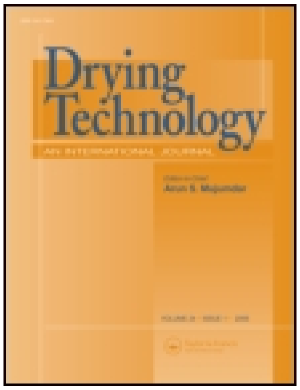

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Performance Analysis and Assessment of an Industrial Dryer in Ceramic Production

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In recent years, exergy analysis has been widely used in the design, operation, and performance assessment of various thermal systems, among which drying, which is an energy intensive operation, is of a great importance. In the ceramic industry, it is aimed at utilizing a minimum amount of energy in order to remove the maximum moisture for the desired final conditions of the product to be dried. In this study, energy and exergy analyses of a ceramic plant, located in Izmir, Turkey, with a yearly production capacity of 24 million m^2 were performed using the actual operational data over a period of 12 months. The drying system at the three stages was analyzed and the values for exergy destruction and efficiency for each component of the system and the whole system at a reference (dead state) temperature of 22°C were calculated. For the month of January, energy and exergy efficiencies for the spray dryer (SD) were determined to be 65.50 and 53.7%, respectively. Energy and exergy efficiency values of the vertical dryer (VD) were 45.12 and 43.3%, respectively, and those of the furnace (F) were 35.08 and 16%, respectively. Based on this one-year assessment, the energy efficiency values for the SD, VD, and F varied between 58.48 and 65.50%, 42.44 and 50.87%, and 30.44 and 36.99%, and the exergy efficiency values were in the range of 44.85–65.16%, 34.92–45.42%, and 12.73–16.41%, respectively.

Keywords Ceramic sector; Drying; Efficiency; Energy analysis; Thermodynamic analysis

INTRODUCTION

Drying can be regarded as one of the most important and most frequently applied unit operation in all sectors producing solid products. Removal of the liquid by evaporation from a system is called *drying*, which is an energy-intensive[1–5] and essential stage of many industrial processes. The term drying generally refers to the removal of moisture or liquid from a wet solid by bringing this moisture into a gaseous state. In most drying operations, water is the liquid evaporated and air is the drying gas normally employed.[1–3] However, drying in ceramic processes, removal of water in clays, and consumption of water through hydration of cementitous materials are involve liquid transport processes in porous media.[1–5]

In many practical applications, drying is a process that requires high energy input because of the high latent heat of water evaporation and relatively low energy efficiency of industrial dryers. Industrial dryers consume on average about 12% of the total energy used in manufacturing processes. In manufacturing processes where drying is required, the cost of drying can approach 60–70% of the total cost.[6,7] Thus, one of the most important challenges of the drying industry is to reduce the cost of energy sources for good quality dried products.[8]

Due to the high prices of energy and decreasing fossil fuel resourses, the optimum application of energy and energy consumption management methods have become very important. This, in fact, requires accurate thermodynamic analysis of thermal systems for design and optimization purposes. Therefore, collection and evaluation of periodical data concerning industry and other final energy-consuming sectors is a primary condition in the determination of targets for the studies of energy savings and regular canalization of applications. In this regard, there are two essential tools available; that is, energy analysis and exergy analysis.

Exergy analysis is the modern thermodynamic method used as an advanced tool for engineering process evaluation.[9] Whereas energy analysis is based on the first law of thermodynamics, exergy analysis is based on both the first and second laws of thermodynamics. The main purpose of exergy analysis is to discover the causes and quantitatively estimate the magnitude of the imperfection of a thermal or chemical process. Exergy analysis leads to a better understanding of the influence of thermodynamic phenomena on the process effectiveness, comparison of the importance of different thermodynamic factors, and

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determination of the most effective ways to improve the process under consideration.[10–15]

It is important to highlight that the exergy of an energy form or a substance is a measure of its usefulness or quality or potential to cause change.[7,16–20] A thorough understanding of exergy and the insights it can provide into the efficiency and environmental impact of drying systems is required for engineers or researchers working in the area of drying technology.[21] Although many experimental and theoretical investigations of heat and moisture transfer analyses of drying of wet materials have been made, energy and exergy analyses of drying systems and processes of wet materials have been studied by few researchers.[7,16–22]

A large amount of energy is consumed in the ceramic industry. A significant number of studies have been published in this field as well.[8,22–24] Among these, there are very important and deductive papers that show not only energy approach to the ceramic industry but the potentials and means of improvement in energy consumption of ceramic industry.

The main objective of this contribution is to determine energy and exergy efficiencies of a ceramic drying process (CDP) during drying of moist particles. This analysis was undertaken based on the actual operational data for a period of 12 months. The structure of the article is as follows: The following section provides a theoretical analysis using mass, elemental, energy, and exegy balance equations. A description of the ceramic production process and the energy utilization in the ceramic drying process is then provided. Mass, elemental, energy, and exergy analysis methods are applied to the plant studied and the results obtained are discussed next, followed by our conclusions.

THEORETICAL ANALYSIS

For a general steady-state, steady-flow process, the following balance equations are applied to determine the work and heat interactions, the rate of exergy decrease, the rate of irreversibility, and the energy and exergy efficiencies.[7,11,12,25]

The mass balance equation can be expressed in the rate form as

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

where $\dot{m}$ is the mass flow rate, and the subscripts *in* and *out* stand for inlet and outlet, respectively.

The general energy balance can be expressed as

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \tag{2}$$

$$\dot{Q} + \sum \dot{m}_{in} h_{in} = \dot{W} + \sum \dot{m}_{out} h_{out} \tag{3}$$

where $\dot{E}_{in}$ is the rate of net energy transfer in; $\dot{E}_{out}$ is the rate of net energy transfer out by heat, work, and mass; $\dot{Q} = \dot{Q}_{net,in} = \dot{Q}_{in} - \dot{Q}_{out}$ is the rate of net heat input; $\dot{W} = \dot{W}_{net,out} = \dot{W}_{out} - \dot{W}_{in}$ is the rate of net work output; and h is the specific enthalpy.

Assuming no changes in kinetic and potential energies with any heat or work transfers, the energy balance given in Eq. (3) can be simplified to flow enthalpies only:

$$\sum \dot{m}_{in} h_{in} = \sum \dot{m}_{out} h_{out} \tag{4}$$

The general exergy balance can be expressed in the rate form as

$$\begin{gathered} \sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{dest} \text{ or} \\ \sum \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_k - \dot{W} + \sum \dot{m}_{in} \psi_{in} - \sum \dot{m}_{out} \psi_{out} \\ = \dot{E}x_{dest} \end{gathered} \tag{5}$$

with

$$\psi = (h - h_0) - T_0(s - s_0) \tag{6}$$

where $\dot{Q}_k$ is the heat transfer rate through the boundary at temperature T_k at location k, $\dot{W}$ is the work rate, ψ is the flow exergy, s is the specific entropy, and the subscript 0 indicates properties at the dead state of P_0 and T_0.

The exergy destroyed or the irreversibility may be expressed as follows:

$$\dot{I} = \dot{E}x_{dest} = T_0 \dot{S}_{gen} \tag{7}$$

where $\dot{S}_{gen}$ is the rate of entropy, and the subscript 0 denotes conditions of the reference environment.

The amount of thermal exergy transfer associated with heat transfer Q_r across a system boundary r at constant temperature T_r is[9,13]

$$ex = [1 - (T_0/T_r)]Q_r \tag{8}$$

The exergy of an incompressible substance may be written as follows:

$$ex_{ic} = C\left(T - T_0 - T_0 \ln \frac{T}{T_0}\right) \tag{9}$$

where C is the specific heat.

Different ways of formulating exergetic efficiency proposed in the literature have been given in detail elsewhere.[26] The exergy efficiency expresses all exergy input as used exergy and all exergy output as utilized exergy. Therefore, the exergy efficiency ε_1 becomes

$$\varepsilon_1 = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} \tag{10}$$

Often, there is a part of the output exergy that is unused; that is, an exergy wasted, $\dot{E}x_{waste}$ to the environment. In this case, exergy efficiency may be written as follows:[26]

$$\varepsilon_2 = \frac{\dot{E}x_{out} - \dot{E}x_{waste}}{\dot{E}x_{in}} \tag{11}$$

Rational efficiency was defined by Kotas[27] and Cornelissen[28] as the ratio of the desired exergy output to the exergy used; namely,

$$\varepsilon_3 = \frac{\dot{E}x_{desired,output}}{\dot{E}x_{used}} \tag{12}$$

where $\dot{E}x_{\mathrm{desired,output}}$ is the total exergy transfer rate from the system, which must be regarded as constituting the desired output plus any by-products produced by the system and $\dot{E}x_{used}$ is the required exergy input rate to the process to be performed. The exergy efficiency given in Eq. (13) may be also expressed as follows:[29]

$$\varepsilon_3 = \frac{\text{Desired exergetic effect}}{\text{Exergy used to drive the process}} = \frac{\text{Product}}{\text{Fuel}} \tag{13}$$

To define the exergetic efficiency, both a *product* and a *fuel* for the system being analyzed are identified. The product represents the desired result of the system (power, steam, a combination of power and steam, etc.). Accordingly, the definition of the product must be consistent with the purpose of purchasing and using the system. The fuel represents the resources expended to generate the product and is not necessarily restricted to being an actual fuel such as a natural gas, oil, or coal. Both the product and the fuel are expressed in terms of exergy.[30]

