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Comprehensive exergy analysis of an industrial-scale yogurt production plant

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A B S T R A C T

In this study, a comprehensive and detailed exergy analysis was carried out to investigate an industrial-scale pasteurized yogurt production plant located in the north-west of Iran, West Azarbaijan province. For this goal, the plant was subdivided into four main subsystems, including steam generation, above-zero refrigeration, milk standardization and pasteurization, and yogurt production lines. Accordingly, exergetic efficiency and exergy destruction rate were defined and computed for each component of the four lines individually. Moreover, this analysis was conducted to find the amount of exergy consumed in producing a given amount of the pasteurized yogurt. The main contributors to the exergy destruction of the entire plant were in descending order of importance: boiler & air compressor combination of the steam generator (12484.88 kW), ice-water tank & agitator combination of the above-zero refrigeration system (2900.59 kW), and pressure reducer #2 of the steam generator (731.82 kW). Moreover, the specific exergy consumption of the pasteurized yogurt was found to be 841.34 kJ/kg based on the mass allocation concept. More specifically, the percentile contributions of the steam generation, above-zero refrigeration, milk standardization and pasteurization, and yogurt production lines to the specific exergy consumption were determined as 82.62%, 9.36%, 2.80%, and 5.21%, respectively.

1. Introduction

Dairy processing is one of the most energy-intensive sectors of the food industry. According to Munir et al. [1], the dairy industry is the fifth largest manufacturing sector in terms of energy consumption after oil, chemical, pulp and paper mill, and iron and steel making industries. Interestingly, the majority of energy consumed in this sector is still met by fossil-based energy sources, leading to a remarkable amount of greenhouse gas emissions (i.e. CO_2, SO_x, NO_x, and PMs). On the other hand, fluctuating prices and depleting resources of fossil fuels have introduced serious challenges in the global energy market [2–4]. Like other energy-intensive industries, the dairy industry is looking for ways to reduce its energy consumption for discounting the production costs and preventing the detrimental environmental impacts [1]. These in turn have spurred the search for constantly replenished renewable energy resources and/or more efficient utilization of available fossil fuel energy resources. This is why powerful engineering tools such as energy and exergy analyses have been extensively applied during the past few decades for analyzing and optimizing the energetic performance of various energy-intensive industries.

Traditionally, energy analysis based on the first law of thermodynamics was often employed for improving the performance of various energy systems [5]. However, energy analysis has been criticized because of its obvious weakness in providing useful insights on the quality of different energy forms and is, therefore, insufficient for sustainable design or optimization goals. Thus, a relatively new version of the thermodynamic analysis, namely exergy approach, has been increasingly applied to overcome the shortcomings of energy analysis in evaluating and optimizing the efficiency of various energy-intensive manufacturing processes. Generally speaking, exergy is the maximum obtainable work from a system as it moves towards a complete thermodynamic equilibrium with its surroundings through reversible processes [6–10]. This approach has appeared to be a powerful tool for designing, analyzing, optimizing, and retrofitting the energy-intensive manufacturing plants due to its unique conceptual features in identifying both the energy quantity and quality more accurately than the classical energy analysis [11–13]. Accordingly, exergy and its extensions have become very popular in recent years for

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Notations

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

Greek letters

$\Re$	universal gas constant (8.314 J/mol K)
φ	fuel quality factor (−)
ε	standard chemical exergy (kJ/mol)
ψ	exergy efficiency
$\mathcal{M}$	molar mass (g/mol)
ω	humidity ratio (kg water/kg dry air)
υ	specific volume (m^3/kg)
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
A	agitator
AFSD	automatic fat standardization device
AS	ammonia Separator
B	bactofuge
BFT	buffer tank
BFT&A	buffer tank & agitator combination
BLT	balance tank
BO&AC	boiler & air compressor combination
C	compressor
ch	chemical
CF	cup filler
conf	configurational entropy
CO&F	condenser & fan combination
des	destruction
D&VP	deaerator & vacuum pump combination
E&VP	evaporator & vacuum pump combination
EV	expansion valve
FC	flow controller
fo	fat-formation exergy
H	homogenizer
HE	heat exchanger
HT	holding tube
i	numerator
IWT&A	ice-water tank & agitator combination
M	mixer
P	pump
PC	plate cooler
ph	physical
PHE	plate heat exchanger
QL	heat loss
S	separator
SC	source condensate
ST	steam trap
v	vapor
VP	vacuum pump
w	water

evaluating the sustainability and performance of energy systems. The relation between exergy efficiency and sustainability and environmental impact has been representatively illustrated by Dincer [14] (Fig. 1). It is obvious from Fig. 1 that increasing exergy efficiency of an energy system decreases its environmental impact and increases its sustainability index and vice versa.

In the two past decades, exergy analysis and its extensions have been extensively employed to scrutinize and optimize various energy-intensive operations from the sustainability and efficiency viewpoints [15–22]. In the case of food industry, for instance, Bayrak et al. [23] assessed the exergetic performance of four sugar production stages, including sherbet production, distillation, thickening, and crystallization. The exergetic efficiencies of the sugar production stages were determined at 49.3%, 62.1%, 91.9%, and 61.7%, respectively. Later, Apaiah et al. [24] used exergy analysis to compare the environmental impact of three food supply chains, including pork mincemeat, pea-protein based product, and pea soup. The exergetic efficiencies of the chains were obtained 0.09%, 0.2%, and 0.48%, respectively, by considering the renewable resources. In the same year, Ozgener and Ozgener [25] exergetically analyzed an industrial final macaroni (pasta) drying process using actual system data. The exergy efficiency of pasta drying process was found to be in the range of 72.98–82.15%. In continuation, Waheed et al. [26] presented a general methodology to study the energy consumption pattern in Nigeria orange juice manufacturing industry using energy and exergy analyses. The average energy

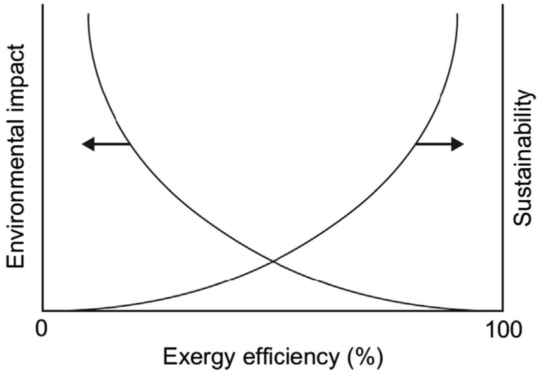

Fig. 1. Representative illustration of the relationship between the environmental impact and sustainability of an energy system and its exergetic efficiency (Dincer [14]). Copyright (2015), with permission from Elsevier.