Sudan University of Science and Technology

College of Graduate Studies

Application of Exergy Analysis on the Dairy Industry (A Case Study of Yogurt Production Plant)

تطبيق تحليل الإكسرجي على صناعة الألبان (دراسة حالة مصنع إنتاج الزبادي)

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of M.Sc. in Mechanical Engineering (Power)

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استهلال

قال تعالى: **(**يُسَبِّحُ لِلَّهِ مَا فِي السَّمَاوَاتِ وَمَا فِي الْأَرْضِ لَهُ الْمُلْكُ وَلَهُ الْحَمْدُ وَهُوَ عَلَى كُلِّ شَيْءٍ قَدِيرٌ**)**

صدق الله العظيم

سُورَةُ التغابن، الآية (1)

Dedication

To:

My Dear Mother

My Dear Father

My Brothers

To All My Friends

ACKNOWLEDGMENT

This thesis could not be possible without the help of several people who shared their time and offered guidance to me.

Above all, I thank God, the merciful and gracious, for all the blessing he brings into my life.

I acknowledge and express my gratitude to my Supervisor Dr. Abdallah Mokhtar who was abundantly helpful and offered invaluable assistance.

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My deep and heartily thanks to my family, my beloved parents and caring sisters, I am grateful for all your love, guidance, and prayers.

Utmost thanks go to staff of CABO factory for good dealing, also I’d like to thank my friends ElzubeirBadawi, SafaFaduldeen, SafiaTajAdeen, Selma ali, AbdAlaziz for their great help, support and encouragement.

Abstract

The dairy industry ranks fifth among the most energy-intensive industries after oil, chemical, pulp and paper mill, and iron and steel making industries. The majority of energy demand in the dairy processing sector is still provided by fossil-based fuels such as coal, oil, and natural gas for heat and electricity generation. Hence, the dairy industry has a nontrivial contribution to the pollutant emissions like COx, SOx, NOx, CxHy, soot, ash, and organic compounds as a result of fossil fuel combustion which imposes reducing the energy demand and increasing the process efficiency.

Exergy analysis and its extensions are famous tools used regarded extensively for analyzing and optimizing the various energy-intensive operations from the sustainability and efficiency viewpoint.

This study has evaluated the exergetic efficiency and exergy destruction rate for each component in a yoghurt drink production plant. The major exergy destruction rate was found in the boiler & air compressor combination of the steam generation system, accounting for over 65.45% of the exergy destruction. Therefore, how to reduce the irreversibility rate in this unit is the key point to energy saving and to improving the overall system performance. For future progression, it is strongly suggested to carry out exergoeconomic and exergoenvironmental analyses, which are combinations of exergy with economics and environment, to obtain useful insights on the real costs and environmental impacts of dairy products processing

The result of this research will extend existing knowledge about the exergy of the dairy Industry by investigating the exergy yogurt drink production plan and reducing yogurt production cost by optimizing energy utilization. Being the first study in Sudan it's hoped to promote for similar studies to be carried out.

المستخلص

صناعة الألبان تحتل المرتبة الخامسة من حيث استهلاك الطاقة وذلك بعد صناعة النفط، الكيماويات، الورق، الحديد والصلب. يتم توفير الجزء الأكبر من الطاقة المستهلكة في صناعة الألبان عن طريق استخدام الوقود الأحفوري كالفحم والنفط والغاز الطبيعي والذي يستخدم لأغراض التسخين وتوليد الطاقة الكهربائية. وعليه فإن صناعة الألبان تسهم مساهمة مقدرة في انبعاث الغازات الملوثة للغلاف الجوي مثل أكاسيد الكربون، أكاسيد الكبريت، أكاسيد النيتروجين، الهيدروكربونات، السناج، الرماد والمواد العضوية التي تنتج عن احتراق الوقود الأحفوري، الشيء الذي يؤكد على ضرورة تقليل استهلاك الطاقة وزيادة كفاءة العمليات.

تحليل الطاقةومشتقاتها هي من أشهر الوسائل المستخدمة بصورة كبيرة لتحليل وترشيد العمليات المستنفذة للطاقة من حيث الكفاءة والاستدامة.

قامت هذه الدراسة بتقييم كفاءة الإكسيرجي (exergeticefficiency) ومعدل تفكك الإكسيرجي (exergy destruction) لكل مكون من مكونات محطة إنتاج شراب الزبادي. وجد أن أعلى معدل تفكيك كان في الغلاية والضاغط الهوائي في نظام إنتاج البخار حيث بلغ المعدل 65.45% من معدل تفكيك الإكسيرجي. وعليه فإن تقليل المعدل اللارجوعية (Their reversibility rate) لهذه الوحدة هو المفتاح نحو حفظ الطاقة وتحسين أداء المنظوم.

ينصح بأن يتم في المستقبل إجراء دراسات (exergoeconomic and exergo-environmental analyses,) و هي مزيج بين الدراسات الاقتصادية والبيئية للإكسيرجي للوصول الى رؤى مفيدة حول التكلفة الحقيقة والاثر البيئي لصناعة منتجات الألبان.

نتائج هذه الدراسة سوف توسع المعرفة بالاكسيرجي لصناعة منتجات الألبان وذلك بدراسة مصنع إنتاج شراب الزبادي وتقليل تكلفة إنتاج الزبادي عن طريق الاستخدام الأمثل للطاقة.

يرجى أن تكون هذه الدراسة كونها الأولى في السودان، حافزاً لمزيد من الدراسات المستقبلية في هذا المجال.

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ABBREVIATIONS

a	Carbon number of hydrocarbon fuel (-)
b	Hydrogen number of hydrocarbon fuel (-)
C_p	Specific heat capacity (KJ/kg K)
$cos\emptyset$	Power factor
ex	Specific exergy (KJ/kg)
$\dot{En}$	Energy rate (kW or kJ/s)
$\dot{Ex}$	Exergy rate (kW or kJ/s)
h	Specific enthalpy (kJ/kg)
I	Current intensity (kJ/kg)
M	Molar mass (kg/mol)
$\dot{m}$	Mass flow rate (kg/s)
n	Specific mole number (mol/kg)
P	Pressure (kPa)
q_{LHV}	Lower heating value (kJ/kg)
$\dot{Q}$	Heat transfer (KJ/s)
R	Universal gas constant (8.314 J/mol K)
$\bar{R}$	Air (0.287 kJ/kg K) or vapour (0.4615 kJ/kg K) constant
s	Specific entropy (kJ/kg K)
S	Entropy (kJ/K)
T	Temperature (K)
v	Specific volume (m^3/kg)
V	Voltage (Volt)
w	Humidity ratio (kg water/kg dry air)
$\dot{W}$	Work rate (kW)
x	Mole fraction (-)
X	Mass fraction (-)

Greek letters

φ	Fuel quality factor (-)
ε	Standard chemical exergy
ψ	Exergy efficiency
ϕ	Relative humidity
ρ	Density (kg/m^3
μ	Efficiency

0	Reference state
a	Air
ash	Ash
$carb$	Carbohydrate
ch	Chemical

$cold$	Cold
$dest$	Destruction
$elec$	Electrical
fat	Fat
hot	Hot
in	Inlet
i, k	Numerator
OM	Organic matter
out	Outlet
$mech$	Mechanical
ph	Physical
pro	Protein
QL	Heat loss
v	Vapour
vs	Saturated vapour
w	Water

CHAPTER ONE
INTRODUCTION

1.1 Background

The world is gradually marching towards a severe energy crisis, what with an ever-increasing demand of energy overstepping its supply. We have always known that the energy we use every day is not unlimited, yet we take it for granted. Oil, gas, power, even water has limited availability. Yet, we have not taken enough precautions to deal with a possible energy crisis. Oil and gas have already become too expensive, and with each passing day, they are moving towards being extinct. Prices have been rapidly increasing for the last five years, thanks to the ever-increasing demand and the increasing shortage of energy resources[1].

All the human activities are driven by one form of energy or the other. Most of these energy forms are made up of carbon and other compounds that generate gases that are referred to as greenhouse gases which prevent the heat from the earth surface from escaping into the atmosphere resulting in greenhouse effect. On the other hand, most of the energy forms emit gases that are inimical to the ozone layer and as a result, react and eat up the ozone layer, hence ozone layer depletion results. These two phenomena (greenhouse effect and ozone layer depletion) result in the uncontrollable rise in the global temperature (otherwise known as global warming) which alters the general climate conditions of the earth's surface. This alteration, when continued over a long period of time, results in climate change [2].

Improving energy efficiency and reducing energy demand are widely considered as the most promising, fastest, cheapest and safest means to mitigate climate change. Many opportunities appear to be cost-effective at current energy prices and can deliver additional benefits such as improved energy security, reduced fuel poverty and increased economic productivity. Energy efficiency is the ratio of useful outputto energy input for a specified system [3]. This measure provides a more accurate description of how energy is being used. It can also be expressed as energy efficiency is the ratio of exergy output to exergy input. Exergy is a thermodynamic concept, used for many years within engineering analyses of chemical and mechanical processes and systems [4]. This is what we will highlight in this research.

