A comprehensive exergy analysis of a propylene refrigeration unit

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Abstract—**This work aims to evaluate the energy performance of a propylene refrigeration unit using the exergetic analysis method. The data for the exergetic calculation are provided by a simulation of the refrigeration unit using Aspen Plus ™ software. The obtained results showed that the total exergy losses generated in the unit of refrigeration is about 431,47kW. Compression and condensation sections contribute about 68% of the exergy losses in the refrigeration cycle. These losses are mainly due to the high temperature gradient that exists between flow of gas to be compressed and condensed and the thermal losses released into the atmosphere through the hot air leaving the tubular bundles of the air-condenser.**

***Keywords*— Exergetic Analysis, Exergy losses, , Propylene refrigeration unit, Aspen Plus, Air -condenser**

I INTRODUCTION

Controlling future energy demand and supply conditions is a major challenge for the entire planet. It is made all the more difficult because it is necessary to find the effective means to reduce the overconsumption of energy. This will satisfy the energy needs of a world population, which will grow further in the coming decades, and a large part of which aspires to economic and social development based on increased demand for energy.

Industries in the world have naturally taken an interest in this position, which plays a very important role in the cost of the finished product. Thus, it gradually emerged that, in industrial units, the function of the objective to be maximized was not only the short-term profile or the increase in the amount of work, but also to make the equipment fully functional with maximum efficiency.

The objective of this work is to evaluate a propylene refrigeration unit from the thermodynamic point of view.

The exergetic analysis is one of the most powerful tools for identifying sources of energy degradation in the various equipment of an installation and to assess their impact on overall plant performance, it is based on the simultaneous establishment of the first and second laws of thermodynamic [1]. Exergy analysis can be used to improve the efficiency of a system. Number of studies has been conducted in performance evaluation of refrigeration cycle [2,3,4,5,6].

(Mehmet Kanoglu, 2002) studied a multistage cascade refrigeration cycle used for natural gas liquefaction by means both first and second law analysis. The exergetic efficiency obtained is determined to be 38.5% indicating a great potential for improvements. (Yumrutaş, R, Kunduz, M., & Kanoğlu, M,2002) found that the evaporating and condensing temperatures have strong effects on the exergy losses in the evaporator and condenser, and on the second law of efficiency and COP of the cycle but little effects on the exergy losses in the compressor and the expansion valve. (Ahamed, J. U., Saidur, R., & Masjuki, H. H, 2011) in his study found that exergy depends on evaporating temperature, condensing temperature, sub-cooling and compressor pressure.

In this work, an exergy analysis of a simple refrigeration cycle is discussed in detail. For each section component, the exergy losses, exergy losses ratio, and the exergetic efficiency are calculated. The evaluation of these variables provides useful information for improving the thermodynamic performance of the refrigeration cycle.

The simulation of the refrigeration unit is done in advance using ASPEN PLUS software. This will allow us to obtain the characteristics of the main flows as well as the energy exchanges between the main equipment and the environment.

II Process Description

This unit is designed primarily to cool the deethanizer head product of the liquefied petroleum gas fractionation unit using propylene as a refrigerant. The functional diagram of the unit is shown in Figure1. It consists mainly of the following equipments: Two twin-stage screw compressors GB-1301-A /

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B, which aspirate the propylene vapours and compress them at 17 bar. The vapours discharged by the compressors are condensed in the air- condenser EC-1306 at the temperature of 46°C .In addition, it is composed of a propylene cooler EA-1309, two expansion valves (LV-3989, LV-3986), an economizer FA-1310 and an evaporator EA-1304.
To achieve its refrigeration mission, propylene circulating in closed circuit, undergoes a series of transformations in the equipments unit.

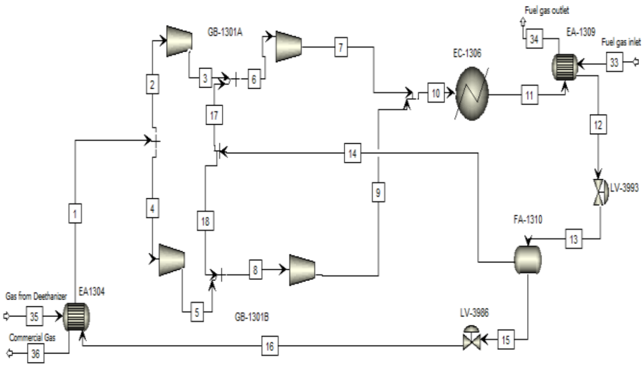

Fig. 1 Aspen plus simulation flowsheet of the refrigeration unit.

