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Sustainable Dairy Industry by Using Renewable Energy Source

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Abstract

Renewable energy system is a crucial issue for sustainable development. Thermodynamic analysis, especially exergy analysis plays an important role to evaluate sustainability of the industrial processing systems. Food production industry is one of the energy consuming sectors and dairy industry could be placed at one of the top substantial amount of energy consuming food industry segments. Hence, in this study, thermodynamic analysis of a milk pasteurization system assisted by a renewable energy resource -geothermal energy was investigated. In this regard, for the pasteurization of 1 kg/s milk at 76°C the required pasteurization capacity was 21.88 kW. In case of using geothermal fluid at 100°C the exergetic efficiency of the whole system was computed 71.05% as the first law efficiency and 56.81% as second law efficiency, respectively. According to the exergy analysis the biggest exergy destruction rate was seen in the absorber as 4.577 kW. Additionally, in order to develop the system' efficiency the optimum operating conditions of the system components were determined such as absorber, condenser, evaporator, heat exchanger.

Keywords — Energy, Exergy, Geothermal Energy, Milk Pasteurization, Optimization

1. Introduction

One of the essential component of healthy and balanced diet is milk which is consumed by more than 6 billion people. According to Food and Agricultural Organization statistics the global dairy production reached to 703,996,079 metric tons [1]. For this reason, pasteurization is a critical step in the processing of milk.

Dairy industry is accepted as one of the most energy intensive industry. Turkey is globally in top ten countries with the number of the milk processing facilities with a number of which is 1,250,947 [2]. In dairy industry, heating and cooling are the most used and energy intensive processes. Although it might changes due to processing system in a dairy facility the most used heat treatment is the pasteurization which is done between 60-75°C. The heat necessary for the pasteurization operation is provided by energy carriers such as natural gas, coal and electricity.

As the global need to the energy increases day by day, unfortunately the fossil energy resources decreases dramatically. For this reason, the demand for the renewable energy rises rapidly. Turkey is one of the richest country in terms of geothermal resources which is widely accepted as renewable energy. Geothermal energy is not only used in power generating, but also used in industrial process and domestic heating and cooling. Geothermal energy is mostly preferred since it is an environmentally friendly, economic and sustainable source [3,4]. In this sense, geothermal energy could be used in the milk pasteurization process as well.

The energy analysis of the systems is conducted according to the first law of thermodynamics, known as conservation of energy. Unfortunately, first law analysis does not give any information related to energy quality and irreversibility within the system. Exergy analysis which is an analysis of the second law of thermodynamics is one of the effective tools used to measure the systems' performances [5]. By defining the irreversibility within the system through exergy analysis could help to improve and increase the system performance.

There are various researches in common literature related to energy and exergy analysis of milk and dairy processing stages. Quijera and Labidi [6] used exergy analysis to compare two different systems to see whether integration of the thermos solar technology in a dairy process would be used to support fossil fuels. Electricity and natural gas are used as energy carrier within the first system. Natural gas and sun energy is used within the second system. In comparison of the first and second systems, the exergy efficiencies were

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found as 10.3% and between 5.2 and 14.3%. The variation in the second system efficiency results is depending on the solar fractions. In another research, Soufiyan et al. [7] conducted an exergy analysis of a milk processing plant and found that the largest exergy destruction rate with the value of 12695.34kW occurred in the compressor and boiler combination of the steam generation system. Yıldırım and Genc [8] studied thermodynamic analysis of a milk pasteurization process consists of a cooling section equipped with vapor absorption refrigeration cycle assisted by geothermal energy. This thermodynamic analysis was conducted both for each component and whole system. Total exergy destruction rate of the whole system was calculated as 13.66kW and it was found that 51.07% of this value resulted from the absorption cooling system. And these results indicate to focus on VAC system not only component based but also as a whole to obtain higher exergetic efficiencies.

The aim of this study is to find the optimum operating conditions in order to increase exergy efficiency through studying the thermodynamic optimization of the milk pasteurization system assisted by geothermal energy.