1.2 Problem Statement

The dairy industry ranks fifth among the most energy-intensive industries after oil, chemical, pulp andpaper mill, and iron and steel making industries. The majority of energy demand in the dairy processing sector is still provided by fossil-based fuels such as coal, oil, and natural gas for heat and electricity generation. Hence, the dairy industry has a nontrivial contribution to the pollutant emissions like COx, SOx, NOx, CxHy, soot, ash, and organic compounds as a result of fossil fuel combustion. On the other hand, the declining reserves and fluctuating prices of fossil fuels have introduced serious challenges to the future energy supply. This is why energy-intensive manufacturing sectors like dairy industry are seeking the most cost-effective and environmental-benign strategies to reduce the production costs and environmental impacts by diminishing the present over-dependence on fossil fuels. In the field of the food industry, exergy analysis and its extensions have been extensively used during the past decades to analyse and optimize various energy-intensive operations from the sustainability and efficiency viewpoints [13].

1.3 Research Objectives

1. To evaluate the exergetic efficiency and exergy destruction rate for each component of the three lines individually**.**

2. To find the amount of exergy consumed in producing a given amount of the pasteurized milk**.**

1.4 Significance of Research:

1. The result of this research will extend existing knowledge about the exergy of the dairy Industry by investigating the exergy yogurt drink production plan.
2. Reducing milk production cost by optimizing energy utilization.
3. Being the first study in Sudan it's hoped to promote for similar studies to be carried out**.**

CHAPTER TWO

LITREATURE REVIEW

2.1 Introduction

Energy is an essential component of all development programmers. Without energy, modern life would cease to exist. We need energy to maintain physical comfort in much of the world, to win and manufacture useful materials and artefacts, for transport, for communications, for agriculture and for industry in general. Energy can be made available by harnessing natural energy flows such as moving water, solar radiation and wind, and mainly by using fuels such as wood, coal, oil, natural gas and uranium. However, the harnessing and utilization of energy is associated with worrying problems, namely, depletion and environmental damage [2].

2.2 Energy in Industry

Industry uses many energy sources including:

1. Natural gas.
2. Petroleum, such as distillate and residual fuel oils and hydrocarbon gas liquids.
3. Electricity.
4. Renewable sources, mainly biomass such as pulping liquids (called black liquor) and other residues from paper making and residues from agriculture, forestry, and lumber milling operations.
5. Coal and coal coke.

Most industries purchase electricity from electric utilities or independent power producers. Some industrial facilities generate electricity for use at their plants using fuels that they purchase or the residues from their industrial processes. A few produce electricity with solar photovoltaic systems located on their properties. Some of them sell some of the electricity that they generate.

Industry uses fossil fuels and renewable energy sources for:

1. Heat in industrial processes and space heating in buildings.
2. Boiler fuel to generate steam or hot water for process heating and generating electricity.
3. Feed stocks (raw materials) to make products such as plastics and chemicals.

Electricity is used for operating industrial motors and machinery, lights, computers, and office equipment and for facility heating, cooling, and ventilation equipment [9].Every industry uses energy, but there are some industries account for most of the industrial sector energy consumption and the dairy industry is the fifth largest manufacturing sector in terms of energy consumption [5].

2.3 Food Industry

The food and kindred products industry sector is a grouping of all food related manufacturing industries. This sector is large, growing, and competitive. The food industry had the second highest value of shipments when compared to all other industry sectors [10]. The food industry is crucial to foreign trade because it is one of the few industries in which exports exceed imports [11].The food industry is also a majorconsumer of energy in the form of electricity and other fuels. The food industry was the fifth largest energyconsumer in the manufacturing sector. Figure [1] shows the top six energy consuming industry sectors in1991. The food industry produces a wide variety of products that include meat products, dairy products, preserved fruits and vegetables, grain mill products, bakery products, sugar and confectionery products, fatsand oils, beverages, miscellaneous food and kindred products. The food industry is dependent on energy for processing, which adds to the value of food products. In addition to adding value, processing insures a fresh, safe, aesthetic product.

Preservation techniques typically rely on heating and cooling and ensure quality products [12].

2.4 Energy in Dairy Factory

Dairy processing is one of the most energy-intensive sectors of the food industry [5], the dairy industry is the fifth largest manufacturing sector in terms of energy consumption after oil, chemical, pulp and paper mill, and iron and steel making industries. Interestingly, the majority of energy consumed in this sector is still met by fossil-based energy sources, leading to a remarkable amount of greenhouse gas emissions (i.e. CO2, SOx, NOx, and PMs). On the other hand, fluctuating prices and depleting resources of fossil fuels have introduced serious challenges in the global energy market [6-7]. Like other energy-intensive industries, the dairy industry is looking for ways to reduce its energy consumption for discounting the production costs and preventing the detrimental environmental impacts [5]. These in turn have spurred the search for constantly replenished renewable energy resources and/or more efficient utilization of available fossil fuel energy resources. This is why powerful engineering tools such as energy and exergy analyses have been extensively applied during the past few decades for analyzing and optimizing the energetic performance of various energy-intensive industries.

2.5 Exergy and Exergy Analysis

Exergy is a useful quantity that stems from the Second Low of Thermodynamic, and helps in analyzing energy and other systems and processes. Exergy has the characteristic that it is conserved only when all processes occurring in a system and the environment are reversible. Exergy is destroyed whenever an irreversible process occurs. When an exergy analysis is performed on a plant such as a power station, a chemical processing plant or a refrigeration facility, the thermodynamic imperfections can be quantified as exergy destructions, which represent losses in energy quality or usefulness (e.g., wasted shaft work or wasted potential for the production of shaft work). Like energy, exergy can be transferred or transported across the boundary of a system. For each type of energy transfer or transport there is a corresponding exergy transfer or transport. Exergy analysis takes into account the different thermodynamic values of different energy forms and quantities, e.g., work and heat. The exergy transfer associated with shaft work is equal to the shaft work. The exergy transfer associated with heat transfer, however, depends on the temperature at which it occurs in relation to the temperature of the environment [2].

2.6 Exergy in the dairy factory

Exergy efficiency and exergy destruction rate of each subcomponent of four main subsystems of the plant, including steam generation, above-zero refrigeration, milk reception, pasteurization, and standardization, and yogurt drink production lines will be derived independently. This analysis will be performed to quantify thermodynamic inefficiencies of all subcomponents of the plant in order to identify the breakthrough points for further energy savings [13].

2.7 Previous Studies

Mohamad Mojarab Soufiyan, Mortaza Aghbashlo (2016) indicated that the highest exergy destruction rate occurred in the boiler & compressor combination of the steam generator, followed by ice-water tank &agitator combination in the above zero refrigeration system. The specific exergy destruction of the pasteurized yogurt drink was determinedas442 kJ/kg according to the mass allocation method. The steam generator had the highest contribution to the specific exergy destruction of the pasteurized yogurt drink, followed by yogurt drink production, above-zero refrigeration, and milk reception, pasteurization, and standardization lines, respectively [13].

Majid Jafar yani Jokandan, Mortaza Aghbashlo, Seyed Saeid Mohtasebi (2015) their analysis was conducted to find the amount of exergy consumed inproducing a given amount of the pasteurized yogurt. The main contributors to the exergy destruction of the entire plant were in descending order of importance: boiler & air compressor combination of the steam generator (12484.88 kW), ice-water tank & agitator combination of the above-zero refrigeration system (2900.59 kW), and pressure reducer #2 of the steam generator (731.82 kW). Moreover, the specific exergy consumption of the pasteurized yogurt was found to be (841.34kJ/kg) based on the mass allocation concept. More specifically, the percentile contributions of the steam generation, above-zero refrigeration, milk standardization and pasteurization, and yogurt production lines to the specific exergy consumption were determined as 82.62%, 9.36%, 2.80%, and 5.21%, respectively[14].

Esra Sorgüven, Mustafa Özilgen (2012) their study investigated the impact of food production processes on the environment in terms of energy and exergy utilization and carbon dioxide emission. There are three different energy utilization mechanisms in food production: Utilization of solar energy by plants to produce agricultural goods; feed consumption by herbivores to produce meat and milk; fossil fuel consumption by industrial processes to perform mixing, cooling, heating, etc. Production of strawberry-flavored yogurt, which involves these three mechanisms, is investigated here thermodynamically. Analysis starts with the cultivation of the ingredients and ends with the transfer of the final product to the market. The results show that 53% of the total exergy loss occurs during the milk production and 80% of the total work input is consumed during the plain yogurt making. The cumulative degree of perfection is 3.6% for the strawberry-flavored yogurt. This value can rise up to 4.6%, if renewable energy resources like hydropower and algal biodiesel are employed instead of fossil fuels. This paper points the direction for the development of new technology in food processing to decrease waste of energy and carbon dioxide accumulation in the atmosphere [15].

Fabian Bühler, Tuong-Van Nguyen, Jonas Kjær Jensen and Brian Elmegaard, Energy, exergy and advanced exergy methods are used in this study to analyze a milk processing facility which is one of the largest energy consumers within the food industry in Denmark. While a conventional energy analysis maps the energy flows of the system and suggests opportunities for process integration, an exergy analysis pinpoints the locations, causes and magnitudes of thermodynamic losses. The advanced exergy analysis further identifies the real potential for thermodynamic improvements of the system by splitting exergy destruction into its avoidable and unavoidable parts, which are related to technological limitations, and into its endogenous and exogenous parts, which illustrate the interactions between the different sub-systems. This analysis is based on actual factory data from one of Europe's largest dairy producers: the complete production line is modeled, and includes the production of milk, cream and milk powder. The results show the optimization potential based on 1st and 2nd law analyses. An evaluation and comparison of the applicability of exergy methods, including advanced exergy methods, to the dairy industry is made. The comparison includes typical energy mappings conducted onsite, and discusses the benefits and challenges of applying advanced thermodynamic methods to industrial processes [16].

