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Evaluation of the performance of a hydrogen enriched combustion system for ceramic sector

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ABSTRACT

In this experimental study, the energy and exergy analyses were performed to determine optimum hydrogen mass flow rate for hydrogen enrichment application in a ceramic kiln. The effects of multiple-point and single-point injection of hydrogen at different mass flow rates on energy and exergy efficiencies were evaluated. The hydrogen-enriched natural gas combustion experiments were carried out for a ceramic kiln including 102 burners. Optimum hydrogen flow rates were determined as 1.08 kg/h and 1.16 kg/h for multiple-point and single-point applications, respectively. For 40 × 40 cm ceramic tile production at the optimum hydrogen mass flow rate and with minimum natural gas consumption, energy efficiencies were found as 63.13% and 62.63% and exergy efficiencies were reached as 43.12% and 42.74% for multiple-point and single-point applications, respectively. A significant difference between multiple-point and single-point applications has not been found for both energy and exergy efficiencies. The hydrogen enrichment system has a short payback time after the first three months of operation in the present study. It is concluded that application of hydrogen enrichment in ceramic kilns have a great potential for energy saving and energy efficiency.

1. Introduction

In today's world, energy demand is largely supplied by the fossil fuels such as oil, coals, natural gases etc. It is the fact that fossil fuels will run out in the near future. Mankind has to utilize their energy sources very efficiently and has to find different ways to prevent run out increasingly. Furthermore combustion of fossil fuels has very important negative effects to the environment. The main negative effect is the emissions of NO_x, CO_x, SO_x and unburned hydrocarbons. It could be possible to minimize the disadvantages of fossil fuels by hydrogen enrichment applications in combustion systems. At the same time, combustion efficiency could be increased by hydrogen enrichment.

There are numerous studies on investigation and application of hydrogen enrichment [1–11]. It was resulted that the addition of hydrogen at a high volumetric ratio could significantly extend the lean burn limit, improve the engine lean burn ability, decrease burn duration, and yield higher thermal efficiency. The CO, CH_4 emissions were reduced and NO_x emission could be kept an acceptable low level with high hydrogen content under lean burn conditions when ignition timing were optimized [5,7,9].

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Nomenclature

e	Specific exergy (kJ/mol)
h	Enthalpy (kJ/kg)
m	Mass (kg)
$\dot{Q}$	Heat transfer rate (kJ/h)
s	Specific entropy (kJ/kgK)
C_p	Heat capacity (kJ/kgK)
$\dot{E}$	Energy rate (kW)
e_{ch}	Chemical exergy (kJ)
e_{ph}	Physical exergy (kJ)
P	Pressure (bar)
P_0	Dead state pressure (bar)
R_u	Universal gas constant (kJ/kmolK)
T	Temperature (K)
T_0	Dead state temperature (K)
$\dot{S}_{gen}$	Entropy generation rate (kW/K)
$\dot{E}x_{dest}$	Exergy destruction rate (kJ/h)
$\dot{E}x_{in}$	Inlet exergy (kJ/h)
$\dot{E}x_{out}$	Outlet exergy (kJ/h)
η_I	I. Law (energy) efficiency
η_{II}	II. Law (exergy) efficiency
U_0	Internal energy
V_0	Control volume
S_0	Entropy
NPV	Net present value
a	Net present value factor
B	gain
p	period
I	Discount rate

It could be listed many advantages for hydrogen enrichment applications. According to the studies in the literature, it could be concluded that thermal efficiency values of any combustion system could be increased and fuel consumption could be decreased by the application of hydrogen enrichment. Furthermore this process could reduce carbon monoxide and unburned hydrocarbon emissions. Also the studies in the literature point that the burning speed of methane accelerates with hydrogen injection [6,7].

Conventional energy sources have been run out rapidly in today's world, while the energy cost increases. The first law of thermodynamics deals with the quantity of energy and asserts that energy cannot be created or destroyed. The second law of thermodynamics has proved to be a very powerful tool in the optimization of complex thermodynamic systems. It is concerned with the degradation of energy during a process and the entropy generation. Recently, the exergy concept has been commonly used to analyze the energy utilization of an energy system to gain insights into its efficiency. It is very helpful to perform exergy analysis to determine optimum operation conditions for a thermal system [12]. Besides, exergy analysis is a very important approach to understand how much any real energy system closes to a reversible system and to determine improvement potential of any energy system. Exergy analysis leads to a better understanding of the influence of thermodynamic processes 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 [13]. A better understanding of sites of exergy destructions can help to improve the system operation and help in better design and optimization. A higher exergetic performance of a system translates into energy savings and environmental benefits [14].

There is not any study on the energy and exergy analyses of hydrogen enrichment for any industrial sector in the open literature. However, numerous studies exist on energy–exergy analyses for any other industrial processes in the literature. For the last decade, there is a growing interest in the use of both the energy and the exergy analyses for energy utilization to save energy and thereby achieve financial savings and numerous studies have been performed energy-exergy analyses for industrial processes [14–23]. Madlool et al. reviewed (2012) the exergy analysis, exergy balance, and exergetic efficiency for the units which relate to the production processes in the cement industries [17]. Also Ahamed et al. (2012) focused on improving the energy, exergy and recovery efficiencies of a grate cooling system through the optimization of its operational parameters such as masses of cooling air and clinker, cooling air temperature, and grate speed. They used the energy and exergy analyses to determine how the operational parameters of the grate clinker cooling system and the recovery of heat from the hot exhaust air, affect the efficiencies [18]. Sanaei et al. (2012) performed the exergy and energy analyses to assess the use of quality of energy in Iran's industrial sector. They obtained that the energy and exergy efficiencies for the entire industrial sector of Iran as 63% and 42%, respectively [19]. Atmaca and Kanoglu (2012) performed the first and second law analysis of a raw mill and certain measures are implemented in an existing raw mill in a cement factory in order to reduce the amount of energy consumption in grinding process. They found the energy and exergy efficiencies as 61.5% and 16.4%, respectively [20]. Söğüt et al. (2010) examined heat recovery from rotary kiln for a cement plant by performed energy-exergy analyses. They pointed that the energy-exergy efficiency values of a rotary kiln for cement production as respectively [23]. Asprion et al. (2011) showed how the incorporation of exergy analysis into the workflow of the chemical industry help to identify potentials for reduced energy consumption. They proposed a workflow by applying the exergy analysis for multi-objective optimization studies [24]. Gutiérrez et al. (2013) analyzed the energy and exergy consumptions of the calcination process in vertical shaft kilns, in order to identify the factors affecting fuel consumption. They resulted that the most irreversible processes taking place in the kiln are the exergy destruction due to fuel combustion and the exergy destruction due to internal heat and momentum transfer both accounting for about 40% of the efficiency loss [21].

Ceramic industry consumes a great amount energy; however it has also a high potential for energy saving. There are very limited studies on the energy issues for ceramic industry. Apak (2007) performed the energy and exergy analysis for different processes in a ceramic factory burning natural gas and showed that the energy efficiency is 43% on ceramic combustion kiln and exergy efficiency is 11% [25]. Utlu et al. (2011) studied the thermodynamic analysis of an industrial drying kiln and found the energy and exergy efficiencies as 35% and 16% respectively [26]. Enhancing exergy efficiency for