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# Application of conventional and advanced exergy analyses to evaluate the performance of a ground-source heat pump (GSHP) dryer used in food drying

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ABSTRACT

Inefficiencies in an energy system can be quantitatively determined through conventional exergy analysis while sources of the irreversibilities and real improvement potential can be deducted using a relatively new method named as advanced exergy analysis. For the first time, an advanced exergy analysis is applied to a ground-source heat pump (GSHP) drying system used in food drying for evaluating its performance along with each component in this study. The results indicate that the most important system component is the condenser due to the design standpoint. The inefficiencies within the compressor could particularly be improved by structural improvements of the whole system and the remaining system components. Furthermore, the inefficiencies of other system components except for the condenser and the evaporator are mainly affected by the internal operating condition. Both the equipment design and system components' interactions of the condenser and the evaporator have a significant effect on their inefficiencies. The conventional and modified (advanced) exergy efficiency values are calculated to be 77.05% and 93.5%, respectively.



## 1. Introduction

Drying is traditionally defined as the unit operation that converts a liquid, solid, or semi-solid feed material into a solid product of significantly lower moisture content and has been widely used in various industries. In food industry, foods are dried, starting from their natural form or after handling [1]. There are more than 400 types of dryers and many of them have been commercially utilized [2]. However, the improvements in dryer design proceed as drying is a notoriously energy-intensive process. It is reported that energy consumption value of drying process was 10–25% of the total energy consumption in all industries in developed countries [2].

Heat pumps (HPs) have been utilized in drying operations due to their energy efficient nature [3,4]. They are unique systems in drying applications with their ability to convert the latent heat of condensation into sensible heat at the hot gas condenser. Therefore, many studies focused on the food drying applications of HPs, i.e., [5–7]. Ground-source heat pumps (GSHPs), often referred to as geothermal heat pumps, are recognized to be outstanding heating, cooling and water heating systems. GSHPs offer significant reductions of electrical energy use due to their relatively higher energy utilization efficiencies. They also have very low levels of maintenance requirements and attract researchers as environmentally friendly devices [8,9]. As a consequence, there are various studies on the GSHP systems [10], whereas few studies have been conducted regarding utilization of these devices for drying applications [11–13].

Combined with modeling and simulation techniques, exergy analysis has proven to be a powerful and an effective tool in synthesis, design and operation of the industrial processes as well as in performance evaluation of energy systems [14,15]. The process or system can be detected and the imperfections of the process or system under consideration can be evaluated by employing conventional exergy analysis. However, this information is not enough for creating solution oriented approaches. To reveal the realistic potentials and conclude the methods for improvement, advanced exergy analysis based on the splitting of the exergy destructions should be used. Although exergy destructions can be detected by conventional exergy analysis, the destructions cannot be sorted in a more detail. In other words, exergy destructions may be unavoidable due to the present technical limitations while their part may be due to the exergy destruction occurring within the other components of the system being considered. Through an advanced exergy analysis, the potential improvements for each component in the whole system due to the present-day technical possibilities can be done, and hence it may be worthwhile to improve other components

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**Nomenclature**

| | |
|---|---|
| $C_P$ | specific heat (kJ kg$^{-1}$ °C$^{-1}$) |
| $ex$ | specific exergy (kJ kg$^{-1}$) |
| $\dot{E}x$ | exergy rate (kW or kJ s$^{-1}$) |
| $f$ | exergetic factor (%) |
| $h$ | specific enthalpy (kJ kg$^{-1}$) |
| $\dot{IP}$ | improvement potential rate (kW) |
| $\dot{m}$ | mass flow rate (kg s$^{-1}$) |
| $P$ | pressure (kPa) |
| $\dot{Q}$ | heat transfer rate (kW) |
| $R$ | gas constant (kJ kg$^{-1}$ K$^{-1}$) |
| $RI$ | relative irreversibility (%) |
| $s$ | specific entropy (kJ kg$^{-1}$ K$^{-1}$) |
| $SI$ | sustainability index (–) |
| $T$ | temperature (K or °C) |
| $\dot{W}$ | work rate or power (kW) |

*Greek letters*

| | |
|---|---|
| $\varepsilon$ | exergy (second law) efficiency (%) |
| $\varepsilon^*$ | modified exergy (advanced) efficiency (%) |
| $\omega$ | absolute humidity of air (kg water/kg dry air) |

