Experimental Investigation on Exergy Analysis of a Milk Powder Production System

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Abstract- **Milk is an essential component of daily life and it is used in various forms like curd, cheese, butter, milk powder, ghee etc. Among them, milk powder is dried form of milk and popular for its longer shelf life and can be stored at ambient temperature. Milk powder manufacturing unit consists of various thermal processes like pasteurization, evaporation, drying and these processes consume very high energy. In last decade energy has become a topic of major concern due to various reasons like hike in price of fossil fuel, strict emission standards and increase in energy consumption. The objective of the paper is to apply a detailed exergy analysis by using different performance parameters such as exergy efficiency, exergy destruction rate for the milk powder manufacturing process. Here in this paper milk powder manufacturing process is analysed using exergy analysis tool.**

Index Terms- **Exergy analysis, pasteurization, evaporation.**

1. INTRODUCTION

Dairy industry is one of the most important energy consuming sectors of the food industry. According to Munir et al. [1], the dairy industry is the 5th largest production section in terms of energy consumption. Interesting point is that, the most of energy used in this section is still met by energy sources based on fossil fuels, leading to a significant quantity of emissions of greenhouse gas (i.e. CO2, SOx, NOx, and PMs).

Due to the energy crisis and environmental concerns, a great deal of attention has been paid to find the most cost-effective and eco-friendly ways of energy utilization. This can be achieved with the application of very useful engineering tools like energy and exergy analyses to improve and optimize the performance of energy consuming systems. Energy analysis is a traditional approach applied to investigate various energy conversion systems [2]. Nevertheless, the energy concept has been criticized due to its obvious weakness in measuring and evaluating the quality of energy sources. Exergy analysis has been considered to be a most useful method for energy consuming production systems because of the fact that it helps to locate and quantify the thermodynamics inefficiencies more precisely than the conventional energy analysis [2].

Milk powder manufacturing system consists of various thermodynamic processes like rapid heating and cooling in pasteurisation, refrigeration, evaporation, drying etc. that requires significant amount of energy. In the last two decades reducing energy consumption is gaining attention of research field. First Law of Thermodynamics gives conventional energy analysis. Unlike from the First Law, the Second Law of thermodynamics gives qualitative analysis of exergy (defined as available or useful work), while this analysis not only estimate quantity but also quality of energy. In this thesis, thermodynamic analysis of a milk powder manufacturing unit, mainly divided into four subsystems steam generation, refrigeration, milk pasteurisation and milk drying which will be presented. The project aims to apply a thermodynamic analysis including detailed exergy analysis by using various operational parameters such as exergy efficiency, exergy destruction rate for the milk powder manufacturing unit.

The case study was conducted on a local dairy plant located in Amravati, Maharashtra. Overall, the plant is divided into four main subsystems, including steam generation system, refrigeration system, milk pasteurization system and milk powder production lines.

2. DESCRIPTION OF SYSTEM

Fig. 1 shows block diagram of ammonia refrigeration system. It consists of compressor, condenser, expansion valve and chiller. A cooling tower is provided to lower the temperature of condenser water from 350C to 290C. The system uses ammonia as refrigerant. In chiller water is cooled to 20C which is further used to cool the milk.

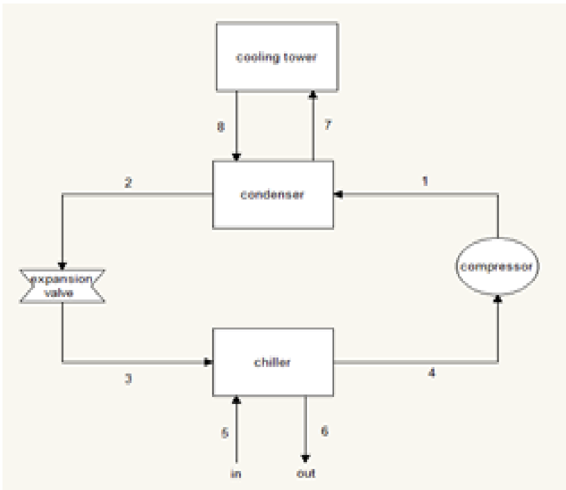

Fig. 1 Ammonia Refrigeration System

Fig. 2 shows block diagram of steam generation system. It consists of boiler, pump and condensate tank. The water from pump is fed to boiler where it converts to steam at temperature 1640C. Further the steam from boiler is supplied to the various systems of the plant.

