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Energy and exergy analyses of a raw mill in a cement production

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Abstract

Cement production has been one of the most energy intensive industries in the world. In order to produce raw materials preparation, clinker and rotary kilns are widely used in cement plants. The objective of this study is to perform energy and exergy analysis of a raw mill (RM) and raw materials preparation unit in a cement plant in Turkey using the actual operational data. The RM has a capacity of 82.9 ton-material hourly. Both energy and exergy efficiencies of the RM are investigated for the plant performance analysis and improvement, and are determined to be 84.3% and 25.2%, respectively. The present technique is proposed as a useful tool in the analysis of energy and exergy utilization, developing energy policies and providing energy conservation measures.

Keywords: Cement; Efficiency; Energy; Exergy; Energy analysis; Exergy analysis; Raw mill; Turkey

1. Introduction

Known energy sources have been exhausted rapidly nowadays and so, efficient and effective utilization of energy has started to gain a vital importance. For this reason, the collection and evaluation of periodical data concerning industry and other final energy consuming sectors are primary conditions in the determination of targets for the studies on energy saving.

The energy balance is the basic method of a process investigation. It makes the energy analysis possible, points at the needs to improve the process, is the key to optimization and is the basis for developing the exergy balance. Analysis of the energy balance results would disclose the efficiency of energy utilization in particular parts of the process and allow comparing the efficiency and the process parameters with the currently achievable values in the most modern installations. They will also establish the priority of the processes requiring consideration, either because of their excessive energy consumption or because of their particularly low efficiency.

The exergy analysis is the modern thermodynamic method used as an advanced tool for engineering process evaluation [1]. Whereas the energy analysis is based on the first law of thermodynamics, the exergy analysis is based on both the first and the second laws of thermodynamics. Both analyses utilize also the material balance for the considered system. Analysis and optimization of any physical or chemical process, using the energy and exergy concepts, can provide the two different views of the considered process.

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

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Nomenclature

C	specific heat (kJ/kg K)
D	diameter (m)
E	energy (kJ)
$\dot{E}$	energy rate (kW)
ex	specific exergy (kJ/kg)
Ex	exergy (kJ)
$\dot{\mathrm{E}}\mathrm{x}$	exergy rate (kW)
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)
$\mathrm{I}\dot{\mathrm{P}}$	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)
s	specific entropy (kJ/kg K)
$\dot{S}$	entropy rate (kW)
T	temperature (K)
W	work (kJ)
$\dot{W}$	work rate or power (kW)

Greek Letters

η	energy (first law) efficiency (%)
ε	exergy (second law) efficiency (%)
ψ	flow exergy (kJ/kg)

Indices

a	air
ave	average
bs	back separator
c	clay
cm	clay moisture
dest	destroyed
dr	drying room
fr	farine
gen	generation
g	gas
gd	gas dust
gr	grinding room
m	moisture
inc	incompressible
in	input
l	limestone
la	leak air
lm	limestone moisture
mix	mixture
p	pyrite
pm	pyrite moisture
sf	surface
v	vapor
0	dead state or reference environment
out	outlet, existing

Abbreviation

RM	raw mill

of thermodynamic phenomena on the process effectiveness, comparison of the importance of different thermodynamic factors, and the determination of the most effective ways of improving the process under consideration [1]. A true understanding of exergy and the insights it can provide into the efficiency, environmental impact and sustainability of energy systems are required for the engineer or scientist working in the area of energy systems and the environment. Dincer also reported the linkages between energy and exergy, exergy and the environment, energy and sustainable development, and energy policy making and exergy in detail elsewhere [2,3].

Recently, there has been increasing interest in using energy and exergy analysis modeling techniques for energy-utilization assessments in order to attain energy saving, and hence financial savings. Energy and exergy analysis studies conducted on cement factories have done up to now have been all about rotary kiln. As the process was examined according to the distribution of energy, quite a large quantity of mass and energy flow was observed at the raw mill. The source of heat that is needed to obtain farine in the raw mill (RM) is the exhausts gas taken from the rotary kiln. Heat losses in the RM affect the whole system. Heat losses that come out especially at the beginning stage of the process show problem with the efficiency of the system. Heat losses will be decreased if necessary precautions are taken in the RM. It will also cause saving of fuel at the rotary kiln.

Szargut [1], Kotas [4] and Wall [5] have performed most extensive studies in the exergy field. Szargut is the first scientist introducing the cumulative exergy consumption and cumulative degree of perfection for industrial processes and making the distinction between second law efficiency (exergetic efficiency or rational efficiency) and cumulative degree of perfection for industrial processes. However, Kotas has followed a similar approach giving different industrial processes such as sulfuric acid, gas turbine and refrigeration plants. Wall [5] presented the exergy flows for a pulp and paper mill and a steel plant by establishing the energy flows in processes and drawing up the exergy losses.

Cement industry is consuming large amount of energy in industrial sector. A significant number of studies have been published in this field as well. Among them, there are very important and deductive papers, showing not only energy approach to the cement industry, but also the potentials and means of improvement in energy consumption of cement industry.

Schuer et al. [6] gave energy consumption values and described the energy saving methods and potentials for German Cement Industry The study consisted of two parts, namely electrical energy saving methods and thermal energy saving methods. The results were presented in the form of energy flow diagrams that made the results easy to understand.