2.7.1 System Description:

2.7.1.1 Overall Description of the Yoghurt Drink Production Plant

Figure 1 represents an overall schematic of the yogurt drink production plant of the dairy company with the daily intake of the freshly harvested milk. Overall, the plant consisted of four main subsystems, including steam generation, above-zero refrigeration, milk reception, pasteurization, and standardization, and yogurt drink production lines.

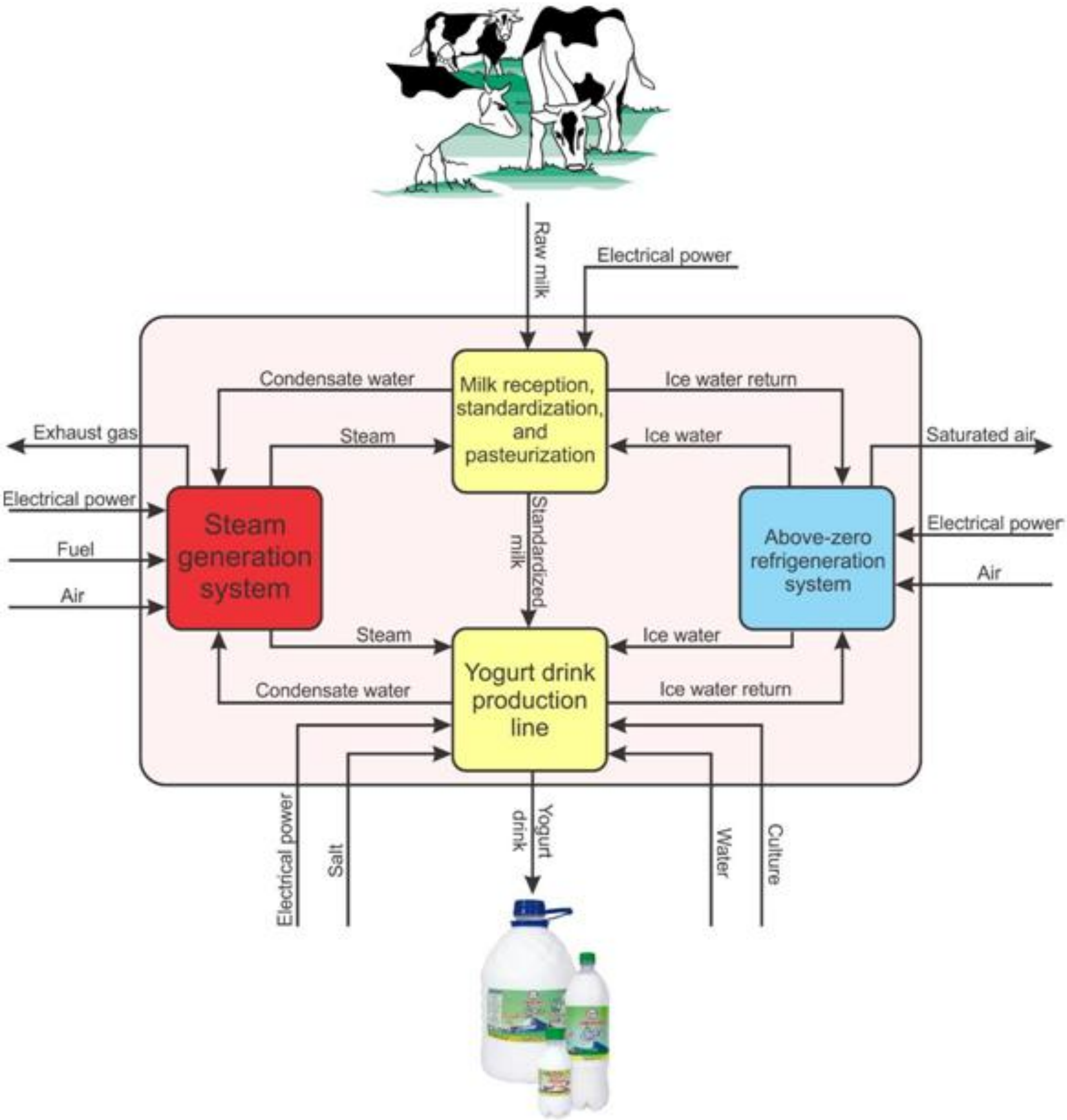


Figure [2.1]: Overall description of the yoghurt drinks production plant

2.7.1.2 The Central Steam Generator of the Dairy Company:

The steam generator was composed of a condensate tank, two different pumps, a tubular heat exchanger, a fire-tube boiler & an air compressor combination, three different pressure reducing valves, and three different steam trapping devices [13].

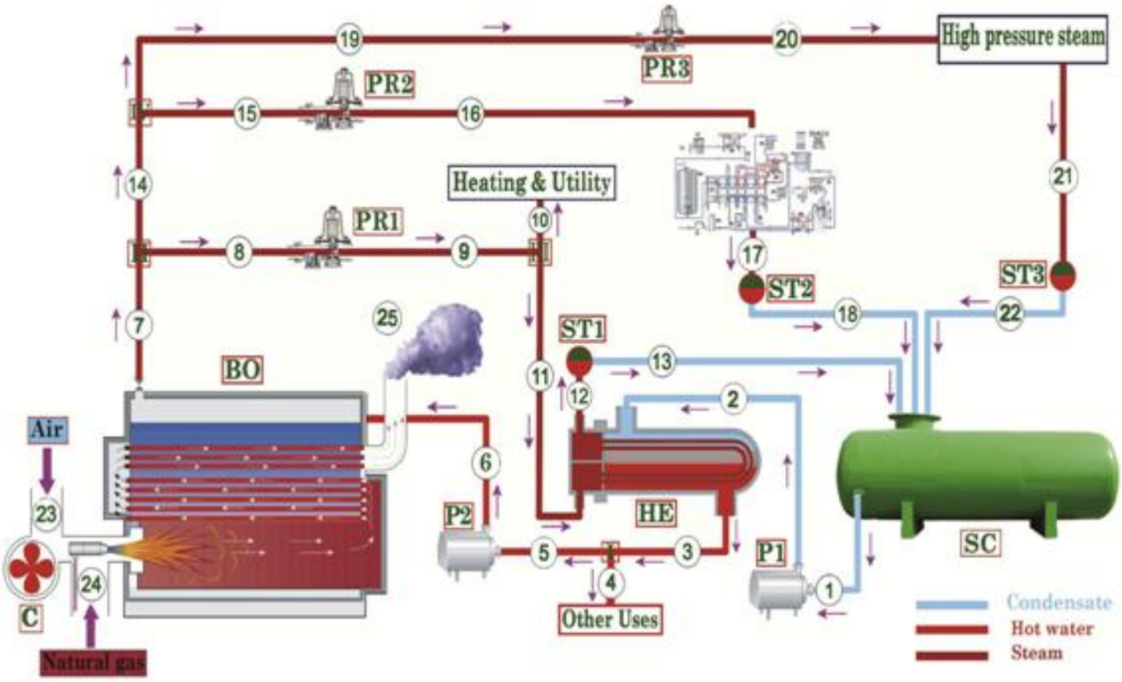


Figure [2.2]: Schematic view of the central steam generator

2.7.1.3The Central above-Zero Refrigeration System

Figure 2.3the above-zero refrigeration system contained an ice-water tank & an agitator combination, an ammonia separator, a refrigerant compressor, a condenser, an expansion valve, and three different pumps [13].

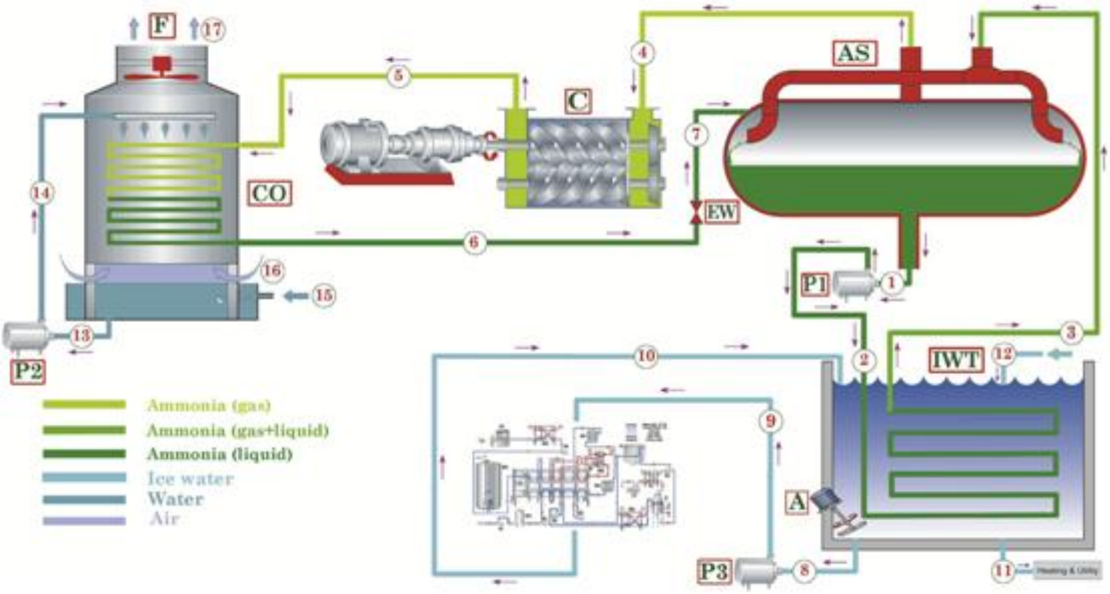


Figure [2.3]: Schematic representation of the central above-zero refrigeration

2.7.1.4 The milk reception, pasteurization, and standardization line

Figure [2.4] the milk reception, pasteurization, and standardization line comprised of pre-cooling heat exchanger, a buffer tank with agitator, a balance tank, a central heat exchanger, a deaerator & a vacuum pump combination, a flow controller, a fat separator, an automatic fat standardization device along with a mixing device, a mixing device, a homogenizer, a bactofuge, a holding tube, and a plate heat exchanger.

