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Assessment of cost sources and improvement potentials of a ground-source heat pump food drying system through advanced exergoeconomic analysis method

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ABSTRACT

Advanced exergoeconomic analysis, the so-called new exergetic approach combined with the economic analysis, is applied to a ground-source heap pump (GSHP) drying system in this study. The thermodynamic inefficiencies and cost performance of the system components are evaluated in parts. Moreover, the results of the advanced exergoeconomic analysis are compared to those of the conventional exergoeconomic analysis. The results show that total costs in the overall system are 4.008 $/h whereas 2.569 $/h of the total costs are avoidable. The avoidable investment costs are significantly lower than avoidable destruction costs. Advanced exergoeconomic analysis indicates that the most important system components are the drying duct and the condenser with respect to reducing the costs. It is possible to reduce 34.6% of the total costs by developing improvement strategies focused on the drying duct and the condenser. It may be concluded that the conventional exergoeconomic analysis is an effective approach to specify the components, in which costs are accumulated while the advanced exergoeconomic approach is essential to determine the cost sources and to develop cost effective improving strategies.

1. Introduction

Drying has been used in several sectors to obtain different utilities. Energy consumption ratio of drying is in the range of 10–25% of the total energy consumption in developed countries while drying is one of the most significant energy-intensive process with low thermal efficiencies between 25% and 50% [1]. Moreover, the product's quality, especially during the drying of biological products, changes in substantial ratios because of the applied heat treatment and these changes are often undesirable. Therefore, biological products are generally dried at low temperatures and use of high quality energy sources in low-temperature processes increases the irreversibilities [2]. Because of all, studies focused on improvements in the energy efficiencies and operation costs of drying systems have been of great importance in recent years.

The ground-source heat pump (GSHP) systems are clean technologies that use renewable energy sources and they are worldwide accepted to be as utilized green technology for heating and cooling applications due to their higher energy utilization efficiencies [3–5]. GSHPs use the advantage of the relatively stable temperature of underground and their high energy utilization efficiencies introduce them as one of the most efficient kinds in heat pumps (HPs) [6,7]. Generally, GSHPs are classified in two types as (i) open-loop systems using surface or groundwater sources and (ii) closed-loop systems combined with (vertical or horizontal type) ground heat exchanger (GHE) [5]. These systems extract heat from the ground or a body of water to provide low-temperature heat [8]. Therefore, apart from space heating/cooling applications, the applications of GSHP systems to drying processes have been a promising alternative. However, a few studies about the drying applications of GSHP systems have appeared in the open scientific literature [9–13].

Exergy may be defined in various ways, and the most frequently used definition of exergy is the maximum amount of work obtainable from a stream of matter, heat or work, when some matter is brought to a state of thermodynamic equilibrium with the common components of natural surroundings by means of reversible processes. Exergy analysis differs from energy analysis with the inclusion of entropy concept and the second law of

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thermodynamics [14–16]. The performance of a drying system or drying process can be efficaciously tested and losses occurred in the components of energy systems can be separately evaluated through exergy analysis method. The most recent studies focused on the food drying performance, which were performed using conventional exergy methods, are listed in Table 1 [17–34]. Moreover, the cost of the addition of exergy to a stream or material and charge to the unit, which makes use of that exergy can be determined by exergoeconomic (called in Europe) or thermoeconomic (called in U.S.) analysis, which combines economic constraints with exergy analysis to give the information that cannot be gained by energetic and economic evaluations [35]. By performing these two methods combined with modeling and simulation techniques, energy systems can be analyzed and imperfections, which cause inefficiencies and increases costs, can be investigated. However, the information obtained by these analyses is not enough for generating solutions because conventional exergetic/exergoeconomic analyses do not release information about the sources of losses and costs.