Van Gool[31] reported that maximum improvement in the exergy efficiency for a process or system is obviously achieved when the exergy loss or irreversibility ($\dot{E}x_{in} - \dot{E}x_{out}$) is minimized. Consequently, he suggested that it is useful to employ the concept of an exergetic improvement potential when analyzing different processes or sectors of the economy, as given in the rate form as follows:[32]

$$I\dot{P} = (1 - \varepsilon)(\dot{E}x_{in} - \dot{E}x_{out}) \tag{14}$$

DESCRIPTION OF INDUSTRIAL DRYER AND ENERGY UTILIZATION IN THE CERAMIC INDUSTRY

Description of the Ceramic Process

Ceramics are defined as inorganic, nonmetallic materials that are consolidated and acquire their desired properties under the application of heat. This application of heat in practice takes place inside high-temperature kilns, usually for long periods of time. Therefore, the ceramics industry is by definition an energy-intensive one. All ceramics production industries are characterized by the lengthy operation of high-temperatures kilns and furnaces; not only is a high amount of energy consumed during the production process, but the energy cost is a significant percentage of the total production cost.[8,22–24]

The industries of the ceramic sector are usually divided into two broad categories: traditional ceramics such as wall and floor tiles, tableware, sanitary ware, and brick and heavy clay and so-called advanced ceramics (electrical and electronic ceramics, technical ceramics, bioceramics, ceramic coatings). Traditional ceramics are the bulk of the overall production of the ceramic sector.[8]

The generalized production scheme for the ceramic industries consists of four basic stages: preparation of raw materials, shaping, drying, and firing. The differences between each particular sector—especially with respect to the shaping process but also with respect to the raw materials used and the drying and firing temperatures employed—depend on the specific requirements of the particular products.[1–5,8]

Ceramic drying and firing process are highly energy intensive and involve the slow and gentle expulsion of water from the green products before the final firing, so that no damage is caused within the body. Temperatures encountered at this stage can vary from 60 to 1200°C. Various types of energy sources are used for heating purposes, including fuel oil, diesel fuel, liquid petroleum gas (LPG), methane or natural gas, coal, and electricity. The main steps in the ceramic drying process studied are illustrated in Fig. 1, which mainly include spray drying (SD), vertical drying (VD), and furnace (F) drying.

Depending on the specific product description in the factory, dusted raw materials are turned into mud and the inter raw material masse emerges as they enter the spray dryer. Masse compound is later formed in the forming presses according to the size of the formworks. Moisture content is reduced while it is in the VD. After this process, it is subjected to the process of tile glazing. This represents the glass that covers the surface as a thin layer of ceramic glaze. Glaze consists of a mixture of water-soluble substances and dissolved substances. Because the water-soluble substances cause various uncontrollable problems when performed on the ceramic layer, the glaze is made as a solution dissolved in water. The baking process starts after the glazing process. The process is put into effect in furnaces with lengths of 85–100 m. Following quality control at the exit of the factory, the products are packed in the packaging section.[33]

The General Structure of the Spray Dryer

SDs used in ceramic factories as a means of drying the tiles are used for converting the wet mud combination into masse. The type of the SD used in this ceramic production process is based on the principle of direct heat transfer. This type of

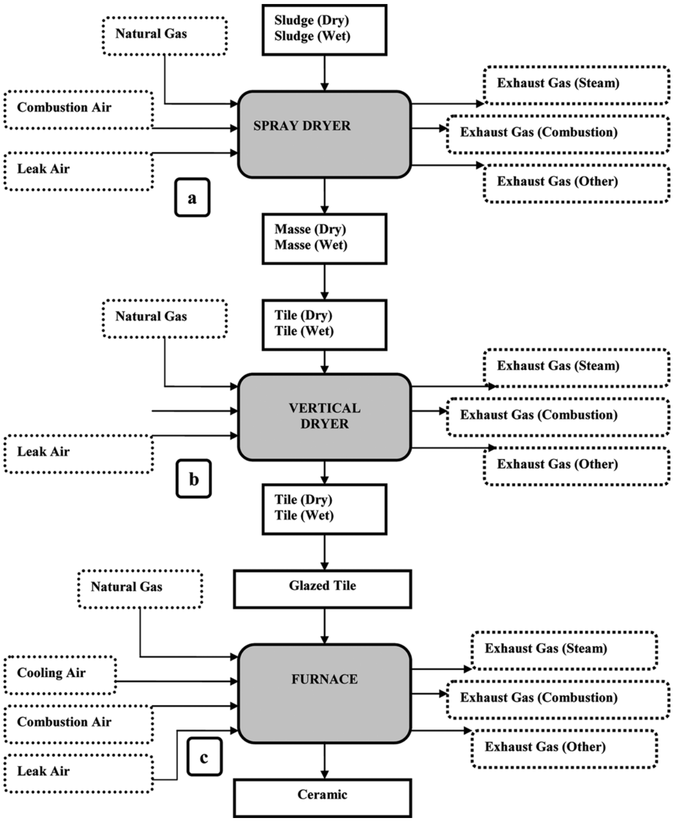

FIG. 1. Flow diagram of the ceramic drying process studied.

spray dryer operates by making the combustion gases counter-currently contact the damp raw material causing heat transfer directly from the hot effluent gas to the water in the raw material resulting in effective evaporation. The schematic perspective of the SD are indicated in Figs. 1a and 2.[34]

General Structure of the Vertical Dryer

Dryers used in the ceramic industry for drying of tile are called vertical and horizontal dryers. In VDs, the wet tile's moisture (5–6%) is reduced to values below 1%. The reduced moisture value is determined by R&D units according to the ceramic raw material recipe.

In a verticle dryer, the file is moved vertically and shaped by the press while it is placed into beds in dryers. The VD system consists of loading–unloading baskets, the system drive, combustion section, and hot air circulation and pneumatic and electric units. The VD system is shown in Fig. 1b.

The General Structure of the Furnace

Baking is one of the most important steps in the production process because it uses a large amount of energy in the drying system. The glazed tile is turned into ceramics in the furnace. Glazed tile in the furnace becomes a crystalline structure when it passes through the hell fire region with temperatures as high as 1200°C and at the exit it takes the form of a ceramic. The schematic perspective of the furnace is indicated in Fig. 1c.

The average length of the furnace is 85–100 m. Baking and internal temperature steps take place in the sections as follows:

- 10% for pre-entrance (0 and 500°C)
- 30% for pre-baking (500 and 1000°C)
- 20% for baking (1000 and 1200°C)
- 6% for fast cooling (1250 and 600°C)
- 20% for slow cooling (600 and 450°C), and
- 14% for final cooling (450 and 65°C)

as the total length of the furnace parts. The objective of this percentage dispersion is a proper cooking temperature

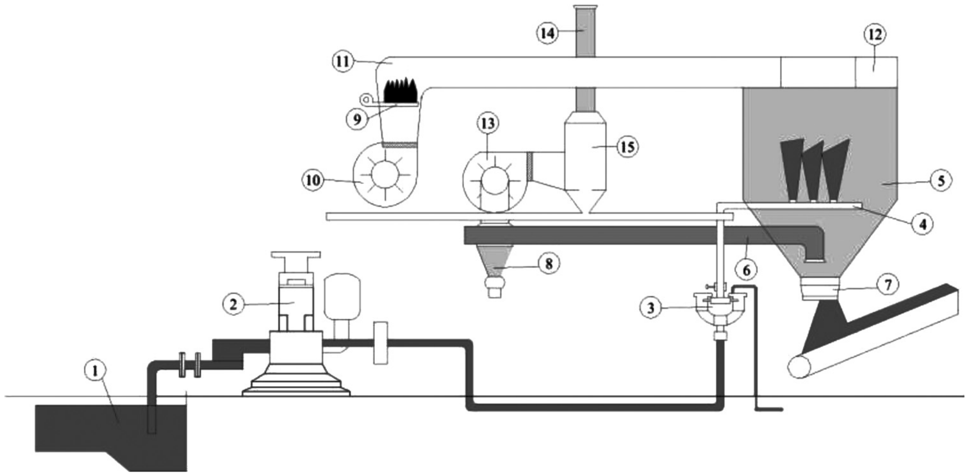

FIG. 2. Spray drying flowchart. 1, Stock pools; 2, sludge feed pumps; 3, mud filters; 4, distributor ring; 5, drying tower; 6, gas–masse dust suction pipe; 7, masse outlet valve; 8, cyclone separator; 9, fuel feed system and burner; 10, combustion air vent; 11, heat transmission channel; 12, hot air distributor; 13, suction air vent; 14, chimney; 15, wet dust holder.

for ceramicswhile regulating heat distribution and temperature changes with the speed of cooking to control the internal stress.[34]

Energy Utilization in the Ceramic Industry

The ceramic industry is an energy-intensive industry. In Turkey, the industry accounted for 12.3% of the total natural gas consumption in the manufacturing sector in 2007.[33] In terms of the primary energy utilization, about 54% of the input energy was natural gas, 38% was LPG, and the remainder was electricity.[33] The specific energy consumption was about 92.93 $\mathrm{kJ/m^2}$ for the process. The higher specific energy consumption in Turkey is partly due to the harder raw material and the poor quality of the fuel. Waste heat recovery from the hot gases in the system has been recognized as a potential option to improve energy efficiency.[33] However, there are few detailed thermodynamic analyses of operating ceramic drying process that evaluate the option of waste heat recovery.[33,34] Specific energy consumption values of the SD, VD, and F are indicated in Table 1.

The values used in the analysis of the system are based on the actual operating data, which we obtained by visiting the plant many times as well as by collecting the measured and recorded properties.

RESULTS AND DISCUSSION

Here, the energy and exergy modeling technique discussed in the previous section is applied to the ceramic drying process studied using the actual operational data.