Saxena et al. [7] studied on improving the energy efficiency of a cement industry in India and presented energy consumption figures and means of conservation together with estimated savings. The study was a complete one in the respect that it considered all the parts of the cement production process, since many of the other studies focused on only energy intensive portions of the process.

Worell et al. [8] performed an energy analysis for the US for the years 1970 and 1997. They reported an in-depth analysis of the US cement industry, identifying carbon dioxide saving, cost-effective energy efficiency measures and potentials between 1970 and 1997. They demonstrated that the use of blended cements is a key cost-effective strategy for energy efficiency improvement and carbon dioxide emission reductions in the US cement industry.

Khurana et al. [9] performed an energy balance of a cogeneration system for a cement plant in Indiana. They found that about 35% of the input energy was being lost with the waste heat streams. A steam cycle was selected to recover the heat from the streams using a waste heat recovery steam generator and it was estimated that about 4.4 MW of electricity could be generated.

Engin and Ari [10] made an energy audit analysis of a dry type rotary kiln system working in a cement plant in Turkey. The kiln has a capacity of 600 ton-clinker per day. It was found that about 40% of the total input energy was being lost through hot flue gas (19.15%), cooler stack (5.61%) and kiln shell (15.11% convection plus radiation). It was also indicated that approximately 15.6% of the total input energy (4 MW) could be recovered.

Camdali et al. [11] carried out energy and exergy analyses for a dry system rotary burner with pre-calcinations in a cement plant of an important cement producer in Turkey. Heat losses by conduction, convection and radiation from the rotary burner were obtained to be about 3% of the heat coming into the system.

The previous studies conducted in the literature focused on energy and exergy analysis of preheater and rotary kiln. In this study, energy and exergy analyses of a raw mill (RM) and raw materials preparation unit in a cement plant in Balikesir, Turkey were performed for evaluating the performance of the plant using the actual plant operational data.

In this regard, the structure of the paper is organized as follows. The first section includes the introduction. Section 2 makes a theoretical analysis using mass, energy and exegy balance equations. The description of the cement process and the energy utilization in the Turkish cement industry are given in Section 3. Energy and exergy analysis method is applied to the plant studied and the results obtained are discussed in Section 4, while Section 5 concludes.

2. Theoretical analysis

For a general steady state, steady-flow process, the following balance equations are applied to find the work and heat interactions, the rate of exergy decrease, the rate of irreversibility, the energy and exergy efficiencies [4,12–15].

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

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

where $\dot{m}$ is the mass flow rate, and the subscript 'in' stands for inlet and 'out' for outlet.

The general energy balance can be expressed as

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

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

where $\dot{E}_{\text{in}}$ is the rate of net energy transfer in, $\dot{E}_{\text{out}}$ is the rate of net energy transfer out by heat, work and mass, $\dot{Q} = \dot{Q}_{\text{net,in}} = \dot{Q}_{\text{in}} - \dot{Q}_{\text{out}}$ is the rate of net heat input, $\dot{W} = \dot{W}_{\text{net,out}} = \dot{W}_{\text{out}} - \dot{W}_{\text{in}}$ 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:

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

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

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

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 zero indicates properties at the dead state of P_0 and T_0.

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

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

where $\dot{S}_{\text{gen}}$ is the rate of entropy, while 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 [14,15]

$$ex^Q = [(1 - (T_0/T_r)]Q_r \quad (8)$$

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

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

where C is the specific heat.

Different ways of formulating exergetic efficiency proposed in the literature have been given in detail elsewhere [16,17]. The exergy efficiency expresses all exergy input as used exergy, and all exergy output as utilized exergy. Therefore, the exergy efficiency ε_1 becomes

$$\varepsilon_1 = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} \quad (10)$$

Often, there is a part of the output exergy that is unused, i.e. an exergy wasted, $\dot{E}x_{waste}$ to the environment. In this case, exergy efficiency may be written as follows [17]:

$$\varepsilon_2 = \frac{\dot{E}x_{out} - \dot{E}x_{waste}}{\dot{E}x_{in}} \quad (11)$$

The rational efficiency is defined by Kotas and Cornelissen [4,16] as the ratio of the desired exergy output to the exergy used, namely

$$\varepsilon_3 = \frac{\dot{E}x_{desired,output}}{\dot{E}x_{used}} \quad (12a)$$

where $\dot{E}x_{desired,output}$ is all exergy transfer rate from the system, which must be regarded as constituting the desired output, plus any by-product that is produced by the system, while $\dot{E}x_{used}$ is the required exergy input rate for the process to be performed. The exergy efficiency given in Eq. (12a) may also express as follows [18]:

$$\varepsilon_3 = \frac{\text{Desired exergetic effect}}{\text{Exergy used to drive the process}} = \frac{\text{Product}}{\text{Fuel}} \quad (12b)$$

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, some 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 [19].

Van Gool [20] has also noted 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. Hammond and Stapleton [21] give this improvement potential in a rate form, denoted IP.

$$\dot{IP} = (1 - \varepsilon)(\dot{E}x_{in} - \dot{E}x_{out}) \quad (13)$$

3. Description of cement process and energy utilization in the Turkish cement industry

3.1. Description of cement process

Cement production is highly energy intensive and involves the chemical combination of Calcium carbonates (limestone), silica, alumina, iron ore, and small amounts of other materials, which are chemically altered through intense heat to form a compound with binding properties. The main steps in cement production studied are illustrated in Fig. 1. These steps include mainly raw materials preparation, clinker production and finish grinding.