III Process Simulation

Before applying the exergetic analysis, the propylene refrigeration unit was modelled in Aspen Plus™ process simulation software developed by Aspen Tech. The simulation provided the properties of the stream (T, P, enthalpy, entropy, etc.) at different locations.

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A. Simulation data

To calculate the exergy balance we have to estimate the enthalpy and the entropy of each stream of the refrigeration unit at its current temperature and pressure, as well as those of reference (T_0=298K and P_0 =1atm) .The thermodynamic properties were calculated using the Peng-Robinson equation of state. The Peng-Robinson model is selected for natural gas systems in the petroleum industry [7]. Operational data required for simulation are clustered in table I and II.

The calculation assumptions adopted in this work are as follows:

- All transformation operations are performed in steady state.
- The pressure losses in the circuits of the installation and the losses thermal in the equipments are considered negligible.
- The reference temperature and pressure are: T_0=298K, P_0 =1atm
- Condensers and reboilers are assumed to be adiabatic.

TABLE I

CHARACTERISTICS OF VARIOUS DEVICES OF THE REFRIGERATION UNIT

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Devices	Characteristics
GB1301A_1,B_1	Discharge pressure3.5 bar, Isentropic efficiency 0.57
GB1301A_2,B_2	Discharge pressure 17bar, Isentropic efficiency 0.95
EC 1306	Propylene outlet temperature 46°C
EA1309	Propylene outlet temperature 11°C
Lv3993	Propylene outlet pressure 5bar
Lv3986	Propylene outlet pressure1.003bar
FA 1310	Adiabatic, loss of charge negligible
EA1304	Propylene outlet temperature -46.8°C

- The indices (1) and (2) respectively denote the 1st and 2nd floor of each compressor.
- The mass flow rate of propylene circulating in the refrigeration circuit is 12490 kg / h.

TABLE II
CHARACTERISTICS OF INLET GASES

Characteristics	Fuel gas	Gas from deethanizer
Pressure(bar)	31	31
Temperature(°C)	18.83	-32.78
Molar fraction (%) N_2 CO_2 CH_4 C_2H_6 C_3H_8	 0,021 0,007 0,822 0,122 0,028	 0,019 0,007 0,779 0,146 0,049
Molar Flow(kmol/h)	1766.33	1915.14

IV Exergy Analysis

Thermodynamics has identified the first two laws of conservation and degradation of energy or matter to first describe relatively simple processes. It focused on the accomplishment of a work by a system receiving a given amount of heat [8, 9]. The purpose of the exergy theory is to develop an integrated analysis method that includes the first two principles of thermodynamics, and thus allow for taking into account the energy quantities involved and their quality,

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which the first principle does not allow to do. Its interest is that it provides a very rigorous framework to quantify the thermodynamic quality of any system, open or closed, dynamic or not.

The first allusions to the concept of exergy go back to the end of 19 century.Indeed, in 1889, Gouy was the first to introduce the notion of "usable energy" that he defines as "The changed sign variation of the usable energy is the greatest value of the work that the system can provide to the operator passing from one state to another, a value that is reached when this transition is reversible ". [10,11]

A. *Exergy balance*

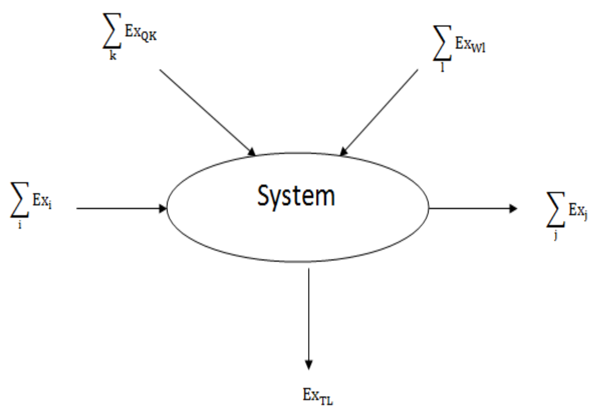

Fig. 2 Inputs - outputs of an open system operating in steady state

The total exergy lost is given by:

$$Ex_L = \sum_i Ex_i - \sum_j Ex_j + \sum_k Ex_{Q_k} + \sum_l Ex_{w_l} \quad (1)$$

- Ex_L : Total exergy lost by the system.
- Ex_i : Exergetic content of the material flow (i) entering the system
- Ex_j : Exergetic content of the material flow (j) leaving the system.
- Ex_{Q_k}: Thermal exergy associated with the amount of heat Q_k at temperature T_k
- Ex_{w_l} : Pure energy corresponding to noble energies (potential, kinetic, electrical, mechanical ...).

