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Exergetic performance analysis of an ice-cream manufacturing plant: A comprehensive survey

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ABSTRACT

In this study, a comprehensive exergetic performance analysis of an ice-cream manufacturing plant was conducted in order to pinpoint the locations of thermodynamic inefficiencies. Exergetic performance parameters of each subunit of the plant were determined and illustrated individually through writing and solving energy and exergy balance equations on the basis of real operational data. The required data were acquired from a local ice-cream factory located in Tehran, Iran. The plant included three main subsystems including water steam generator, refrigeration system, and ice-cream production line. An attempt was also made to quantify the specific exergy destruction of the ice-cream manufacturing process. The functional exergetic efficiency of the water steam generator, refrigeration system, and ice-cream production line was determined at 17.45%, 25.52%, and 5.71%, respectively. The overall functional exergetic efficiency of the process was found to be 2.15%, while the specific exergy destruction was calculated as 719.80 kJ/kg. In general, exergy analysis and its derivatives could provide invaluable information over the conventional energy analysis, suggesting potential locations for the plant performance improvement.

1. Introduction

Ice-cream is a frozen blend of a sweetened food mostly consumed as a dessert or a snack. In general, ice-cream consists of seven categories of food ingredients including water, fat, milk solids-not-fat (MSNF), sweeteners, emulsifiers, stabilizers, and flavorings [1]. According to the ingredients used, ice-cream can be categorized into various groups. The basic steps of the ice-cream manufacturing are respectively as follows: ingredients blending, pasteurization, homogenization, maturing, flavoring and coloring, freezing, incorporating fruits and nuts, packaging, and hardening.

Global consumption of ice-cream was about 2.4 L per capita in 2010 [1]. Therefore, the ice-cream industry can be a nontrivial contribution to economic growth and development around the world. However, a huge amount of energy in the forms of steam and electricity utilized in pasteurizing and freezing the raw product is the critical aspect of the ice-cream manufacturing process. According to the 'cradle-to-grave' analysis carried out by Konstantas et al. [2], ice-cream manufacturing and plastic production are the 'hotspots' for energy consumption in vanilla ice-cream production. Therefore, one of the utmost important challenges of this industry is to discount the manufacturing energy cost.

Today, most of energy needs of the ice-cream industry are met by fossil fuels in the direct form or indirect electrical power. However, the energy crisis and, more importantly, the environmental problems have spurred research into the efficient use of fossil energy resources and development of environmentally-benign alternative energies to discontinue or at least decelerate this tragic trend. On the other hand, the energy cost has a significant contribution to the unit cost of processed food products. These are why food manufacturers consider energy saving strategies with a more interest. Nowadays, advanced engineering tools like thermodynamic approaches are promising remedies for coping with the problems faced in the energy production, transport, storage, and utilization as well as end-of-life waste management.

In the past few decades, design, analysis, and optimization of energy-intensive manufacturing processes have been concreted with exergy analysis and its derivatives because of their unique

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Nomenclatures

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)
F	Function of the independent variables
G	Gibbs free energy (kJ/kg)
h	Specific enthalpy (kJ/kg)
$\dot{IP}$	Exergetic improvement potential rate (kW)
K_B	Boltzmann constant (1.38×10^{-23} J/K)
$\dot{m}$	Mass flow rate (kg/s)
n	Specific mole (mol/kg)
$\mathbb{N}$	Number of droplets of dispersed phase per kg milk (1/kg)
P	Pressure (kPa)
q_{LHV}	Lower heating value (kJ/kg)
$\dot{Q}$	Heat transfer rate (kW)
s	Specific entropy (kJ/kg K)
S	Entropy (kJ/K)
T	Temperature (K)
R	Gas constant (kJ/kg K)
$\overline{R}$	Universal gas constant (8.314 J mol/K)
u	Uncertainty in the independent variables
U	Uncertainty in the result
$\dot{W}$	Work rate (kW)
x	Mass fraction (−)
y	Mole fraction (−)

Greek letters

α	Exergetic allocation factor of steam generator for ice-cream manufacturing
β	Exergetic allocation factor of refrigeration system for ice-cream manufacturing
ϕ	Chemical exergy factor (−)
ε	Standard chemical exergy (kJ/mol)
ψ	Exergy efficiency (%)
ω	Humidity ratio (kg water/kg dry air)
υ	Specific volume (m^3/kg)
ρ	Density (kg/m)
γ_{AB}	Interfacial tension between phases A and B (kJ/m)
φ	Relative humidity (%)
$\varnothing$	Dispersed phase volume fraction
Δ	Increment

Subscripts

0	Dead state
a	Air
ch	Chemical
$conf$	Configurational entropy
des	Destruction
fo	Fat-formation exergy
i,j	Numerator
IC	Ice-cream production line
in	Inlet
ph	Physical
HA	Heat absorption
HL	Heat loss
out	Outlet
RF	Refrigeration system
s	Source
ST	Steam generator
TOT	Total plant
v	Vapor
vs	Statured vapor

conceptual features in providing in-depth information about the physical, thermodynamic, and ecological costs. It is well-documented that exergy analysis determines the locations and true magnitudes of energy quality loss (irreversibility) and, accordingly, identifies the environmental impacts of energy conversion systems more accurately compared with the other existing techniques. Simply speaking, exergy measures and evaluates the quantity and quality of energy flows mutually. Due to these reasons, exergy and its derivatives have been extensively used as a key engineering tool for analyzing, optimizing, and retrofitting various food manufacturing and processing plants [3–6].

For example, Balkan et al. [7] applied exergy analysis to evaluate the performance of a forward-feed triple-effect evaporator in an orange juice concentrate production plant. The overall exergetic efficiency of the plant was determined at 85%. In another study, Waheed et al. [8] measured the energy consumption pattern of an orange juice manufacturing industry using energy and exergy analyses. The average energy intensity of the orange juice processing was found to be 1.12 MJ/kg. Furthermore, pasteurization unit was responsible for over 90% of the overall thermodynamic inefficiency (exergy loss). Furthermore, Sogut et al. [9] exergetically assessed the performance of a quadruple-effect evaporation unit in a tomato paste production factory on the basis of actual plant data. Exergy efficiency of the evaporation units varied from a minimum value of 30.3% to a maximum value of 93.3%. In continuation, Fadare et al. [10] attempted to estimate the energy intensity and exergy inefficiencies of malt drink processing. The average energy intensity of the process was found to be 261.63 MJ/hl. In addition, the packaging house operation was found responsible for 92.16% of the overall thermodynamic inefficiency of the process.

Genc and Hepbasli [11] exergetically explored the performance of a potato crisp frying system consisting of a combustor, a heat exchanger, and a fryer. The universal exergetic efficiency of combustor, heat exchanger, and fryer was found to be 58%, 82%, and 77%, respectively. In the same year, Yildirim and Genc [12] applied exergy analysis for a milk pasteurization process assisted by geothermal energy. The overall exergetic efficiency of the system was determined at 56.81%, while the total exergy destruction rate was calculated as 13.66 kW. Later, Nasiri et al. [13] carried out a comprehensive exergy analysis of an industrial-scale ultrafiltrated cheese production plant on the basis of actual plant data. The average specific exergy destruction of the process was found to be 2330.42 kJ/kg. Steam generator also contributed to over 57% of the specific exergy destruction of the ultrafiltrated cheese process. Moreover, Kizilkan et al. [14] analyzed an ice-cream factory integrated with parabolic trough solar collectors from the energetic and exergetic viewpoints. The total energy consumption of the system was determined at 85.81 kWh per day. Furthermore, the overall