Mass Balance and Elemental Analysis in the Ceramic Drying Process

The mass balance and chemical composition analysis of the ceramic drying process (COP) were determined on the basis of the chemical reactions between the input and output elements throughout the overall process, as shown in Tables 2–4. The mass balance in the CDP is conceived ased on the law of conservation using Eqs. (1), (15), and (16) as follows:

$$\sum \dot{m}_{in} = \dot{m}_{sdy} + \dot{m}_{svm} + \dot{m}_{fg} + \dot{m}_{ca} + \dot{m}_{al} + \cdots + \tag{15}$$

$$\sum \dot{m}_{out} = \dot{m}_{m} + \dot{m}_{mm} + \dot{m}_{fg} + \dot{m}_{fgc} + \dot{m}_{fgo} + \cdots + \tag{16}$$

Mass Balance and Elemental Analysis in the Spray Dryer

Input materials to the SD are sludge dry matter (Al_2O_3, SiO_2, Na_2O, Fe_2O_3, CaO, MgO, and others), sludge wet matter, natural gas, and combustion air, while output materials are masse and flue gas as shown in Fig. 1 and Tables 2–4. Sludge consisting of 35% moisture is altered to masse with 5% moisture in the spray dryer. For calculation of the mass balance, the ratio of dry and wet materials was investigated in different ways; furthermore, flame gases were examined in three parts as evaporation of sludge exhaust gas, and air leakage. Mass balance and elemental analysis of input and output materials in the SD are illustrated in Table 2.

Mass Balance and Elemental Analysis in the Vertical Dryer

Input materials to the VD are as follows: tile (Al_2O_3, SiO_2, Na_2O, Fe_2O_3, CaO, MgO, and other), natural gas, combustion air, and air leakage while output materials are tile, and flammable gas. The tile consisting of moisture 5% turns into a heated tile which has 0.3% moisture in the VD. In the calculation of mass balance, the ratio of dry and wet materials was examined in different ways; furthermore, flame gases were studied in three parts as evaporation of sludge, exhaust gas, and air leakage. Mass balance and elemental analysis of input and output materials in the VD are shown in Table 3.

Mass Balance and Elemental Analysis in the Furnace

Input materials to the furnace are as follows: glazed tile (Al_2O_3, SiO_2, Na_2O, Fe_2O_3, CaO, MgO, and other), air leakage, cooler air, and combustion air, and output materials are ceramics and flammable gas. The glazed tile consisting of 5% moisture is purified of moisture in the furnace and becomes ceramic. In the calculation of mass balance, flame gases were examined in three parts as evaporation of tile, exhaust gas, and air leakage. Mass balance and element analysis of input and output materials to the furnace are indicated in Table 4.

Energy Analyses of the Ceramic Drying Process

In order to analyze the CDP thermodynamically, the following assumptions were made:

1. The system is assumed as a steady-state, steady-flow process.
2. Kinetic and potential energy changes of input and output materials are ignored.
3. No heat is transferred to the system from the outside.
4. Electrical energy produces the shaft work in the CDP.
5. The change in the ambient temperature is neglected.

Under the above-mentioned conditions and using the actual operating data of the plant, an energy balance is applied to the CDP. Calculation of the energy balance of the SD, VD, and F is made using Eqs. (2) and (4). The references, enthalpy, mass flow rate, entropy, and input energy are considered in the calculations. The reference value for the enthalpy is considered to be 0°C for calculations. The complete energy balance for the system CDP is shown in Table 5a. It is clear from this table that the main heat source in the process is the gas, and the electrical energy is converted into heat energy flow of the CDP, as illustrated in Fig. 3. The results of these energy analyses in the form of a Sankey diagram of the CDP are shown in Fig. 4.

TABLE 1
Specific enery consumption values of the ceramic dryer process (for the month of January)

	Spray dryer			Vertical dryer			Furnace		
Item	Parameters	Unit	Value	Parameters	Unit	Value	Parameters	Unit	Value
1	Amount of sludge input	kg/h	77,133	Number of tiles falling	kg/h	57,677	Numer of input glazed tiles	kg/h	42,678
2	Sludge dry matter ratio	%	65	Number of tiles	kg/h	57,677	Number of ceramics output	kg/h	40,544
3	Sludge wet matter ratio	%	35	Ratio of input tiles moisture	%	5	Ratio of input glazed tiles moisture	%	5
4	Masse production	kg/h	50,141	Ratio of output tiles moisture	%	0,3	Ambient temperature	K	295
5	Ratio of masse moisture	%	5	Ambient temperature	K	295	Glazed tiles input temperature	K	298
6	Ambient temperature	K	295	Tile inlet temperature	K	303	Combustion air inlet temperature	K	385
7	Sludge inlet temperature	K	303	Tile outlet temperature	K	368	Cooler air inlet temperature	K	298
8	Flammable gas inlet temperature	K	298	Combustion air inlet temperature	K	298	Leakage of air inlet temperature	K	298
9	Combustion air inlet temperature	K	298	Leakage of air inlet temperature	K	298	Ceramic output temperature	K	343
10	Leakage of air inlet temperature	K	298	Flue gas outlet temperature	K	343	Flue gas outlet temperature	K	403
11	Produced masse outlet temperature	K	327	Natural gas mass flow rate	kg/h	711	Natural gas mass flow rate	kg/h	1,821
12	Flue gas outlet temperature	K	375	Combustion air mass flow rate	kg/h	13,457	Combustion air mass flow rate	kg/h	43,704
13	Combustion air mass flow rate	kg/h	9,986	Leakage of air mass flow	kg/h	6756	Cooler air mass flow rate	kg/h	41,543
14	Combustion air mass flow rate	kg/h	67,960	Flue gas mass flow rate	kg/h	23766	Combustion air mass flow rate	kg/h	11,847
15	Flue gas mass flow rate	kg/h	102,741	Lower heating value of fuel	kJ/m^3	34,541	Flue gas mass flow rate	kg/h	101,049
16	Natural gas mass flow rate	kg/h	441	Total electric power consumption	kWh	1580	Lower heating value of fuel	kJ/m^3	34,541
17	Lower heating value of fuel	kJ/m^3	34,541				Total electric consumption	kWh	3,795
18	Total electric consumption	kWh	1,220						

TABLE 2
Mass balance and elemental analysis of input and output materials to the spray dryer

Input materials	Element	Temperature (K)	Ratio (%)	Mass flow rate (kg/h)	Output materials	Element	Temperature (K)	Ratio (%)	Mass flow rate (kg/h)
Sludge dry matter	Al_2O_3	303	15.13	7,586	Masse	Al_2O_3	327	15.13	7,586
	SiO_2	303	75.46	37,836		SiO_2	327	75.46	37,836
	Na_2O	303	7.8	3,911		Na_2O	327	7.8	3,911
	Fe_2O_3	303	0.14	70		Fe_2O_3	327	0.14	70
	CaO	303	0.37	185		CaO	327	0.37	186
	MgO	303	0.71	356		MgO	327	0.71	356
	Other	303	0.39	197		Other	327	0.39	196
Total				50,141	Total				50,141
Sludge wet matter (H_2O)	H_2O	303	100	26,992	Masse moisture	H_2O	327	100	2,638
Total				26,992	Total				2,638
Flammable gas (CH_4)	C	298	0.75	330.75	Flue gas (stream)	H_2O	375	100	24,354
	H_4	298	0.25	110.25					
Total				441	Total				24,354
Combustion air	N_2	298	77.37	7,727	Flue gas (combustion)	CO_2	375	1.65	86
	O_2	298	20.76	2,074		CO	375	0.0002	0.01
	CO_2	298	0.03	3		NO	375	0.004	0.2
	Ar	298	0.92	91		NO_2	375	0.00004	0.002
	H_2O	298	0.01	1		O_2	375	17.36	907
	Other	298	0.91	90		H_2O	375	3.3	172
Total				9,986		N_2	375	77.68	4,060
Air leakage	N_2	298	77.37	52,586	Total				5,226
	O_2	298	20.76	14,114	Flue gas (other)	N_2	375	77.37	52.581
	CO_2	298	0.03	22		O_2	375	20.76	14.108
	Ar	298	0.92	619		CO_2	375	0.03	20
	H_2O	298	0.01	7		Ar	375	0.92	625
	Other	298	0.91	612		H_2O	375	0.01	7
Total				67,960		Other	375	0.91	618
					Total				67,960
	Overall total			155,520		Overall total			155,520

TABLE 3
Mass balance and elemental analysis of input and output materials to the vertical dryer

Input materials	Element	Temperature (K)	Ratio (%)	Mass flow rate (kg/h)	Output materials	Element	Temperature (K)	Ratio (%)	Mass flow rate (kg/h)
Tile	Al_2O_3	303	15.13	8,727	Tile	Al_2O_3	368	15.13	8,727
	SiO_2	303	75.46	43,523		SiO_2	368	75.46	43,523
	Na_2O	303	7.8	4,499		Na_2O	368	7.8	4,499
	Fe_2O_3	303	0.14	81		Fe_2O_3	368	0.14	81
	CaO	303	0.37	213		CaO	368	0.37	213
	MgO	303	0.71	410		MgO	368	0.71	410
	Other	303	0.39	225		Other	368	0.39	225
Total				57,677	Total				57,677
Moisture of tile (H_2O)	H_2O	303	100	3,035	Moisture of tile (H_2O)	H_2O	368	100	193
Total				3,035	Total				193
Combustiongases (CH_4)	C	298	75	533.3	Flue gas (stream of tile)	H_2O	343	100	2,842
	H_4	298	25	177.8					
Total				711	Total				2,842
Combustion air	N_2	298	77.37	10,388	Flue gas (combustion)	CO_2	343	1.76	92
	O_2	298	20.76	2,787		CO	343	0.002	0.1
	CO_2	298	0.03	4		NO	343	0.0008	0.0
	Ar	298	0.92	124		NO_2	343	0.00002	0.001
	H_2O	298	0.01	1		O_2	343	17.1	894
	Other	298	0.91	122		H_2O	343	3.52	184
Total				13,427		N_2	343	77.61	4,057
Air leakage	N_2	298	77.37	5,227	Total				14,168
	O_2	298	20.76	1,403	Flue gas (other)	N_2	343	77.37	0
	CO_2	298	0.03	2		O_2	343	20.76	0
	Ar	298	0.92	62		CO_2	343	0.03	0
	H_2O	298	0.01	1		Ar	343	0.92	0
	Other	298	0.91	61		H_2O	343	0.01	0
Total				6,756		Other	343	0.91	0
					Total				6,756
	Overall total			81,636		Overall total			81,636