Fig. 3 shows block diagram of milk pasteurisation system. It consists of three plate type heat exchanger. In heat exchanger 1 milk is heated to 750c using hot water and heat exchanger 2 milk is cooled down to 40c using ice water. In regenerative heat exchanger incoming stream of chilled milk is heated by outgoing stream of hot milk.

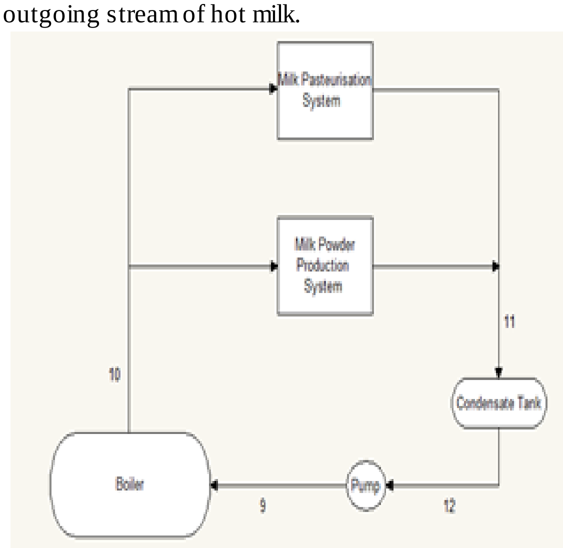

Fig. 2 Steam Generation System

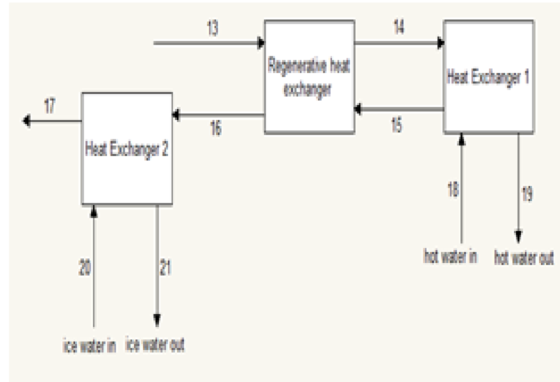

Fig. 3 Milk Pasteurization System

Fig. 4 shows block diagram of milk powder production system. It consists of evaporator, pump and twin drum drier. In the evaporator, skim milk is concentrated upto 45 % w/w total solid. Further milk is supplied to drier through pump. In the drier milk comes in contact with steam heated drums and water content in the milk evaporates. Thin layer of dried milk is taken away from the drums and converted into fine powder.

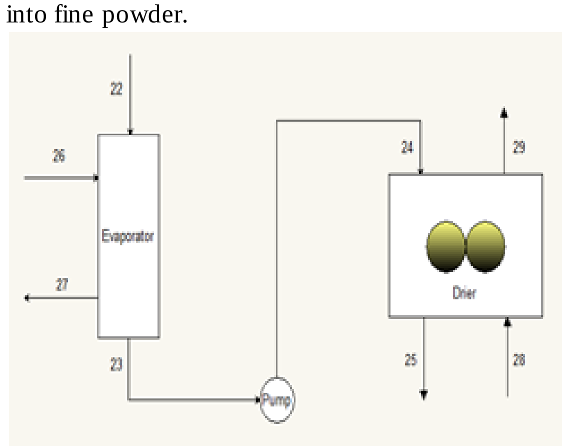

Fig. 4 Milk Powder Production System

3. ASSUMPTIONS MADE

a) The plant and its subcomponents performed in a steady-state condition.
b) The kinetic and potential exergies of various streams were neglected due to their insignificant contributions to the total exergy.
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 are neglected.
e) All throttle valves are operated under adiabatic condition, which results in constant enthalpy process.