2. Mathematical Model

2.1. System Description

Figure 1 illustrates a schematic diagram of the considered system of a milk pasteurization system assisted by geothermal energy. In this regard, all energy required for pasteurized milk production was supplied by a system where a geothermal fluid was used in an absorption refrigeration cycle consists of ammonia-water mixture.

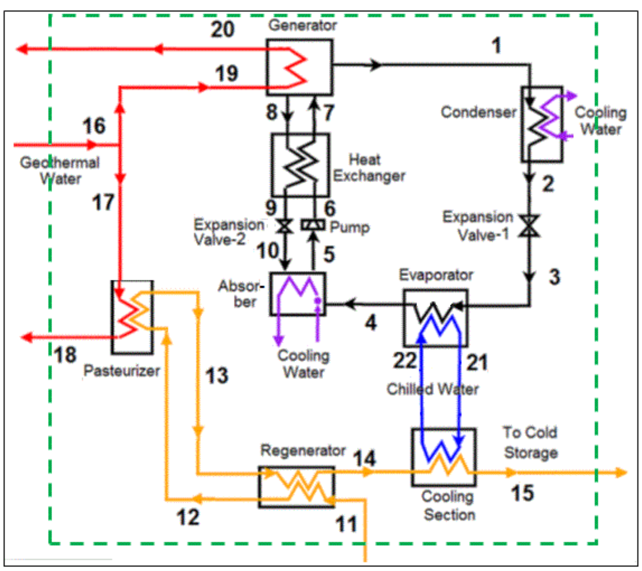


Figure 1. Schematic diagram of the milk pasteurization system assisted by geothermal energy [8].

The system basically consists of (i) the cooling system (for obtaining of heat for the pasteurization as well as cooling of milk), respectively (ii) regenerator (preheating and precooling of milk), (iii) the pasteurizer and (iv) the cooling unit (for cooling pasteurized milk). In this system, the geothermal fluid is divided in two streams called as stream 17 and 19. The first one (stream 17) goes to the pasteurizer and provides heat for pasteurization process (stream 13) and stream 19 run to the absorption cooling system where water and ammonia are used as an absorbent and a refrigerant, respectively. The absorption cooling system's components are the generator, the condenser, the evaporator, the absorber, the pump, two expansion valves and the heat exchanger.

The assumptions for the pasteurization system analysis are as follows:

(a) The whole system and its components are assumed to be run in steady state condition.
(b) Ammonia-water solutions are assumed to be in equilibrium in the generator and the absorber at their respective pressures and temperatures.
(c) The directions of heat transfer to the system and work transfer from the system are positive.
(d) The pressure and heat losses in the pipelines and the system components (generator, condenser, evaporator, absorber, regenerator, pasteurizer cooler, etc.) are ignored.
(e) All throttle valves are assumed to be operated under adiabatic condition, which results in constant enthalpy process.
(f) The generator temperature is considered as 5°C less than geothermal resource temperature.
(g) The milk temperature at the pasteurizer entrance is 2°C less than temperature of the geothermal resource.
(h) The cold storage temperature of the milk is assumed as 4°C.
(i) The heat exchanger thermal efficiency is considered as 0.80.
(j) The effectiveness of the regenerator is accepted as 0.95.
(k) Specific heat of the milk is kept constant and taken as 3.85 kJ/kg K.
(l) The pasteurization temperature of the milk is assumed as 76°C.
(m) The condenser, the evaporator and the absorber temperatures are assumed to be 30°C, 2°C and 30°C, respectively.
(n) The geothermal resource pressure is considered as same with the generator pressure.
(o) The pressure of the chilled water is assumed as atmospheric pressure.
(p) The reference temperature and pressure are taken to be 25°C and 101.325 kPa, respectively.

2.2. Modeling

The fundamental mass, energy, and exergy balance equations are carried out in order to calculate exergy destructions and efficiencies within the system (Eqns. 2.1 - 2.5).