TABLE 4
Mass balance and elemental analysis of input and output materials to the furnace

Input materials	Element	Temperature (K)	Ratio (%)	Mass flow rate (kg/h)	Output materials	Elements	Temperature (K)	Ratio (%)	Mass flow rate (kg/h)
Glazed tile	Al_2O_3	298	14.53	6,201	Ceramic	Al_2O_3	343	14.6	6,231
	SiO_2	298	73.85	31,518		SiO_2	343	73.7	31,454
	Na_2O	298	7.8	3,329		Na_2O	343	7.8	3,329
	Fe_2O_3	298	0.14	60		Fe_2O_3	343	0.14	60
	CaO	298	0.37	158		CaO	343	0.37	158
	MgO	298	0.71	303		MgO	343	0.71	303
	Other	298	2.6	1,110		Other	343	2.68	1,144
Total				42,678	Total				40,544
Methane (CH_4)	C	298	75	1,365.75	Flue gas	H_2O	403	100	2,134
	H_4	298	25	455.25	Total				2,134
Total				1,821	Flue gas (combustion)	CO_2	403	1.56	710
Combustion air	N_2		77.37	33,814		CO	403	0.005	2
	O_2		20.76	9,073		NO	403	0.02	9
	CO_2		0.03	13		NO_2	403	0.002	1
	Ar		0.92	402		O_2	403	17.55	7,990
	H_2O		0.01	4		H_2O	403	3.12	1,420
	Other		0.91	398		N_2	403	77.753	35,397
Total				43,704	Total				45,525
Cooler air	N_2	298	77.37	32,142	Flue gas (other)	N_2	403	77.37	41,308
	O_2	298	20.76	8,624		O_2	403	20.76	11,084
	CO_2	298	0.03	12		CO_2	403	0.03	16
	Ar	298	0.92	382		Ar	403	0.92	491
	H_2O	298	0.01	4		H_2O	403	0.01	5
	Other	298	0.91	378		Other	403	0.91	486
Total				41,543	Total				53,390
Air leakage	N_2	298	77.37	9,166		Overall total			141,593
	O_2	298	20.76	2,459					
	CO_2	298	0.03	4					
	Ar	298	0.92	109					
	H_2O +Other	298	0.01 0.91	1 + 108					
Total				11,847					
	Overall total			141,593					

TABLE 5
Energy analyses of input and output materials to the ceramic dryer process

		Item	Material	T (K)	C_p (kJ/kgK)	$\dot{m}$ (kg/h)	$\dot{Q}$ (kJ/h)
(a) Spray dryer	Input	1	Sludge (dry material)	303	0.749	50,141	11,379,350
		2	Sludge (wet material)	303	4.18	26,992	34,186,448
		3	Heating of natural gas combustion				23,074,048
		4	Natural gas heating	298	2.22	441	291,748
		5	Combustion air	298	1.005	9,986	2,990,707
		6	Air leakage	298	1.005	67,960	20,353,340
		7	Electrical energy is converted into heat				4,392,000
			Total				96,667,641
	Output	1	Masse	327	0.76	50,141	12,461,041
		2	Moisture of masse	327	4.183	2,638	3,608,365
		3	Flue gas (mud water vapor)	375	1.903	24,354	17,379,623
		4	Flue gas (combustion)	375	1.05	10,427	4,105,631
		5	Flue gas (other)	375	1.011	67,960	25,765,335
		6	Heat loss				33,347,646
			Total				96,667,641
(b) Vertical dryer	Input	1	Tile	303	0.749	57,677	13,089,622
		2	Moisture of tile	303	4.18	3,035	3,843,949
		3	Heating of natural gas combustion				37,211,962
		4	Natural gas heating	298	2.22	711	470,369
		5	Combustion air	298	1.005	13,457	4,030,237
		6	Air leakage	298	1.005	6,756	2,023,354
		7	The electrical energy is converted into heat				5,688,000
			Total				66,357,494
	Output	1	Tile	368	0.771	57,677	16,364,580
		2	Moisture of tile	368	4.19	193	297,591
		3	Flue gas (tile water vapor)	343	1.885	2,842	1,837,509
		4	Flue gas (combustion)	343	1.05	14,168	5,102,605
		5	Flue gas (other)	343	1.011	6,756	2,342,798
		6	Heat loss				40,412,411
			Total				66,357,494
(c) Furnace	Input	1	Glazed tile	298	0.749	42,678	9,525,815
		2	Heating of natural gas combustion				95,337,990
		3	Natural gas heating	298	2.22	1,821	1,204,701
		4	Combustion air	385	1.005	43,704	16,910,170
		5	Cooler air	298	1.005	41,543	12,441,713
		6	Air leakage	298	1.005	11,847	3,548,058
		7	Electrical energy is converted into heat				13,662,000
			Total				152,630,447
	Output	1	Ceramics	343	0.771	40,544	10,721,982
		2	Flue gas (mud water vapor)	403	1.916	2,134	1,647,764
		3	Flue gas (combustion)	403	1.055	45,525	19,355,637
		4	Flue gas (other)	403	1.014	53,390	21,817,396
		5	Heat loss				99,087,668
			Total				152,630,447

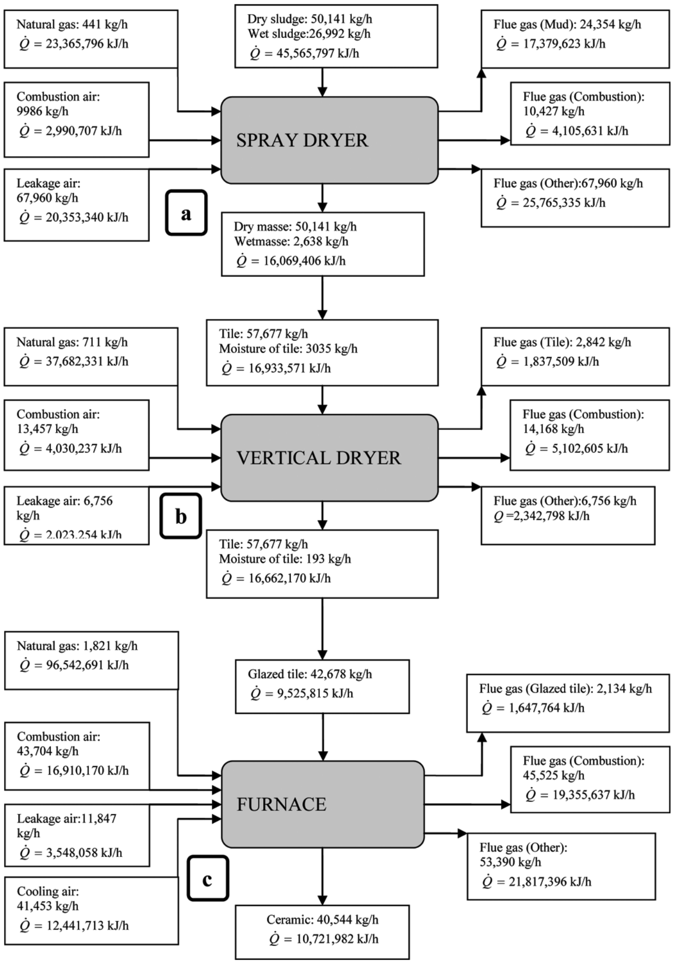

FIG. 3. Energy flow diagram of the ceramic drying process studied.

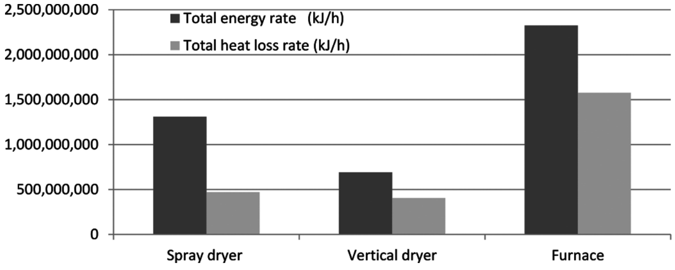

FIG. 5. Comparative values for total energy and heat loss rates of each unit.

Energy Analyses of the Spray Dryer

The unit energy input rate to the SD is 96,667,641 kJ/h. The main heat source in the process is natural gas and the unit input heat rate is 23,074,048 kJ/h. Figure 3a illustrates the energy flow of the SD. According to the results of the analysis, the amount of heat loss in the SD was 35.8%. One of the reasons for this loss is that it does not reach the intended temperature values in the preheating process, which causes extra fuel costs. Another problem in this unit is that heat leaks in the surface due to the insufficient isolation. Failures in the mud feeding system eventually cause fluctuations in the dry substance/water ratio. This increases the demand for energy to remove the extra water. This extra energy consumed in order to achieve the intended moisture of the masse results in extra energy costs. The energy balance of the SD is given in Table 5a.

Energy Analyses of the Vertical Dryer

The unit energy input rate to the VD is 66,357,494 kJ/h. The main heat source in the process is gas and the electrical energy is converted into heat. The total input heat rate is 37,780,762 kJ/h. Figure 3b illustrates the energy flow in the VD unit in which the share of the heat loss is 58.6%. The main reason for the heat loss from the VD is insufficient insulation, which is similar to the spray dryer. However, another possible source of heat loss is any defect in the lifting system which carries dried pieces through the dryer at various times. The energy balance in the VD is given in Table 5b.

