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Research Paper

Exergoeconomic performance assessment of a pilot-scale spray dryer using the specific exergy costing method

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In this study, exergoeconomic analysis was performed to evaluate the performance of a pilot scale spray dryer during white cheese powder production by the specific exergy costing (SPECO) method. Drying experiments were carried out at an inlet drying air temperature range of 160–230 °C, an outlet drying air temperature range of 60–100 °C and an atomisation pressure range of 294.2–588.4 kPa. The components of drying system were separately analysed and the effects of operating conditions on system components and the overall system were discussed. Improvements for the drying cabinet should be focused on for process optimisation, whereas structural improvements of the atomiser should strongly be considered for reducing investment costs. Furthermore, investment costs for the feed pump used in the drying system should be decreased or the feed pump should be replaced with a cheaper one. While results showed high inlet and low outlet air temperatures caused high effectiveness for the overall system performance, the operating costs were the most important variable due to expenses.

1. Introduction

Drying is widely used in various industries for a variety of benefits. The process conditions for drying systems must be determined for every dryer to improve quality of product and system efficiency. It is reported that there are more than 400 types of dryers and many of them commercially utilised (Mujumdar, 2006). Nevertheless, improvements in dryer design continues as drying is a notoriously energy-intensive process. The studies showed that energy consumption of drying processes accounts for 10–25% of total energy consumption for all industries in developed countries, especially for agricultural and food processing sectors which must meet high quality standards of dried product (Kudra, 2004; Mujumdar, 2006; Vadivambal & Jayas, 2007). Furthermore, drying is an important process to optimise when considering worldwide issues such as the depletion of fossil fuels and

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Nomenclature

c	unit exergy cost (TL GJ^{-1})
$\dot{C}$	exergy cost rate (TL h^{-1})
C_p	specific heat (kJ kg^{-1} °C^{-1})
CR	cost rate (–)
CRF	capital recovery factor (–)
ex	specific exergy (kJ kg^{-1})
$\dot{E}x$	exergy rate (kW)
f	exergoeconomic factor (%)
F	function of the independent variables
h	specific enthalpy (kJ kg^{-1})
i	interest rate on capital
$\dot{m}$	mass flow rate (kg s^{-1})
n	period of payment (year)
P	pressure (kPa)
PEC	purchase equipment cost (TL)
r	relative cost difference (–)
R	gas law constant (kJ kg^{-1} K^{-1})
$\dot{R}_{ex}$	the ratio of thermodynamic loss rate to capital cost (MW TL^{-1})
$\dot{Q}$	heat transfer rate (kW)
s	specific entropy (kJ kg^{-1} K^{-1})
T	temperature (K or °C)
t_{op}	time of operation of plant per year (h)
U	uncertainty in the result
$\dot{W}$	work rate or power (kW)
X	mass fraction
z	independent variable
$\dot{Z}$	hourly averaged cost of investment (TL h^{-1})

Greek letters

φ	factor of the operating and maintenance cost
η	energy efficiency (%)
ε	exergy (second law) efficiency (%)
ω	absolute humidity of air (kg water kg dry air^{-1})

Subscripts

a	air
b	boundary or surface location
CI	capital investment
comp	Compressor
d	destruction or destroyed
dcabinet	drying cabinet
dducts	drying ducts
elec	electrical
evap	evaporation
f	fuel
in	inflow
k	k^{th} component
mech	mechanical
OM	operating and maintenance
out	outflow
pump	feed pump
p	product
T	total
v	vapour
w	water
0	dead (reference) state

Abbreviations

OS	overall system
SD	spray dryer
SPECO	specific exergy costing

environmental pollution. Briefly, drying is arguably the oldest, the most common, most diverse, and most energy-intensive unit operation, and due to these characteristics, engineering of drying processes and systems has become increasingly important (Erbay & Icier, 2010).

The most energy-intensive method for drying is spray drying, subsequent to freeze drying (Bhandari, Patel, & Chen, 2008). It is estimated that over 25,000 spray dryers are in use commercially worldwide (Filkova, Huang, & Mujumdar, 2006) and it is estimated that approximately twice that number are used in pilot plants and laboratories (Masters, 1996; Wang & Langrish, 2009). Although the advantages of spray drying are high product quality along with continuous and automated process possibilities, installation and operation costs of spray drying are high, and thus the greatest disadvantage of spray dryers (SDs). Consequently, research and development that focuses on the design and optimisation of spray drying remains important. A major food sector using SDs is the dairy industry and the demand for dried dairy products is currently increasing (Bhandari et al., 2008). In dairy industry, spray drying operations are the primary type of drying operation and they are the most critical processes due to their energy consumption ratio (IDF, 2005).

Exergy is defined as the maximum amount of work, which can be produced by a stream of matter, heat or work as it comes to equilibrium within a reference environment and is an important tool to analyse, optimise and thus, to improve the energy efficiency of spray drying process and SDs (Dincer & Sahin, 2004). Magnitudes and locations of exergy destructions (irreversibilities) in the process or system can be successfully specified by exergy analyses. Although performances of various kinds of food dryers were evaluated in literature by exergy analysis (Colak, Erbay, & Hepbasli, 2013; Erbay, Icier, & Hepbasli, 2010; Gungor, Erbay, & Hepbasli, 2011; Hepbasli, Erbay, Colak, Hancioglu, & Icier, 2010; Kuzgunkaya & Hepbasli, 2007), there're few studies concentrated on spray drying process (Aghbashlo, Mobli, Madadlou, & Rafiee, 2012; Aghbashlo, Mobli, Rafiee, & Madadlou, 2012; Erbay & Koca, 2012a; Jin & Chen, 2011) and SDs (Erbay & Koca, 2012b).

Exergoeconomy is the branch of engineering that combines exergy analysis with economic constraints to provide the information that cannot be obtained by conventional energy analysis and economic evaluation. The results of exergoeconomic analysis yield opportunities to find ways for improving the performance of a system in a cost effective way (Sahoo, 2008). There are different thermoeconomic