3.1.1. Raw materials preparation

Raw materials, including limestone, chalk, and clay, are mined or quarried, usually at a site close to the cement mill. These materials are then ground to a fine powder in the proper proportions needed for the cement. These can be ground as a dry mixture or combined with water to form slurry. The addition of water at this stage has important implications for the production process and for the energy demands during production. Production is often categorized as dry process and wet process. Additionally, equipment can be added to remove some water from the slurry after grinding; the process is then called semi-wet or semi-dry.

3.1.2. Clinker production

The mixture of raw materials enters the clinker production (or pyroprocessing) stage. During this stage, the mixture is passed through a kiln (and possibly a preheated system) and exposed to increasingly intense heat, up to 1400 °C. This process drives off all moisture, dissociates carbon dioxide from calcium carbonate, and transforms the raw materials into new compounds. The output from this process, called clinker, must be cooled rapidly to prevent further chemical changes.

Clinker production is the most energy-intensive step, accounting for about 80% of the energy used in cement production. Produced by burning a mixture of materials, mainly limestone ($CaCO_3$), silicon oxides (SiO_2), aluminum, and iron oxides, clinker is made by one of two production processes: wet or dry; these terms refer to the grinding processes although other configurations and mixed forms (semi-wet, semi-dry) exist for both types.

In the wet process, the crushed and proportioned materials are ground with water, mixed, and fed into the kiln in the form of slurry. In the dry process, the raw materials are ground, mixed, and fed into the kiln in their dry state. The choice among different processes is dictated by the characteristics and availability of raw materials. For example, a

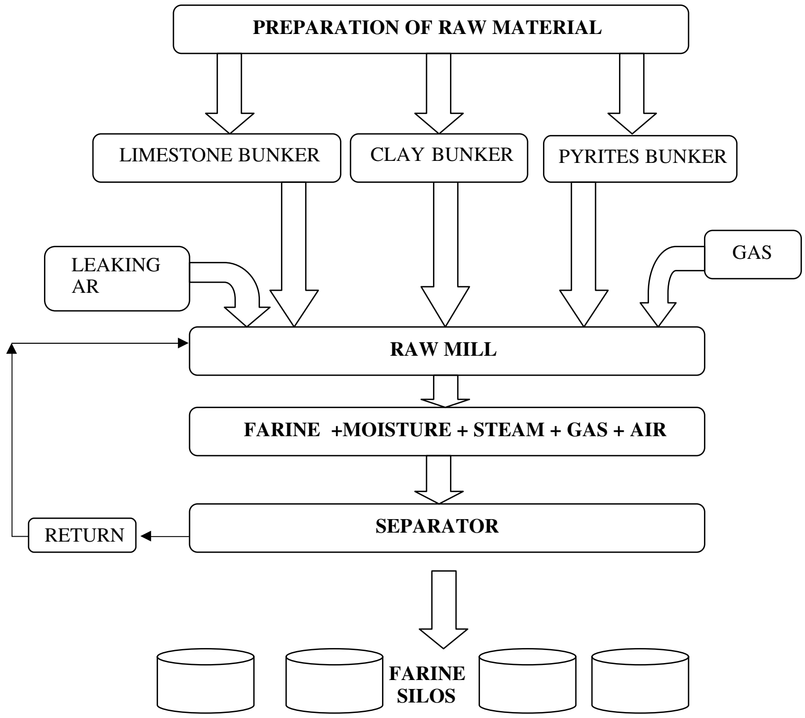

Fig. 1. Flow diagram of a cement plant process operation line.

wet process may be necessary for raw materials with high moisture content (greater than 15%) or for certain chalks and alloys that can best be processed as a slurry. However, the dry process is the more modern and energy-efficient configuration.

Once the materials are ground, they are fed into a kiln for burning. In modern kilns, the raw material is preheated (in 4–5 stages) using the waste heat of the kiln, or it is precalcined. During the burning or pyroprocessing, the water is first evaporated after which the chemical composition is changed, and a partial melt is produced. The solid material and the partial melt combine into small marble-sized pellets called clinker.

3.1.3. Finish grinding

Cooled clinker is ground in tube or roller mills and blended by simultaneous grinding and mixing with additives (e.g., gypsum, anhydrite, pozzolana, fly-ash or blast furnace slags) to produce the cement. Drying of the additives may be needed at this stage.

Cement is an inorganic, non-metallic substance with hydraulic binding properties, and is used as a bonding agent in building materials. It is a fine powder, usually gray in color, which consists of a mixture of the hydraulic cement minerals to which one or more forms of calcium sulfate have been added [22]. Mixed with water it forms a paste, which hardens due to formation of cement mineral hydrates. Cement is the binding agent in concrete, which is a combination of cement, mineral aggregates and water. Concrete is a key building material for a variety of applications.

