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Energy and exergy assessments of a perlite expansion furnace in a plaster plant

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ABSTRACT

In this study, energy and exergy assessments of a perlite expansion furnace in a plaster factory are performed. Chemical properties of the perlite and its application areas are described. Energy and exergy relations according to the First and Second Law of Thermodynamics are derived. Energy and exergy efficiencies, losses and exergy destructions are calculated based on the measurements obtained from the system. Evaluations of environmental impact, energy management and economic are finally generalized according to the obtained results. Energy and exergy efficiencies of the furnace are determined to be 66% and 26%, respectively. Reference temperature effects on exergy efficiency, destruction and sustainability index are also presented. The results showed that the furnace has not been well designed in terms of thermal aspects due to high energy and exergy losses and the manufacturer producing the perlite expanded should establish an energy management structure.

1. Introduction

Energy consumers should have responsibility for energy efficiency, energy saving, environmental and sustainable concepts, etc. The First and Second Laws of Thermodynamics has been widely applied to any system for evaluating its performance. The First Law of Thermodynamics implies the conservation of energy [1]. Energy analysis is concerned with the amount of energy, but does not include the quality of energy and the direction of change of state. Energy analysis is inadequate in this respect. The Second Law of Thermodynamics overcomes with concepts of entropy and exergy. There is no study on energy and exergy analysis of the perlite expansion furnace based on literature survey. It may be discussed with the furnaces used for different purposes and research on producing building material systems.

Engin and Ari [2] performed an energy audit of dry type cement rotary kiln systems that consume intensive energy. Energy losses were found from the hot flue gas, the kiln shell and the cooler stack while some possible ways of recovering the heat losses were introduced and discussed. The results showed that 15.6% of the total input energy rate (4 MW) could be recovered. Sardeshpande et al. [3] presented a model based approach for benchmarking of energy intensive industrial processes and illustrated this approach for industrial glass furnaces. A simulation model for a glass furnace was developed by using mass and energy balances, and heat loss equations for the different zones and empirical equations based on operating practices. Their model results indicated the potential for improvement and the impact of different operating and design preferences on specific energy consumption. Madlool et al. [4] reviewed energy utilization and savings in cement industries. Their study covered energy saving, carbon dioxide emission reductions and various technologies used to improve the energy efficiency in the cement industry. Madlool et al. [5] studied on overview of exergy analysis for cement industries. Their paper reviewed exergy analysis, exergy balance, and exergetic efficiencies for cement industry. Chirattananon and Gao [6] assessed the operation performance of an electric arc furnace. Their paper integrated an electrical model of the furnace with the thermal model and included exothermic heat from chemical reaction in an energy balance consideration. Sakamoto et al. [7] studied on estimating the energy consumption for each process in the Japanese steel industry. Their paper exhibited that the energy consumption was estimated by a statistical process to evaluate the possibility of reducing the energy consumption. Lee and Jou [8] studied on improving the furnace energy efficiency through adjustment of damper angle. They adjusted the furnace flue damper angle to lower the pressure in the furnace for reducing the velocity of hot gas rising in the furnace. This allowed more time for the heat to be transferred to the thermal flow that improved the furnace overall thermal efficiency. Chen et al. [9] analyzed the energy consumption and performance of reheating furnaces in a hot strip mill through both numerical predictions

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Nomenclature

A	area (m^2)
AFR	air–fuel rate
C_p	specific heat capacity (kJ/kg K)
$\dot{E}x$	exergy rate (kW)
$\dot{E}$	energy rate (kW)
$\dot{e}_{ex}$	specific exergy (kJ/kg)
D	diameter (m)
g	gravity (m/s^2)
Gr	Grashof number
h	specific enthalpy (kJ/kg)
H	heat convection coefficient (W/m^2 K)
k	thermal conductivity coefficient (W/m K)
LHV	low heating value (kJ/kg)
L	length (m)
M	molar mass (kg/kmol)
$\dot{m}$	mass flow rate (kg/s)
m	mass (kg)
Nu	Nusselt number
Pr	Prandtl number
$\dot{Q}$	heat flow rate (kW)
Ra	Rayleigh number
R	universal gas constant (kJ/kmol K)
s	specific entropy (kJ/kg K)
SI	sustainability index
T	temperature (K)
$\dot{W}$	work rate (kW)
x	mole fraction