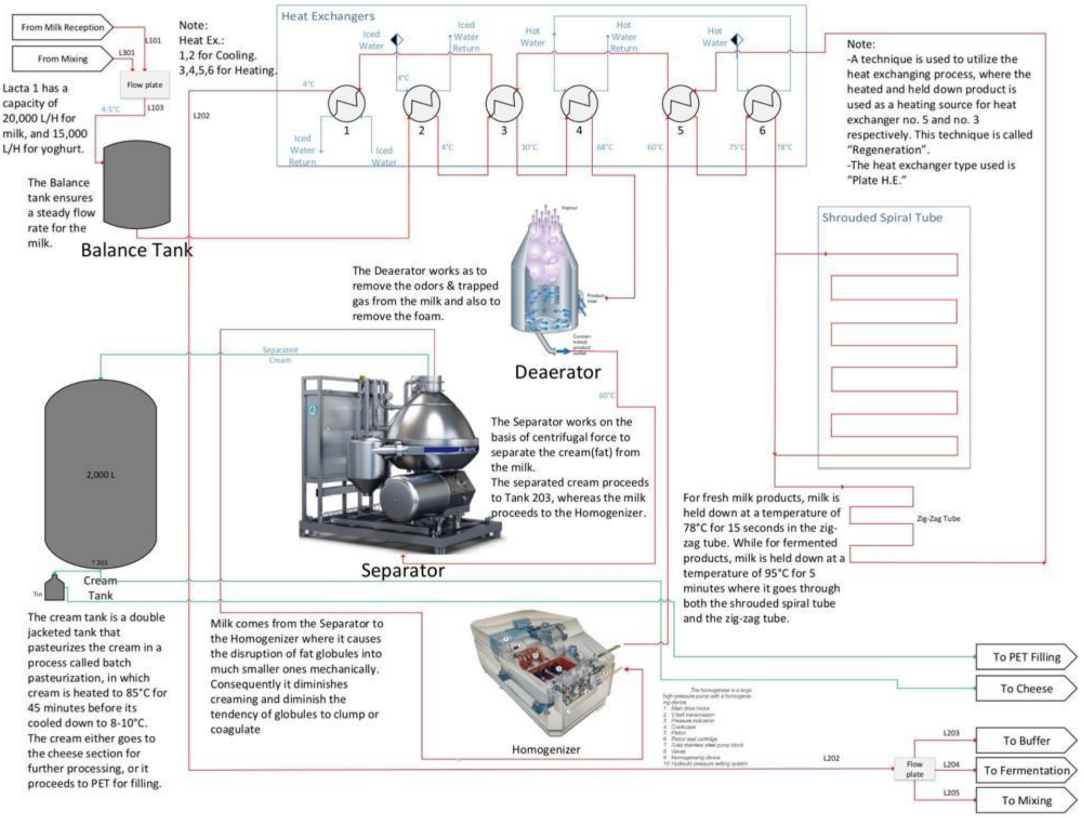


Figure [2.4]: Schematic representation of the milk reception, pasteurization, and standardization line

CHAPTER THREE
THE METHODOLOGY

3.1 Assumptions Made

The following assumptions were adopted in this study for analyzing the overall plant and its main subcomponents:

1. The plant and its subcomponents were operated in a steady-state condition.
2. The kinetic and potential exergies of various streams were neglected owing to their trivial contributions to the total exergy.
3. The fat formation exergy of milk and its derivatives was ignored according to our pervious finding [13].
4. The combustion of the natural gas in the steam generator was assumed to be a complete chemical reaction.
5. The ideal gas principles were applied to inlet air and outlet combustion gas.
6. The ambient temperature and pressure were taken into account to be 25 °C and 1 bar, respectively.
7. The change in the ambient temperature was neglected.
8. The exergy of sludge was overlooked because of its lower mass flow (<0.1% of the main flow) compared to the main flow.
9. The standard molar percentages of different species in the reference state were considered according to [13].

3.2 Theoretical Considerations

The mass balance equation for a general steady-state and steadyflow system can be expressed in the rate form as below:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (1)$$

In addition, the general energy balance can be expressed as follows

$$\sum \dot{E}n_{in} = \sum \dot{E}n_{out} \quad (2)$$

$$\dot{Q} + \sum \dot{m}_{in} h_{in} = \dot{W} + \sum \dot{m}_{out}\ h_{out} \quad \text{......} \quad (3)$$

The general exergy balance can be written as

$$\sum \dot{\mathrm{Ex}}_{\mathrm{in}} - \sum \dot{\mathrm{Ex}}_{\mathrm{out}} = \sum \dot{\mathrm{Ex}}_{\mathrm{des}} \quad \text{......} \quad (4)$$

Or

$$\sum \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_k - \dot{W} + \sum \dot{m}_{in}\ ex_{in} - \sum \dot{m}_{out}\ ex_{out} = \dot{Ex}_{des} \quad \text{......} \quad (5)$$

Where

$$\dot{Ex} = \dot{m}ex \quad \text{......} \quad (6)$$

The specific physical exergy of cold- and hot-water as well as steam and ammonia at different points of the plant will be computed using the following basic equation are summarized in table 3.1 and table 3.2 respectively.

$$ex^{ph} = h - h_0 - T_0(s - s_0) \quad \text{......} \quad (7)$$

Table [3. 1]: Fluid type, temperature, pressure, mass flow rate, and exergy rate for the streams of steam generation system

State No.	Fluid Type	Temp. °C	Pressure bar	Mass flow Rate (Kg/s)	Enthalpy (Kg/Kg)	Entropy (Kg/KJ)	Exergy Rate
1	Steam	179	10	2.222	2778	6.586	1822.127
2	steam	150	3	1.166	2762	7.078	766.898
3	Steam (lacta2)	133.500	3	1.166	2725	6.993	753.283
4	Condensate (pumping flow)	64	1.012	2.250	267.957	0.8811	22.442
5	Condensate (pumping flow)	64.300	5	2.250	270.457	0.8839	26.190
6	feed water tank	95	1.0125	2.600	398.030	1.2501	78.222
7	steam extracted	159	5	0.300	2765.050	6.8601	217.597
8	feed water pump	95	16	2.222	399.170	1.249	70.111
9	fuel	25	4	0.673	-	-	29789.916
10	Air	25	1.012	16.500	-	-	0
11	Exhaust	240	1.300	17.170	-	-	**17940.16**

Table [3. 2]:Fluid type, temperature, pressure, mass flow rate, and exergy rate for the streams of aboverefrigeration system.

State.no	Fluid type	Temp. °C	Gauge pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg)	Total exergy rate (kW)
1	Ammonia (liquid)	-9.271	3	45.712	157.343	0.841	15003.920
2	Ammonia (gas +liquid)	-2	2.91	45.712	1469.698	5.976	5044.414
3	Ammonia (gas)	75	11.4	9.3	1615.12	5.679	3201.805
4	Ammonia (liquid)	35	14	9.3	366.081	1.566	2984.510
5	Ammonia (liquid)	-2	3	9.3	1468.75	5.507	2317.245
6	Ice water in	9	2	189	37.788	0.136	79146.030
7	Ice water out	2	4	83.4	13.91	0.05	35070.710

The specific exergy of milk and its derivatives at different processing points as well as the natural gas entering the boiler will beconsidered as the summation of their physical and chemical exergies.

$$ex = ex^{ph} + ex^{ch} \quad (8)$$

The physical exergy rates of milk and its derivatives will bedetermined as follows:

$$ex^{ph} = C_p\left(T - T_0 - T_0 \ln\left(\frac{T}{T_0}\right)\right) + v(P - P_0) \quad (9)$$

Table [3.3]: Fluid type, temperature, pressure, mass flow rate, and exergy rate for the streams of the milk standardization and pasteurization line.