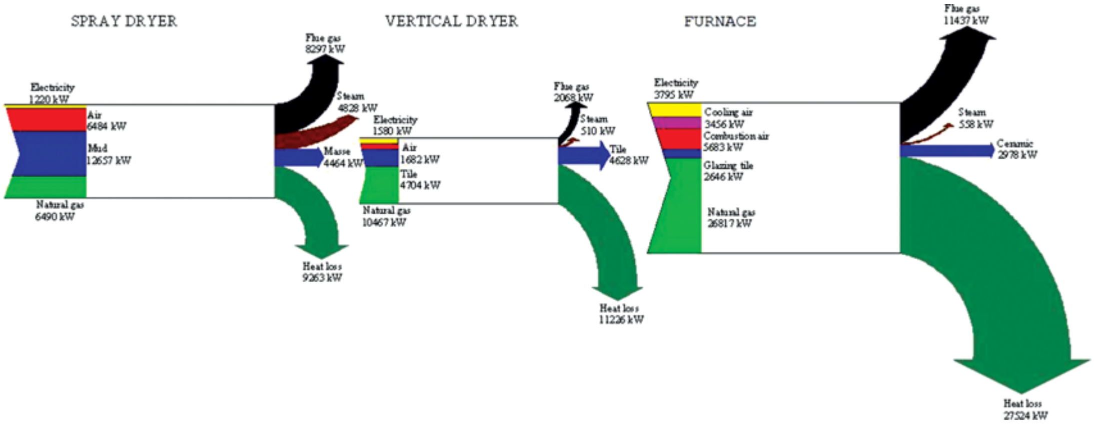

FIG. 4. Sankey (energy flow) diagram of the ceramic drying process studied (color figure available online).

TABLE 6
Exergy analyses of input materials to the spray dryer process

Item	Composition	M (kg/mol)	e (kJ/mol)	T_0 (K)	T (K)	ln (T/T_0)	$\dot{m}$ (kg/h)	C_p (kJ/kgK)	R (kJ/kgK)	Enthalpy (kJ/h)	Entropy (kJ/h.K)	Physical exergy rate (kJ/h)	Chemical exergy rate (kJ/h)	Total exergy rate (kJ/h)	Grand total exergy rate (kJ/h)
1	Sludge dry material						45,141								38,005,686
	Al_2O_3	0.1019	200.4	295	303	0.026	7,586	0.77	0.081	46,730	152	1,928	14,575,621	14,577,549	
	SiO_2	0.06	7.9	295	303	0.026	37,836	0.74	0.138	223,989	728	9,240	4,547,137	4,556,377	
	Na_2OH	0.0629	296.6	295	303	0.026	3,911	1.49	0.132	46,619	152	1,923	18,053,138	18,055,061	
	Fe_2O_3	0.1596	16.5	295	303	0.026	70	0.65	0.052	364	1	15	169	184	
	CaO	0.056	110.2	295	303	0.026	185	0.75	0.148	1,110	4	46	318,761	318,807	
	MgO	0.0403	66.8	295	303	0.026	356	0.92	0.206	2,620	9	108	483,065	483,173	
	Other	0.06	8.2	295	303	0.026	197	0.74	0.138	1,166	4	48	14,487	14,536	
2	Sludge wet material						26,992								1,386,833
	H_2O	0.018	0.9	295	303	0.026		4.18	0.461	902,612	2,933	37,233	1,349,600	1,386,833	
3	Natural gas combustion heating						441								22,614,063
4	Natural gas heating						441								12,524,453
	C	0.012	413.6	295	298	0.01	330.75	0.71	0.692	704	2	12	11,380,449	11,380,460	
	H_4	0.04	418.44	295	298	0.01	110.25	6.7	2.078	2,216	7	37	1,143,956	1,143,993	
5	Combustion air						9,986								−1,676
	N_2	0.028	0.72	295	298	0.01	7,727	1.04	0.296	24,108	80	402	25,424	25,825	
	O_2	0.032	3.97	295	298	0.01	2,074	0.918	0.26	5,712	19	95	7,419	7,514	
	CO_2	0.044	19.87	295	298	0.01	3	0.844	0.189	8	0.03	0.1	−2	−1	
	Ar	0.0399	11.69	295	298	0.01	91	0.52	0.208	142	0.5	2	438	440	
	H_2O	0.018	9.5	295	298	0.01	1	4.18	0.461	13	0.0	0.2	−727	−727	
	Other	0.028	0.72	295	298	0.01	90	0.48	0.296	130	0.4	2	−34,730	−34,728	
6	Air leakage							67,960							
N_2		0.028	0.72	295	298	0.01	52,586	1.04	0.296	164,068	546.9	2,734	173,021	175,755	−11,364
O_2		0.032	3.97	295	298	0.01	14,114	0.918	0.26	38,870	129.6	648	50,487	51,134	
CO_2		0.044	19.87	295	298	0.01	22	0.844	0.189	56	0.2	1	−12	−11	
Ar		0.0399	11.69	295	298	0.01	619	0.52	0.208	966	3.2	16	2,980	2,996	
H_2O		0.018	9.5	295	298	0.01	7	4.18	0.461	88	0.3	1	−5,090	−5,089	
Other		0.028	0.72	295	298	0.01	612	0.48	0.296	881	2.9	15	−236,164	−236,150	
Overall					74,517,995										

TABLE 7
Exergy analyses of output materials from the spray dryer process

Item	Composition	M (kg/mol)	e (kJ/mol)	T_0 (K)	T (K)	ln (T/T_0)	$\dot{m}$ (kg/h)	C_p (kJ/kgK)	R (kJ/kgK)	Enthalpy (kJ/h)	Entropy (kJ/h.K)	Physical exergy rate (kJ/h)	Chemical exergy rate (kJ/h)	Total exergy rate (kJ/h)	Grand total exergy rate (kJ/h)
1	Masse						50,141								38,070,457
	Al_2O_3	0.1019	15	295	327	0.102	7,586	0.780	0.081	189,355	604	11,302	14,575,621	14,586,923	
	SiO_2	0.06	8.2	295	327	0.102	37,836	0.750	0.138	908,074	2,894	54,201	4,547,137	4,601,338	
	Na_2OH	0.0629	296.2	295	327	0.102	3,911	1.510	0.132	188,979	602	11,280	18,053,138	18,064,418	
	Fe_2O_3	0.1596	12.4	295	327	0.102	70	0.670	0.052	1,505	5	90	169	259	
	CaO	0.056	110.2	295	327	0.102	186	0.790	0.148	4,690	15	280	318,761	319,041	
	MgO	0.0403	59.1	295	327	0.102	356	0.950	0.206	10,822	34	646	483,065	483,711	
	Other	0.06	8.2	295	327	0.102	196	0.750	0.138	4,693	15	280	14,487	14,768	
2	Moisture of masse						2,638								42,123
	H_2O	0.018	0.9	295	327	0.102		4.18	0.461	352,859	1,125	21,061	21,061	42,123	
3	Flue gas (swamp water vapor)						24,354								1,412,137
	H_2O	0.018	0.9	295	327	0.102		4.18	0.461	3,257,591	10384	194,437	1,217,700	1,412,137	
4	Flue gas (combustion)						5,226								−70,850
	CO_2	0.044	19.87	295	375	0.239	86	0.917	0.189	6,326	19	751	19,214	19,965	
	CO	0.028	275.1	295	375	0.239	0.01	1.405	0.298	1	0.004	0.14	91	91	
	NO	0.03	88.9	295	375	0.239	0.2	1.004	0.277	17	0.1	2	447	448	
	NO_2	0.046	55.6	295	375	0.239	0.002	0.865	0.18	0.1	0.0004	0.02	1	1	
	O_2	0.032	3.97	295	375	0.239	907	0.934	0.26	67,788	203	8,046	−169,062	−161,016	
	H_2O	0.018	9.5	295	375	0.239	172	1.903	0.461	26,255	78	3,116	10,889	14,005	
	N_2	0.028	0.72	295	375	0.239	4,060	1.042	0.296	338,405	1,011	40,164	15,490	55,655	
5	Flue gas (other)						67.960								635,250
	N_2	0.028	0.72	295	375	0.239	52.581	1.042	0.296	4,383,123	13,095	520,222	173,003	693,225	
	O_2	0.032	3.97	295	375	0.239	14.108	0.934	0.26	1,054,187	3,149	125,119	50,467	175,586	
	CO_2	0.044	19.87	295	375	0.239	20	0.917	0.189	1,496	4	178	−11	167	
	Ar	0.0399	11.69	295	375	0.239	625	0.55	0.208	27,510	82	3,265	3,010	6,275	
	H_2O	0.018	9.5	295	375	0.239	7	1.903	0.461	1,035	3	123	−4,942	−4,819	
	Other	0.028	0.72	295	375	0.239	618	0.59	0.296	29,190	87	3,465	−238,648	−235,184	
	Overall														40,089,117