Nomenclature

Cp	specific heat (kJ/kg K)
ex	specific exergy (kJ/kg)
E	energy rate (kW)
Ex	exergy rate (kW)
h	specific enthalpy (kJ/kg)
m	mass flow rate (kg/s)
P	pressure (kPa)
Q	heat transfer rate (kW)
R	gas constant (kJ/kg K)
s	specific entropy (kJ/kg K)
T	temperature (K or ^{0}C)
W	rate of work or power (kW)
x	mass fraction
ε	exergy efficiency (%)

Subscripts

D	destruction
F	fuel
in	input
out	output
p	product
0	reference environment

4. MATHEMATICAL MODELLING

The basic mass, energy and exergy balance equations are as following and exergy efficiency is calculated in which the system is at steady state

Mass balance equation:

$\sum m_{in} = \sum m_{out}$

Energy balance equation:

$Q + \sum m_{in} h_{in} = W + \sum m_{out} h_{out}$

Exergy balance equation:

$\sum Ex_{in} - \sum Ex_{out} = \sum Ex_D$

Exergy is given by:

$Ex = (h - h_0) - T_0(s - s_0)$

Where,

$(h - h_0) = c_p(T - T_0)$

$(s - s_0) = c_p \ln(T/T_0) - R \ln(P/P_0)$

5. EXERGY ANALYSIS

In thermodynamics, exergy of a system is defined as maximum useful work output that can be obtained from a process until the system comes to dead state i.e. equilibrium with surrounding. Exergy is the energy that is available to be used. After the system and surroundings reach equilibrium, the exergy is zero. A detailed exergy analysis of each component of every subsystem of a plant has been done and equations used to determine exergy destruction rate are tabulated in Table 1.

Table 1. Equations used to determine exergy destruction rate of various component

System	Component	Exergy destruction rate(kW)
Refrigeration system	Compressor	16.08
	Condenser	1.78
	Expansion valve	3.81
	Chiller	3.318
Steam generation system	Boiler	693.7
	Pump1	3.03
Milk pasteurisation system	Regenerative heat exchanger	0.64
	Heat Exchanger 1	2.09
	Heat Exchanger 2	2.94
Milk powder production system	Evaporator	53.54
	Pump2	2.11
	Drier	65.75

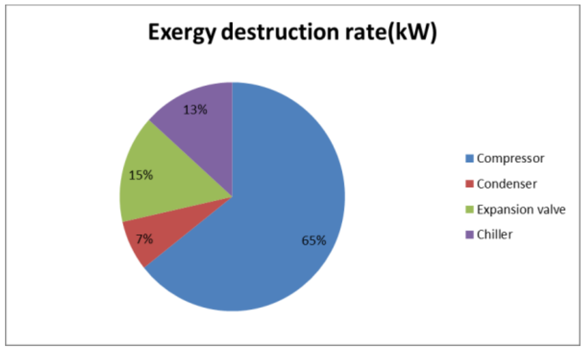

Fig. 5 Exergy destruction rate for Refrigeration system

Figure 5 shows exergy destruction rate of various components of refrigeration system. The highest exergy destruction rate occurred in the compressor followed by expansion valve, chiller and condenser. The highest exergy destruction rate in the compressor is due to high rate of heat transfer with the large temperature difference.

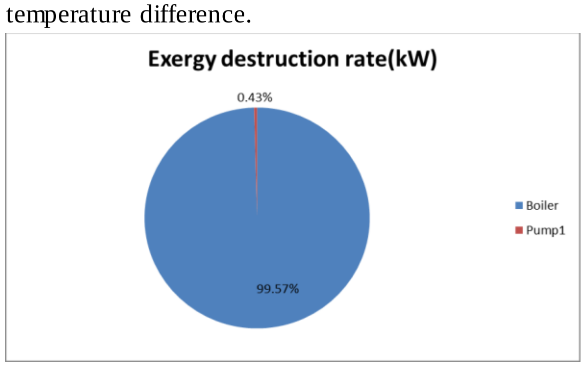

Fig. 6 Exergy destruction rate for Steam generation system

Figure 6 shows exergy destruction rate of various components of steam generation system. The highest exergy destruction rate is observed in the boiler due to intense combustion process, fast water evaporation and intense mixing process prevalent in industrial steam generation system.