State.no	Fluid type	Cp	v	Temp. ℃	Temp. K	Gauge press-ure (bar)	Mass flow rate (kg/s)	Total exergy rate (kW)
1	Whole milk (3.6%fat)	3.884	0.0009	12	285	3	5.71	1.136242376
1.1	Cold water in	4.18	1	2	275	3	7.8	5.902780433
1.2	Cold water out	4.18	1	7.5	280.5	2.7	7.8	3.925835768
2	Whole milk (3.6%fat)	3.883	0.00097	3.8	276.8	5.5	5.71	3.079234283
3-Room2	Whole milk (3.6%fat)	3.8831	0.00097	3.7	276.7	5.2	5.71	3.10883851
4- Room3	Whole milk (3.6%fat)	3.9068	0.00099	63	336	2.7	5.71	8.732329194
5-Room4	Whole milk (3.6%fat)	3.909	0.000992 824	67	340	2	5.71	10.58680871
5.1-Room4	Hot water in	4.18	1	74.8	347.8	2.2	1.4	16.86012447
5.2-Room4	Hot water out	4.18	1	56.2	329.2	1.2	1.4	6.575155971
6-Deaerator	Whole milk (3.6%fat)	3.902	0.00098	56	329	3.5	5.71	5.889189576
7-Separator	Skim milk (0.05%fat)	3.972	0.00098	59	332	4.5	5.5	7.167471295
8-Homogenizer	Semi fat milk (12%fat)	4.361272 863	0.001238	60.2	333.2	3.5	5.5	8.413673962
9-Room5	Skim milk (0.05%fat)	3.981	0.00099	73.1	346.1	3	5.5	13.97125645
10-Room6	Skim milk (0.05%fat)	3.985	0.00099	78	351	5.8	5.5	16.81970618
10.1-Room6	Hot water in	4.18	1	80	353	2.7	6.9	20.61026009
10.2-Room6	Hot water out	4.18	1	75.1	348.1	2.2	6.9	17.04014251
11-Shrouded spiral tube	Skim milk (0.05%fat)	3.986	0.00099	79.1	352.1	5.5	5.5	17.49151173
13-Room5 (regeneration)	Skim milk (0.05%fat)	3.977	1	67.7	340.7	5.2	5.5	15.30637609
14-Room3 (regeneration)	Skim milk (0.05%fat)	3.953	0.00097	8.9	281.9	4.2	5.5	1.786863171
15- Room1	Skim milk (0.05%fat)	3.952	0.00097	4	277	3.4	5.5	3.071608017
15.1-Room1	Ice water in	4.18	1	2	275	3	6.94	5.902780433
15.2-Room1	Ice water out	4.18	1	9	282	2.6	6.94	3.452406687

In addition, the specific heat capacities and specific volumes of milk constituents can be presented as a function of the processing temperature. The equations describing the specific heat capacities and densities of milk constituents based on temperature are summarized in Table.

Table [3.4]: Specific heat capacities and densities of the milk components as function of temperature (°C).

Component	Specific Heat Capacity Equation	Density equation
Protein	$C_p = 2.0082 + \frac{1.2089}{10^3}T - \frac{1.3129}{10^6}T^2$	$\rho = 1.3299 * 10^3 - \frac{5.184}{10}T$
Fat	$C_p = 1.9842 + \frac{1.4733}{10^3}T - \frac{4.8008}{10^6}T^2$	$\rho = 9.2559 * 10^2 - \frac{4.1757}{10}T$
Carbohydrate	$C_p = 1.5488 + \frac{1.9625}{10^3}T - \frac{5.9399}{10^6}T^2$	$\rho = 1.5991 * 10^3 - \frac{3.1046}{10}T$
Ash	$C_p = 1.0926 + \frac{1.8896}{10^3}T - \frac{3.6817}{10^6}T^2$	$\rho = 2.4238 * 10^3 - \frac{2.8063}{10}T$
Water	$C_p = 4.1762 - \frac{9.0864}{10^5}T + \frac{5.4731}{10^6}T^2$	$\rho = 9.9718 * 10^2 - \frac{3.1439}{10^3}T - \frac{3.7574}{10^3}T^2$

Accordingly, the following equations were used to compute Unknown specific heat capacities and specific volumes of milk and its derivatives, respectively, at different points of the plant.

$$C_p = \sum_i Y_i C_{p,i} \quad \text{……} (10)$$

$$v = \sum_i \frac{X_i}{\rho_i} \quad \text{……} (11)$$

The compositions of milk and its derivatives used in the calculation of specific heat capacity and specific volume are given in Table [3.5].

Table [3.5]: Compositions of milk and its derivatives used in the calculation of their specific heat capacity and specific volume

Component	Fraction 3.6% Fat whole milk	Fraction in 0.05% Fat cream	Fraction in 40% Fat cream	Fraction in 12% Fat cream	Fraction in 3% Standardized milk
Water	0.8780	0.9103	0.5465	0.8015	0.8835
Fat	0.0360	0.0005	0.4000	0.1200	0.0300
Carbohydrate	0.0458	0.0475	0.0285	0.0418	0.0461
Protein	0.0324	0.0336	0.0202	0.0296	0.0326
Ash	0.0078	0.0081	0.0048	0.0071	0.0078

Table [3.6]: Standard chemical exergies of the inlet and exhaust gas components and mathematical equations describing their specific heat capacities based on temperature (K).

Component	Formula	Standard Chemical Exergy
Nitrogen (N_2)	$C_p = 1.11 - \frac{0.48T}{10^3} + \frac{0.96T^2}{10^6} - \frac{0.42T^3}{10^9}$	0.72
Oxygen (0_2)	$C_p = 0.88 - \frac{0.0001T}{10^3} + \frac{0.54T^2}{10^6} - \frac{0.33T^3}{10^9}$	3.97
Water Vapor (H_2O)	$C_p = 1.79 - \frac{0.107T}{10^3} + \frac{0.586T^2}{10^6} - \frac{0.20T^3}{10^9}$	9.5
Carbon Dioxide (CO_2)	$C_p = 0.45 - \frac{1.67T}{10^3} + \frac{0.127T^2}{10^6} - \frac{0.39T^3}{10^9}$	19.87
Argon (Ar)	0.52	11.69
Neon (Ne)	1.03	27.19
Helium (He)	5.193	30.37
Krypton (Kr)	0.247	34.36

The following equation will beapplied to determine the specific chemical exergy of hot flue gas from the boiler as well as milk and its derivatives are calculated in table 3.7 and table 3.8 respectively.

$$ex^{ch} = n(\sum_i x_i \varepsilon_i + RT_0 \sum_i x_i \ln(x_i)) \quad (12)$$

Table [3.7]: Chemicals Exergies of Exhaust Gases

item	mi	Ei	Xi	XiEi	LnXi	LNXi*Xi
CO2	7.21	19.48	0.1206	2.3497	-2.1151	-4.970
H2O	6.6	9.50	0.1104	1.0489	-2.2035	-2.311
N2	43.32	0.72	0.7247	0.5218	-0.3220	-0.168
SO2	0.0094	313.40	0.0002	0.0493	-8.7576	-0.432
O2	2.635	3.97	0.0441	0.1750	-3.1217	-0.546
Total	59.7744			4.1447		-8.427

Table [3.8]: Compositions and specific chemical exergies of the milk and its derivatives in the yogurt production plant.

No	Essential nutrients of Milk	Component Standard chemical	Exergy (kJ/mol)	g/kg of 3.6% fat whole milk	g/kg of 0.05% fat skim milk	g/kg of 3% fat standardized milk	g/kg of 40% fat cream	g/kg of 12% fat cream	g/kg of 3.75% fat concentrated milk
		Water	9.50E-01	878	910.33	883.46	546.47	801.49	854.33
		Lactose	5988.1	45.82	47.5	46.11	28.51	41.83	57.63
	Fat	Butyric	2319.96	1.58	2.20E-02	1.32	17.63	5.29	1.65
		Caproic	3625.67	8.65E-01	1.20E-02	7.20E-01	9.62	2.89	9.02E-01
		Caprylic	4931.29	5.05E-01	7.01E-03	4.21E-01	5.61	1.68	5.26E-01
		Capric	6236.89	9.64E-01	1.35E-02	8.30E-01	10.85	3.25	1.01
		Lauric	7542.6	1.19	1.65E-02	9.50E-01	13.22	3.97	1.24
		Myristic	8848.22	3.93	5.46E-02	3.28	43.7	13.11	4.1
		Pentadecylic	9501.16	3.30E-01	4.50E-03	2.70E-01	3.61	1.08	3.38E-01
		Palmitic	10153.84	11.04	1.53E-01	9.2	122.65	36.79	11.5
		Magaric	10806.64	1.46E-01	2.00E-03	1.10E-01	1.6	4.81E-01	1.60E-01
		Stearic	11459.47	4.4	6.11E-02	3.67	48.9	14.67	4.58
		Arachidic	12765.11	7.20E-02	1.00E-03	6.13E-02	8.01E-01	2.41E-01	7.50E-02
		Caproleic	6019.62	1.10E-01	1.50E-03	9.21E-02	1.2	3.61E-01	1.13E-01
		Myristoleic	8630.98	2.90E-01	4.00E-03	2.53E-01	3.21	9.62E-01	3.01E-01

		Palmitoleic	9936.66	3.60E-01	5.01E-03	3.01E-01	4.01	1.2	3.76E-01
		Heptadecenoic	10589.49	3.60E-02	5.01E-04	3.22E-02	4.01E-01	1.21E-01	3.80E-02
		Oleic	11242.32	8.23	1.15E-01	6.85	91.39	27.41	8.57
		Linoleic	11024.81	5.78E-01	8.01E-03	4.81E-01	6.41	1.92	6.01E-01
		Linolenic	10807.32	2.53E-01	3.50E-03	2.10E-01	2.8	8.42E-01	2.63E-01
		Trans Palmitoleic	9936.66	1.44E-01	2.00E-03	1.20E-01	1.6	4.81E-01	1.50E-01
		Vaccenic acid	11242.32	7.60E-01	1.05E-02	6.50E-01	8.42	2.53	7.89E-01
		Linoelaidic acid	11024.81	7.20E-02	1.00E-03	6.00E-02	8.01E-01	2.41E-01	7.52E-02
		Conjugated linoleic acid	11024.81	1.45E-01	2.00E-03	1.20E-01	1.6	4.80E-01	1.50E-01
		α_{s1}-casein	583656.1	10	10.36	10.06	6.22	9.13	12.58
		α_{s2}-casein	614493.3	2.6	2.69	2.62	1.62	2.37	3.27
		β-casein	617581.4	10.2	10.57	10.26	6.35	9.31	12.83
		κ-Casein	483240.3	3.3	3.42	3.32	2.05	3.01	4.15
		β-Lactoglobulin	473442.3	3.2	3.31	3.22	1.99	2.92	4.02
		α-Lactalbumin	358455.6	1.2	1.24	1.21	7.51E-01	1.1	1.51
		Serum albumin	1690882	4.90E-01	4.60E-01	3.72E-01	2.50E-01	3.65E-01	5.03E-01
		Immunoglobulin G1	4113457	5.20E-01	5.35E-01	5.03E-01	3.11E-01	4.56E-01	6.29E-01
		Immunoglobulin G2	3832413	5.00E-02	5.18E-02	5.12E-02	3.10E-02	4.60E-02	6.32E-02
		Immunoglobulin A	10245317	1.00E-02	1.03E-02	1.01E-01	6.20E-03	9.10E-03	1.30E-02
		Immunoglobuln M	25549420	9.00E-02	9.00E-02	9.10E-02	5.60E-02	8.00E-02	1.13E-01
		Lactoferrin (LF)	1905587	5.00E-02	5.08E-02	5.01E-02	3.10E-02	4.60E-02	6.20E-02