TABLE 8

Exergy analyses of input materials to the vertical dryer process

Item	Composition	M (kg/mol)	e (kJ/mol)	T_0 (K)	T (K)	ln (T/T_0)	$\dot{m}$ (kg/h)	C_p (kJ/kgK)	R (kJ/kgK)	Enthalpy (kJ/h)	Entropy (kJ/h.K)	Physical exergy rate (kJ/h)	Chemical exergy rate (kJ/h)	Total exergy rate (kJ/h)	Grand total exergy rate (kJ/h)
1	Tile						57,677								43,719,490
	Al_2O_3	0.1019	200.4	295	303	0.026	8727	0.77	0.081	53,755	175	2,217	16,767,018	16,769,235	
	SiO_2	0.06	7.9	295	303	0.026	43,523	0.74	0.138	257,657	837	10,628	5,230,610	5,241,238	
	Na_2OH	0.0629	296.6	295	303	0.026	4,499	1.49	0.132	53,626	174	2,212	20,766,445	20,768,657	
	Fe_2O_3	0.1596	16.5	295	303	0.026	81	0.65	0.052	420	1	17	195	213	
	CaO	0.056	110.2	295	303	0.026	213	0.75	0.148	1,280	4	53	367,703	367,756	
	MgO	0.0403	66.8	295	303	0.026	410	0.92	0.206	3,014	10	124	555,669	555,793	
	Other	0.06	8.2	295	303	0.026	225	0.74	0.138	1,332	4	55	16,542	16,597	
2	Moisture of tile						3,035								155,936
	H_2O	0.018	0.9	295	303	0.026		4.18	0.461	101,490	330	4,186	151,750	155,936	
3	Natural gas combustion heating						711								37,211,962
4	Natural gas heating						711								20,192,486
	C	0.012	413.6	295	298	0.01	533.3	0.71	0.692	1,136	4	19	18,348,070	18,348,089	
	H_4	0.04	418.44	295	298	0.01	177.8	6.7	2.078	3,573	12	60	1,844,337	1,844,396	
5	Combustion air						13,457								−2,708
	N_2	0.028	0.72	295	298	0.01		10,388	1.04	0.296	32,412	108	540	34,181	34,721
	O_2	0.032	3.97	295	298	0.01	2,787	0.918	0.26	7,677	26	128	9,971	10,099	
	CO_2	0.044	19.87	295	298	0.01	4	0.844	0.189	10	0.03	0.2	−2	−2	
	Ar	0.0399	11.69	295	298	0.01	124	0.52	0.208	193	0.6	3	595	598	
	H_2O	0.018	9.5	295	298	0.01	1	4.18	0.461	17	0.06	0.3	−976	−976	
	Other	0.028	0.72	295	298	0.01	122	0.48	0.296	176	0.6	3	−47,150	−47,147	
6	Air leakage						6,756								−1,363
	N_2	0.028	0.72	295	298	0.01	5,227	1.04	0.296	16,309	54.4	272	17,198	17,470	
	O_2	0.032	3.97	295	298	0.01	1,403	0.918	0.26	3,863	12.9	64.38	5,017	5,081	
	CO_2	0.044	19.87	295	298	0.01	2	0.844	0.189	5	0.02	0.1	−1	−1	
	Ar	0.0399	11.69	295	298	0.01	62	0.52	0.208	97	0.3	2	299	301	
	H_2O	0.018	9.5	295	298	0.01	1	4.18	0.461	8	0.03	0.1	−491	−491	
	Other	0.028	0.72	295	298	0.01	61	0.48	0.296	89	0.3	1	−23,724	−23,723	
	Overall														101,275,804

TABLE 9
Exergy analyses of output materials from the vertical dryer process

Item	Composition	M (kg/mol)	e (kJ/mol)	T_0 (K)	T (K)	ln (T/T_0)	$\dot{m}$ (kg/h)	C_p (kJ/kgK)	R (kJ/kgK)	Enthalpy (kJ/h)	Entropy (kJ/h.K)	Physical exergy rate (kJ/h)	Chemical exergy rate (kJ/h)	Total exergy rate (kJ/h)	Grand total exergy rate(kJ/h)
1	Tile						57,677								44,075,361
	Al_2O_3	0.1019	15	295	368	0.221	8,727	0.790	0.081	503,259	1,524	53,807	16,767,018	16,820,825	
	SiO_2	0.06	8.2	295	368	0.221	43,523	0.760	0.138	2,414,660	7,310	258,170	5,230,610	5,488,780	
	Na_2OH	0.0629	296.2	295	368	0.221	4,499	1.510	0.132	495,903	1,501	53,021	20,766,445	20,819,466	
	Fe_2O_3	0.1596	12.4	295	368	0.221	81	0.680	0.052	4,008	12	429	195	624	
	CaO	0.056	110.2	295	368	0.221	213	0.810	0.148	12,619	38	1,349	367,703	369,053	
	MgO	0.0403	59.1	295	368	0.221	410	0.960	0.206	28,698	87	3,068	555,669	558,738	
	Other	0.06	8.2	295	368	0.221	225	0.760	0.138	12,480	38	1,334	16,542	17,877	
2	Moisture of masse						193								15,947
	H_2O	0.018	0.9	295	368	0.221		4.18	0.461	58,892	178	6,297	9,650	15,947	
3	Flue gas (water evaporation of tile)						2,842								186,648
	H_2O	0.018	0.9	295	343	0.15		4.18	0.461	570,219	1,782	44,548	142,100	186,648	
4	Flue gas (combustion)						14,168								−263,889
	CO_2	0.044	19.87	295	343	0.15	249	0.917	0.189	10,976	34	857	55,564	56,421	
	CO	0.028	275.1	295	343	0.15	0.3	1.405	0.298	19	0.060	1.49	2,458	2,460	
	NO	0.03	88.9	295	343	0.15	0.1	1.004	0.277	5	0.0	0	242	243	
	NO_2	0.046	55.6	295	343	0.15	0.003	0.865	0.18	0.1	0.0004	0.01	2	2	
	O_2	0.032	3.97	295	343	0.15	2,423	0.934	0.26	108,616	339	8,486	−451,472	−442,986	
	H_2O	0.018	9.5	295	343	0.15	499	1.903	0.461	45,554	142	3,559	31,489	35,048	
	N_2	0.028	0.72	295	343	0.15	10,996	1.042	0.296	549,965	1,719	42,966	41,958	84,924	
5	Flue gas (other)						6.756								23,911
	N_2	0.028	0.72	295	343	0.15	5,227	1.042	0.296	261,439	817	20,425	17,198	37,623	
	O_2	0.032	3.97	295	343	0.15	1,403	0.934	0.26	62,879	196	4,912	5,017	9,929	
	CO_2	0.044	19.87	295	343	0.15	2	0.917	0.189	89	0	7	−1	6	
	Ar	0.0399	11.69	295	343	0.15	62	0.55	0.208	1,641	5	128	299	427	
	H_2O	0.018	9.5	295	343	0.15	1	1.903	0.461	62	0	5	−491	−486	
	Other	0.028	0.72	295	343	0.15	61	0.59	0.296	1,741	5	136	−23,724	−23,588	
	Overall														39,689,987

TABLE 10
Exergy rate values of input materials to the furnace

Item	Composition	M (kg/mol)	e (kJ/mol)	T_0 (K)	T (K)	ln (T/T_0)	$\dot{m}$ (kg/h)	C_p (kJ/kgK)	R (kJ/kgK)	Enthalpy (kJ/h)	Entropy (kJ/h.K)	Physical energy rate (kJ/h)	Chemical exergy rate (kJ/h)	Total exergy rate (kJ/h)	Grand total exergy rate (kJ/h)
1	Glazed tile						42,678								31,885,813
	Al_2O_3	0.1019	200.4	295	298	0.01	6,201	0.77	0.081	14,325	48	239	11,907,557	11,907,796	
	SiO_2	0.06	7.9	295	298	0.01	31,518	0.74	0.138	69,969	233	1,166	3,759,460	3,760,626	
	Na_2OH	0.0629	296.6	295	298	0.01	3,329	1.49	0.132	14,880	50	248	15,366,096	15,366,344	
	Fe_2O_3	0.1596	16.5	295	298	0.01	60	0.65	0.052	117	0	2	144	146	
	CaO	0.056	110.2	295	298	0.01	158	0.75	0.148	355	1	6	272,019	272,025	
	MgO	0.0403	66.8	295	298	0.01	303	0.92	0.206	836	3	14	411,037	411,051	
	Other	0.06	8.2	295	298	0.01	1,110	0.74	0.138	2,463	8	41	167,784	167,825	
2	Natural gas combustion heating														95,337,990
3	Natural gas heating						1,821								51,716,619
	C	0.012	413.6	295	298	0.01	1,365.75	0.71	0.692	2,909	10	48	46,992,737	46,992,785	
	H_4	0.04	418.44	295	298	0.01	455.25	6.7	2.078	9,151	31	153	4,723,681	4,723,834	
4	Combustion air						43,704								499,651
	N_2	0.028	0.72	295	385	0.266	33,814	1.05	0.296	3,195,403	9,444	409,367	111,255	520,622	
	O_2	0.032	3.97	295	385	0.266	9,073	0.92	0.26	751,240	2,220	96,242	32,454	128,697	
	CO_2	0.044	19.87	295	385	0.266	13	0.85	0.189	1,003	2.96	128.5	−7	122	
	Ar	0.0399	11.69	295	385	0.266	402	0.532	0.208	19,251	56.9	2,466	1,936	4,402	
	H_2O	0.018	9.5	295	385	0.266	4	4.18	0.461	1,644	4.86	210.6	−3,178	−2,967	
	Other	0.028	0.72	295	385	0.266	398	0.49	0.296	17,539	51.8	2,247	−153,471	−151,224	
5	Cooler air						43,704								−8,378
	N_2	0.028	0.72	295	298	0.01	32,142	1.04	0.296	100,282	334.3	1,671	105,754	107,426	
	O_2	0.032	3.97	295	298	0.01	8,624	0.918	0.26	23,751	79.2	395.86	30,850	31,246	
	CO_2	0.044	19.87	295	298	0.01	12	0.844	0.189	32	0.11	0.5	−7	−6	
	Ar	0.0399	11.69	295	298	0.01	382	0.52	0.208	596	2.0	10	1,840	1,850	
	H_2O	0.018	9.5	295	298	0.01	4	4.18	0.461	52	0.17	0.9	−3,021	−3,020	
	Other	0.028	0.72	295	298	0.01	378	0.48	0.296	544	1.8	9	−145,882	−145,873	
6	Air leakage						11,847								7,434
	N_2	0.028	0.72	295	318	0.075	9,166	1.04	0.296	219,251	714.9	8,341	30,158	38,500	
	O_2	0.032	3.97	295	318	0.075	2,459	0.918	0.26	51,929	169.3	1,975.54	8,798	10,773	
	CO_2	0.044	19.87	295	318	0.075	4	0.844	0.189	69	0.22	2.6	−2	1	
	Ar	0.0399	11.69	295	318	0.075	109	0.52	0.208	1,304	4.3	50	525	574	
	H_2O	0.018	9.5	295	318	0.075	1	4.18	0.461	114	0.37	4.3	−861	−857	
	Other	0.028	0.72	295	318	0.075	108	0.48	0.296	1,190	3.9	45	−41,602	−41,557	
Overall															179,439,129

