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Exergoeconomic analysis of energy utilization of drying process in a ceramic production

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HIGHLIGHTS

- Thermo-economic cost analysis of a ceramic plant was performed using the actual operational data.
- Spray dryer, Vertical dryer and Furnace were analyzed.
- Energy utilization efficiency values for this sector ranged from 30.44% to 65.5%.
- Exergy utilization efficiency values for this sector ranged from 12.73% to 61.66%.
- The ratio of thermodynamic loss rate to capital cost values was obtained in the range of 53.38–135.83.

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ABSTRACT

Thermo economic cost analysis of a ceramic plant, with a yearly production capacity of 24 million m^2, was performed based on the actual operational data. The ceramic drying system was analyzed at the spray dryer, the vertical dryer and the furnace stages. The performances of these three processes and the effects of the process conditions on the process performance were evaluated using energetic, exergetic, and exergoeconomic analysis methods. The performance assessment was performed through energy and exergy efficiencies, the improvement potential rate, the total cost, and the exergoeconomic factor terms. The ratio of the thermodynamic loss rate to the capital cost values was obtained in the range of 53.38–135.83 MW/$. In this process, there is a great potential towards increasing the energy and exergy utilization efficiencies.

1. Introduction

All energy sources are irreversible processes which have an economic value. Additionally despite the fact that these resources have high investment costs, they are continuously consumed. The cost formation process is defined by physical connections with economics and thermo economics. This definition is stated not only as general theory of energy saving but also as cornerstone of energy conservation [1]. Concepts, such as thermodynamic cost, purpose, causation, resources, systems, efficiency, and structure and cost formation process, constitute the essential bases for thermo economics [2].

Exergoeconomics is the branch of engineering that appropriately combines, at the level of system components, the thermodynamic evaluations based on an exergy analysis with the economic principles [3]. The main objectives are to provide the designer or operator of a system with information, that is useful to the design and operation of a cost-effective system, but not obtainable by regular energy or exergy analysis and economic analysis [4].

Many researchers have developed methods of performing economic analyses based on exergy, referring to variety of names (e.g., thermo economics, second-law costing, cost accounting and exergoeconomics). Exergoeconomics analysis has been widely used for the performance evaluation of thermal systems. A lot of studies were conducted in the fields of exergy analysis and exergoeconomics by Tsatsaronis. His studies show many details about exergoeconomic concept, and its applications to thermal systems [4,5]. In this studies; a systematic and general methodology for defining and calculating exergetic efficiencies and exergy related costs in thermal systems is recommended [6,7]. Furthermore methodology of his studies are based on the Specific Exergy Costing (SPECO) approach [8], in which (i) the fuel and product of a

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Nomenclature

I	specific exergy destroyed or irreversibility (kJ/kg)
IP	improvement potential (kJ)
K	capital cost (US$)
L	thermodynamic loss (kJ)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
R	ratio of thermodynamic loss rate-to-capital cost K (kJ/US$)
SD	standard deviation (–)
s	specific entropy (kJ/kg K)
T	temperature (°C or K)
$\dot{Q}_k$	heat transfer rate (kW)
$\dot{W}$	work rate or power (kW)

Greek symbols

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

Subscripts

dest	destruction
f	fuel
en	energy
ex	exergy
ex-e	external exergy
ex-i	internal exergy
j	jth value in a set
m	mean
max	maximum
min	minimum
s	overall station
u	utilize

component are defined by taking a systematic record of all exergy additions to and removals from all the exergy streams of the system, and (ii) the costs are calculated by applying basic principles from business administration. Thus, a direct link between the definitions of fuel and product for a component and the corresponding costing equations are established [8].

On the other hand, Thermoeconomics analysis includes evaluation of the process economically. In this contex; a new methodology for cost allocation, cost optimization, and cost analysis was proposed by Kim [9]. Various forms of energies including exergy can be integrated to wonergy as a new term, and the proposed equations are expressed in terms of wonergy [10]. On the other side, the second-law costing is presented by many investigators [11–14]. Among these, exergy, cost, energy and mass (EXCEM) method proposed by Rosen and Scott [11] could be useful to investigators in engineering and other disciplines. The methodology has also been utilized by Rosen and Dincer [12–14]. It provides a comprehensive assessment by accounting for the EXCEM quantities [13]. In this area, some of the other studies are; Application of exergoeconomic and exergoenvironmental analysis to an SOFC system with an all thermal Biomass Gasifier is investigated by Meyer et al. [15], energetic, exergetic, and exergoeconomic analyses of spray-drying process during white cheese powder production is realised [16], Ozgener and Hepbasli presented two detailed research about exergoeconomic analysis of a solar assisted ground-source heat pump greenhouse heating system [17], and a parametric study on the exergoeconomic assessment of a vertical ground-coupled (geothermal) heat pump system [18]. Ghaebi et al. realised an exergoeconomic optimization of trigeneration system [19]. On the other hand exergoeconomic analysis of a combined cycle system utilizing associated gases from steel production process based on structural theory of thermoeconomics was examined by Yao et al. [20]. These analysis techniques have the following common characteristics: (i) They combine exergy and economic disciplines to achieve the objectives, and (ii) They recognize exergy, a not energy; rather, is the commodity of value in a system, and they consequently assign costs and/or prices to exergy-related variables.

In this study, the authors investigate the relations between the thermodynamic losses and capital costs for the ceramics drying sector based on the actual operational data. The data collected from a ceramic plant, located in Izmir, with a yearly production capacity of 24 million m^2. The ceramic drying system was analyzed at the three stages. There are a lot of studies about energy and exergy analyses of drying systems. Utlu et al. evaluated the performance analysis and assessment of an industrial dryer in ceramic production [21], Peinado et al. made an exergy and exergy analysis in an asphalt plant's rotary dryer [22]. Dincer and Şahin presented a new model about thermodynamic analysis of a drying systems [23]. Ozgener and Ozgener investigated exergy analysis of industrial pasta drying system [24].On the other hand, there are several studies about exergoeconomic analysis of drying systems; Exergoeconomic analysis of small industrial pasta dryer system was presented by Ozgener [25], and Ogura et al. made energy and cost estimation for application of chemical heat pump dryer to industrial ceramics drying [26]. An exergoeconomical analysis was applied to data from a ceramic plant as a unique example, considering the ceramic industry and related literature. In this regard, the structure of the paper is organized as follows: The first section includes some introductory information; the second section describes the ceramic process. Drying process energy-related relations including general energetic, exergetic and process are given in the analysis section. The results and discussions are stated in the following section while the last section concludes.

2. Description of drying process in ceramic production

Ceramics are defined as inorganic, non-metallic 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 these 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 [27].

The generalised production scheme for the ceramics industries consists of four basic stages; preparation of raw materials, shaping, drying and firing [23]. The differences between each particular sector – especially with respect to shaping process – but also with respect to the raw materials used and the drying, firing temperatures employed, depend on the specific needs for the particular products [23]. The ceramic production system plotted schematically, as can be seen Fig 1.

Ceramic drying and firing process is highly energy intensive and involves the slow and gentle expulsion of water from the green