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EFFICIENCY ANALISYS OF THE HEAT PUMP SYSTEM FOR RAW MILK COOLING WITH PRECOOLER AND POSSIBILITY FOR WASTE HEAT RECOVERY THROUGH SANITARY WATER HEATING

ANALIZA EFIKASNOSTI RADA SISTEMA TOPLOTNE PUMPE ZA HLAĐENJE SVEŽEG MLEKA SA PREDHLAĐENJEM I MOGUĆNOŠĆU ISKORIŠĆENJA OTPADNE TOPLOTE ZA DOGREVANJE POTROŠNE VODE

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ABSTRACT

Contemporary livestock production implies production of highly valuable, biologically and chemically safe products. Dairy production has no exception too. On the contrary, the quality standards for raw milk are highly increased. The quality of raw milk is defined by its chemical composition and the total count of microorganisms in control volume. In this paper we discussed the performance of advanced system for heat recovery from raw milk and its application in the process of preheating and preparation of process water. The energy and exergy efficiency of one of such systems were analyzed. It was determined that the implementation of the system for milk cooling with precooling and using the waste heat for preheating process water could achieve significant savings. The system consists of "milk to water" heat pump, pre-cooler for milk cooling and storage tank for process water with heating possibility. Values of exergy efficiency of each component of system and potential improving of components performances were determined. Also, the exergy efficiency and potential improvement of complete system were determined.

Key words: *Energy efficiency, heat pump, milk, cooling, exergy.*

REZIME

Savremena stočarska proizvodnja podrazumeva proizvodnju visoko vrednih, biološki i hemijski bezbednih proizvoda. Proizvodnja mleka nije izuzetak, naprotiv, norme kvaliteta sirovog mleka su sve strožije. Kvalitet sirovog mleka je određen njegovim hemijskim sastavom i ukupnom brojnošću mikroorganizama u kontrolnoj zapremini. U ovom radu biće razmatran rad naprednog sistema za rekuperaciju toplote iz svežeg mleka koja se potom koristi u procesu dogrevanja i pripreme potrošne vode. Primenom sistema za hlađenje mleka sa predhlađenjem i korišćenjem dobijene toplote za zagrevanje potrošne vode mogu se postići značajne uštede. U radu je analizirana energetska i eksergetska efikasnost rada jednog ovakvog sistema. Sistem se sastoji od toplotne pumpe „mleko-voda“, predhladnjaka za hlađenje svežeg mleka i skladišnika potrošne tople vode sa mogućnošću njenog dogrevanja. Ustanovljene su veličine eksergetske efikasnosti komponenata sistema i potencijal poboljšanja svake od komponenata u sistemu. Takođe, ustanovljena je eksergetska efikasnost celokupnog sistema i potencijal njegovog poboljšanja.

Ključne reči: *Energerska efikasnost, toplotna pumpa, mleko, hlađenje, eksergija.*

INTRODUCTION

Modern dairy production involves production of high worth bacteriological safe food product. The overall quality of the raw milk is determined by its chemical composition and bacteriological quality. By keeping the fresh milk at low temperatures, before the thermal processing process is continued, the bacteriological activity is reduced to its minimum. If the milk has a high number of bacteria, its technological value is decreased, because the bacteria need to break down and use some of the milk components for their own metabolism. Major source of milk contamination during the milking process are inadequate preparation procedures and poor udder hygiene (*Radivojević et al., 2011*). Different temperatures of raw milk during the production proces along with the milk fat content have great influence on reologycal and thermal properties of milk *(Hlaváč, 2011)*. To maintain milk quality, milk must be cooled from about 39 °C (cow body temperature) to 3 °C for safe storage. Milk is normally cooled by a refrigeration unit acting as a heat pump moving heat from the milk (heat source) to the air or water (heat sink) using a carrier refrigerant. In the refrigeration unit evaporator, located in the milk tank, the refrigerant absorbs heat from the milk and changes state from a liquid to a gas. This state change has great impact on compressor performance and energy consumption. (*Radivojević et al., 2012*). A heat pump systems application has great potential and provides economical and ecological benefit in different branches of food industry (*Chua et al., 2010; Gong et al., 2008; Zlatanović et al., 2011*). Use of heat recovery systems in milk cooling operation can contribute to most effective energy use. Application of heat recovery system can save 53% of energy compared with conventional electric heater (*Griswold et al., 1984*). However, some studies showed that the total energy use for hot water heating and milk cooling on the farms was not correlated with the herd size. Only measurements of energy use for water heating and milk cooling can provide data for quality energy savings potential assessment (*Kammel et al., 1993*).

