Journal of Cleaner Production xxx (2016) 1–18

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Exergetic performance assessment of a long-life milk processing plant: a comprehensive survey

Mohamad Mojarab Soufiyan, Mortaza Aghbashlo*, Hossein Mobli

Department of Mechanical Engineering of Agricultural Machinery, Faculty of Agricultural Engineering and Technology, College of Agriculture and Natural Resources, University of Tehran, Karaj, Iran

A R T I C L E I N F O

Article history:
Received 10 August 2015
Received in revised form
20 November 2015
Accepted 24 November 2015
Available online xxx

Keywords:
Long-life milk processing
Exergy analysis
Steam generator
Above-zero refrigeration
Milk pasteurization
Specific exergy destruction

A B S T R A C T

The aim of this study was to carry out a comprehensive exergy analysis of an industrial-scale long-life milk processing plant for the first time. The plant consisted of four main lines including steam generator, above-zero refrigeration system, milk reception, pasteurization, and standardization line, and ultra-high-temperature (UHT) milk processing unit. This survey was performed to obtain more in-depth information about the exergy destroyed in the whole plant and its main subcomponents. In addition, an attempt was made to quantify the exergy destroyed for processing a given amount of the long-life milk using the mass allocation method. The results indicated that the largest exergy destruction rate occurred in the compressor and boiler combination of the steam generation system, accounting for 89% of the total exergy destruction of the system. More specifically, the specific exergy destruction of the long-life milk processing was determined as 345.50 kJ kg^{-1}. The steam generation system had the greatest contribution to the specific exergy destruction of the long-life milk processing followed by above-zero refrigeration system, UHT milk processing unit, and milk reception, pasteurization, and standardization line, respectively. Hence, a small improvement in the exergetic performance of the steam generator could profoundly lower the specific exergy destruction of the long-life milk processing. According to the outcomes of the current study, the performance and sustainability parameters of dairy processing plants can be best-evaluated and improved using exergy analysis.

1. Introduction

Dairy products contain invaluable nutritional and health-beneficial compounds. Hence, dairy processing is regarded as one of the most important sectors of the food industry. Moreover, this sector has a substantial contribution to economic growth and job creation in both developed and developing countries. However, milk production and processing require a huge amount of resources leading to a number of devastating environmental impacts like water and air pollution as well as biodiversity degradation. These negative effects of the dairy industry have become even more serious because of the world's increasing population and rising life standards. On the other hand, the dairy processing is ranked the fifth among the most energy-intensive industries after oil, chemical, pulp and paper mill, and iron and steel making industries (Munir et al., 2014). It is worth mentioning that almost all energy demands of this sector are met by fossil-derived fuels such as coal, oil, and natural gas. Therefore, due to the harmful emissions like CO_x, SO_x, NO_x, C_xH_y, soot, ash, and organic compounds during the combustion of fossil fuels, the dairy industry has a nontrivial contribution to environmental pollution. On the other hand, fluctuating prices and fast depleting reserves of fossil fuels have introduced serious problems concerning the future energy security (Oyedepo, 2012; Barchyn and Cenkowski, 2014; De and Luque, 2014; Aladetuyi et al., 2014; Jaber et al., 2015; Kumar et al., 2015). Nevertheless, improvement in the energy efficiency of energy-intensive manufacturing sectors is one of the efficient strategies to counteract the increasing demand for energy and the growing concerns about environmental pollution. Like other energy-consuming industries today, the dairy industry is seeking strategies for coping with the growing production costs and catastrophic environmental impacts resulting from widespread fossil fuel use (Munir et al., 2014). This goal can be achieved through the application of powerful engineering tools such as energy and exergy analyses by scrutinizing and optimizing the energetic performance of energy-intensive operations.

* Corresponding author. Tel.: +98 2632801011; fax: +98 263 2808138.
E-mail address: maghbashlo@ut.ac.ir (M. Aghbashlo).

http://dx.doi.org/10.1016/j.jclepro.2015.11.066
0959-6526/

Notations

a	carbon number of hydrocarbon fuels (–)
A	fat-plasma interfacial area per kg milk (m^2 kg^{-1})
b	hydrogen number of hydrocarbon fuels (–)
C_p	specific heat capacity (kJ kg^{-1} K^{-1})
ex	specific exergy (kJ kg^{-1})
$\dot{E}x$	exergy rate (kW or kJ s^{-1})
F	function of the independent variables
G	Gibbs free energy (kJ kg^{-1})
h	specific enthalpy (kJ kg^{-1})
K_B	Boltzmann constant (1.38×10^{-23} J K^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
n	specific mole number (mol kg^{-1})
$\mathbb{N}$	number of droplets of dispersed phase per kg milk (kg^{-1})
P	pressure (kPa)
PR	pressure reducer
q_{LHV}	lower heating value (kJ kg^{-1})
$\dot{Q}$	heat transfer (kJ s^{-1})
s	specific entropy (kJ kg^{-1} K^{-1})
S	entropy (kJ K^{-1})
T	temperature (K)
u	uncertainty in the independent variables
U	uncertainty in the result
$\dot{V}$	volume flow rate (m^3 s^{-1})
$\dot{W}$	work rate (kW)
z	independent variables
x	mole fraction (–)
Y	mass fraction (–)