Greek letters

λ	fuel–air ratio
τ	excess air coefficient
θ	angle of cone
σ	Stefan–Boltzmann constant (W/m^2 K^4)
ε	thermal diffusion coefficient
β	thermal expansion coefficient (1/K)
ν	kinematic viscosity (m^2/s)
ψ	flow exergy (kJ/kg)
η	energy efficiency
η_{ex}	exergy efficiency

Subscripts

i	inlet
$dest$	destruction
e	exit
cv	control volume
a	air
f	fuel
Ng	natural gas
per	perlite
$E.per$	expanded perlite
p	combustion products
s	surface
l	loss
∞	reference environment

Superscripts

ph	physical
ch	chemical

and practical measurements in their study. The results obtained by them indicated that increasing the production rate of the furnaces was conducive to utilizing fuel more efficiently. Jegla et al. [10] studied on a plant energy saving through efficient retrofit of the furnaces. They applied an efficient methodology for furnaces retrofit, using optimization of both stack temperature and air preheating system. Gutiérrez et al. [11] analyzed the energy and exergy consumption of the calcination process in vertical shaft kilns, in order to identify the factors affecting fuel consumption. In the process, the energy efficiency was found to be higher than the exergy efficiency, e.g. 71.6% and 40.8% for the energy and exergy efficiency of one of the kilns. Camdali et al. [12] applied analysis of the Second Law of Thermodynamics to the ladle furnace in an important alloyed and special steel production company in Turkey. Exergy efficiency was found to be 50% by them. They are investigated irreversibilities which cause the significant production costs in detail. Rasul et al. [13] presented a simple model to assess thermal performance of blast furnace (BF) for efficient utilization of energy with an integrated view to improving the productivity of the plant. The First and Second Law efficiencies of the BF operating system were found to be 77.3% and 39.13%, respectively. Irreversibility of the actual operation of BF was found to be 18.9%, which included the irreversibility due to the transformation of chemical energy and promotion of reduction reactions. Bisio and Rubatto [14] comprehensively reviewed the recent literature about heat and fluid flow and mixing phenomena for some main processes in the iron and steel industry towards their improvement. Hepbasli and Ozalp [15] investigated the development of industrial energy efficiency and management studies in Turkey. They reported that the Turkish industrial sector had an annual energy saving potential of approximately 30% and some efforts towards improving the energy efficiency in the country should be made. Kannan and Boie [16] studied on providing a guideline in energy management for medium scale enterprises. The medium scale enterprise considered was a bakery. Instruction of energy management in the bakery, a reduction of 6.5% on total energy consumption was expected. Though the bakery had some energy conservation programme, this 6.5% energy saving is to be achieved without much investment.

The main objective of this study is to examine a perlite expansion furnace according to energy and exergy analyses. The First and Second Law of Thermodynamics are applied to the furnace. The results obtained are exhibited through the energy and exergy losses, efficiencies, exergy destruction, energy management program and design parameters, etc. They can be used to propose better working conditions of the thermal system considered. They are evaluated in terms of energy management, economic and environment impact.

2. Description of the perlite

The perlite is a vitreous substance that contains 2–6% water. It has gray, silver gray, dark brown and black colors. It is also a lightweight material because it can expand 10–30 times of its volume when heated between 800 and 1150 °C. The density of the perlite decreases as its volume increases, and it can be described as a lightweight material. In Turkey, 8 billion tons of perlite exist, corresponding to 70% of the world reserves. This shows that the perlite is a very important material for the Turkish economy, and it can be used as insulator owing to its low heat conductivity [17]. The chemical composition and the physical properties of the perlite are indicated in Tables 1 and 2, respectively. Utilization areas of the perlite make the product adaptable to numerous applications such as construction, industrial, chemical, horticultural and petrochemical industries. Applications of the perlite include filler,