + E_{waste} \tag{1}$$

The exergy of inputs (Einput) is the sum of exergies of the raw materials and energy inputs. The exergy of products (Eproducts) is the sum of exergies of the products and by products, in other words, is the useful exergy in the exit streams. The exergy of waste (Ewaste) is the sum of exergies of waste heat, gasses vented to the environment without use, and in solid waste. The exergy losses (Elosses) are the amount of exergy consumed in a system due to internal irreversibilities in the process for raw materials and energy resources and flow conversion.

The exergy of products can be calculated from equation (1) as:

$$E_{product} = E_{input} - E_{losses} - E_{waste} \tag{2}$$

The exergy efficiency is the ratio of the exergy of the useful products to the exergy of all input streams. Exergy efficiency of the process (η) is defined as [15]:

$$\eta = \frac{E_{product}}{E_{input}} = 1 - \frac{E_{losses} + E_{waste}}{E_{input}} = 1 - \frac{\text{exergy destroyed}}{\text{exergy input}} \tag{3}$$

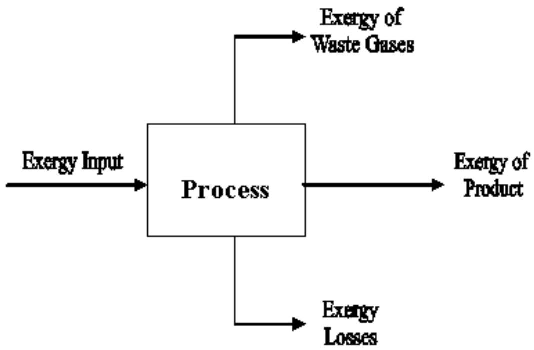

Figure 2: Exergy balance.

The exergy of a system is the sum of the physical exergy, the mixing exergy and the chemical exergy, when other forms of contributions, such as kinetic exergy or potential exergy, etc., are neglected. The total exergy of a stream is given by:

$$E = E_{ph} + E_{mix} + E^{CHEM} \tag{4}$$

where E_{ph} is the physical exergy due to temperature and pressure difference with the environment, E_{mix} is the mixing exergy due to the mixing of the different components, and E^{CHEM} is the chemical exergy due to differences in the materials composition with the environment.

The physical exergy of a given stream is given by the following equation [2]:

$$E_{ph} = H - H_0 - T_0(S - S_0) \tag{5}$$

where H is the enthalpy, H_0 is the enthalpy at atmospheric conditions, T_0 is the temperature of the surroundings, S is the entropy and S_0 is the entropy at atmospheric conditions.

The mixing energy of a gaseous stream is given by the following equation [2]:

$$E_{mix} = RT_0 \sum y_i \ln \frac{y_i}{y_{oi}} \tag{6}$$

where R is the universal gas constant, y_i is the mole fraction in the stream and y_{oi} is the mole fraction in the environment.

The chemical exergy of a substance is given by the following equation [2]:

$$E^{CHEM} = (\mu^0 - \mu_0^0) + RT_0 \ln(\frac{C}{C_0}) \tag{7}$$

where μ^0 is the chemical potential at the standard state, μ_0^0 is the chemical potential at the environmental state, C is the concentration of a substance at the present state and C_0 is the concentration of a substance at the environmental state.

The exergy of heat which represents the maximum amount of work that can be gained reversibly from an amount of thermal energy Q at temperature T is given by the following equation:

$$E_{heat} = (1 - \frac{T_o}{T})Q \tag{8}$$

3.2. Exergy Analysis of Spray Dryer:

The exergy losses as mentioned earlier come mainly from the firing and drying processes. The main exergy losses for drying processes are associated with irreversibilities. The spray dryer which the ceramic factory under consideration uses is of the type air drying. The schematic diagram of the spray dryer is shown in Figure 3. A large amount of exergy is lost with existing air from the dryer. The exergy existing with the product is quite small, since a little exergy is put in the solid products. The exergy loss due to heat rejection from the walls of the dryer is very significant. This loss should be taken into consideration. This amount may reach up to 25% of the total exergy input. This loss can be reduced by appropriately insulating the dryer. The size of the dryer is another important aspect. The jet type ring dryer has smaller dimensions than a spray dryer of an equivalent capacity. Then the jet type ring dryer has a much smaller loss from its walls than a spray dryer [12]. For our ceramic factory, one may recommend to replace the existing spray dyer with a jet type ring dryer.