Energy efficiency in the diary industry is becoming an increasingly important issue due to the rising costs of both electricity and fossil fuel resources. Thoughtful implementation of energy efficiency improvements in agricultural equipment will help reduce the cost of food production (*Gellings, 2008*). Process heat recovery (*Zlatanović et al., 2011*) or waste heat recovery (*Law et al., 2013*) provide considerable savings in energy consumption. The advanced technologies within some form of heat recovery process are preferable in diary industry, like thermosolar technology (*Quiera et al., 2013*) or refrigeration (*Stinson et al., 1987; Radivojević et al., 2012*) technology (heat pump). Figure 1 shows typical distribution of on-farm electrical energy consumption. Although, total energy use can vary widely with the type of building, as well as with the relative age of facility (*Capareda et al., 2010*). The heat recovery systems on larger farms are likely to be more attractive financially, because the increase in return is not matched by a similar increase in cost (*Stinson et al., 1987*).

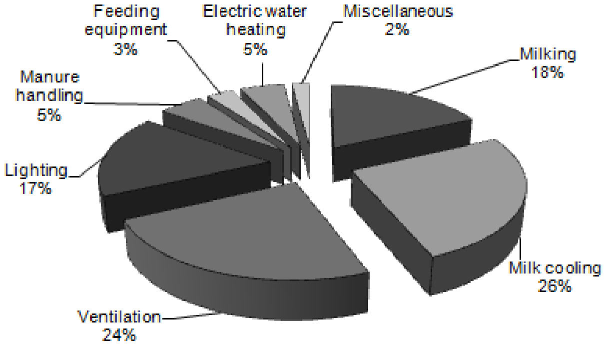

Fig. 1. Dairy farm electric energy consumption (Peterson, 2008)

Some studies (*Edens et al., 2003*) also show that major energy consumers in dairy production are equipment for milking and milk cooling, while outside temperature plays lesser role. Same study notes that cow number is not a factor related to energy use for milk cooling or vacuum pump operation, creating suspicion about the validity of kWh/cow/yr as an energy use indicator.

A new technique for heat recovery system is analyzed in this paper. The proposed system employs a combined milk-cooling and water-heating technique for heat recovery. This system provides not only heating or cooling, but also hot water. Similar system was presented and analyzed in Ref. (*Gong et al., 2008*). The heat recovery system can increase equipment utilization to avoid equipment idle in transition time and decrease equipment investment cost.

Exergy is defined as the maximum useful work that can be produced by a stream or system in a specified environment. Exergy is a quantitative measure of the "quality" or "usefulness" of an amount of energy (*Dincer et al., 2007*). Many researchers and practicing engineers refer to exergy methods as powerful tools for analyzing, assessing, designing, improving and optimizing systems and processes (*van Gool, 1997; Zlatanović et al., 2013*). Efficiencies based on exergy, unlike those based on energy, are always measures of the approach to true ideality, and therefore provide more meaningful information when assessing the performance of energy systems (*Dincer et al., 2007*).

