Separation Science and Technology

ISSN: 0149-6395 (Print) 1520-5754 (Online) Journal homepage: www.tandfonline.com/journals/lsst20

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To cite this article: Emin Açıkkalp, Hasan Yamık, Necmettin Caner & Erol Açıkkalp (2014) Energy and Exergy Evaluation of an Air Separation Facility: A Case Study, Separation Science and Technology, 49:13, 2105-2113, DOI: 10.1080/01496395.2014.907316

To link to this article: https://doi.org/10.1080/01496395.2014.907316

Separation Science and Technology, 49: 2105–2113, 2014
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ISSN: 0149-6395 print / 1520-5754 online
DOI: 10.1080/01496395.2014.907316

Energy and Exergy Evaluation of an Air Separation Facility: A Case Study

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In this study, an air separation plant working according to the principle of separation of two columns and producing argon, nitrogen, and oxygen with a daily capacity of 250 tons was analyzed in detail with respect to the first and second laws of thermodynamics and the results were evaluated. The energy and exergy values for each point defined in the system were obtained. By using these values, thermodynamic evaluations for both the whole system and also its components were made. The efficiency values of energy and exergy, the values of energy losses and exergy destruction rates, the EIP (energetic improvement potential rate), ExIP (exergetic improvement potential rate), and the production of entropy values were found as 0.453, 0.79, 4368.475 kW, 10535.875 kW, 2391.535 kW, 3800.485 kW, and 35.347 kW/K, respectively. The energy and exergy efficiencies of the plant were found to be 45.3% and 13.1% respectively.

Keywords air separation; energy analysis; exergy analysis; energy efficiency; exergy efficiency

INTRODUCTION

The separation of air into its components is carried out for industrial and medical use. The widest use of nitrogen is as an inert blanking gas and as a reactant in chemical processes. Oxygen is used both for industrial and medical purposes. There are three methods of air separation commercially available: the cryogenic distillation process, the pressure swing adsorption (PSA) process, and the membrane separation process. The cryogenic distillation is used when high purity of the products is needed. The PSA process becomes interesting from a commercial point of view when a nitrogen flow between 10 and 100 m^3/h is needed with a purity of 98 to 99.5 vol%. Membrane separation is used for small flows, less than 10 m^3/h, and low purity, lower than 98.5 vol%. Cryogenic distillation is required when the products are needed in a liquid form (1). The first steps in a cryogenic air separation facility are compressing the feed air and removing water, carbon dioxide, and other hydrocarbon contaminants. The resulting mixture consists of nitrogen, oxygen, argon, and some traces of other noble gases. Then, the cleaned air is cooled to cryogenic conditions in the MHE (main heat exchanger) and subsequently fed to the distillation unit. The distillation unit separates the air into an oxygen stream and a nitrogen stream but sometimes an argon stream is produced as well. The product streams are passed again through the MHE and compressed or pumped to pressures that are required downstream of the air separation facility. There exists a wide variety of process designed for the cryogenic separation of air. The main differences are related to the method used for providing refrigeration, to the method used for pressurizing the products, to the operating pressures, and to the column configuration in the distillation section. The type of process chosen depends usually on the feed and product specifications of the specific application (2).

Although there are a lot of studies in the literature about air separation units, evaluation of their performance using energy and exergy analyses are limited. The papers about exergy analysis at air separation units can be seen at (1-6).

As referred to above, this study is all the more important because air separation units are mostly used as utility plants in most industries. Energy and exergy analyses are the most convenient methods to assess the performance of any system. In this study, energy and exergy analysis of an air separation plant which produces nitrogen, oxygen and argon with a capacity of 250 tons/day at Turkey was made and the results were evaluated. There have not been any studies about energy and exergy assessment of an air separation facility at Turkey as of yet. In addition to that, it is the most comprehensive research in the literature about evaluating performance of an air separation facility.