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad \textbf{(2.1)}$$

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \quad \textbf{(2.2)}$$

$$\dot{Q} + \sum \dot{m}_{in} h_{in} = \dot{W} + \sum \dot{m}_{out} h_{out} \quad \textbf{(2.3)}$$

$$\sum \dot{Ex}_{in} - \sum \dot{Ex}_{out} = \sum \dot{Ex}_{D} \quad \textbf{(2.4)}$$

$$\sum \dot{m}_{in}\, e_{in} - \sum \dot{m}_{out}\, e_{out} + \sum \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_k - \dot{W} = \sum \dot{Ex}_{D} \quad \textbf{(2.5)}$$

The exergetic efficiencies of the components which made up the system was calculated by dividing the exergy in (feed) to exergy out (product) (Eqn. 2.6)

$$\varepsilon = \dot{Ex}_{out} / \dot{Ex}_{in} \quad \textbf{(2.6)}$$

The system was modeled by using Engineering Equation Solver (EES) Software package [9] and the graphs were drawn in both EES and Microsoft Office Excel.

3. Results and Discussion

The geothermal energy assisted milk pasteurization system was modelled and the thermodynamic properties of its each stage were calculated and published in authors' previous study [8]. The heat capacities of the system components and the first law efficiency of the system were calculated at certain operating conditions (T_{16}=100°C, T_{gen}=90°C, T_{abs}=30°C, T_{con}=30°C, T_{evap}=2°C, η_{HEX}=80%, $\dot{m}_{milk}$=1 kg/s) and results were tabulated in Table 1. The first law efficiency of the whole system was computed as 71.05%. The exergy destructions and exergetic efficiencies of each system component and the whole system were determined (Table 2). As seen from Table 2, the exergy destruction and exergetic efficiency of the whole system was calculated as 13.66kW and 56.81%, respectively. The greatest irreversibility (exergy destruction) occurs in the vapor absorption cycle which is covering 51.07% (6.974 kW) of the whole system.

Table 1. Main modelling results of the system at typical operating conditions.

Parameter	Value	Unit
Generator heat capacity	59.52	kW
Condenser heat capacity	40.86	kW
Evaporator heat capacity	34.65	kW
Absorber heat capacity	52.38	kW
Heat exchanger heat capacity	17.52	kW
Pasteurizer heat capacity	21.88	kW
Regenerator heat capacity	242.6	kW
Cooling section heat capacity	34.65	kW
Pump power	0.09067	kW
COP of the absorption cooling system	0.5813	-
Reversible COP of the absorption cooling system	2.275	-
Thermal efficiency of the whole system	71.05	%

Additionally, exergetic efficiencies of each component in milk pasteurization system were found as between 39%-99% and the lowest exergetic efficiency belongs to absorber (39.28%) (Table 2).

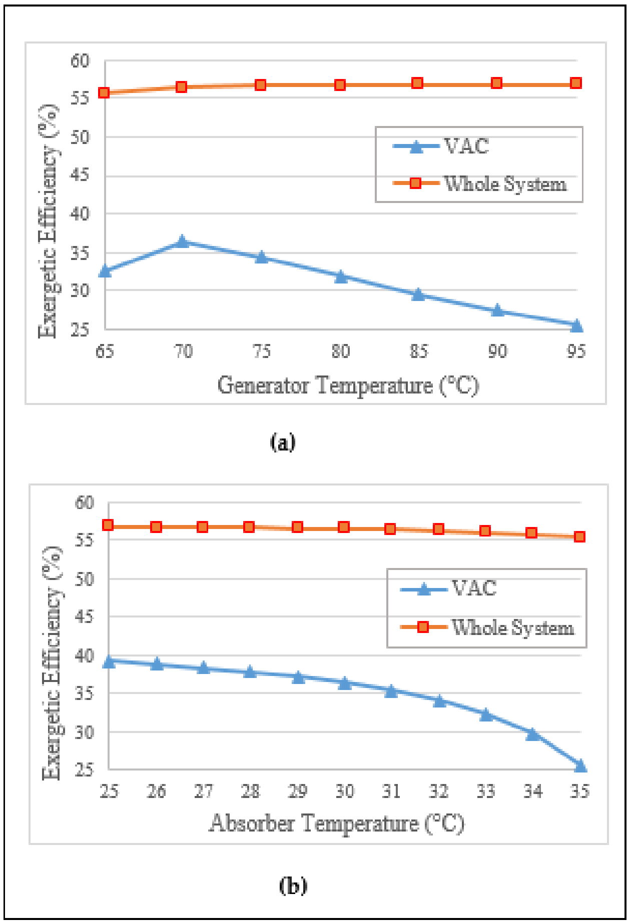
Table 2. Exergy loss of the system components.