Nomenclature

$\dot{m}$ - Mass flow rate, *kg/s*
$\dot{E}$ - Energy rate, *kW*
$\dot{Ex}$ - Exergy rate, *kW*
h - Specific enthalpy, *kJ/kg*
s - Specific entropy, *kJ/kg K*
T- Temperature, *K*
ψ - Exergy efficiency, *dimensionless or %*
IP- Improvement potential rate, *kW*
LMTD- Logarithmic mean temperature difference

Subscript

0 - Dead state
act - Actual
dest- Destroyed
in - Inlet
m - Milk
out - Outlet
s - Isentropic
w - Water

MATERIAL AND METHOD

The experiment involved with this study (Fig. 2) was peformed at small family farm (16 Cows). Data were collected during the period of 24 hours. The capacity of milk tank is 500 litres. After each milking period (1st period 18:00-20:00 h, 2nd period 6:00-8:00 h the next day) the milking equipment (mobile milking equipment) is washed and cleaned with hot water at 60 °C previously heated and storaged in the water thank. The mass flow rate of the milk through the milk thank is averaged in a one milk production period (127 minutes). Similar approach is used to determine the mass flow rate of the water through the water tank.

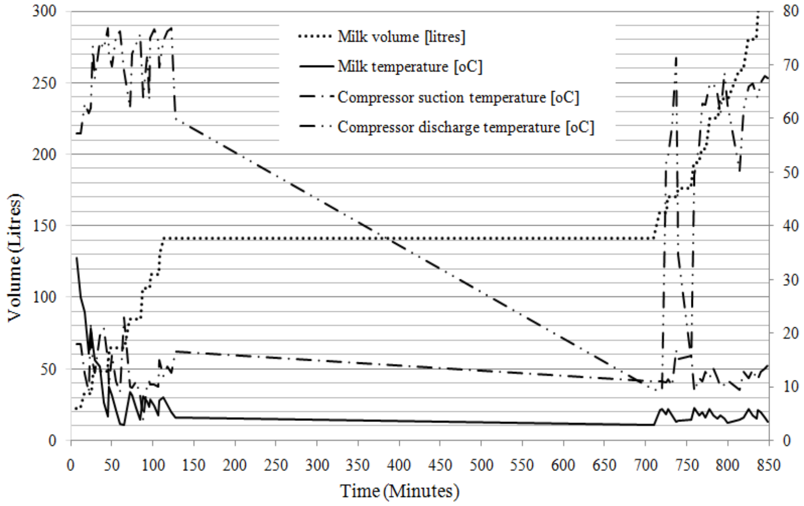

Fig. 2. Experimental data for 24 h period

The heat recovery system (Fig.3) consists of three separate circuits: (1) a heat pump circuit (with refrigerant R134a), (2) a milk cooling circuit and (3) a water distribution circuit. The heat pump circuit consists of a compressor, a condenser placed in water tank, an expansion valve and an evaporator placed in milk tank. Those components operate within simple refrigeration cycle. The refrigerant leaved the evaporator superheated at – + 10 °C, and condenser sub cooled at – 1 °C. The condensing temperature and compressor average discharge temperature were measured + 42 °C and + 68 °C respectively. The evaporating temperature was set to be Δt = 2 °C lower than outlet temperature of milk. The milk and water circuits were crossflowed through 0.4 kW capacity plate heat exchanger, with milk inlet/outlet temperatures + 39 °C / + 21 °C, and water inlet/outlet temperatures + 12 °C / + 35 °C. The calculated value of the logarithmic mean temperature difference of plate heat exchanger was LMTD = 6.17 °C. The heat exchange area was 0,222 m^2.

The raw milk was precooled in plate heat exchanger (precooler). In precooler, the heat was transfered to the cold water. The refrigerant flowed through the evaporator and drew the heat from the lukewarm milk over the large bottom tank surface area. Then, the heat was rejected from the condenser to the water circulating through the water tank.