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SYSTEM DESCRIPTION AND THERMODYNAMIC ANALYSIS

The resolved system is working according to the principle of separation of two columns (high and low pressure distillation columns). The flow chart and the components of the system can be viewed in Fig. 1. Energy and exergy values for each point shown in the system were identified. By using these values, a thermodynamic evaluation for both the entire system and each of its components was made with the parameters defined below.

The assumptions for this study are as follows:

- Environment temperature and pressure are $T_o = 298.15$ K and $P_o = 101{,}13$ kPa.
- All the gases in the system are ideal.
- The system works in the steady-state regime.
- Kinetic and potential energies and exergies may be neglected.

Energy Terms and Energetic Evaluation Parameters

Energy analysis for the control volume can be described as follows (7):

$$\dot{Q} + \dot{W} = \dot{E}_Q + \dot{E}_W = \sum_o \dot{E}_o - \sum_i \dot{E}_i \tag{1}$$

while neglecting magnetic, electrical, nuclear, and surface tension, the energy balance can be expressed as (8, 9):

$$\dot{E} = \dot{E}_{ph} + \dot{E}_{ch} \tag{2}$$

where $\dot{E}_{ph}$ is the physical energy and $\dot{E}_{ch}$ is the chemical energy and the physical energy is (8, 9):

$$\dot{E}_{ph} = \dot{m}\left(h_{(T)} - h_o\right) \tag{3}$$

Energy efficiency (η) is the rate of energy output to energy input. Efficiencies for heat exchangers (7):

$$\eta_{HE} = \frac{\dot{E}_{cold,o} - \dot{E}_{cold,i}}{\dot{E}_{hot,i} - \dot{E}_{hot,o}} \tag{4}$$