TABLE 11
Exergy rate values of output materials from the furnace

Item	Composition	M (kg/mol)	e (kJ/mol)	T_0 (K)	T (K)	ln (T/T_0)	$\dot{m}$ (kg/h)	C_p (kJ/kgK)	R (kJ/kgK)	Enthalpy (kJ/h)	Entropy (kJ/h.K)	Physical exergy rate (kJ/h)	Chemical exergy rate (kJ/h)	Total exergy rate (kJ/h)	Grand total exergy rate (kJ/h)
1	Ceramic						40,544								28,068,434
	Al_2O_3	0.1019	15	295	343	0.15	5,919	0.793	0.081	225,317	704	17,603	10,468,641	10,486,244	
	SiO_2	0.06	8.2	295	343	0.15	29,881	0.761	0.138	1,091,491	3,411	85,273	3,280,222	3,365,495	
	Na_2OH	0.0629	296.2	295	343	0.15	3,162	1.540	0.132	233,767	731	18,263	13,443,691	13,461,954	
	Fe_2O_3	0.1596	12.4	295	343	0.15	57	0.690	0.052	1,880	6	147	126	273	
	CaO	0.056	110.2	295	343	0.15	150	0.830	0.148	5,977	19	467	237,990	238,457	
	MgO	0.0403	59.1	295	343	0.15	288	0.970	0.206	13,403	42	1,047	359,617	360,664	
	Other	0.06	8.2	295	343	0.15	1,087	0.780	0.138	40,682	127	3,178	152,170	155,348	
2	Flue gas (water evaporation of glazed tile)						5,339								189,381
	H_2O	0.018	9.5	295	403	0.311		1.954	0.461	1,126,700	3,244	169,579	266,950	436,529	
3	Flue gas (combustion)						45,525								−278,297
	CO_2	0.044	19.87	295	403	0.311	710	0.996	0.189	76,394	220	11,498	158,250	169,748	
	CO	0.028	275.1	295	403	0.311	2	1.059	0.298	260	0.750	39.18	19,748	19,787	
	NO	0.03	88.9	295	403	0.311	9	1.021	0.277	1,004	2.9	151	19,448	19,599	
	NO_2	0.046	55.6	295	403	0.311	1	0.934	0.18	91.8	0.2645	13.82	498	511	
	O_2	0.032	3.97	295	403	0.311	7,990	0.964	0.26	831,817	2,395	125,196	−1,488,857	−1,363,661	
	H_2O	0.018	9.5	295	403	0.311	1,420	1.953	0.461	299,592	863	45,091	89,684	134,775	
	N_2	0.028	0.72	295	403	0.311	35,397	1.053	0.296	4,025,494	11,592	605,874	135,068	740,942	
4	Flue gas (others)						53,390								877,313
	N_2	0.028	0.72	295	403	0.311	41,308	1.053	0.296	4,697,693	13,528	707,046	135,913	842,959	
	O_2	0.032	3.97	295	403	0.311	11,084	0.964	0.26	1,153,953	3,323	173,681	39,647	213,328	
	CO_2	0.044	19.87	295	403	0.311	16	0.996	0.189	1,723	5	259	−8	251	
	Ar	0.0399	11.69	295	403	0.311	491	0.60	0.208	31,829	92	4,791	2,364	7,155	
	H_2O	0.018	9.5	295	403	0.311	5	1.954	0.461	1,127	3	170	−3,882	−3,713	
	Other	0.028	0.72	295	403	0.311	486	0.61	0.296	32,008	92	4,817	−187,484	−182,667	
	Overall														28,856,831

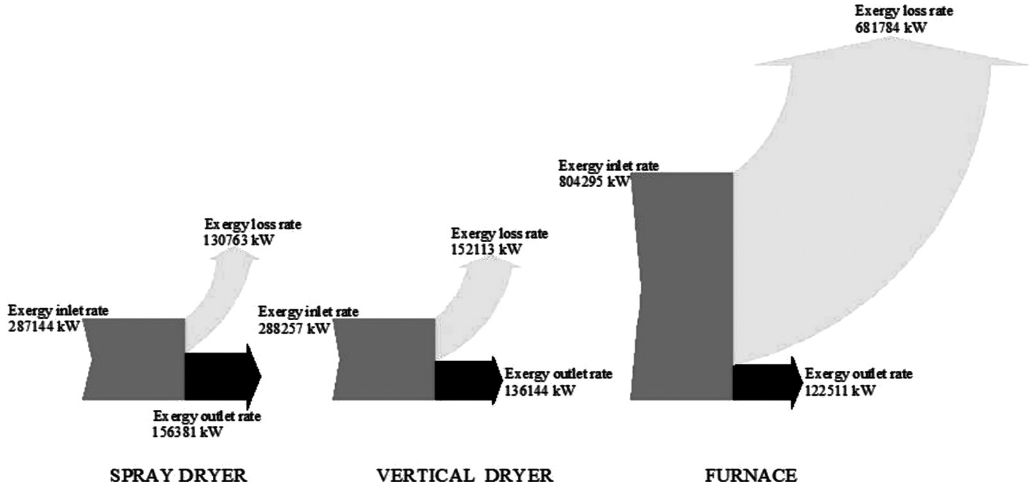

FIG. 6. Grassmann (exergy loss and flow) diagram of the ceramic drying process studied.

Energy Analyses of the Furnace

The unit energy input rate to the furnace is 152,630,447 kJ/h. The main heat source in the process is gas and the electrical energy is converted into heat. The total input heat rate is 108,999,990 kJ/h. Figure 3c illustrates the energy flow in the furnace. The furnace has a heat loss share of 67.8%. The furnace, which consumes the most fuel, operates under a higher temperature process compared to the other systems. One of the fundamental problems associated with the furnace is that the burner isolation is not good. In addition, unstable combustion frequently occurs because of insufficient input air, which causes an increase in natural gas consumption due to insufficient air/fuel ratio. The isolation problem is inadequate in the furnace as well. The inadequacy of the isolation in the hell fire area where the heat is the greatest constitutes the main part of this loss. The energy balance in the furnace is given in Table 5c.

Energy Efficiencies of the Ceramic Drying Process

For all units, the total amount of energy and losses obtained from the energy analysis, which was performed using the first law of thermodynamics, is given in Table 5 and comparisons of these values are provide in Fig. 5.

Energy efficiency of the CDP is calculated from the following relation:

$$\eta = \frac{\sum \mathrm{m_{out}h_{out}}}{\sum \mathrm{m_{in}h_{in}}} \text{ or } \eta = \sum \frac{Q_{in} - Q_{loss}}{Q_{in}} \tag{22}$$

Using energy analysis values and Eq. (22), the energy efficiencies of the SD, VD, and F were calculated for January as follows:

$$\eta_{SD} = \frac{63319995}{96667641} = 0.6550,$$

$$\eta_{VD} = \frac{28852238}{66357494} = 0.4348, \text{ and}$$

$$\eta_{F} = \frac{53542779}{152630447} = 0.3508$$

Exergy Analysis of the Ceramic Drying Process

The irreversibility of each component is calculated from the exergy consideration and may also be found using the entropy balance equations. Using the assumptions, the exergy analysis was made using Eqs. (5)–(13) and the exergy efficiencies were calculated for the CDP. These calculations are provided in Tables . shows the results of these exergy analyses as a Grassmann diagram. The following assumptions were made in the calculations:

1. The system is assumed to be a steady-state, steady-flow process.

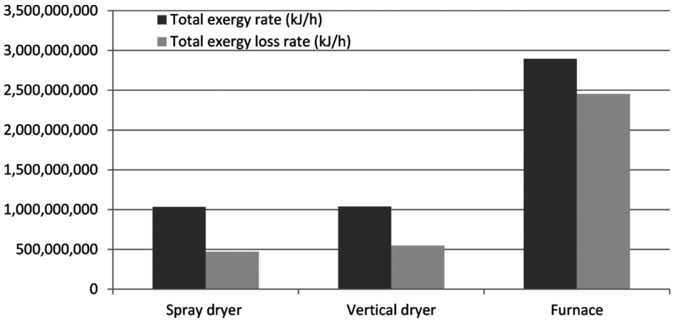

FIG. 7. Comparative values for total exergy and total exergy loss rates of each unit.