Component	Exergy destruction rate (kW)	Exergy destruction fraction (%)	Exergy efficiency (%)
Generator	0.2501	3.587	98.82
Condenser	0.4894	7.018	57.93
Absorber	4.577	65.63	39.28
Heat exchanger	0.4413	6.428	97.25
Evaporator	0.004336	0.044	99.85
Pump	0.01011	0.153	88.85
Expansion valve 1	0.2513	3.603	93.49
Expansion valve 2	0.9501	13.62	91.83
Vapor Absorption cycle	6.974	51.07	25.55
Pasteurizer	0.6739	4.935	81.87
Regenerator	5.076	37.17	64.1
Cooling Section	0.9323	6.827	99.85
Whole system	13.66	100	56.81

The exergetic efficiency of the whole system was computed as 56.81%. It is planned to optimize the current system in order to improve exergetic efficiency of the whole system through parametric analysis. As seen from the results in Table 2, the vapor absorption cycle (VAC) has the greatest exergy destruction and its exergetic efficiency is 25.55%. Therefore, in this parametric study, it is firstly focused to VAC system. Totally 6 parameters of the VAC (generator temperature, absorber temperature, condenser temperature, evaporator temperature, heat exchanger efficiency, and geothermal fluid temperature) were chosen for parametric analysis and once a parameter is changed all remaining are set to typical operating conditions. The parametric analysis has started with the generator, which is the first component of the VAC. As it is presented in Figure 2.a, VAC exergetic efficiency reaches to the maximum value 36.34% when the generator temperature becomes 70°C and it has very limited effect on the exergetic efficiency of the whole system.

When the generator temperature is taken as 70°C and the effect of absorber temperature (25-35°C) on the exergetic efficiency was studied. It was found that the whole system exergetic efficiency is changed in the range of 56.7-55.3% by variation in the absorber temperature, whereas any rise in the absorber temperature causes a drop in the exergetic efficiency of VAC. For this reason, the maximum exergetic efficiency of VAC (39.16%) is calculated when the absorber temperature is 25°C (Figure 2.b).

Figure 2. The effect of (a) generator temperature and (b)



absorber temperature on the exergetic efficiency.

As the condenser temperature changes between 20 and 35°C at the conditions of generator temperature (70°C) and absorber temperature (25°C), where the maximum exergetic efficiency was obtained in the VAC, no significant effect on the whole system exergetic efficiency was observed. The exergetic efficiency was 41.55% at 20°C and it decreased to 36.14% at 35°C (Figure 3.a).

Figure 3.b presents the effect of the evaporator temperature on the exergetic efficiency between -5°C and 5°C. VAC reaches to maximum exergetic efficiency (51.22%) when evaporator is operated at -5°C.