		Proteose-peptone	562086.9	7.00E-01	8.29E-01	8.00E-01	4.90E-01	7.31E-01	1.01
		Calcium chloride	19.7	2.45	2.54	2.47	1.52	2.24	3.09
		Potassium chloride	14.6	2.72	2.82	2.74	1.69	2.49	3.42
		Magnesium chloride	40.4	9.50E-01	9.83E-01	9.01E-01	5.91E-01	8.67E-01	1.19
		Sodium chloride	5.1	1.65	1.71	1.66	1.03	1.51	2.08
		Total specific chemical exergy (kJ/kg)	–	3048.77	1743.93	2828.17	16439.98	6137.89	3522.33

Table [3.9]: Fluid type, temperature, pressure, mass flow rate, and exergy rate for the streams of the milk standardization and pasteurization line.

Fluid type	Mass flow rate (kg/s)	Physical exergy(kW)	Chemical exergy rate (kW)	Total exergy rate (kW)
Whole milk (3.6%fat)	5.71	40.51662567	17408.4767	17409.6129
Cold water in	7.8	46.04168738	-	-
Cold water out	7.8	30.62151899	-	-
Whole milk (3.6%fat)	5.71	19.21732503	17408.4767	17411.5559
Whole milk (3.6%fat)	5.71	19.40111392	17408.4767	17411.5855
Whole milk (3.6%fat)	5.71	56.22595718	17408.4767	17417.209
Whole milk (3.6%fat)	5.71	68.31088613	17408.4767	17419.0635
Hot water in	1.4	23.60417426	-	-
Hot water out	1.4	9.205218359	-	-
Whole milk (3.6%fat)	5.71	37.78938474	17408.4767	17414.3659
Skim milk (0.05%fat)	5.5	44.5041023	9591.615	9598.78247
Semi fat milk (12%fat)	5.5	50.45688611	33758.39	33766.8087
Skim milk (0.05%fat)	5.5	87.41226555	9591.615	9605.58626
Skim milk (0.05%fat)	5.5	105.5187057	9591.615	9608.43471
Hot water in	6.9	142.2107946	-	-
Hot water out	6.9	117.5769833	-	-
Skim milk (0.05%fat)	5.5	102.7838537	9591.615	9609.10651
Skim milk (0.05%fat)	5.5	69.38326901	9591.615	9606.92138
Skim milk (0.05%fat)	5.5	10.78855081	9591.615	9593.40186
Skim milk (0.05%fat)	5.5	18.49103613	9591.615	9594.68661
Ice water in	6.94	40.96529621	-	-
Ice water out	6.94	23.95970241	-	-

The specific physical exergy of the inlet fuel as well as inlet and outlet air entering and leaving the boiler, respectively, will be determined as follows:

$$ex^{ph} = C_p\left(T - T_0 - T_0\ln\left(\frac{T}{T_0}\right)\right) + \bar{R}T_0\ln\left(\frac{P}{P_0}\right) \quad (13)$$

The specific chemical exergy of the fuel will be obtained as follows:

$$ex^{ch} = \varphi q_{LHV} \quad (14)$$

The quality factor of the gaseous hydrocarbon fuels (C_aH_b) can be measured using the following empirical formula [13]:

$$\varphi \cong 1.033 + 0.0169\frac{b}{a} - \frac{0.0698}{a} \quad (15)$$

The specific heat capacities of the fuel as well as inlet and exhaust air entering and leaving the boiler, respectively, will be computed using the following formula:

$$C_p = \sum_i X_i C_{p,i} \quad (16)$$

Fuel compositions and mathematical equations describing the specific heat capacities ofnatural gas components will be obtained from [13]. In order to compute the specific chemical exergy of the outlet combustion gas, the molar percentages of its species will be recomputed based on the complete chemical reaction of the fuel. The general combustion equation for a 25 air/fuel mass ratio can be found in [13]. Thereafter, the chemical exergy rate of the outlet combustion gas will be computed using the standard chemical exergiesof the exhaust gas components can be found elsewhere [13].

3.3 Exergy Destruction Rate and Exergetic Efficiency of Each Subcomponent of the Plant

The exergy destruction rate and exergetic efficiency of various pumping, homogenizing, and ammonia compressing systems of the plant will be computed as follows:

$$\dot{Ex}_{in}^{ph} + \dot{W} - \dot{Ex}_{out}^{ph} = \dot{Ex}_{dest} \quad (17)$$

$$\psi = \frac{\dot{Ex}_{out}^{ph} - \dot{Ex}_{in}^{ph}}{\dot{W}} \quad (18)$$

The following equations will be used to determine exergy destruction rate and exergeticefficiency of various steam trapping devices, pressure reducing units, holding tubes, balance tanks, expansive valves, Bactofuges, and flow controllers:

$$\dot{Ex}_{in}^{ph} - \dot{Ex}_{out}^{ph} = \dot{Ex}_{dest} \quad (19)$$

$$\psi = \frac{\dot{Ex}_{out}^{ph}}{\dot{Ex}_{in}^{ph}} \quad (20)$$

The following relations will be applied to compute exergy destruction rate and exergeticefficiency of both buffer tank & agitator combinations of the plant:

$$\dot{Ex}_{in}^{ph} + \dot{W} - \dot{Ex}_{out}^{ph} = \dot{Ex}_{dest} \quad (21)$$

$$\psi = \frac{\dot{Ex}_{out}^{ph}}{\dot{Ex}_{in}^{ph} + \dot{W}} \quad (22)$$

The exergy destruction rate and exergetic efficiency of plate cooler (II) in the steamgeneration system, plate heat exchanger (XXI) in the milk reception, pasteurization, and standardization line, and plate heat exchangers (XVI and XX) in the yogurt production line will be measured as follows:

$$\left(\dot{Ex}_{hot,in}^{ph} - \dot{Ex}_{hot,out}^{ph}\right) - \left(\dot{Ex}_{cold,out}^{ph} - \dot{Ex}_{cold,in}^{ph}\right) = \dot{Ex}_{dest} \quad (23)$$

$$\psi = \frac{\dot{Ex}_{cold,out}^{ph} - \dot{Ex}_{cold,in}^{ph}}{\dot{Ex}_{hot,in}^{ph} - \dot{Ex}_{hot,out}^{ph}} \quad (24)$$

CHAPTER FOUR

RESULTS & DISSCUTION

4.1 Results and Discussion

The fluid type, temperature, pressure, mass flow rate, exergy rate for the streams of the steam generation, above-refrigeration Tables 1-2, respectively, according to their state numbers as specified in Figures 2–3. Table 3 summarizes exergy destruction rate, and exergetic efficiency of the most important subcomponents of the plant wasting exergy by applying the actual operational data.

4.1.1 Steam generation system

According to Table 3.1, the largest exergy destruction rate of the plant (10417.042kW) occurred in the boiler & fan combination, as expected. The exergy destruction of this combination corresponded to 91.54 of the total input exergy and exergy destruction of the steam generation system, respectively. The next largest exergy destruction rates occurred in the pressure reducer, open heater, feed water pump and condensate pump accounting for 9.27%,1.45%,0.07% and 0.03% of the total exergy destruction of the steam generation system as shows in figure 4.1.

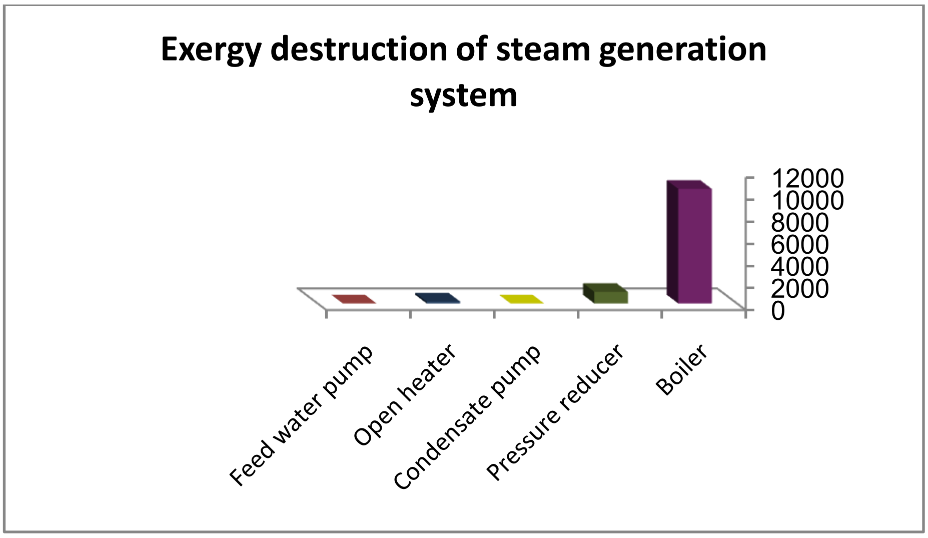


Figure 4.1Exergy destruction of steam generation system

The highest exergy rate in the boiler & compressor combination could be related to:

1. The high rate of heat transfer with the large temperature difference.
2. Intense combustion process.
3. Fast water evaporation.
4. And intensive mixing process prevalent in industrial steam generation systems.