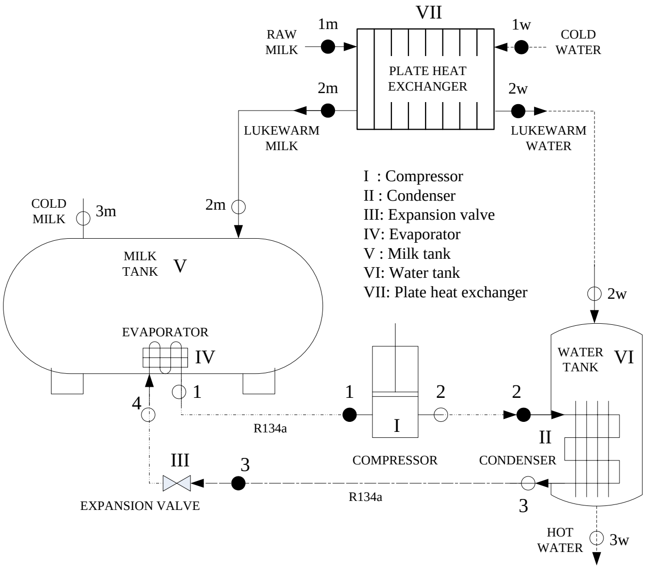

Fig. 3. A milk/water heat pump system with pre-cooling

The heat recovery system components energy balance, the exergy destruction rate and exergy efficiencies were determined under the assumption of steady-state and steady-flow processes in the observed system (*Dincer and Rosen 2007*). All calculations were based on mass (Eq. 1) and energy (Eq. 2) conservation principles and system exergy balance (Eq. 3).

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

$$\dot{E}_{in} = \dot{E}_{out} \tag{2}$$

$$\dot{E}x_{dest} = \dot{E}x_{in} - \dot{E}x_{out} \tag{3}$$

The exergy rate of refrigerant, milk or water was determined by using Eq. 4.

$$\dot{E}x_{in} = \dot{m}\left[\left(h - h_0\right) - T_0\left(s - s_0\right)\right] \tag{4}$$

The exergy efficiency was calculated as the ratio of total exergy output to total exergy input (Eq. 5), and the improvement potential on a rate basis was expressed with Eq. 6 (*van Gool, 1997*).

$$\psi = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} \tag{5}$$

$$IP = \left(1 - \psi\right)\left(\dot{E}x_{in} - \dot{E}x_{out}\right) \tag{6}$$

The following assumptions were used in energy and exergy analysis: (a) all processes are steady-state and steady-flow with negligible potential and kinetic energy effects and no chemical reactions; (b) the properties of milk are approximated with water during entropy calculations; (c) heat transfer and refrigerant pressure drops in the pipelines connecting the components are negligible; (d) the compressor motor electrical efficiency is 88 %.

RESULTS AND DISCUSSION

Temperature pressure and mass flow rate data for the refrigerant (R134a), milk and water are given in Table 1 according to the state numbers described on Fig. 2. The calculated exergy rates are provided at Table 1. The references state (dead state) was taken to be the state of the room where the heat pump system is placed, with the ambient temperature of 20 °C and atmospheric pressure of approximately 100 kPa. The thermal properties of water and refrigerant were found from the water properties tables. The properties of milk were found in the literature (*Božikova, 2008; Чубик анд Маслов, 1965*).

Table 2 presents exergy, energy and IP data for a representative unit of the heat pump system. The exergy efficiency on an outlet/inlet basis for the overall heat recovery system is 31.36 %.

According to the results presented in Table 2, the greatest irreversibility occurs in compressor and evaporator / milk tank, and it was manifested through the highest values of exergy destruction rate. The large degree of superheat achieved at the end of the compression process causes the exergy destruction through compressor.

Compressor power depends on the inlet and outlet pressures. The heat exchanger improvements that reduce the temperature difference will reduce compressor power by reducing the temperature differences between condensing and evaporating temperatures.