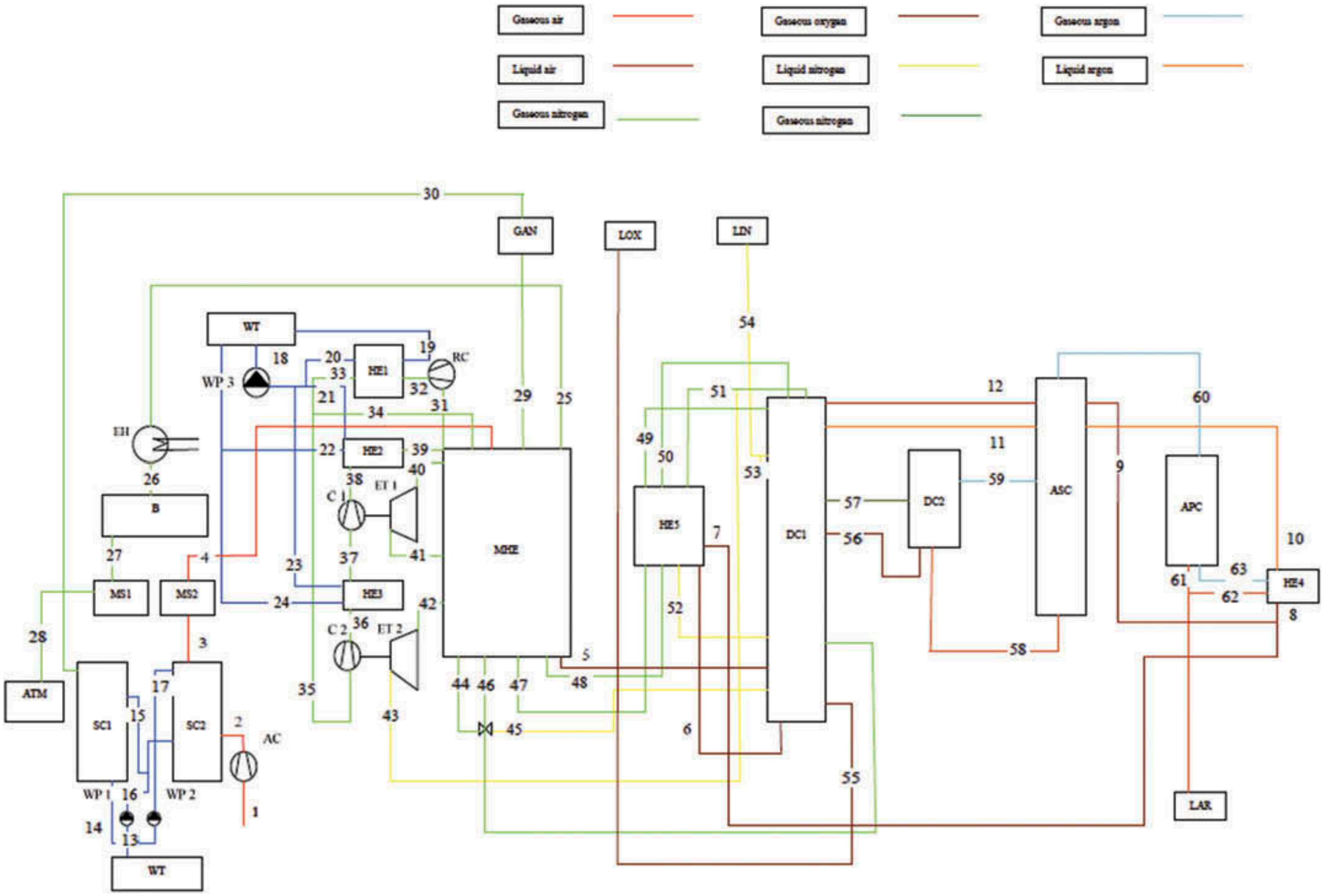

FIG. 1. The Schematic of air separation system.

Efficiency for pump η_{pump} (7):

$$\eta_{pump} = \frac{\dot{E}_o - \dot{E}_i}{\dot{W}_{pump}} \tag{5}$$

Efficiency of any component of the air separation system is (7):

$$\eta_j = \frac{\dot{E}_{o,j}}{\dot{E}_{i,j}} \tag{6}$$

Energetic improvement potential (EIP) is (7):

$$EIP_k = (1 - \eta)\, E_{L,k} \tag{7}$$

where $E_{L,k}$ is the energy loss of the considered component and relative energy loss ratio (β_k) is (7):

$$\beta_k = \frac{\dot{E}_{L,k}}{\dot{E}_{TL}} \tag{8}$$

where the $\dot{E}_{TL}$ total energy loss of the system.

Exergy Terms and Exergetic Evaluation Parameters

Exergy analysis for the control volume can be described as follows (7):

$$\sum\left(1 - \frac{T_o}{T_k}\right)\dot{Q}_K + \dot{E}x_W + \sum_o \dot{E}x_o - \sum_i \dot{E}x_i = \dot{E}x_D \tag{9}$$

where $\dot{Q}_K$ is the heat transfer rate, $\dot{E}x_W$ is the work exergy rate, $\dot{E}x_o$ is the output exergy rate, $\dot{E}x_i$ is the input exergy rate, $\dot{E}x_D$ is the exergy destruction rate, T_o is the environment temperature, and T_k is the heat source temperature. While neglecting magnetic, electrical, nuclear, and surface tension, the exergy balance can be expressed as (8, 9):

$$\dot{E}x = \dot{E}x_{ph} + \dot{E}x_{ch} \tag{10}$$

where $\dot{E}x_{ph}$ is the physical exergy and $\dot{E}x_{ch}$ is the chemical exergy and the physical exergy is (7-9):

$$\dot{E}x = \dot{m}\left[(h - h_o) - T_o\,(s - s_o)\right] \tag{11}$$

where h is enthalpy, s is entropy. The chemical exergy rate of a gas $\dot{E}x_{ch}$ is (3):

$$\dot{E}x_{ch} = -RT_o \sum \frac{P_{og}}{P_o} \tag{12}$$

where R is the ideal gas constant and P is the pressure. Chemical exergy rates are listed in Table 1. Exergy efficiency (ψ) is the rate of energy output to energy input. Exergy efficiencies for heat exchangers ψ_{HE} (7):