3.2. Energy utilization in the turkish cement production

The cement industry is an energy intensive industry. In Turkey, the industry accounted for 10.3% of the total fuel consumption in the manufacturing sector in 2002 the energy costs amounted to about 26% of the manufacturing cost of cement [23]. In terms of the primary energy utilization, about 25% of the input energy was electricity while the remainder was thermal energy [24]. The specific energy consumption varied from about 3.40 GJ/t for the dry process to about 5.29 GJ/t for the wet process. The best practice specific energy consumption in Turkey is 3.06 GJ/t while in some countries of the world it is lower than 2.95 GJ/t [10,24]. 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 [24]. However, there are few detailed thermodynamic analyses of operating cement plants that evaluate the option of waste heat recovery.

The process of manufacture of cement can be divided into three basic steps, preparation of raw materials, pyroprocessing to produce clinker, and grinding and blending clinker with other products to make cement. For raw material preparation and cement grinding, the main energy carrier is electricity, so these estimates are given in terms of kWh per tone of material throughout. Cembureau [25] report gives energy utilization data for the various available technologies, while the Conroy report focuses only on the most efficient technology, the roller press. Energy requirements for cement grinding are roughly double those for raw material preparation because the cement is harder and need to be ground more finely than the raw materials. An important issue when considering "best practice" energy requirements for grinding is that energy use is related to the hardness of the raw materials and the additives included before cement grinding as well as the desired fineness of the finished product. These features can vary, so it is important to specify the fineness and composition of the product when discussing energy use.

Pyroprocessing consumes 99% of the fuel energy while electricity is mainly used to operate both raw materials (33%) and clinker (38%) crushing and grinding equipment. Pyroprocessing requires another 22% of the electricity hence it is the most energy intensive step of the production process [22]. The energy consumption in raw materials preparation accounts for a small fraction of overall primary energy consumption (less than 5%) although it represents a large part of the electricity consumption. When the energy consumption in this cement plant is examined by fuel types, the largest fuel types being coal with 57.66%, electricity 14.63%, and petro-coke with 27.72%, respectively, and total energy consumption is about 2.04 PJ in this plant for per year. These three fuels constitute 2.23% of the total energy is consumed in raw mill process.

4. Results and discussion

Here, the energy and exergy modeling technique discussed in the previous section is applied to a RM in the cement plant studied using actual data.

4.1. Mass balance in the raw mill

The mass balance of the RM, which is arranged according to the chemical reactions of input materials, is stated in their chemical components given in Table 1. The mass balance in the RM is conceived on the law of conservation using Eq. (1) as follows.

$$\sum \dot{m}_{in} = \dot{m}_{la} + \dot{m}_{g} + \dot{m}_{l} + \dot{m}_{c} + \dot{m}_{p} + \dot{m}_{lm} + \dot{m}_{cm} + \dot{m}_{pm} + \dot{m}_{bs} + \dot{m}_{gd} \tag{14a}$$

$$\sum \dot{m}_{out} = \dot{m}_{a} + \dot{m}_{g} + \dot{m}_{v} + \dot{m}_{fr} + \dot{m}_{m} \tag{14b}$$

4.2. Heat losses from the raw mill

4.2.1. Determining the input temperature of the raw mill

Farine consists of two sections. Input materials after being mixed in the drying room are taken into the grinding section so that the mixture changes into farine. The mixture is then, continuously turned with steel winglet until it owns the desired properties and it is sent to the separator with the effect of vacuum pressure from the RM.

The temperature of the mixture room is determined by balancing the mass and temperatures of the input materials and the mass and temperatures of the collected materials in the mixture room, as given in Eq. (15). The temperature of the mixture room is calculated from this equation, while it is given in Table 2.

$$\sum \dot{m}_{in} = \dot{m}_{la} + \dot{m}_{g} + \dot{m}_{l} + \dot{m}_{c} + \dot{m}_{p} + \dot{m}_{lm} + \dot{m}_{cm} + \dot{m}_{pm} + \dot{m}_{bs} + \dot{m}_{gd} \tag{15a}$$

$$\begin{aligned} &\dot{m}_{la}C_{p1}T_1 + \dot{m}_{g}C_{p2}T_2 + \dot{m}_{l}C_{p3}T_3 + \dot{m}_{c}C_{p4}T_4 + \dot{m}_{p}C_{p5}T_5 \\ &\quad + \dot{m}_{lm}C_{p6}T_6 + \dot{m}_{cm}C_{p7}T_7 + \dot{m}_{pm}C_{p8}T_8 + \dot{m}_{bs}C_{p9}T_9 \\ &\quad + \dot{m}_{gd}C_{p10}T_{10} \\ &\quad = (\dot{m}_{a}C_{pa} + \dot{m}_{g}C_{pg} + \dot{m}_{v}C_{pv} + \dot{m}_{f}C_{pf} + \dot{m}_{m}C_{pm})T_{mix} \end{aligned} \tag{15b}$$

Using Eq. (15b), the temperature of the mixture room ($T_{mix} = T_{in}$) was calculated to be 422.79 K.

Drying room temperature is accepted as input temperature for the RM. There is a logarithmic relation between drying room temperature and output temperature in order to determine the inner temperature of mill grinding section. This relation is given in the following.

$$\Delta T_{ave} = (T_{in} - T_{out}) / \ln(T_{in}/T_{out}) \tag{16}$$

$$\Delta T_{ave} = (422.79 - 377) / \ln(422.79/377) = 401.66 \text{ K}$$

4.2.2. Heat losses from the raw mill

Evidently, the occurring heat losses are determined according to the difference between the input and output temperatures to and from the farine. In addition, this flow of heat losses increases as it moves toward the exit of the farine according to the values of the surface temperature.

