ARTICLE IN PRESS

Energy Conversion and Management xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Energy and exergy analysis of a milk powder production system

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A R T I C L E I N F O

Article history:
Received 7 December 2016
Received in revised form 20 January 2017
Accepted 26 January 2017
Available online xxxx

Keywords:
Milk powder
Energy
Exergy
Evaporator
Spray dryer
Geothermal

A B S T R A C T

Milk has been consumed since time immemorial because of its unique nutritional properties and produced almost 816 million tonnes in the year of 2016. Due to its highly perishable characteristic, milk is processed into more stable milk products such as cheese, yoghurt, and butter and milk powder. Among them, milk powder is distinctive for its longer shelf life and can be stored at ambient temperature. The other advantages of milk powder are less volume requirement during its transportation and higher selling price. Therefore, it is widely used in many food products such as ice cream, bakery products, and sausages. According to a recent study on the statistics from Food and Agriculture Organization, world production of whole dried milk was 3,597,015 tonnes in 2014: Oceania 36.5%, Americas 36.1% and Europe 24.1% of the World production.

Milk powder production is a process that requires high energy, especially for evaporation. Recently, reducing energy use has been gaining importance by increasing energy and exergy efficiency. Conventional energy analysis is performed based on the First Law of Thermodynamics. Unlike from the First Law, the Second Law or exergy analysis (defined as useful work) has appeared in the literature, while this analysis not only assesses quantity but also quality of energy. In this study, exergy analysis of a milk powder production system, mainly includes 3 processes (pasteurization, evaporation and spray drying) which will be presented. The aim of the study is to apply a thermodynamic analysis including comprehensive exergy analysis by using different performance parameters such as exergy efficiency, improvement potential rate, sustainability index, relative irreversibility and exergetic factor for the milk powder production system. As a result, exergetic efficiencies of the system components were found in the range of 9–83%. The overall energy and exergy efficiencies of the whole milk powder production system were calculated as 85.4 and 57.45%, respectively. Additionally, it was found that the evaporator and the heater have a higher impact in improvement actions.

1. Introduction

Milk and milk products are among the World's major food products, consumed by millions of people from all over the World on an everyday basis. The World total milk production is forecasted as 816 million tonnes in 2016 [1]. Because of milk's perishable characteristics, it is processed as in other products (such as cheese, butter, and yoghurt) for not only new product design but also add-value to the product. Additionally, dairies use their surplus milk to transport it to other parts of the World where local demand outstrips supply. In this case, milk powder production would be one of the best options for both having longer shelf life and lower transportation cost.

Turkey is the 10th largest milk producer in the World. Total raw milk and milk powder production of Turkey was 18.5 million tonnes and 182,868 tonnes in 2014, respectively. Izmir province, having very rich geothermal resources, is the 2nd largest milk producer [2].

Fluid milk and milk products are produced through applying thermal treatments such as heating and cooling which requires significant amount of energy. Hence, energy consumption is a crucial issue in dairy industry for both economic and environmental point of view. The dairy industry is an energy intensive sector and has a significant capability for energy efficiency. Thereof, increasing energy utilization efficiency of dairy industry and adapting renewable energy sources to the milk manufacturing lines, can reduce greenhouse gas emissions and protect global environment [3].

Demand for non-renewable energy resources have been increasing day by day and the current situation indicates that fossil

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http://dx.doi.org/10.1016/j.enconman.2017.01.064
0196-8904/

Please cite this article in press as: Yildirim N, Genc S. Energy and exergy analysis of a milk powder production system. Energy Convers Manage (2017), http://dx.doi.org/10.1016/j.enconman.2017.01.064

Nomenclature

C_p	specific heat (kJ/kg K)
ex	specific exergy (kJ/kg)
$\dot{E}$	energy rate (kW)
$\dot{Ex}$	exergy rate (kW)
f	exergetic factor (%)
h	specific enthalpy (kJ/kg)
$\dot{IP}$	improvement potential rate (kW)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
$\dot{Q}$	heat transfer rate (kW)
R	gas constant (kJ/kg K)
RI	relative irreversibility (%)
s	specific entropy (kJ/kg K)
SI	sustainability index (–)
T	temperature (K or °C)
$\dot{W}$	rate of work or power (kW)
x	mole fraction
Y	mass fraction