*Superscripts*

| | |
|---|---|
| AV | avoidable |
| EN | endogenous |
| EX | exogenous |
| $M$ | mechanical |
| REAL | experimental operation conditions |
| UN | unavoidable |
| $T$ | thermal |
| $th$ | theoretical operation conditions |

*Subscripts*

| | |
|---|---|
| $a$ | air |
| comp | compressor |
| cond | condenser |
| $d$ | destruction |
| dcabinet | drying cabinet |
| dduct | drying duct |
| elec | electrical |
| exp | expansion valve |
| evap | evaporation |
| $f$ | fuel |
| in | inflow |
| $k$ | $k$th component |
| mech | mechanical |
| out | outflow |
| $p$ | product, constant pressure |
| pump | circulation pump |
| $r$ | refrigerant |
| tot | total |
| $v$ | vapor |
| $w$ | water |
| 0 | dead state |

*Abbreviations*

| | |
|---|---|
| AVEN | avoidable-endogenous |
| AVEX | avoidable-exogenous |
| GHE | ground heat exchanger |
| GSHP | ground-source heat pump |
| HP | heat pump |
| RAC | reversible adiabatic cooler |
| RAH | reversible adiabatic heater |
| UNEN | unavoidable-endogenous |
| UNEX | unavoidable-exogenous |

[16]. Advanced exergy analysis has capability to determine, which part of the inefficiencies caused by component interactions, and which part can be avoided through technological improvements of a plant. Exergy destructions are split into two main groups, namely (i) endogenous–exogenous exergy destructions and (ii) avoidable–unavoidable exergy destructions [17].

Advanced exergy analysis is a new method and its applications to various energy-related systems are relatively low in numbers [16–20]. In addition to this, according to the current knowledge of the authors, there are only two studies, which assessed a drying system through advanced exergy analysis method [21,22]. While Erbay and Hepbasli [21] analyzed a conventional HP drying system using advanced exergy analysis method, Gungor et al. [22] investigated the performance of a gas engine driven HP drying system. In this study, a different type HP drying system, which uses ground as heat source, has been evaluated. The above presented aspects provide the prima motivation behind performing this contribution with the objectives of (i) applying advanced exergy analysis to a GSHP drying system and evaluating its performance in parts, (ii) comparing the results obtained by the conventional and the advanced exergy analysis with each other, and (iii) discussing the performance and possible improvements in the drying system.

## 2. Experimental setup and drying procedure

Experimental data obtained by Kuzgunkaya and Hepbasli [11] are processed in this study to perform an advanced exergy analysis. In that study, fresh laurel leaves were dried at an inlet drying air temperature of 45 °C and a relative humidity of 16–19% in a GSHP dryer, which was designed and constructed in the Solar Energy Institute, Ege University, Izmir, Turkey. The leaves, which were dried on three trays with 12 g (±0.5 g) in each tray, were selected as 90–100 mm long and 30–40 mm wide with no blemish.

Fig. 1 illustrates a modified schematic diagram of the system, which consists of mainly three separate circuits, namely: (i) a ground coupling circuit (a brine circuit or a water–antifreeze solution circuit), (ii) a refrigerant circuit (or a reversible vapor compression cycle) and (iii) a drying cabinet circuit (air circuit). While the ground coupling circuit consists of a ground heat exchanger (GHE) and a circulation pump, the main components of the refrigerant circuit (HP system) are an evaporator, a condenser, a compressor and an expansion valve. To avoid freezing the water under the working condition and during the winter, a 10% ethyl glycol mixture by weight is prepared. The refrigerant circuit is built on the closed loop copper tubing. The working fluid is R-22. Fresh air is fed to the system at the inlet of the condenser to balance the rise of relative humidity [11].

The ambient temperature and relative humidity values were measured during the drying process. Temperatures at all state points indicated in Fig. 1 were measured. Additionally, the surface temperatures of the drying cabinet, the drying ducts and the product were taken with an infrared thermometer (Fluke 61, USA). Mass flow rates were determined with an orifice meter and relative humidity of the drying air was observed with hygrometers along the drying air circuit of the system. Pressures of the refrigerant at the HP components were measured by Bourdon type manome-