Figure 7 shows exergy destruction rate of various components of milk pasteurisation system. As all heat exchanger in the pasteurisation system are of plate type, exergy destruction rate values are not so significant.

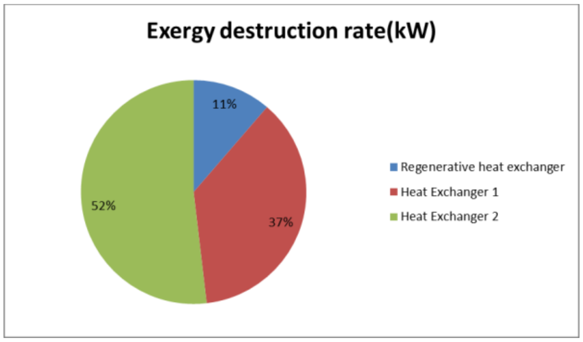

Fig. 7 Exergy destruction rate for milk pasteurisation system

Figure 8 shows exergy destruction rate of various components of milk powder production system. This system includes two important components that are evaporator and drier. The highest exergy destruction rate occurred in the drier followed by evaporator. The highest exergy destruction rate in the drier is due to exergy carried away by exhaust steam.

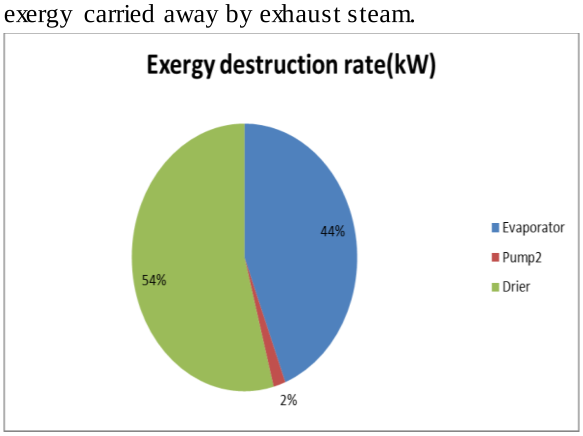

Fig. 8 Exergy destruction rate for milk powder production system

Exergy destruction rate of all the four systems is shown in Figure 9. It can be observed that exergy destruction rate in the boiler is much higher than the other components of the plant. The components like compressor, drier and evaporator are also significantly contributed to exergy destruction rate.

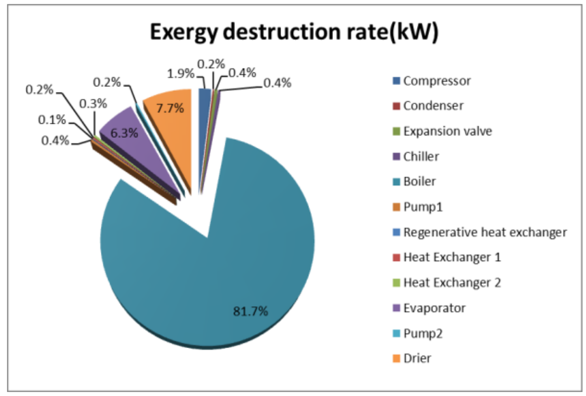

Fig. 9 Exergy destruction rate for entire plant

7. CONCLUSION

In this study, a local dairy plant was investigated using actual operational data. A detailed exergy analysis was performed to evaluate the performances of all components of the steam generation system, refrigeration system, milk pasteurisation system, and milk powder production system, individually. From above study we can conclude that the highest exergy destruction rate is observed in the boiler (81.7%) followed by drier (7.7%), evaporator (6.3%) and compressor (1.9%). Therefore to reduce the irreversibility rate in these unit is the key point to energy saving and to improving the overall system performance. The work performed in this study can be an important step for future developments of dairy processing plants in order to reduce the energy consumption.

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