Table 1
Mass balance of the raw mill investigated

Item #	Input material	T_i (K)	$\dot{m}$ (kg/h)	Output material	T_o (K)	$\dot{m}$ (kg/h)
1	Leaking air	295	5053.00	Air	377	5053.00
2	Gas	602	49464.00	Gas	377	49464.00
3	Limestone	300	61764.51	Steam	377	5350.09
4	Clay	300	19331.30	Farine	377	121582.09
5	Pyrites	300	1419.28	Moisture	377	714.82
6	Return from separator	353	36000.00			
7	Moisture in the limestone	300	775.49			
8	Moisture in the clay	300	5138.70			
9	Moisture in the pyrites	300	150.72			
10	Dust in the gas	602	3067.00			
	Total		182164.00			182164.00

Table 2
Determination of mixture room temperature

Item #		Input				Mixture room			
		C_p (kJ/kg K)	T (K)	$\dot{m}$ (kg/h)	$\dot{Q}$ (kJ/h)	C_p (kJ/kg K)	$\dot{m}$ (kg/h)	$\dot{m}C_p$ (kJ/h.K)	T_{mix} (K)
1	Leaking air	1.01	295	5053.00	1498088.18	1.01	5053	5078.27	422.79
2	Gas	1.55	602	49464.00	46119721.15	1.55	49464	76610.83	422.79
3	Limestone	0.82	300	61764.51	15202518.84	0.82	61764.5	50675.06	422.79
4	Clay	0.92	300	19331.30	5340774.24	0.92	19331.3	17802.58	422.79
5	Pyrites	0.64	300	1419.28	272696.77	0.64	1419.28	908.99	422.79
6	Return from separator	0.80	353	36000.00	10213572.10	0.80	36000	28 933.63	422.79
7	Moisture in the limestone	4.19	300	775.49	973860.34	4.19	775.49	3246.20	422.79
8	Moisture in the clay	4.19	300	5138.70	6453179.46	4.19	5138.7	21510.60	422.79
9	Moisture in the pyrites	4.19	300	150.72	189274.18	4.19	150.72	630.91	422.79
10	Dust in the gas	1.05	602	3067.00	1932188.53	1.05	3067	3209.62	422.79
	Total				88195873.79		5053	208606.69	422.79

The distribution of the grinder temperatures is illustrated in Fig. 2.

Heat losses in the farine grinder take place in the three various forms. Heat losses with the convection are between the inside temperatures and the surface of grinder. The heat losses with the conduction are due to the temperature difference between inner and outer surfaces of the grinder. Heat losses with the convection and radiation occur from the outer surface to the environment. The total heat losses are calculated as follows (Fig. 3).

$$Q_{total} = Q_{cv1} + Q_{cd} + Q_{cv2} + Q_r \tag{17}$$

with

$$Q_{cd} = \frac{(T_{in} - T_{sf})}{\frac{\ln(r_o/r_i)}{2\pi kl}} \tag{18}$$

$$Q_{cv1} = \pi D_i hl(T_{in} - T_{sf}) \tag{19}$$

$$Q_r = \pi D_o \varepsilon\sigma(T_{sf}^4 - T_{out}^4) \tag{20}$$

$$Q_{cv2} = \pi D_o hl(T_{sf} - T_{out}) \tag{21}$$

The RM consist of two sections, which are called; "drying room" and "grinding room" as shown in Fig. 2. Total heat losses include all the RM sections. The surface of drying room is made of lining plates. The grinding room is composed of lining, bump lining, and out mirror plates. Inlet diameter of the RM could not be calculated exactly because of this complex structure while calculating the heat losses. In this case, an arithmetic average diameter has been calculated for both rooms, considering the cross-sections of drying room and grinding room.

Heat convection coefficient of the RM is necessary for the calculation of heat losses, which are due to the convection. This coefficient is determined using the values of total heat losses. Heat losses of both rooms are calculated using

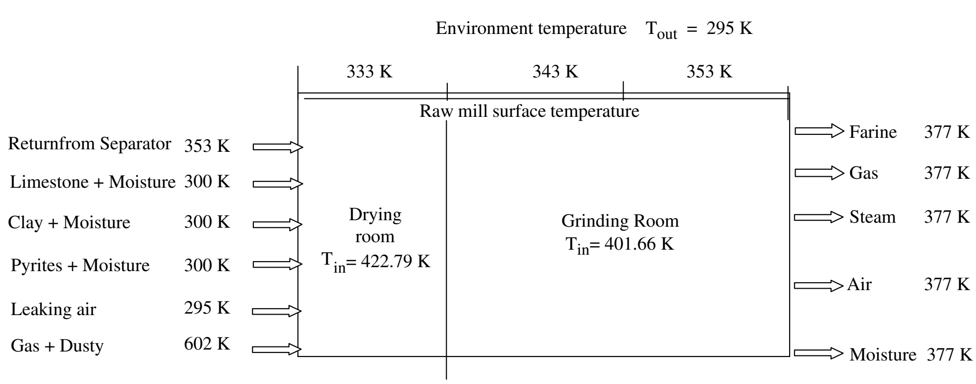

Fig. 2. Distribution of the temperatures in the raw mill.