The exergy destruction rate of industrial boilers can be reduced by:

1. Oxygen enrichment and air preheating.
2. Reducing the air–fuel ratio.

   These remedies can reduce the irreversibility rate by two mechanisms, i.e., maintaining the flame temperature at higher values and keeping the temperature gradient in the combustor at lower values. However, such strategies suffer from their shortcomings like higher energy loss from the outflow combustion gas and larger heat transfer to the ambient.

3. The exergetic performance of the boiler & compressor combination can be slightly enhanced by its thermal insulation.

4. Installing turbulators can be another way to augment the exergetic efficiency of fire tube boilers.

The high exergy destruction rate occurred in the pressure reducer was mostly caused bythe large temperature decrease and the high pressure.It should be mentioned that a portion of this irreversibility can be recovered by using a simple mixing valve.

In general, the exergy destruction rates of all the other components were found to be zero because there were no temperature and pressure changes as given in table 4.1.

Table [4.1]: Exergy destruction and exergeticefficiency of steam generation system.

Component	Exergy Destruction	Efficiency %
Boiler	10417.042	65.450
Pressure Reducer	1055.229	42.080
Open Heater	165.566	32.080
Feed Water Pump	8.111	89.630
Condensate Pump	3.747	100

4.1.2 The energy above refrigeration system

As can be seen from Table 3.2, the largest exergy destruction rates of the above refrigeration system occurred in the Plate Cooler (54046.15kW), Expansion valve (667.2657 kW), and compressor (0.2979 kW), respectively as represented in figure 4.2.

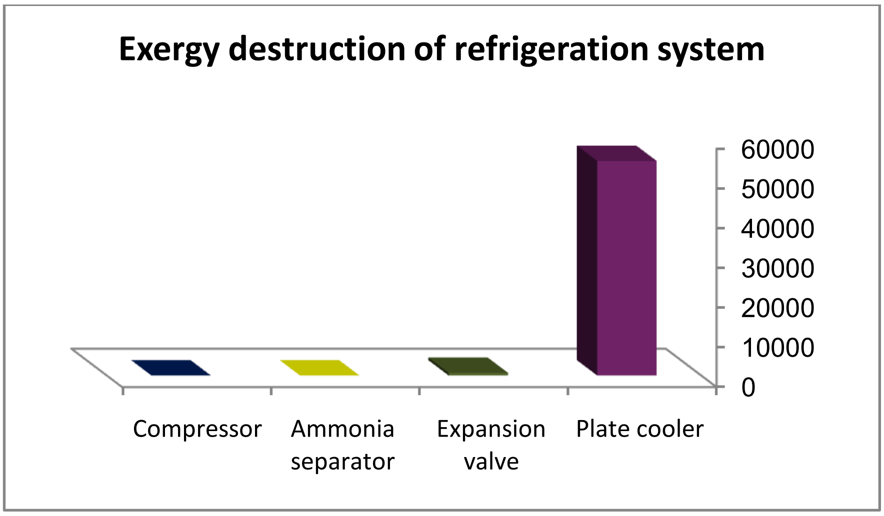


Figure [4.2]:Exergy destruction of refrigeration system

The high exergy destruction rate of the Plate cooler could beattributed to the large and quick heat transfer with the large temperature difference. As well, the high quantity of the applied mechanical work in the refrigerant compressor could also be mentioned as the cause of its high irreversibility rate.

It was observed that the best exergetic performance of the above-zero refrigeration system (90.39%) belonged to the ammonia separator. The higher exergetic efficiency of the ammonia separator could be related to its trivial exergy destruction rate compared to the total inlet exergy rate. In addition, the compressor was ranked third among the subcomponents of the above-zero refrigeration system in terms of exergetic efficiency as summarize 4.2. The exergetic performance of refrigerant compressors can be further boosted by using variable-speed drive (VSD) controllers.

Table [4.2]: Exergy destruction and exergeticefficiency of refrigeration system

Component	Exergy Destruction	Efficiency
plate cooler	54046.15	42.58
Expansion Valve	667.265	77.64
Ammonia Separator	0.724	90.39
Compressor	0.297	95.01

4.1.3 Milk standardization and pasteurization line.

As can be seen in Table [ ], the main contributors to the exergy destruction in the milk standardization and pasteurization system were in descending order of importance: Heat exchanger (58.59 kW), Plate cooler(36.71 kW), Deaerator & vacuum pump combination (30.52 kW), Separator(9.30 kW), Shrouded spiral tube(3.30 kW) as shows in figure [4.3].

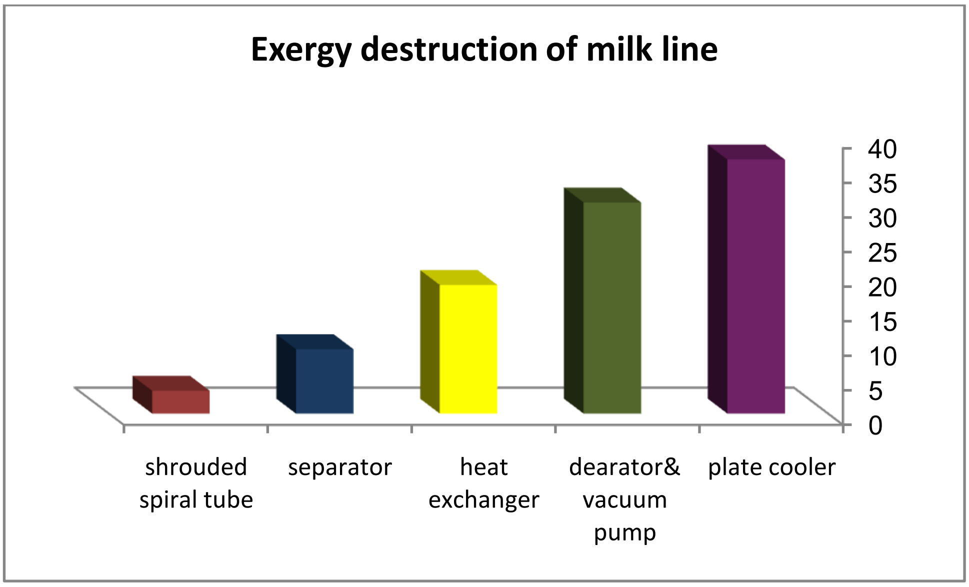


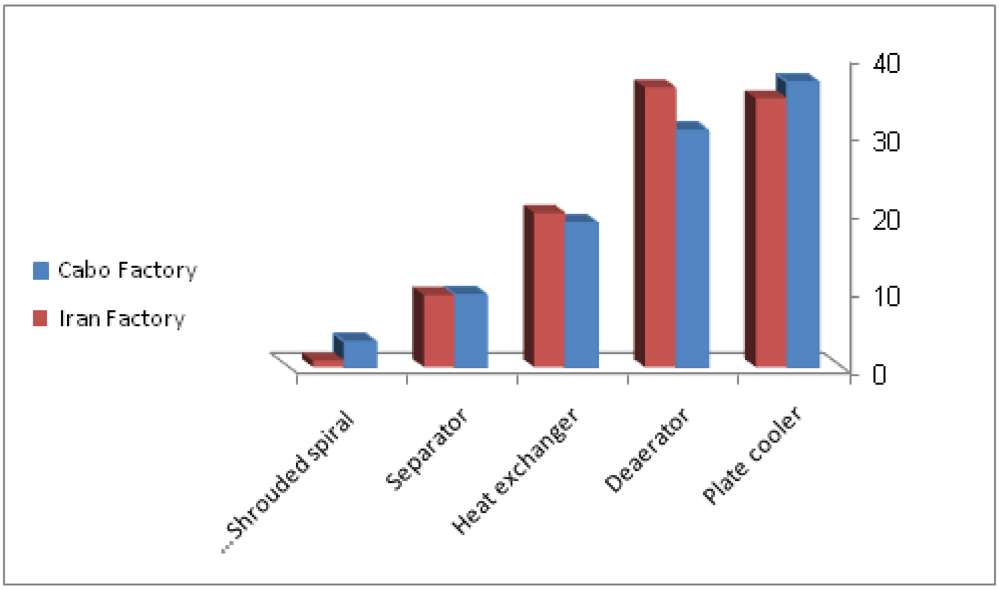
Figure [4.3]: Exergy destruction of refrigeration system of milk standardization and pasteurization line.

Obviously, the plate heat exchanger had the greatest exergy destruction rate, accounting for 37.29%of the total exergy destruction of the line. This could be related to the large temperature difference between the high pressure steam and hot water. Furthermore, the deaerator & vacuum pump combination had the second highest exergy destruction rate, accounting for 31.00% of the total exergy destruction of the line. The high irreversibility rate of the deaerator & vacuum pump combination could be ascribed to the severe heat and mass transfer occurred in this unit. These in turn accelerated water vaporization from the milk stream and its subsequent condensation and, accordingly, sped up the rate of exergy destruction. The Heat exchanger had the third highest exergy destruction rate among the components of the milk standardization and pasteurization line.