B. *Exergy definition of the various terms of the exergy balance*

1) *Thermal Exergy*

The exergetic content of a quantity of heat (Q) at the temperature (T) is then determined by: [12,13]

$$Ex_Q = Q\left(1 - \frac{T_0}{T}\right) \quad (2)$$

The exergy of a quantity of heat at a temperature (T) is the mechanical energy that would produce a Carnot motor (ideal motor) operating between the temperatures (T) and the reference of the environment at (T_0).The quality in terms of potential of a quantity of heat (Q) depends on the temperature (T) at which it is available and its environment. More the heat is at high temperature, more its quality and therefore its exergy are important. In the case of temperatures below (T_0), more the temperature is low, the exergy of this quantity of heat is important.

2) *Exergy associated with matter*

The exergy associated with matter can be broken down into 4 terms. [14]

$$Ex = Ex_{Kin} + Ex_{pot} + Ex_{ph} + Ex_{ch} \quad (3)$$

With
Ex_{kin}: Kinetic exergy
Ex_{pot}: Potential exergy
Ex_{ph}: Physical exergy
Ex_{ch}: Chemical exergy

Note that exergy kinetics and potential exergy are most often negligible in the other terms.

3) *Physical exergy*

The physical exergy is defined as the maximum theoretical useful work obtained as a system interacts with an equilibrium state. The physical exergy of a stream is given by: [15,16]

$$Ex = (H - H_0) - T_0(S - S_0) \quad (4)$$

4) *Chemical exergy:*

Chemical exergy is equal to the maximum amount of work that can be obtained when a substance is brought from the reference-environment state to the dead state by a process including heat transfer and exchange of substances only with the reference environment. For ideal solutions and gas mixtures, the chemical exergy of one mole of the mixture is given by this expression:

$$Ex_{Ch} = \sum x_i \varepsilon_{0i} + RT_0 \sum x_i \ ln(x_i) \quad (5)$$

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With
x_i: Molar fraction of the constituent i.
ε_{0i}: Standard chemical exergy of constituent i.

5) Exergy evaluation

- **Exergy efficiency**

Efficiency can be defined as "the ability to produce the maximum results with the least amount of effort or expense". Efficiency can only be defined if an objective is fixed.
So the technical definition can be used, to know what is "produced" by the system divided by what is "given" to the system; or what comes out on what enters:

$$\eta = \frac{\sum Ex_{out}}{\sum Ex_{in}} \qquad (6)$$

V RESULTS AND DISCUSSION

The simulation of the refrigeration unit by the ASPEN Plus software allowed us to determine the characteristics of the different flows of the unit as well as the thermal loads major equipments. The main results obtained are grouped in the tables III and IV

TABLE III

ELECTRICAL POWERS OF MOTORS EQUIPMENTS

Equipments	Power (KW)
GB-1301A	413,834
GB-1301B	347,047
EC1306	10,21

TABLE IV

EXERGY RELATED TO

THE FLOW OF THE REFRIGERATION UNIT.

Flow	Mass Flow(Kg/h)	Exergy(KW)
1	12490	58,32639
2	7244,23	33,82944
3	7244,23	142,5636
4	5245,77	24,49696
5	5245,77	103,2348
6	7928,46	156,0333
7	7928,46	363,8678
8	7723,17	152,4982
9	7723,17	348,2778
10	15651,63	711,9965
11	15651,63	596,1573
12	15651,63	586,8431
13	15651,63	556,3921
14	12490	81,70051
15	12490	473,2725
16	3161,63	432,4453
17	684,23	17,6814
18	2477,	64,01911
33	32967	3986,225
34	32967	3986,572
35	37850	4496,856
36	37850	4816,962

We remember the equation of exergy balance for an open system without chemical reaction is.

$$Ex_L = \sum Ex_{in} - \sum Ex_{out} \qquad (7)$$

The exergy loss values of each equipment in the refrigeration unit are presented in tables below:

TABLE V
EQUIPMENTS EXERGY LOSSES

Equipments	Ex_{in} (kW)	Ex_{out}(kW)	Ex_L(kW)
GB-1301A	603,66	506,47	97,19
GB-1301B	524,04	451,48	72,56
EC-1306	722,20	596,15	126,05
EA-1309	4582,37	4573,41	8,96
Lv-3993	586,84	556,39	30,45
FA- 1310	556,39	554,97	1,42
Lv-3986	473,27	432,44	40,83
EA-1304	4929,30	4875,29	54,01

TABLE VI
EQUIPMENTS EXERGY EFFICIENCY

Equipments	η_{Ex}(%)	Ex_l (%)
GB-1301A	83,90	22,52
GB-1301B	86,15	16,82
EC-1306	82,55	29,21
EA-1309	99,80	2,08
Lv-3993	94,81	7,06
FA- 1310	99,74	0,33
Lv-3986	91,37	9,46
EA-1304	98,90	12,52

The following figures show the contribution of each device and section to the total exergy losses.

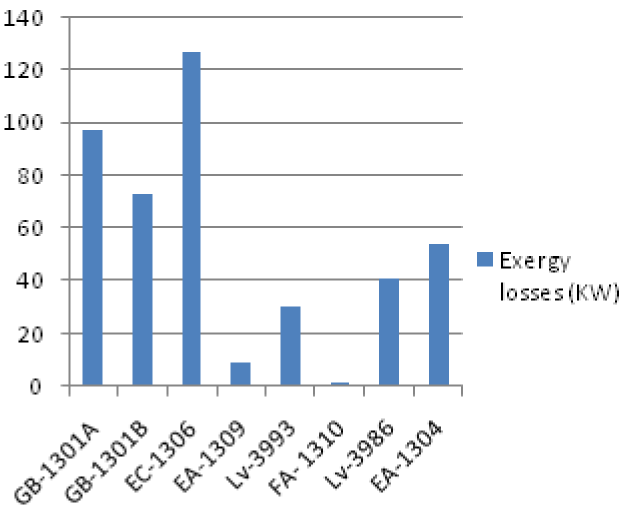
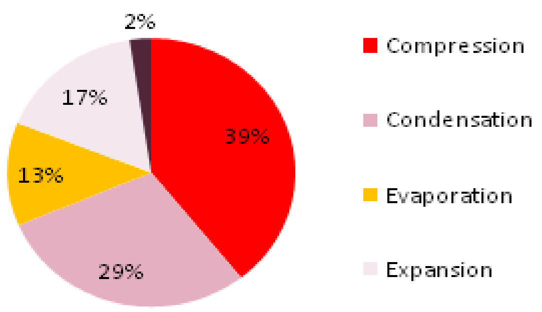


Fig. 3 Total exergy losses in different equipments of refrigeration unit



Fig;4 Exergy losses by section

The results thus obtained show that more than two thirds of the exergy losses of the refrigeration cycle come from the compression and condensation stages. In addition, about 17% and 13% of energy degradation come from the expansion and evaporation section, the remaining 2% is spread over the rest of the equipment.

Note that the difference in the losses of the two compressors is due to the difference between the processed loads. On the other hand, the degradation of energy in these two equipments is mainly due to pressure and temperature differences.

Indeed, we have a compression ratio of about 4.87 in the first two stages and 3.73 in the second two stages.

Note that these compressions are accompanied by a temperature increase that can reach 170°C in each compressor. It should be noted that the loss identified at the level of the aerocondenser represents more than that associated with the evaporator. This is explained by the fact that the quantity of heat extracted from propylene at the aerocondenser is released into the atmosphere, while that exchanged at the evaporator is recovered by propylene.

VII Conclusions

The present work addresses an exergetic analysis of propylene refrigeration unit. The exergetic analysis involves a simulation of the unit using the aspen Plus software.
The main findings of this research can be summarized in these points:

- More than two thirds of the exergy losses of the refrigeration cycle come from the compression and condensation stages.
- The air condenser is the main source of thermodynamic imperfections of the propylene refrigeration unit.

As a result of this work, we propose to conduct studies further to reduce energy consumption in the unit, by applying the thermal pinch method that will detect inefficiencies in energy use and identify cost-effective energy saving projects in unit.

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