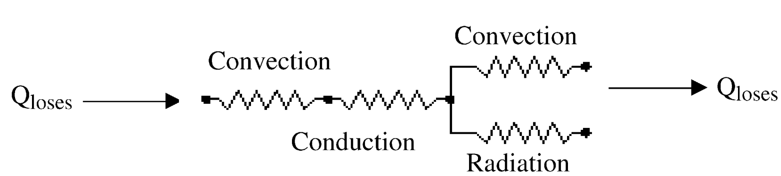

Fig. 3. Heat losses with electrical resemblance cycle.

the following data on the RM: $k = 52$ W/m K, $h = 163.15$ W/m^2 K, $\varepsilon = 0.8$, $D_o = 1.925$ m, $D_{i,dr} = 1.625$ m (in the drying room), $D_{i,gr} = 1.717$ m (in the grinding room), $l_{gr} = 3.4$ m, $l_{dr} = 3.55$ m.

4.2.2.1. Drying room total heat losses. Using Eqs. (18)–(21) and the data on the RM given above along with $T_{sf} = 333$ K, $T_{in} = 422.79$ K and $T_{out} = 295$ K, the drying room total heat losses were found to be 1 363 110.71 W.

4.2.2.2. Grinding room total heat losses. Grinding room total heat losses are calculated for two sections as follows:

(a) *Section 1*. Using Eqs. (18)–(21) and the data on the RM given above along with $T_{sf} = 343$ K, $T_{in} = 401.66$ K and $T_{out} = 295$ K, the grinding room total heat losses in Section 1 were calculated to be 1 356 146.68 W.

(b) *Section 2*. Using Eqs. (18)–(21) and the data on the RM given above along with $T_{sf} = 353$ K, $T_{in} = 401.66$ K and $T_{out} = 295$ K, the grinding room total heat losses in Section 2 were calculated to be 1 253 123.76 W. By taking into account all the losses calculated previously, total heat losses from the RM ($Q_{tot,rm}$) were obtained to be 14300478.91 kJ/h.

4.3. Energy analyses of the raw mill

In order to analyze the RM thermodynamically, the following assumptions are made:

(a) The system is assumed as a steady state, steady flow process.
(b) Kinetic and potential energy chances of input and output materials are ignored.
(c) No heat is transferred to the system from the outside.
(d) Electrical energy produces the shaft work in the RM.
(e) The change in the ambient temperature is neglected.

Under the above-mentioned conditions and using the actual operational data of the plant, an energy balance is applied to the RM. The references for enthalpy, entropy and input energy are considered for the calculations. The reference value for the enthalpy is considered to be 0 °C for calculations. The complete energy balance for the system is shown in Table 3. It is clear from this table that total energy input to the farine system is 749.39 kJ/kg, and the main heat source is the gas, given a total heat of 117.62 kJ/kg. Energy flow of the RM is also illustrated in Fig. 4.

In addition, the enthalpies of the materials going into and leaving the RM are given for the chemical components in Table 4, while the energy balance is given in Table 3. Relatively good consistency between the total heat input and total heat output is obtained.

4.4. Energy and exergy efficiencies of the raw mill

Energy efficiency of the RM is calculated from the following relation

$$\eta = \frac{\sum m_{out} h_{out}}{\sum m_{in} h_{in}} \tag{22}$$

Using energy analysis values and Eq. (22), the energy efficiency of the RM is calculated as follows:

$$\eta = \frac{76811394.87}{91111873.79} = 0.843 \quad \text{(or 84.3\%)}$$

The overall thermal efficiency of the RM was found to be 84.3% and is close to the best practice with the current technological limitations. The waste heat was estimated at about 16% of the energy input. This represented an improvement of about 16% in terms of primary energy efficiency of the RM.

4.5. Exergy analysis of the raw mill

The irreversibility of each of the components is calculated from the exergy consideration, while it may also be found using the entropy balance equations. Entropy balance of the RM is illustrated in Table 5, while exergy bal-

Table 3
Mass and energy balances of the raw mill

Item #	Input material	C_p (kJ/kg K)	T (K)	$\dot{m}$ (kg/h)	$\dot{Q}$ (kJ/h)	Output material	C_p (kJ/kg K)	T (K)	$\dot{m}$ (kg/h)	$\dot{Q}$ (kJ/h)
1	Leaking air	1.01	295	5053.00	1498088.18	Air	1.27	377	5053.00	2420697.46
2	Gas	1.55	602	49464.00	46119721.15	Gas	1.45	377	49464.00	26970125.31
3	Limestone	0.82	300	61764.51	15202518.84	Steam	2.05	377	5350.09	4126749.12
4	Clay	0.92	300	19331.30	5340774.24	Farine	0.92	377	121582.10	42151197.52
5	Pyrites	0.64	300	1419.28	272 696.77	Moisture	4.24	377	714.82	1142625.47
6	Return from separator	0.80	353	36000.00	10213572.10	Heat losses from surface				14300478.91
7	Moisture in the limestone	4.19	300	775.49	973860.34					
8	Moisture in the clay	4.19	300	5138.70	6 453179.46					
9	Moisture in the pyrites	4.19	300	150.72	189274.18					
10	Dust in the gas	1.05	602	3067.00	1 932188.53					
11	Heat from electrical energy				2916000.00					
	Total			182164	91111873.79				182164	91111873.79