In the last decade, a new strategy called advanced exergetic/exergoeconomic analyses has been developed and improved [36–38]. Advanced techniques focus on the splitting exergy destructions and costs into two main groups as (i) avoidable (AV) and unavoidable (UN), (ii) endogenous (EN) and exogenous (EX) parts. Although all system components have exergy destructions and cost rates associated with exergy destructions, part of them may be UN according to given present technical limitations. Further, part, which is named as EX may be arisen from the exergy destructions coming off in the other components of the system being considered. Through advanced exergetic/exergoeconomic methods, researchers can determine at what rate the inefficiencies and costs can be avoided through technological improvements of the system and/or components, and in which proportion the inefficiencies and costs are resulted from component interactions. By this way, the potential developments for each component in the overall system according to the current technical opportunities can be done, and as a result of this, it may be very beneficial to focus on the improvements in other components [11,38,39].

The exergy destruction sources and realistic improvement potentials of various kinds of refrigeration/HP systems have been analyzed in the open literature. In these studies, a refrigeration machine using a Voorhees' compression process [40], an electric driven HP [41], a gas engine-driven HP [42], an absorption refrigeration machine [43], and an ejector refrigeration system [44] have been examined. However, the authors can find only one paper focused on the performance analysis of GSHP systems with advanced exergy analysis [11]. Variations of cost rates associated with exergy destructions for a few refrigeration/HP systems such as a multi-effect evaporation-absorption heat pump [45], and a multistage mixed refrigerant systems [46] are investigated by using advanced exergoeconomic analysis; moreover, so few ones are published about the drying applications of an electrical HP system [47], and a gas engine-driven HP system [48]. The authors could not find any studies focused on the advanced exergeoconomic analysis of the GSHP systems.

In this paper, the performance of a GSHP food drying system has been evaluated by advanced exergoeconomic analysis. The main motivation behind performing this contribution aims at (i) applying advanced exergoeconomic analysis to a GSHP system for the first time to the best of authors' knowledge and evaluating the system performance in parts, (ii) discussing the sources of cost formation and possible improvements in the GSHP system, and (iii) comparing the results of conventional and advanced exergoeconomic analysis methods with each other.

2. Experimental setup and measurements

2.1. Experimental apparatus

In the present paper, a food drying system composed of a GSHP system and a drying cabinet was tested. The drying system was designed and constructed at the Solar Energy Institute of Ege University in Izmir, Turkey and was schematically illustrated in Fig. 1. The details of the system were given in the previous study of the authors [13]. The experimental data were obtained by using laurel leaves as test material [9]. The drying experiments were performed with a drying air temperature of 45 °C at the condenser outlet and with an ambient air relative humidity range of 16–19%.

The numbered points in Fig. 1 represent the streams in the whole drying system. While the refrigerant streams were coded with numbers from 1 to 4, the water streams were enumerated from 5 to 7. The work streams in electrical energy form were denoted with numbers 11 and 12. The stream number 13 stated the heat transfer stream from the ground whereas the stream number 14 specified the evaporation stream from the laurel leaves during drying.

2.2. Measurements and uncertainty

Temperatures and pressures of the refrigerant streams, and temperatures and relative humidities of the air streams at all the

Table 1
The most recent food drying studies conducted by using conventional exergy methods.

Focus	Drying equipment	Product	Year
Process performance	Microwave-assisted fluidized bed dryer	Soybean	2013 [17]
	Rotary dryers	Paste	2013 [18]
	Fluidized bed dryer	Rough rice	2013 [19]
	Solar dryer	Red chili	2014 [20]
	Solar dryer	Coriander leaves	2014 [22]
	Fluidized bed dryer	Paddy	2015 [23]
	Solar dryer	Palm oil fronds	2015 [21]
	Spray dryer	Cornelian cherry	2015 [24]
	Solar-assisted fluidized bed dryer	Mint leaves	2016 [25]
	Microwave dryer	Kiwi slices	2016 [26]
	Solar dryer	Pistachio	2016 [27]
	Diagonal-batch dryer	Potato slices	2016 [28]
Performance comparison	Heat pump dryer/Infrared-assisted heat pump dryer	Grated carrot	2017 [29]
	Solar dryer/Solar dryer integrated with latent heat storage module	Ghost chili pepper, Ginger slices	2017 [30]
Process optimization	Spray dryer	Cheese powder	2015 [31]
Modeling	Infrared dryer		2015 [32]
	Combined infrared-convective dryer		2016 [33]
System performance	Rotating tray dryer	Apple slices	2016 [34]