Greek letters

ε	exergetic (the second law) efficiency (%)
ρ	density (kg/m^3)
η	thermal efficiency (%)
ω	humidity ratio of air (kg water vapor/kg dry air)
ν	specific volume (m^3/kg)

Supercripts

ph	physical

Subscripts

D	destruction
f	saturated liquid state, fuel
g	saturated vapor state
i	numerator
in	input
k	location
out	output
p	product
0	reference environment
rev	reversible
tot	total
v	vapor

fuel reserves will be not enough for the near future [4]. Therefore, utilization of renewable energy resources such as solar energy, wind energy, biomass is inevitable [5].

Geothermal energy, heat derived from the earth, is one of the renewable energy resources having extensive application area for both residential and industrial utilizations such as space heating, greenhouse and open heating, aquaculture pond and race heating, industrial process heating, agricultural drying, snow melting and cooling.

The World's direct utilization of geothermal energy at the end of 2014 was 70,329 MWt. This amounts to energy saving of about 52.5 million tonnes of equivalent oil annually preventing 46 million tonnes of carbon and 148 million tonnes of carbon dioxide that would have otherwise been released into the atmosphere [6].

Turkey has a lot of potential geothermal resources ranging from low to high enthalpy and Turkey has the World's fourth largest direct use installed capacity (2,886 MWt) [6]. The most of the geothermal energy resources of Turkey are used for electricity generation, residential and greenhouse heating and balneological applications. However, direct use of geothermal energy for the industry in Turkey is still much lower than some developed countries such as America, Iceland, Japan and New Zealand.

Unlike from the most of the renewable energy sources, geothermal energy can be used directly in a variety of applications, where the combination of a variety of applications in the synergies and chain system can be called as a cascading or combined system. In general, there is brine from a separator in existing power plants, which still contains high heat, but unfortunately, the residual heat from the brine has not been utilized. The hot brine is injected directly back into the well. Whereas the hot brine can be used for various direct use applications before injected to the well. The required heat of dairy industry can be extracted from geothermal brine. Sustainable food production and processing is increasingly gaining global prominence. Because of intense thermal energy requirement of dairy industry, geothermal energy can become an alternative solution from sustainability point of view [7].

Milk powder (also called as dried milk) is one of the foodstuff of dairy industry. It is produced by dehydrating water found in milk using several processes. The aim of producing milk powder is to have longer shelf life and store it in room temperature [8]. Among milk products, whole milk powder is an important product used in confectionary, chocolate industry, ice cream, etc. and all over the World. In 2014, 3,6 million tonnes of whole milk powder were produced and five export countries of whole milk powder ranged as New Zealand, Brazil, Argentina, France and, Mexico, respectively [9].

Drying, is a staple unit operation, used in a various production industry such as chemical, pharmaceutical, textile, paper, food and many others. Drying process operation involves a consequential percentage of industrial energy utilization [10]. Energy consumption from drying accounts for about 18% of total energy usage in the UK [11]. According to a survey performed in the UK in 2000, the average energy consumption/use for all dryers was found as 4.87 GJ/t and the results of this survey indicates that around 29% of the energy supplied to the dryers was lost as a waste energy [12].

Spray drying is one of the well-known drying techniques in dairy industry, which is especially used for large scale production of milk powder. During spray drying operation, liquid state feed is turned into a solid-state product by spraying the liquid into a hot air environment [10]. During milk powder production, the water in the milk is removed by boiling the milk under reduced pressure at low temperature in a process known as evaporation. In the evaporator, the preheated milk is boiled under a vacuum at temperature around 80 °C and it is concentrated up to 45–55% dry weight. The resulting concentrated milk is then fed to the spray drier, where it is atomized into fine droplets. The spray drier is composed of a large drying chamber containing hot air flow and the water content of milk droplets are reduced by evaporation of remaining water thus forming a fine powder with around 3.5–6% moisture content [13]. Fig. 1 shows the general flowsheet for the milk powder production process.

Milk powder production process mainly utilizes electrical and thermal energy, where the largest consumer of electrical energy is the dryer (24%) and the largest consumer of thermal energy are the dryer (52%) and the evaporator (39%) [14]. Thermal processes constitute around 15% of total energy use in the dairy

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