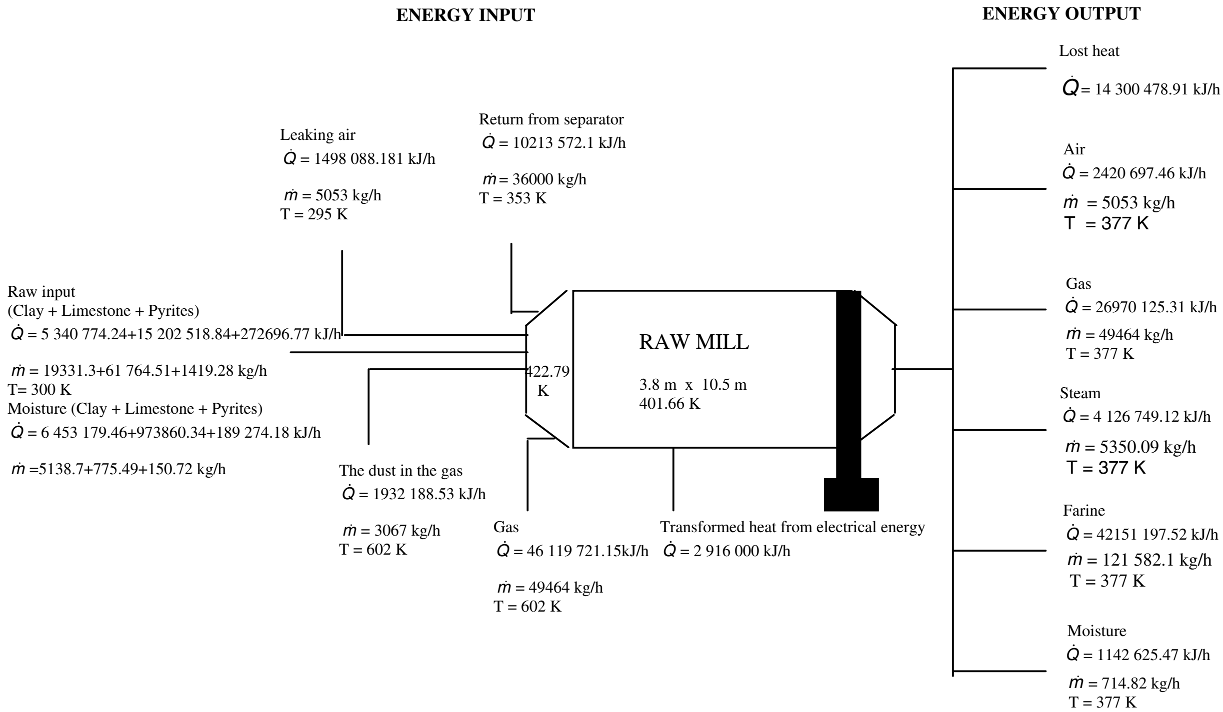

Fig. 4. Energy flow diagram of the raw mill.

Table 4
Enthalpy balance of the raw mill

Item #	Input material	C_p (kJ/kg K)	T_0 (K)	T (K)	$\dot{m}$ (kg/h)	h (kJ/kg)	Output material	C_p (kJ/kg K)	T_0 (K)	T (K)	$\dot{m}$ (kg/h)	h (kJ/kg)
1	Leaking air	1.01	295	295	5053	0.00	Air	1.27	295	377	5053.00	526517.75
2	Gas	1.55	295	602	49464	2519525.57	Gas	1.45	295	377	49464.00	5866181.10
3	Limestone	0.82	295	300	61765	253 375.31	Steam	2.05	295	377	5350.09	897595.30
4	Clay	0.92	295	300	19331	89012.90	Farine	0.92	295	377	121582.00	9168164.98
5	Pyrites	0.64	295	300	1419.28	4544.95	Moisture	4.24	295	377	714.82	248528.62
6	Return from separator	0.80	295	353	36000.00	1678150.66						
7	Moisture in the limestone	4.19	295	300	775.00	16231.01						
8	Moisture in the clay	4.19	295	300	5139.00	107552.99						
9	Moisture in the pyrites	4.19	295	300	150.72	3154.57						
10	Dust in the gas	1.05	295	602	3067.00	985351.96						

Table 5
Entropy balance of raw mill

Item #	Input material	C_p (kJ/kg K)	T_0 (K)	T (K)	$\dot{m}$ (kg/h)	Δs (kJ/kg K)	Output material	C_p (kJ/kg K)	T_0 (K)	T (K)	$\dot{m}$ (kg/h)	Δs (kJ/kg K)
1	Leaking air	1.01	295	295	5053.00	0	Air	1.27	295	377	5053.00	1573.13
2	Gas	1.55	295	602	49464.00	54623.52	Gas	1.45	295	377	49464.00	17527.00
3	Limestone	0.82	295	300	61764.51	861.48	Steam	2.05	295	377	5350.09	2681.84
4	Clay	0.92	295	300	19331.3	302.64	Farine	0.92	295	377	121582.1	27392.69
5	Pyrites	0.64	295	300	1419.28	15.45	Moisture	4.24	295	377	714.82	742.56
6	Return from separator	0.80	295	353	36000.00	5179.12						
7	Moisture in the limestone	4.19	295	300	775.49	55.19						
8	Moisture in the clay	4.19	295	300	5138.7	365.68						
9	Moisture in the pyrites	4.19	295	300	150.72	10.73						
10	Dust in the gas	1.05	295	602	3067.00	2288.46						

