Energy 90 (2015) 987–996

Contents lists available at ScienceDirect

Energy

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

Thermodynamic analysis of a milk pasteurization process assisted by geothermal energy

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ARTICLE INFO

Article history:
Received 10 June 2015
Received in revised form
1 August 2015
Accepted 4 August 2015
Available online 29 August 2015

Keywords:
Milk pasteurization
Geothermal energy
Thermodynamic analysis
Exergy analysis

ABSTRACT

Renewable energy system is an important concern for sustainable development of the World. Thermodynamic analysis, especially exergy analysis is an intense tool to assess sustainability of the systems. Food processing industry is one of the energy intensive sectors where dairy industry consumes substantial amount of energy among other food industry segments. Therefore, in this study, thermodynamic analysis of a milk pasteurization process assisted by geothermal energy was studied. In the system, a water–ammonia VAC (vapor absorption cycle), a cooling section, a pasteurizer and a regenerator were used for milk pasteurization. Exergetic efficiencies of each component and the whole system were separately calculated. A parametric study was undertaken. In this regard, firstly the effect of the geothermal resource temperature on (i) the total exergy destruction of the absorption cycle and the whole system, (ii) the efficiency of the VAC, the whole system and COP (coefficient of performance) of the VAC, (iii) the flow rate of the pasteurized milk were investigated. Then, the effect of the geothermal resource flow rate on the pasteurization load was analyzed. The exergetic efficiency of the whole system was calculated as 56.81% with total exergy destruction rate of 13.66 kW. The exergetic results were also illustrated through the Grassmann diagram.

1. Introduction

Milk constitutes an important part of a balanced and healthy diet with its excellent nutritional properties. It is one of the most popular beverages where more than 6 billion people consume milk and milk products around the World . According to a recent study on the statistics from FAO (Food and Agriculture Organization) world total milk production is 703,996,079 tonnes/year [1,2]. Therefore, producing safe milk by pasteurization process is a vital issue for human health.

The production of fluid milk requires crucial amounts of energy and raw materials. The main energy costs for dairy companies arise from their energy systems, the cleaning of the equipment and operating the machineries. In the case of complete milk processing plants, the energy requirement for pasteurization is about 600 MJ of thermal and 200 MJ of electrical energy per ton of the final product [1]. On the global scale, the food and tobacco industry consumes 5% of total industrial energy use and Turkey is one of the top ten largest milk producing countries with almost 19,000,000 tonnes/year of milk production. The dairy industry is of great importance including 1,250,947 firms in Turkey [3,4].

Heating and cooling are common processes in dairy industry and tubular or plate heat exchangers are used for these processes. In a milk processing plant, one of the best known heat treatments is pasteurization which is carried out between 60–75 °C according to the process type [2]. The heat transfer is especially provided by hot water in the pasteurization process and the required energy is supplied by using different energy sources such as natural gas, coal, electricity, renewable energies, etc. In today's World, the demand on energy has been rising parallel to the technological development and increasing population. However, fossil energy reserves on the Earth have been diminishing and the utilization of renewable energy resources (solar, wind, geothermal energy etc.) have been gaining importance for a sustainable future [5–7]. Among the renewable energies, geothermal energy has found wide application areas not only for power generation but also heating/cooling purposes both in industrial and residential usage [8–11]. Since milk pasteurization process needs both heating and cooling applications

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http://dx.doi.org/10.1016/j.energy.2015.08.003
0360-5442/

Nomenclature

c_p	specific heat (kJ/kgK)
COP	coefficient of performance (-)
e	specific exergy (kJ/kg)
$\dot{E}$	energy rate (kW)
$\dot{E}x$	exergy destruction rate (kW)
$\dot{F}$	exergetic fuel (kW)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat transfer rate (kW)
P	pressure (kPa)
$\dot{P}$	exergetic product (kW)
R	gas constant (kJ/kgK)
s	specific entropy (kJ/kgK)
T	temperature (K or °C)
$\dot{W}$	rate of work or power (kW)
VAC	vapor absorption cycle

Greek letters

η	thermal (the first law) efficiency (–)
ε	exergetic (the second law) efficiency (–)

Subscript

abs	absorber
con	condenser
cooling	cooling section
D	destruction
eva	evaporator
ev-1	expansion valve-1
ev-2	expansion valve-2
f	functional
gen	generator
hex	heat exchanger
in	input, inlet
k	location
max	maximum
out	output
past	pasteurizer
regen	regenerator
rev	reversible
u	universal
vac	vapor absorption cycle
0	reference environment

Superscript

ph	physical

together, geothermal energy can be considered one of the best options as a renewable energy resource for dairy processes.