TABLE 1
Chemical exergy rates

Substance	Air	Argon	Nitrogen	Oxygen	Water
Exergy Rate (kJ/kg)	952.920	0.293	25.714	124.066	0.654

$$\psi_{HE} = \frac{\dot{E}_{cold,o} - \dot{E}_{cold,i}}{\dot{E}_{hot,i} - \dot{E}_{hot,o}} \tag{13}$$

Exergy efficiency for pump (ψ_{pump}) (7):

$$\psi_{pump} = \frac{\dot{E}x_o - \dot{E}x_i}{\dot{W}_{pump}} \tag{14}$$

Exergy efficiency of any component of the air separation system is (7):

$$\psi_j = \frac{\dot{E}x_{o,j}}{\dot{E}x_{i,j}} \tag{15}$$

The exergetic improvement potential ($ExIP$) can be expressed as follows (7):

$$ExIP_k = (1 - \psi)\, Ex_{D,k} \tag{16}$$

where Ex_D is the exergy destruction rate. Relative exergy loss ratio (α) (7):

$$\alpha_k = \frac{\dot{E}x_{D,k}}{\dot{E}x_{TD}} \tag{17}$$

where $\dot{E}x_{TD}$ is the total exergy destruction rate of the system and the entropy generation (σ) of any component or system is (11):

$$\sigma_k = \frac{\dot{E}x_{D,k}}{T_o} \tag{18}$$

RESULTS AND DISCUSSION

An air separation plant producing argon, nitrogen, and oxygen of daily capacity of 250 tons were analyzed in detail with respect to the first and second laws of thermodynamics. The most important parameters are energy loss, exergy destruction, entropy generation, energy efficiency, and exergy efficiency.

TABLE 2
Air separation system, temperature, pressure, mass flow rate, energy rate and exergy rates

Point	Temperature (K)	Pressure (kPa)	Flow Rate (kg/s)	Energy Rate (kW)	Physical Exergy Rate (kW)	Chemical Exergy Rate (kW)	Total Exergy Rate (kW)
1	298.15	100	9.620	0.000	0.000	9167.100	9167.100
2	373.15	640	9.620	721.13	1505.750	9167.100	10672.850
3	284.15	630	9.620	−148.54	1349.250	9167.100	10516.350
4	287.65	616	7.750	−91.84	1030.120	7385.130	8415.250
5	101.15	600	1.670	−397.01	563.487	1591.380	2154.867
6	101.15	600	1.230	−292.41	415.023	1172.092	1587.115
7	96.65	570	1.230	−479.70	801.031	1172.092	1973.123
8	96.65	570	0.810	−315.90	527.508	771.870	1299.378
9	96.65	570	0.420	−163.80	273.523	400.220	673.743
10	83.85	167	0.810	−283.63	429.677	771.870	1201.547
11	83.75	156	0.810	−265.75	447.566	400.220	847.786
12	81.35	137	0.420	−128.03	339.180	771.870	1111.050
13	294.15	100	18.340	−307.09	2.630	11.990	14.620
14	285.25	100	3.060	−165.460	3.817	2.000	5.817
15	294.55	100	3.060	−47.99	0.390	2.000	2.390
16	294.55	100	15.280	−230.26	1.970	9.990	11.960
17	286.30	100	3.060	−151.79	6.460	2.000	8.460
18	20.60	100	13.800	−254.17	2.174	9.030	11.204
19	294.15	2940	4.600	−77.23	0.770	3.010	3.780
20	297.65	2932	4.600	−9.91	0.749	3.010	3.759
21	294.15	4130	4.600	−77.23	0.770	3.010	3.780
22	299.15	4100	4.600	18.95	0.740	3.010	3.750
23	294.15	5760	4.600	−77.23	0.770	3.010	3.780
24	299.15	5750	4.600	18.95	0.740	3.010	3.750
25	290.15	119	2.130	−18.19	38.970	54.760	93.730
26	466.15	115	2.130	372.92	99.840	54.760	154.600
27	457.15	115	2.130	353.73	93.360	54.760	148.120
28	433.15	110	2.130	300.07	65.100	54.760	119.860
29	290.15	119	1.800	15.37	32.930	46.280	79.210
30	290.15	118.7	1.740	14.86	31.830	44.740	76.570
31	307.15	570	2.250	16.41	192.126	57.850	249.976
32	333.15	2940	2.250	88.12	681.410	57.850	739.260