Table 6
Exergy balance in the raw mill

No.	Input material	h (kJ/kg)	T_0 (K)	T (K)	Δs (kJ/kg K)	ψ (kJ)	Output material	h (kJ/kg)	T_0 (K)	T (K)	Δs (kJ/kg K)	ψ (kJ)
1	Leaking air	0.00	295	295	0	0.00	Air	526517.75	295	377	1573.13	62443.72
2	Gas	2519525.57	295	602	54623.52	7405586.12	Gas	5866181.10	295	377	17527.00	695714.77
3	Limestone	253375.31	295	300	861.48	−760.13	Steam	897595.30	295	377	2681.84	106452.61
4	Clay	89012.90	295	300	302.64	−267.04	Farine	9168164.98	295	377	27392.69	1087322.00
5	Pyrites	4544.95	295	300	15.45	−13.63	Moisture	248528.62	295	377	742.56	29474.89
6	Return from separator	1678150.66	295	353	5179.12	150310.22						
7	Moisture in the limestone	16231.01	295	300	55.19	−48.69						
8	Moisture in the clay	107552.99	295	300	365.68	−322.66						
9	Moisture in the pyrites	3154.57	295	300	10.73	−9.46						
10	Dust in the gas	985351.96	295	602	2288.46	310257.48						
	Total					7864732.21						1981408.00

ance of the RM is shown in Table 6. The following assumptions are made in the calculations.

(a) The system is assumed as a steady state, steady flow process.
(b) Chemical exergies of the substances are neglected.
(c) Kinetic and potential exergies of materials are ignored.

Total exergy values of the input and output materials are calculated to be 7864.73 and 1981.40 MJ, respectively.

4.6. Exergy efficiency of the raw mill

The exergy efficiency of the RM is calculated from

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

Using exergy analysis values and Eq. (23), the exergy efficiency of the RM is computed as follows:

$$\varepsilon = \frac{1\,981\,408.00}{7\,864\,732.21} = 0.252 \quad (\text{or } 25.2\%)$$

The overall exergy efficiency of the RM was determined as 25.2%. The major heat loss sources have been determined to be 34.13% and 65.87% as drying and grinding room total heat losses, respectively.

5. Conclusions

The aim of this study was to determine energy and exergy utilization efficiencies for a raw mill in a cement production. Mass balance and heat losses, energy and exergy utilization efficiencies of the RM were analyzed using the actual plant operational data. The main conclusions drawn from present study may be summarized as follows:

(a) Exergy analysis is a powerful tool, which has been successfully and effectively used in the design and performance evaluation of energy-related systems.
(b) The energy efficiency values for the RM are obtained to be 84.3% in this study, while the exergy efficiency values for that are found to be 25.2%.
(c) Heat losses by conduction, convection and radiation from the surface of the RM are about 14 300 MJ/h. Hence, the energy saving potential for the only RM system is estimated to be nearly 14 300 MJ/h, which indicates an energy recovery of 15.70% of the total input energy into the RM.
(d) Heat losses that come out especially at the beginning stage of the process shows problem with the efficiency of the system. Heat losses will decrease if necessary precautions are taken in the RM. It will also cause saving of fuel at the rotary kiln.
(e) This study has indicated that exergy utilization in the RM was even worse than energy utilization. In other words, this process represents a big potential for increasing the exergy efficiency. It is clear that a conscious and planned effort towards building an energy management structure within the plant studied is needed to improve exergy utilization in the RM. Considering the existence of energy-efficient technologies in the similar sectors, the major problem is delivering these technologies to consumers or, in other words, using effective energy-efficiency delivery mechanisms.Some suggestions are given below to increase the efficiency of the RM.
  - The mixing temperatures of the materials, which constitute farine and gas coming from the preheater cyclones and being the energy source of the RM should be reevaluated. Cement plants are designed at a full production capacity. The system productivity would be increased when the raw material input capacity would be held at the highest capacity and when the turning speed of the farine mill and the material flow rate could be decreased because the system output temperature would be raised.
  - The waste energy in the RM and the leaving temperature of the farine could be recovered by means

of a heat recovery system. Thus, the efficiency of the system would be increased.

(f) It may also be concluded that the analyses reported here will provide the investigators with knowledge about how effectively and efficiently a sector uses its energy resources.

(g) The technique presented here is beneficial for analyzing sectoral energy and exergy use for providing the real picture of the industry. It is also helpful in establishing energy conservation policies. Further work is required to cover cost accounting in the exergy analysis, referring to the exergoeconomic (or thermo economic) analysis. This is crucial in the determination of: (i) the appropriate allocation of economic resources to optimize the design and/or operation of a system or a sector; and/or (ii) the economic feasibility and profitability of a system or a sector (by obtaining the actual costs of products, and their appropriate prices).

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