The inputs and outputs in the spray dryer are shown in Figure 3.

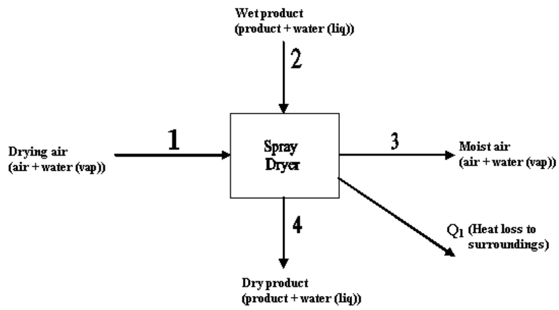

Figure 3: Schematic diagram of the inputs and outputs in the spray dryer.

In this paper, we can use the model of a drying process presented by Dincer and Sahin [16]. Here, the reference environment used in our paper is shown in Table 1.

Table 1: Reference environment model [12].

Temperature	T_0 = 298.15K	
Pressure	P_0 = 1 atm.	
Composition	Atmospheric air saturated with water at Reference conditions has the following composition:	
	Air Constituents	Mole fraction
	N_2	0.7567
	O_2	0.2035
	H_2O	0.0303
	Ar	0.0091
	CO_2	0.0003
	H_2	0.0001

Also, the raw data for the spray dryer in addition to some necessary data are shown in Tables 2 and 3, respectively. These data are used to conduct the exergy analysis to determine the exergy efficiency of the drying process.

Table 2: Raw data associated with the spray dryer.

State	*T* (K)	*P* (kPa)	*ha* or *hw* (kJ/kg)	*hv* or *hp* (kJ/kg)
1	373	150	402	2680
2	298	101.3	104.87	23.17
3	343	125	345	2630
4	363	195	380.9	57.2

Table 3: Some necessary data.

$(C_p)_a$	1.005 kJ/kg.K
$(C_p)_v$	1.8723 kJ/kg.K
R_a	0.287 kJ/kg.K
R	0.4615 kJ/kg.K
ω_o	0.0153
$(x_v)_o$	0.024

Now, the exergy efficiency for the drying process can be defined as the ratio of exergy use in the drying of the product to the exergy of the drying air supplied to the system [12]. That is:

$$\eta = \frac{\text{Exergy input for evaporation of moisture in product}}{\text{Exergy of drying air supplied}} \qquad (9)$$

The analysis has been carried out based on the raw data by applying the procedure given by Dincer and Sahin [16]. The results are given in Tables 4, 5 and 6.

Table 4: Mass balance results.

Mass Balance	
$\dot{m}_p$	3000 kg/h
$\dot{m}_a$	25000 kg/h
ω_1	0.018
$(\dot{m}_w)_2$	300 kg/h
$(\dot{m}_w)_4$	130 kg/h
ω_3	0.0248

Table 5: Energy balance results.

Energy Balance	
h_1	450.24 kJ/kg
h_3	410.72 kJ/kg
$\dot{Q}_1$	867854 kJ/kg
$\dot{E}_q$	321087.63 kJ/kg

Table 6: Exergy balance results.

Exergy Balance	
$(\dot{m}_w)_{ev}$	170 kg/h
$(e_w)_3$	391.03 kJ/kg
$(e_w)_2$	52.9 kJ/kg
e_1	28.82 kJ/kg
η	51%

3.3. Exergy Analysis of the Kilns:

The biscuit and glaze kilns used in the factory considered are roller hearth kilns. This type of kilns is designed as a continuous kiln. A roller conveyer is installed from the kiln inlet to the kiln outlet. Each roller rotates to carry the product to be fired from the inlet to the outlet. This structure eliminates the use of the kiln car.

