Energy Conversion and Management 73 (2013) 309–316

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Splitting the exergy destruction into avoidable and unavoidable parts of a gas engine heat pump (GEHP) for food drying processes based on experimental values

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ARTICLE INFO

Article history:
Received 23 January 2013
Accepted 23 April 2013
Available online 5 June 2013

Keywords:
Drying
Gas engine driven heat pump
Exergy analysis
Advanced exergy analysis

ABSTRACT

Some limitations in a conventional exergy analysis may be significantly reduced through an advanced exergy analysis. In this regard, the latter is a very useful tool to assess the real potential for improving a system component by splitting the exergy destruction into unavoidable and avoidable parts. This may provide a realistic measure to deduct the improvement potential for the thermodynamic efficiency of a component. For this purpose, improvement efforts are then made by focusing only on these avoidable parts.

In this paper, a gas engine heat pump (GEHP) drying system was analyzed using both conventional and advanced exergy analyses. Three medicinal and aromatic plants (*Foeniculum vulgare*, *Malva sylvestris* L. and *Thymus vulgaris*) were dried in a pilot scale GEHP drier, which was designed, constructed and installed in Ege University, Izmir, Turkey. Drying experiments were performed at an air temperature of 45 °C with an air velocity of 1 m/s. For each system component, avoidable and unavoidable exergy destructions, modified exergy efficiency values and modified exergy destruction ratios were determined. Except for the compressor, the evaporator and the drying cabinet, most of the exergy destructions in the system components were avoidable and these avoidable parts can be reduced by design improvements. For the HP unit and the overall drying system, the values for exergy efficiency were obtained to be in the range of 82.51–85.11% and 79.71–81.66% while those for the modified exergy efficiency were calculated to be in the range of 85.70–89.26% and 84.50–86.00%, respectively.

1. Introduction

Improving the energy utilization efficiency of systems represents basis of integrating the environmental dimension into energy policy. In this context, heat pumps (HPs) may offer the best prospects for attaining this goal in a wide variety of heating applications [1]. The application of HPs to the agricultural sector was started out with their use as supplementary devices for heating. Subsequent research and development has resulted in developing of drying processes that run solely with a HP. Drying is one of the best ways of minimizing the loses while it makes easier and cheaper the packing, handling, and transporting of the dried products due to less weight and volume [2]. Drying is also an energy-intensive operation and consumes 9–25% of national energy in the developed countries. In reducing energy consumption per unit of product moisture, it is necessary to scrutinize various methodologies for improving the energy efficiency of the drying equipment [3]. The commercial use of HP assisted dryer has been reported in many parts of Europe, Asia and Australia where technology has been applied mostly in the marine food-processing sector [4].

Based on the type of input energy to rotate the compressor shaft (an electrical motor or a gas engine), HPs may be categorized as electric HPs (EHPs) or gas engine driven HPs (GEHPs). Natural gas driven HPs are technically simpler and, therefore, less costly than the combination of cogeneration units with electrically driven HPs; thus, the natural gas driven HPs are favorable from an economic point of view. Natural gas engine driven HPs use the engine's heat to reduce the temperature difference across the system, thus their efficiencies show less sensitivity to the source and sink temperatures compared to electrically driven HPs. If HPs are driven directly by a combustion engine instead of an electric motor, losses

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http://dx.doi.org/10.1016/j.enconman.2013.04.033

Nomenclature

$\dot{E}x$	exergy rate (kW)
e	specific exergy (kJ/kg)
$\dot{F}$	exergy rate of the fuel (kW)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
$\dot{P}$	exergy rate of the product (kW)
s	specific entropy (kJ/kg K)
T	temperature (K or °C)
$\dot{W}$	work rate or power (kW)
y	exergy destruction ratio

Greek letters

Δ	difference
ε	exergy (second law) efficiency (%)
η	energy efficiency (%)

Subscripts

a	air
act	actual
COMP	compressor
COND	condenser
D	destruction or destroyed
DCABINET	drying cabinet
DDUCTS	drying ducts
EXP	expansion valve
EVAP	evaporator
i	any (i) gas
is	isentropic (%)
in	inflow
k	kth component
r	refrigerant
w	water
0	dead (reference) state
Over dot	quantity per unit time

Superscripts

AV	avoidable
UN	unavoidable
M	mechanical
T	thermal
PH	physical
$*$	modified

Abbreviations

DC	drying chamber
DPHE	double pipe heat exchanger
EAHE	exhaust air heat exchanger
GE	gas engine
GEHP	gas engine driven heat pump
HP	heat pump
HRECJ	heat recovery from engine cylinder jacket
RAH	reversible adiabatic heater
OS	overall system

attributed to the productions and transports of electricity are eliminated. Additionally, the use of the combustion engine's heat leads to a reduced temperature difference across the HP [5]. Considering the importance of GEHPs in air conditioning systems, modeling and optimizing of these systems are essential from technical and economic points of view. Many investigations on modeling of the GEHP are available in the literature [6–12] while there is a lack of analyzing the GEHPs performance using advanced exergy analysis method. Thus, the present work is carried out with the aim of exergetic evaluation of the performance characteristics of a GEHP system for food drying purposes.

An exergy analysis identifies the location, magnitude and sources of thermodynamic inefficiencies in a thermal system. This information, which cannot be provided by other means (e.g., an energy analysis), is very useful for improving the overall efficiency and cost-effectiveness of a system or for comparing the performance of various systems [13]. A conventional exergy analysis identifies the system components with the highest exergy destruction and the process that cause them. Efficiencies within a system's component can then be improved by reducing the exergy being destroyed within the component [14]. However, none of the conventional analyses are able to reveal interactions among plant components or to estimate the real potential for improvement. Without consideration of component interactions, optimization strategies can be misguided, especially when complex systems with a large number of mutually affected components are considered. Knowledge of the interactions among components and of the potential for improving each important component is very useful in improving the overall system [15].

Therefore, it is important to understand the genesis of the rate of exergy being destroyed in a component's process. Hence by splitting the exergy destruction within a component, a better approach related to the improvement of the energy conversion system can be attained. Advanced exergy based analyses attempt to address this shortcoming. The theory of splitting the exergy destruction allows for the further understanding of the exergy destruction values from an exergy analysis and hence improves the accuracy of the analysis, thereby facilitating the improvement of thermal systems [16].

Conventional exergy-based methods pinpoint components and processes with high irreversibilities. However, they lack certain insight. It is, therefore, important to understand the genesis of the rate of exergy being destroyed in a component's process. The theory of splitting the exergy destruction helps us further understand the exergy destruction values from an exergy analysis and hence improves the accuracy of the analysis. It facilitates the improvement of energy-related systems. In order to perform this process, only an advanced exergy analysis method could be applied.

Splitting the exergy destruction into unavoidable and avoidable parts in the kth component provides a realistic measure of the potential for improving the thermodynamic efficiency of a component. The exergy destruction rate that cannot be reduced due to technological limitations such as availability and cost of materials and manufacturing methods is the unavoidable part of the exergy destruction. The remaining part represents the avoidable part of the exergy destruction [17]. The purpose of this contribution is to demonstrate that additional information, which is crucial for improving a system, can be obtained when the exergy destruction within each component is split into unavoidable and avoidable parts on this novel GEHP drying system. This was the main motivation behind performing this study, which was applied to the system considered for the first time to the best of the authors' knowledge.

2. System description

Foeniculum vulgare, *Malva sylvestris* L. and *Thymus vulgaris* were dried in a pilot scale GEHP belt conveyor drier, designed and constructed in the Department of Mechanical Engineering, Faculty of Engineering, Ege University, Izmir, Turkey.