Greek letters

$\Re$	universal gas constant (8.314 J mol^{-1} K^{-1})
φ	fuel quality factor (–)
ε	standard chemical exergy (kJ mol^{-1})
ψ	exergy efficiency
$\mathscr{M}$	molar mass (g mol^{-1})
ω	humidity ratio (kg water kg dry air^{-1})
υ	specific volume (m^3 kg^{-1})
ρ	density (kg m^{-3})
γ_{AB}	interfacial tension between phases A and B (kJ m^{-2})
$\varnothing$	dispersed phase volume fraction

Subscripts

0	dead state
a	air
ch	chemical
$conf$	configurational entropy
fo	fat-formation exergy
i	numerator
ph	physical
QL	heat loss
v	vapor
w	water

In recent years, exergy concept has received an increasing attention among the researchers from academia and industry for designing, analyzing, optimizing, and retrofitting energy systems (Aghbashlo et al., 2008, 2012; Tyagi et al., 2013; Özahi and Demir, 2015). It could be attributed to the fact that exergy analysis measures and evaluates the quantity and quality of energy simultaneously (Pandey et al., 2013; Park et al., 2014; Dadak et al., 2015; Hosseini et al., 2015). Simply speaking, exergy is the maximum amount of theoretical work that could be recovered from a system as it brings to a reversible equilibrium with its surroundings (Keenan, 1932; Rant, 1956). It is well documented that the exergy analysis not only identifies the quantities, positions, and causes of thermodynamic imperfections occurring in various energy systems, but also provides more comprehensive and in-depth information into the individual subcomponent efficiency of the systems. In fact, exergy analysis can determine the actual energy losses of various manufacturing plants more accurately compared to the traditional energy analysis in order to diagnose and introduce energy saving strategies. Hence, numerous research attempts have been undertaken to use exergy concept for analyzing and optimizing energy systems during the past decades (Özahi and Demir, 2013, 2015; Oyedepo et al., 2015; Aghbashlo et al., 2015).

In the case of the food industry, exergy analysis and its extensions have been widely employed to scrutinize and optimize various food processing operations from the sustainability and productivity viewpoints. For instance, Icier et al. (2010) compared three different drying systems including tray, fluidized bed, and heat pump dryers during drying of Broccoli florets from exergetic point of view. Furthermore, Gungor et al. (2011) applied exergy analysis for a pilot scale gas engine driven heat pump dryer during drying of three medicinal and aromatic plants. In another study, the cumulative exergy consumption (CExC) methodology was used to study the environmental impact of the flavored yogurt production process (Sorgüven and Özilgen, 2012). In the same year, Aghbashlo et al. (2012) performed an exergy analysis of spray drying during microencapsulation of fish oil. Additionally, a laboratory–scale plug flow fluidized bed dryer was exergetically assessed during drying of rough rice from the sustainability viewpoint (Khanali et al., 2013). Recently, Zisopoulos et al. (2015) reviewed the application of exergetic indicators for sustainability evaluation of food processing operations.

According to the outcomes of the above-mentioned surveys, there is no doubt that exergy concept can serve as a powerful tool for quantifying and minimizing the thermodynamic inefficiencies of a given system. To the best of our knowledge, there is no published report on the use of exergy concept for comprehensive analysis of an industrial long-life milk processing plant. Therefore, this study was aimed at presenting a detailed exergy analysis of a long-life milk processing plant based on actual operational data for the first time. This analysis included four main lines of the plant including steam generator, above-zero refrigeration system, milk reception, standardization, and pasteurization line, and UHT milk processing unit. More specifically, this analysis was carried out to determine the exergy efficiencies and exergy destruction rates of all subcomponents of the plant involved in the processing of the long-life milk. Additionally, the specific exergy destruction of the UHT milk processing was determined based on the mass allocation method. It should be also mentioned that the UHT processing of milk requires a lot of energy for inactivating all microorganisms and heat-resistant enzymes. The outcomes of such surveys would be envisaged to be of great interest to engineers, researchers, and plant managers whose research works are focused on the development, retrofitting, and managing of industrial dairy processing plants.