The kilns consume great amount of energy in the production processes. The kilns consume about 50% of the total energy consumption while the spray dryer consumes approximately the other 50%.

The input exergy comes mainly from the combustion of diesel and kerosene in addition to electricity in the following percentages: 9% from electricity, 50.05% from kerosene and 40.95% from diesel. The exergy coefficient of electricity is assumed to be 1. This means that electrical energy and exergy are equivalent.

The composition of diesel and kerosene is given in Table 7. The composition of both diesel and kerosene does not sum up to 100% because there is also a small percentage of water and ash in both of them.

Table 7: Composition of diesel and kerosene as percentage of mass.

Fuel	Carbon (C)	Hydrogen (H)	Oxygen (O)	Nitrogen (N)	Sulfur (S)	Heating value, DH (MJ/kg)
Diesel	87.5	11.5	0.11	0.21	0.5	42.4
Kerosene	86	12	0.09	0.26	0.44	40.2

The chemical exergy of both diesel and kerosene entering the system is calculated by using the following equation [2]:

$$E^{CHEM} = \Delta H(1.0401 + 0.1728\frac{x_H}{x_C} + 0.0432\frac{x_O}{x_C} + 0.2196\frac{x_S}{x_C}(1 - 2.0628\frac{x_H}{x_C})) \quad (10)$$

where xH, xC, xO, and xS are mass fractions of H, C, O, and S, respectively.

Applying equation (10) for diesel and kerosene we get:

$$E^{CHEM}_{Diesel} = 45.1 MJ/kg.$$
$$E^{CHEM}_{Kerosene} = 42.824 MJ/kg.$$

Exergy of the system for both Biscuit and Glaze kilns can be calculated form Equation 8. The results are summarized in Table 8 shown below.

Table 8: Heat input, exergy and energy availability.

	Biscuit kiln	Glaze kiln
Q [kJ]	26946×10^3	69992.72×10^3
E [kJ]	12425.37×10^3	30111.59×10^3
λ_Q	0.46	0.43

The exergy input to the biscuit kiln 2704.64×103 kJ/kg. While, the exergy output is 1257.66×103 kJ/kg.

Thus, the exergy efficiency for the biscuit kiln is:

$$\eta = \frac{1257.66 \times 10^3}{2704.64 \times 10^3} \times 100\% = 46.5\%.$$

In a similar way, the exergy input to the glaze kiln is 7026.45×103 kJ/kg. While, the exergy output is 3471.07×103 kJ/kg
Thus, the exergy efficiency for the glaze kiln is:

$$\eta = \frac{3471.07 \times 10^3}{7026.45 \times 10^3} \times 100\% = 49.4\%.$$

Now, an analysis of the exergy losses in both the biscuit and glaze kiln is done and shown in Table 9.

Table 9: Exergy losses in the biscuit and glaze kilns.

Heat Loss	Exergy loss glaze kiln [kJ/kg]	% of exergy loss	Exergy loss biscuit kiln [kJ/kg]	% of exergy loss
From the waste exhaust heat	461.12×10^3	32	888.85×10^3	25
From irreversibilities	792.71×10^3	55	2275.30×10^3	64
From radiation and conduction	158.54×10^3	11	248.86×10^3	7
From kilns cars	28.83×10^3	2	142.06×10^3	4

It should be noted that for both kilns the radiation and conduction losses are calculated from the differnces between the energy input and output [11].

As a final result, since the spray dryer, biscuit and glaze kilns are the most energy consuming units in the ceramic production; one can calculate the overall exergy efficiency for the ceramic production in the Jordan ceramic factory to be about 49.48%.

These results are shown schematically using Sankey diagrams, Figures [4] and [5], respectively.