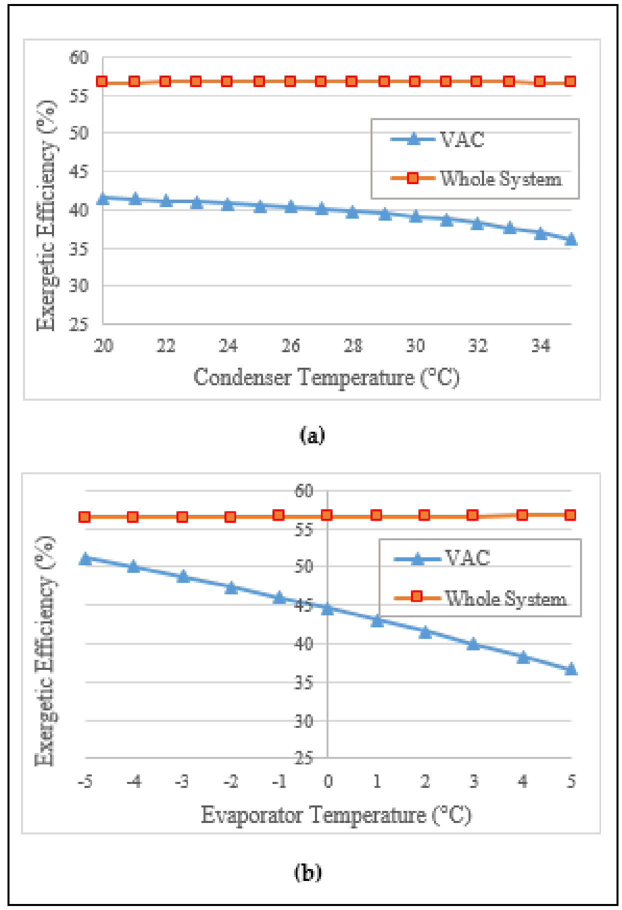


Figure 3. The effect of (a) condenser temperature and (b) evaporator temperature on the exergetic efficiency.

The operating efficiency effect of the heat exchanger on the total exergetic efficiency is examined after the temperatures of generator absorber, condenser and evaporator in the VAC are optimized. As it is seen in Figure 4, the heat exchanger brings the exergetic efficiency from 48.78% (operating at 70% efficiency) to 53.91% when it operates with 90% efficiency.

Lastly, the effect of the geothermal fluid temperature on the exergetic efficiency is examined. It is found that low geothermal fluid temperatures do not effect on VAC exergetic efficiency whereas they increase the whole system exergetic efficiency. Since exergy efficiency of VAC is directly related to generator temperature, the change in geothermal fluid temperature does not affect VAC's exergy efficiency.

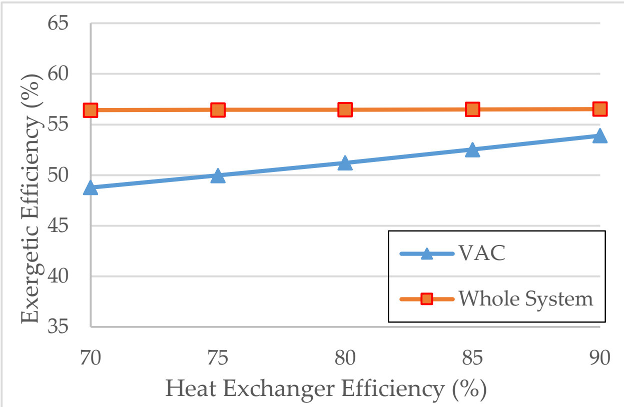


Figure 4. The effect of evaporator temperature on the exergetic efficiency.

At typical operating conditions (T16=100°C) whole system exergetic efficiency is found 56.81% and it increases to 80.61% as the geothermal fluid temperature decreases to 85°C. The reason behind that is, this system is assisted by geothermal fluid as an energy source and the most effective parameter on exergy efficiency is geothermal fluid temperature. Because, exergetic efficiency is defined as the ratio of exergy of product (output) to exergy of fuel (input). The closer the geothermal fluid temperature (input) is to the system conditions, the higher the exergy efficiency. Hence, the required temperature for milk pasteurization (76°C) could be obtained effectively from a geothermal fluid at 85°C.