Moreover, the exergetic efficiency of the central heat exchanger was 88.56%, showing its desirable capability in the regeneration of “cold” and “warm” exergies. However, the exergetic performance of all the heat exchangers can be further improved using the recently developed novel techniques like self-heat recuperation technology by recovering both sensible and latent heat of a stream [50].

Table [4.3]: Exergy destruction and exergeticefficiency of milk standardization and pasteurization line

components	Exergy destruction	Exergy efficiency
Plate cooler	36.7130	56.73%
Deaerator & vacuum pump combination	30.5215	53.32%
Heat exchanger	18.5957	88.56%,
Separator	9.3031	57.83%
Shrouded spiral tube	3.3010	59.35%



Figures 4.4, 4.5 and 4.6 show comparing in exergy destruction rate between Cabo factory and Iran factory for dairy food system.

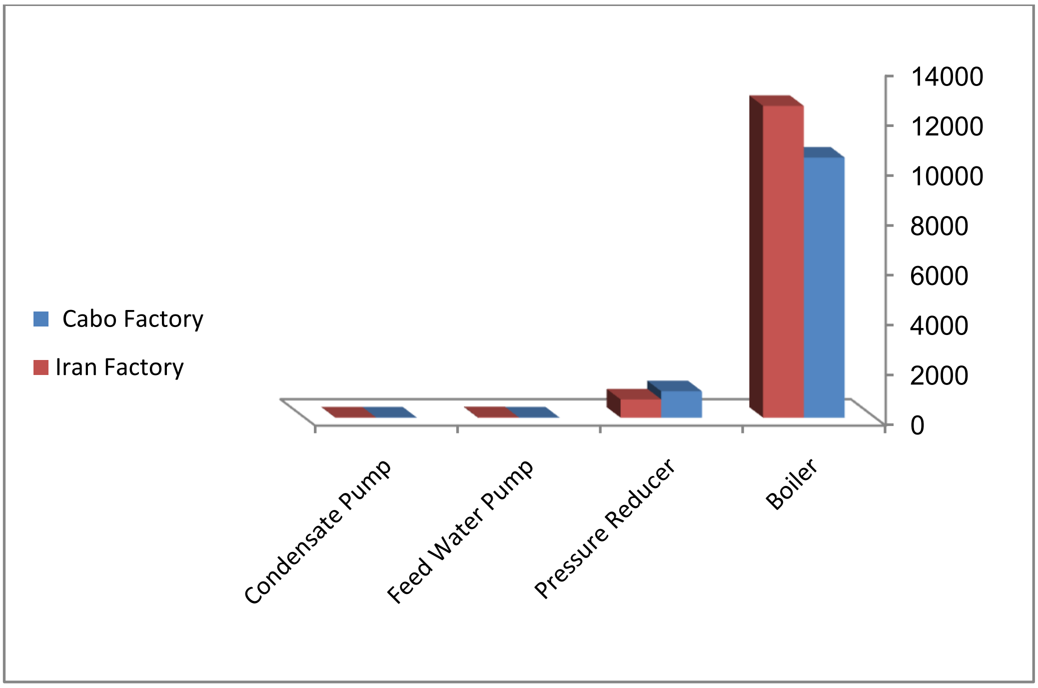


Figure [4.4]: representing comparing in steam generation system.

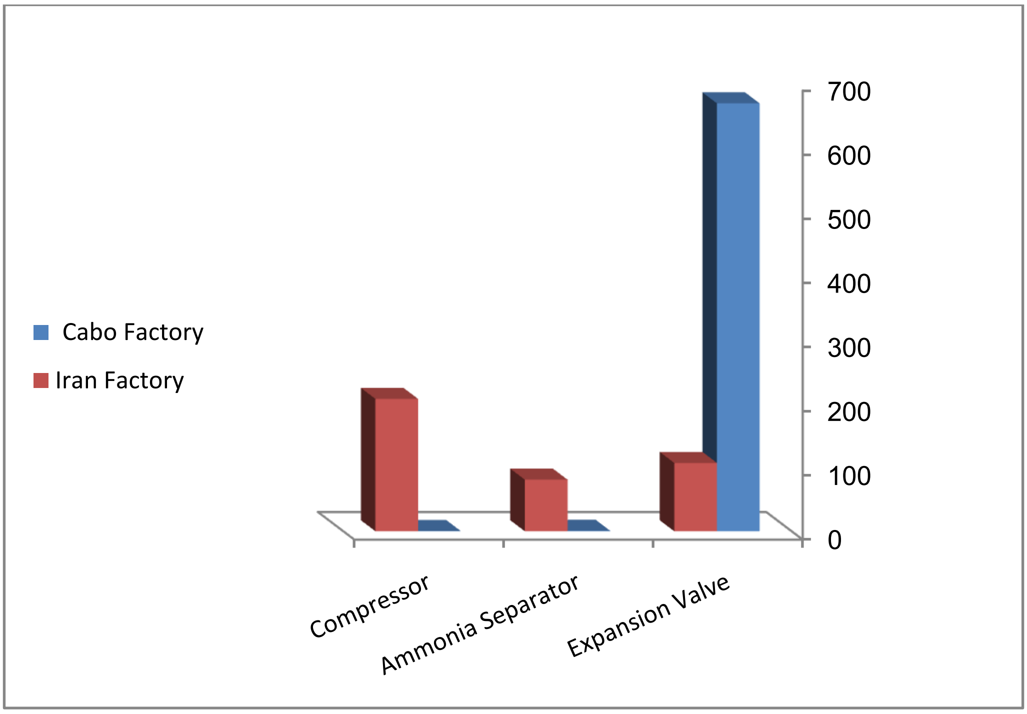


Figure [4.5]: representing comparing in above-zero refrigeration system.

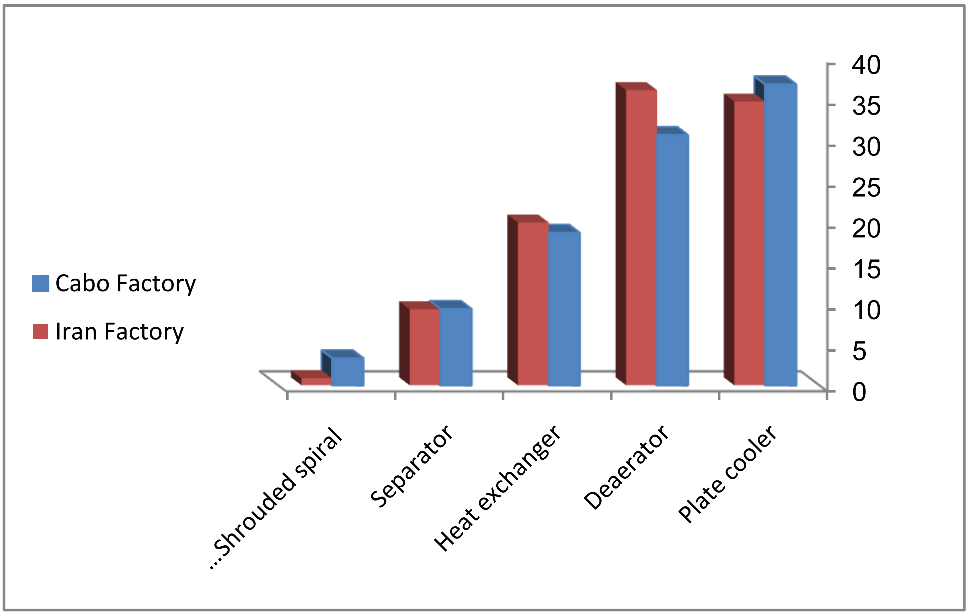


Figure [4.6]: representing comparing in milk standardization and pasteurization system

4.2 Conclusions

In this study, exergy analysis was applied to investigate an industrial yogurt drink production plant using actual operational data. A detailed analysis was conducted to assess the performances of all the subcomponents of the steam generator and theabove-zero refrigeration system. The work presented herein can be an important step for future improvements of dairy processing plants with respect to the sustainability and productivity issues. The exergy destruction rate and exergetic efficiency of each component of the four lines were computed according to the exergy balance equation and exergetic efficiency definition, respectively. The main conclusions could be derived from this investigation are summarized as follows:

- The major exergy destruction rate was found in the boiler & air compressor combination of the steam generator, accounting for over 65.45% of the specific exergy destruction. Therefore, how to reduce the irreversibility rate in this unit is the key point to energy saving and to improving the overall system performance.
- The plate heat exchanger had the greatest exergy destruction rate, accounting for 37.29%of the total exergy destruction in the milk standardization and pasteurizationline. This could be related to the large temperature difference between the high pressure steam and hot water. Furthermore, the deaerator & vacuum pump combination had the second highest exergy destruction.

4.3 Recommendations

- The major exergy destruction rate was found in the boiler & air compressor combination of the steam generator, accounting for over 65.45% of the specific exergy destruction. Therefore, how to reduce the irreversibility rate in this unit is the key point to energy saving and to improving the overall system performance

- Installing turbulators can be another way to augment the exergetic efficiency of fire tube boilers.
- The exergetic performance of refrigerant compressors can be further boosted by using variable-speed drive (VSD) controllers.
- the exergetic performance of all the heat exchangers can be further improved using the recently developed novel techniques like self-heat recuperation technology by recovering both sensible and latent heat of a stream.
- For future progression, it is strongly suggested to carry out exergoeconomic and exergoenvironmental analyses, which are combinations of exergy with economics and environment, to obtain useful insights on the real costs and environmental impacts of dairy products processing.

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