TABLE 12

Mass, energy, and exergy input and output rate values of the dryer process investigated according to months and year

Months			January	February	March	April	May	June	July	August	September	October	November	December	Total
Spray dryer	Input	$\dot{m}$ (kg/h)	50,141	49,382	58,295	58,295	58,458	58,295	59,230	60,098	62,566	64,334	61,147	64,389	704,630
		$\dot{E}$ (kJ/h)	96,667,641	110,890,285	118,016,815	107,628,434	104,969,475	89,899,520	103,571,871	101,030,545	121,716,248	126,136,444	124,612,992	104,417,117	1,309,557,388
		$\dot{E}x$ (kJ/h)	74,517,995	88,200,970	94,290,941	85,570,020	83,111,997	72,648,853	82,256,769	73,553,566	96,805,709	100,326,302	99,236,148	83,200,146	1,033,719,416
	Output	$\dot{m}$ (kg/h)	50,141	49,382	58,295	58,295	58,458	58,295	59,230	60,098	62,566	64,334	61,147	64,389	704,630
		$\dot{E}$ (kJ/h)	63,319,995	70,408,635	69,029,662	70,079,437	68,133,374	55,427,777	67,440,535	65,989,764	78,923,094	81,765,789	80,613,041	68,335,130	839,466,234
		$\dot{E}x$ (kJ/h)	40,089,117	39,560,224	46,669,728	46,582,193	46,680,014	46,351,820	47,270,567	47,929,570	50,059,791	51,485,966	48,980,777	51,312,586	562,972,353
Vertical dryer	Input	$\dot{m}$ (kg/h)	57,677	52,487	50,928	53,228	55,289	54,297	54,297	56,301	57,522	56,736	54,987	38,459	642,208
		$\dot{E}$ (kJ/h)	66,357,494	64,535,610	57,830,779	56,572,769	57,249,416	53,633,673	55,900,698	57,560,501	56,161,783	61,314,449	61,432,325	43,706,511	692,256,006
		$\dot{E}x$ (kJ/h)	101,275,804	94,431,113	86,469,457	86,023,490	87,591,244	81,855,321	82,825,563	86,689,039	85,982,575	87,768,862	91,811,232	65,002,661	1,037,726,361
	Output	$\dot{m}$ (kg/h)	57,677	52,487	50,928	53,228	55,289	54,297	54,297	56,301	57,522	56,736	54,987	38,459	642,208
		$\dot{E}$ (kJ/h)	28,852,238	23,880,038	20,194,674	23,561,216	24,389,229	23,739,640	24,403,258	25,271,122	25,508,894	26,006,404	25,635,414	17,991,753	286,526,723
		$\dot{E}x$ (kJ/h)	39,689,987	40,072,785	38,882,189	40,556,283	42,238,397	41,485,235	41,468,480	43,000,063	43,741,305	43,314,667	41,973,081	29,350,564	490,121,028
Furnace	Input	$\dot{m}$ (kg/h)	42,678	52,487	50,172	52,437	54,855	54,313	51,210	55,454	56,681	54,285	53,385	40,733	618,690
		$\dot{E}$ (kJ/h)	152,630,447	204,699,165	174,322,231	203,124,303	206,100,522	197,410,159	198,868,740	206,427,779	210,017,379	210,687,372	208,648,362	151,519,880	2,324,456,340
		$\dot{E}x$ (kJ/h)	179,439,129	250,975,569	223,293,289	252,732,015	256,415,599	245,467,738	245,837,610	259,426,935	263,813,606	264,532,108	262,190,536	191,338,819	2,895,462,953
	Output	$\dot{m}$ (kg/h)	40,544	49,863	47,663	49,816	52,113	51,597	48,649	52,681	53,847	51,571	50,716	38,697	587,757
		$\dot{E}$ (kJ/h)	53,542,779	66,295,540	64,474,780	62,972,831	64,412,941	62,232,518	61,768,800	63,904,133	73,943,839	64,520,730	63,611,584	46,122,132	747,802,608
		$\dot{E}x$ (kJ/h)	28,856,831	38,293,121	36,643,303	38,251,242	39,912,000	31,240,377	37,326,125	40,389,319	42,242,406	39,339,523	38,904,945	29,642,665	44,1041,857

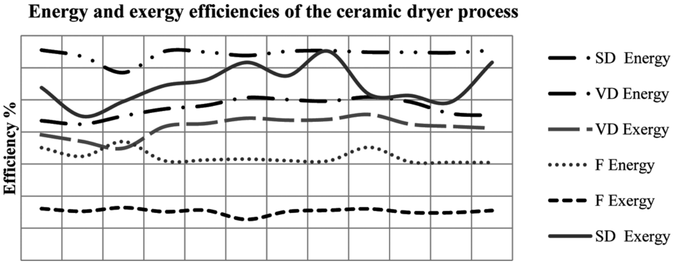

FIG. 8. Variation of energy and exergy efficiencies of the ceramic dryer process over time.

2. Chemical exergies of the substances are neglected.
3. Kinetic and potential exergies of materials are ignored.
4. The reference value for the ambient temperature, and pressure are considered to be $^{T_0} = 295\,\text{K}$ and $^{P_0} = 1\,\text{bar}$ for calculations.

Total exergy values of the input and output materials were calculated to be 7,864.73 and 1,981.40 MJ, respectively.

For all units, a comparison of these values is also given in Fig. 7 using the second law of thermodynamics.

Exergy Analysis of the Spray-Drying Process

Table 6 lists exergy analysis values of the input materials to the SD process and those of the output materials from the SD process are indicated in Table 7. Total exergy values of the input and output materials were calculated to be 74,517,995 and 40,089,117 kJ/h, respectively.

Exergy Analysis of the Vertical Drying Process

Exergy analysis values of the input materials to the VD process are presented in Table 8 and those of the output materials from the VD process are listed in Table 9. Total exergy rate values of the input and output materials were calculated to be 101,275,804 and 39,689,987 kJ/h, respectively.

Exergy Analysis of the Furnace Process

Exergy analysis values for the input materials to the furnace are listed in Table 10 and those of the output materials from the furnace are indicated in Table 11. Total energy rate values of the input and output materials were calculated to be 179,439,129 and 28,856,831 kJ/h, respectively.

Exergy Efficiency of the Ceramic Drying Process

The exergy efficiency of the CDP is calculated from

$$\varepsilon = \frac{\sum \mathrm{m_{out}} \cdot \psi_{\mathrm{out}}}{\sum \mathrm{m_{in}} \cdot \psi_{\mathrm{in}}} \text{ or } \varepsilon = \frac{Ex_{out}}{Ex_{in}} \tag{23}$$

Using exergy analysis values and Eq. (23), the exergy efficiencies of the SD, VD, and F were calculated for January as follows:

$$\varepsilon_{SD} = \frac{40089117}{74517995} = 0.537, \varepsilon_{VD} = \frac{3968998}{101275804} = 0.391,$$
$$\text{and } \varepsilon_F = \frac{28856831}{179439129} = 0.16$$

Exergy Analysis of the Whole Process

Mass, energy, and exergy input and output values of the dryer process investigated are shown in Table 12. A graphical representation of the energy and exergy efficiencies of the SD, VD, and F is presented in Fig. 8.

Apak[34] reported that energy and exergy efficiencies in a ceramic drying sector were 65.3 and 29.9% for the SD, 87.3 and 64.1% for the VD, and 43.4 and 11% for the F, respectively. In the present study, for the month of January, the energy and exergy efficiency values for the SD, VD, and F were 65.50 and 53.7%, 45.12 and 43.3%, and 35.08 and 16%, respectively. The differences between the efficiency values are due to the operating conditions of the two factories.

CONCLUSIONS

In the present study, we determined energy and exergy utilization efficiencies of a ceramic drying process. Mass, elemental analysis and heat losses, and energy and exergy utilization efficiencies of the CDP were analyzed using the actual plant operating data. The main conclusions drawn from the results of the present study may be summarized as follows:

1. For the month of January, the energy efficiency values for the SD, VD, and F were 65.50, 45.12, and 35.08% and the exergy efficiency values were 53.7, 43.3, and 16%, respectively.
2. For the month of January, heat loss rates by conduction, convection, and radiation from the surface of the SD, VD, and F were about 33,348, 40,421, and 99,087 MJ/h, respectively. Hence, the energy saving potential for the those systems was estimated to be nearly 33,348, 40,421, and 99,087 MJ/h, respectively, which indicates an energy recovery of 34.52, 60.91, and 64.67% of the total input energy into the SD, VD, and F, respectively.
3. Over one year, the energy efficiency values for the SD, VD, and F varied between 58.48 and 65.50%, 42.44 and 50.87%, and 30.44 and 36.99%, respectively, and the exergy efficiency values were in the range of 44.85–65.16%, 34.92–45.42%, and 12.73–16.41%, respectively.
4. This study indicated that exergy utilization in the SD, VD, and F was even worse than energy utilization. In other words, those processes had a great potential for increasing the exergy efficiency.

5. Heat losses especially at the second and third stage of the process shows the problem with the efficiency of the system. Heat losses will decrease if necessary precautions are taken in the CDP, which will result in fuel savings in the furnace.
6. A conscious and planned effort toward building an energy management structure within the plant studied is needed to improve exergy utilization in the CDP. Considering the existence of energy-efficient technologies in similar sectors, the major problem is delivering these technologies; in other words, using effective energy-efficiency delivery mechanisms.

NOMENCLATURE

C	Specific heat (kJ/kgK)
D	Diameter (mm)
E	Energy (kJ)
$\dot{E}$	Energy rate (kW)
Ex	Exergy (kJ)
$\dot{E}x$	Exergy rate (kW)
ex	Specific exergy (kJ/kg)
h	Specific enthalpy (kJ/kg) or heat convection coefficient (W/m^{2}K)
I	Irreversibility, exergy consumption (kJ)
$\dot{I}$	Irreversibility rate, exergy consumption rate (kW)
$I\dot{P}$	Improvement potential rate for exergy (kW)
k	Thermal conductivity (W/mK)
l	Length (m)
m	Mass (kg)
$\dot{m}$	Mass flow rate (kg/s)
P	Pressure (Pa)
Q	Heat transfer (kJ)
$\dot{Q}$	Heat transfer rate (kW)
$\dot{S}$	Entropy rate (kW)
s	Specific entropy (kJ/kgK)
T	Temperature (K)
W	Work (kJ)
$\dot{W}$	Work rate or power (kW)

Greek Letters

ε	Exergy (second law) efficiency (%)
η	Energy (first law) efficiency (%)
ψ	Flow exergy (kJ/kg)

Indices

a	Air
ave	Average
c	Combustion
cr	Ceramics
$dest$	Destroyed
dr	Drying room
fg	Flue gas
fr	Furnace
g	Gas
gd	Gas dust
gen	Generation
gt	Glazed tile
h	Heating
in	Input
la	Air leakage
m	Moisture
mix	Mixture
ns	Natural gas
out	Outlet, existing
sdm	Sludge (dry material)
sf	Surface
swm	Sludge (wet material)
t	Tile
v	Vapor
0	Dead state or reference environment

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