For cooling purpose the most common method is conventional vapor absorption systems with their lower initial and operating costs compared to a cooling tower. However, the refrigerants (chlorofluorocarbons) used in the conventional systems are not environmentally friendly. Water–ammonia absorption cycle where water–ammonia mixture is used as a refrigerant is not only nature friendly but also provides refrigeration temperature necessary for a dairy process [12]. On the other hand, if water–ammonia absorption cycle powered by thermal energy resource between 100 and 200 °C, it would be an economical option. Hence, geothermal energy is taken into account as a heat source for water–ammonia VAC (vapor absorption cycle). The absorption cycle is composed of an absorber, an evaporator, a desorber, a condenser, a heat exchanger, expansion valves, and a pump. Ammonia (absorbent) and water (refrigerant) circulate along the system to provide for cooling effect [12,13].

The energy analysis is basically applied by using the first law of thermodynamics, which is defined as the conservation of energy. However, the first law analysis gives no idea about quality of the energy. Exergy can be expressed as the maximum amount of work obtained from a system when it is brought to a state of thermodynamic equilibrium with its surroundings [14]. The second law analysis or exergy analysis assesses performance of the systems and indicates irreversibility to improve the system.

Up to now energy analysis studies performed on fluid milk production process by using geothermal energy are concerned, Kiruja [13] performed energy analysis of a milk pasteurization unit is based on the mass flow rate of milk processed. The system analyzed by Ref. [13] is mainly composed of four units namely the pasteurizer, the regenerator, the water–ammonia absorption cycle and the cooling section. Most of the energy used in the milk pasteurization line was obtained in the regenerator with a value of 237,5 kW due to the heating and cooling of milk during the production line. In the same study, the effect of mass flow rate of raw milk on heat exchanger area, energy requirement of pasteurizer, desorber, evaporator and the mass flow rate of geothermal resource were investigated [13].

Although, exergy analysis has been carried out on thermal systems by various authors [e.g., 8, 11, 12, 15, 16, 17], there are several factors affecting the exergy destruction rate of processes. Genc and Hepbasli studied exergy analysis of potato crisp processes and they showed that the increase in mass flow rate of potato caused a rise in the exergy destruction rate of the fryer [15]. In another study of Aman et al. [12], the efficiency of a VAC used for residential air cooling was studied and they discovered that if the cycle is operated using low temperature heat sources it would be more thermodynamically efficient. On the other hand, the performance of each component of a pilot scale milk processing system was investigated by Fang [17] and the performance of the regenerator was found to be 30% exergetic efficiency value at the optimum operating condition.

Exergy analysis is an intense tool to evaluate the performance of the systems. In this regard, the results of the exergetic analysis indicate the major irreversibility issues and guide us to possible improvements in the systems. To the best of the author's knowledge, there are no studies on exergy analysis of a milk pasteurization process powered by geothermal energy in the open literature and this was the driving force behind doing this study. The aim of the study is to carry out thermodynamic analysis (including energy and exergy analysis) on a milk pasteurization process with a water–ammonia vapor absorption cycle, assisted by geothermal energy which is presented in Section 2. The whole system and component based efficiencies were computed by various parameters such as geothermal resource temperatures and mass flow rates, etc.

2. System description

Fig. 1 illustrates a schematic diagram of the considered system of a milk pasteurization process assisted by geothermal energy. This system was adopted from a study performed by Kiruja [13]. The whole energy requirement of the pasteurization system was supplied from geothermal resource where VAC was used for both heating and cooling purposes.

In the system of interest, the whole energy requirement for the pasteurization of milk was obtained from a geothermal resource