Table 1. Process data for flows in the heat pump system

State no.	Description	Fluid	Phase	Temp.	Press.	Specific enthalpy	Spec. entropy	Mass flow rate	Exergy rate
				°C	*kPa*	*kJ/kg*	*kJ/kgK*	*kg/s*	*kW*
0	-	Refrigerant	Dead state	20	100	270	1.083	-	0
0	-	Milk	Dead state	20	100	82.88	0.2928	-	0
0	-	Water	Dead state	20	100	82.88	0.2928	-	0
1m	Plate heat exchanger inlet	Milk	Compressed liquid	34.1	100	142.3	0.4908	0.0191	0.02711
2m	Plate heat exchanger outlet / Tank inlet	Milk	Compressed liquid	28.81	100	120	0.4174	0.0191	0.01084
3m	Tank outlet	Milk	Compressed liquid	4	100	16.31	0.05927	0.0191	0.03521
1w	Plate heat exchanger inlet	Water	Compressed liquid	15	500	61.93	0.2207	0.0154	0.002513
2w	Plate heat exchanger outlet / Tank inlet	Water	Compressed liquid	21.45	500	88.98	0.3135	0.0154	0.000269
3w	Tank outlet	Water	Compressed liquid	60	500	251.6	0.8323	0.0154	0.1579
1	Evaporator outlet/ Compressor inlet	Refrigerant	Superheated vapor	12	314.6	257.7	0.951	0.0125	0.3285
2,s	Condenser inlet/ Compressor outlet	Refrigerant	Superheated vapor	55.07	1072	284.4	0.951	0.0125	0.6627
2,act	Condenser inlet/ Compressor outlet	Refrigerant	Superheated vapor	68	1072	298.9	0.9944	0.0125	0.6853
3	Condenser outlet/ Expansion valve inlet	Refrigerant	Compressed liquid	41	1072	107.7	0.3913	0.0125	0.5037
4	Expansion valve outlet/ Evaporator inlet	Refrigerant	Mixture	2	314.6	107.7	0.4066	0.0125	0.4479

One way for improving system effectiveness is replacing the reciprocating compressor by a more efficient scroll compressor unit. Also, the improvement of plate heat exchanger heat transfer efficiency will be of great benefit, because it will reduce milk tank inlet milk temperature and reduce evaporator heat load. The second largest irreversibility is associated with the evaporator (milk tank). The component irreversibility results of the overall heat recovery system indicate that the greatest potential for improvement is in the compressor and evaporator components.

Table 2. Data for devices of a representative unit in heat recovery system

Device number	Device	Utilized power	Exergy in	Exergy out	Exergy destruction rate	Exergy efficiency	Improvement potential rate
		kW	*kW*	*kW*	*kW*	*%*	*kW*
I	Compressor	0.5158	0.8443	0.6853	0.159	81.17	0.02995
II	Condenser	2.39	0.6855	0.6615	0.024	96.5	0.00084
III	Expansion valve	-	0.5037	0.4479	0.05579	88.92	0.006179
IV	Evaporator	1.874	0.4587	0.3637	0.09503	79.28	0.01969
V	Milk tank	1.874	0.4587	0.3637	0.09503	79.28	0.01969
VI	Water tank	2.39	0.6855	0.6615	0.024	96.5	0.00084
VII	Plate heat exchanger	0.4	0.02962	0.01111	0.01852	37.49	0.01157
I-VII	Overall heat recovery system	-	0.6158	0.1931	0.4227	31.36	0.2901

CONCLUSION

Comprehensive energy and exergy analyses are presented in this paper in order to evaluate the performance of heat recovery system and its components. Actual data are utilized in the analysis. Exergy destructions in the overall heat recovery system and its components are quantified.

The exergy efficiencies elucidate great potential for each system component improvement. The largest irreversibility in the heat pump unit is associated with the compressor (0.159 kW), followed by the evaporator (0.095 kW), the condenser (0.024 kW), the expansion valve (0.056 kW) and the plate heat exchanger (0.018 kW). The exergy analysis of the overall heat recovery system, with exergy efficiency of 31.36 % indicates that there is the greatest potential for improvement (0.29 kW).

It may be concluded that integration of heat recovery unit in a complex diary process, in combination with other specific devices, must be conducted carefully, in order to obtain its maximum capacity and performance.

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