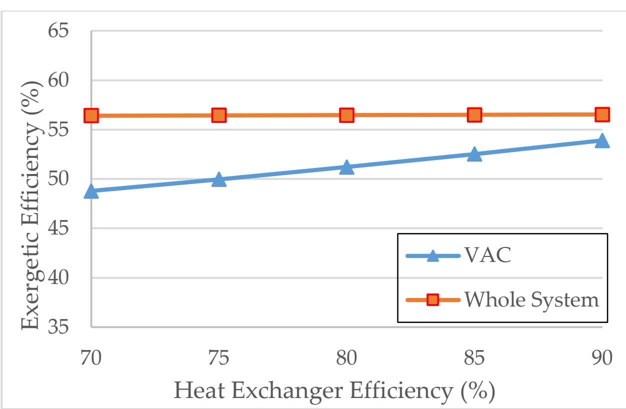


Figure 5. The effect of heat exchanger temperature on the exergetic efficiency.

This study is the first study done for the thermodynamic optimization of a geothermal assisted milk pasteurization system. As there are no similar studies related to thermodynamic optimization in milk pasteurization system, the comparison was made only among the components. In this regard, Aman et al. [10] determined the exergetic efficiency as 32% in ammonia-water mixture VAC. In another study, the exergetic efficiencies were calculated in two different systems, where different energy resources were used. In the first system, natural gas and electricity was used as energy carrier and the exergetic efficiency was found 10.3%. The energy resources were natural gas and sun in the second system and the exergetic efficiency was changing between 5.2-14.3 % due to sun energy usage ratio [6]. The specific exergy destruction of UHT milk was found as 345.50 kJ/kg in a performance assessment of an extended shelf life milk producing facility [7].

4. Conclusions

In this research, thermodynamic optimization of milk pasteurization system assisted by geothermal energy was carried out. The thermodynamic analysis of milk pasteurization process assisted by geothermal energy was presented in the previous study of the authors and VAC was found having a highest portion (51.07%) of exergy destruction [8]. At typical operating conditions the total exergy destruction of the system was calculated as 13.66kW and the greatest exergy destruction was due to absorption cooling unit (6.974kW). The universal exergetic efficiency of the whole system was computed 56.81%. In order to increase the exergetic efficiency of the system a thermodynamic optimization was applied to 5 parameters of VAC (generator temperature, absorber temperature, condenser temperature, evaporator temperature, heat exchanger efficiency) and geothermal fluid temperature. It was determined the effects of those parameters to the exergetic efficiencies of VAC and the whole system. According those results the optimum operating conditions of a VAC for pasteurization of the milk in the flow rate of 1 kg/s were found as T_{gen}=70°C, T_{abs}=25°C, T_{con}=20°C, T_{evap}=-5°C at 100°C geothermal fluid temperature. VAC reaches to maximum exergetic efficieny (53.91%) when the efficiency of the heat exchanger becomes 90%. Additionally by dropping the temperature of geothermal fluid to 85°C just after providing all of the conditions the system exergetic efficiency rises to 80.61% and this amount could be named as the maximum exergetic efficiency value among the previous researches published in the open literature. In conclusion, in order to design an optimum system, it is very critical to choose of the operating temperatures and efficiencies of the VAC components. It is considered that this study could be supportive to further researches in process design and optimization in dairy and/or other food process where absorption cooling systems are applied. As a further study, it is planned to conduct an economic analysis for selection of the components in regard to accurate assessment of the whole system.

Acknowlegement

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Symbols

COP	coefficient of performance (-)
$\dot{E}$	energy rate (kW)

e	specific exergy (kJ/kg)
$\dot{E}x$	exergy rate (kW)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat transfer rate (kW)
T	temperature (K or ºC)
$\dot{W}$	rate of work or power (kW)
VAC	vapor absorption cycle
ε	exergetic (the second law) efficiency (-)
Subscripts	
D	destruction
abs	absorber
con	condenser
evap	evaporator
gen	generator
hex	hexheat exchanger
u	universal
in	input, inlet
k	location
out	output
0	reference environment

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