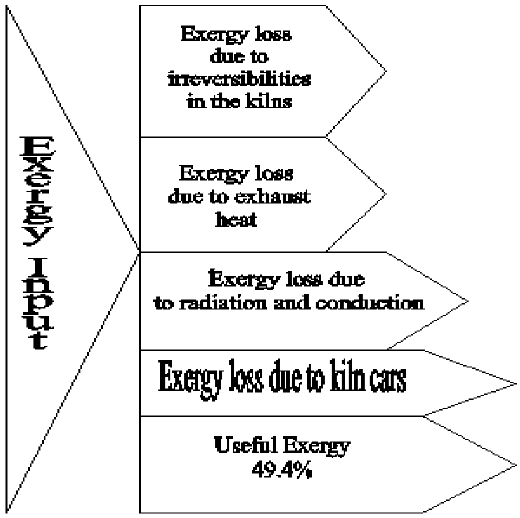

Figure 4: Sankey diagram of the exergy balance for the glaze kiln.

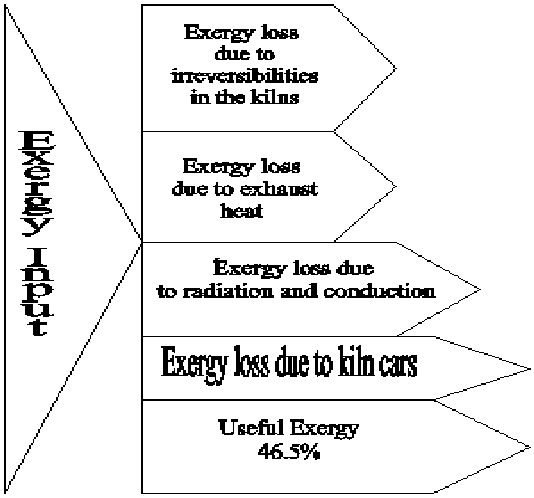

Figure 5: Sankey diagram of the exergy balance for the biscuit kiln.

4. Conclusion

The exergy analysis method is a powerful tool for measuring the efficiency of processes or systems. The results obtained with regard to the exergy efficiency and losses give a clear view of the performance of the considered factory. The exergy efficiency of the ceramic production is calculated to be 49.48. This efficiency is low and means that there is a huge amount of exergy losses.

The spray dryer is the largest energy and exergy consuming unit. Its exergy input represents about 50% of the total consumption of the Jordan ceramic factory. The exergy efficiency of the spray dryer is about 51% which shows that the exergy losses concerned with the spray dryer are 49%. This means that a loss rate is about 433927 kJ/h. The drying equipment is large and it operates at high temperatures. As a result, there is a large amount of heat loss from both convection and radiation. Insulation of the equipment is important to ensure energy efficiency. Large part of these losses is due to internal irreversibilities occurring in the spray dryer.

The second exergy consuming part of the Jordan ceramic factory is the biscuit kiln. The exergy efficiency of the biscuit kiln is about 46.5%. This means that there is an exergy loss of 53.5%. Main loss is due to the irreversibilties during the preheating and cooling processes in addition to the exergy losses of the exhaust gases and waste heat.

The glaze kiln is the third exergy consuming unit. The exergy efficiency of the glaze kiln is about 49.4% which refers to exergy loss of 50.6%. Of these losses, the irreversibilties due the preheating and cooling processes occurred in the glaze kiln represent the largest part as in the biscuit kiln. Also, the exergy losses related to the waste heat and exhaust gases.

Exergy losses by conduction and radiation from the biscuit and glaze kilns are about 7% and 11% of the total exergy losses. This ratio is low but with the time the total amount of losses is considerable. This radiation loss can be reduced by replacing the damaged insulation and improving the existing insulation of the kilns.

A very small exergy loss is due to kiln cars. Kiln cars move the tiles to and from both the glaze and biscuit kilns. These losses are 4% and 2% for the biscuit kiln and glaze kiln respectively.

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