33	310.150	2940	2.250	24.89	576.080	57.850	633.930
34	310.150	2940	0.210	2.32	53.760	5.400	59.160
35	310.150	2940	2.040	22.57	522.320	52.450	574.770
36	352.150	4130	2.040	112.74	673.510	52.450	725.960
37	310.150	4100	2.040	23.40	662.463	52.450	714.913
38	352.150	5760	2.040	114.23	768.489	52.450	820.939
39	310.150	5750	2.040	24.62	760.340	52.450	812.790
40	271.650	2920	0.210	−6.04	58.986	5.400	64.386
41	183.150	580	0.210	−25.36	24.858	5.400	30.258
42	176.150	5690	0.210	−27.17	85.740	2.420	88.160
43	96.150	590	0.210	−44.37	48.182	2.420	50.602
44	132.670	5700	6.080	−1075.01	2747.484	156.306	2903.790
45	93.950	600	6.080	−1298.30	1438.402	156.306	1594.708
46	99.850	590	2.035	−535.10	678.370	52.320	730.690
47	99.950	119.5	1.800	−373.75	264.890	46.280	311.170
48	100.150	121	2.130	−442.27	313.450	54.760	368.210
49	87.150	125	1.800	−396.61	103.323	46.280	149.603
50	78.850	120	2.130	−486.43	160.685	54.760	215.445
51	85.650	600	0.160	−35.82	136.087	4.060	140.147
52	96.350	600	0.158	−34.10	36.598	4.060	40.658
53	79.150	126	0.560	−239.46	421.720	14.400	436.120
54	79.150	126	1.040	−444.71	783.200	26.740	809.940
55	88.150	582	0.450	−184.43	286.500	55.830	342.330
56	88.950	100	1.740	−659.39	1078.840	215.860	1294.700
57	93.750	129	1.740	−639.30	1070.550	215.860	1286.410
58	88.850	180	0.082	−22.17	38.220	0.024	38.244
59	90.850	145	0.097	−10.68	9.860	0.028	9.888
60	91.250	144	0.015	−1.65	1.530	0.004	1.534
61	92.550	117	0.078	−21.09	35.420	0.023	35.443
62	92.250	117	0.020	−5.34	9.090	0.006	9.096
63	92.050	125	1.040	−444.71	783.200	0.305	783.505

TABLE 3
Parameters related to energy for components

Component	Energy input (kW)	Energy output (kW)	Energy Loss (kW)	η	β	EIP (kW)
SC1	−33.130	−165.460	132.330	0.200	0.030	105.834
SC2	339.080	−148.540	487.620	0.441	0.112	272.580
MS1	353.730	300.070	53.660	0.848	0.012	8.140
MS2	−91.840	−148.540	56.700	0.618	0.013	21.643
B	372.920	353.730	19.190	0.949	0.004	0.987
HE1	61.510	−62.060	123.570	0.991	0.028	1.112
HE2	23.550	22.520	1.030	0.956	0.001	0.045
HE3	28.120	27.870	0.250	0.991	0.001	0.002
HE4	−217.490	−519.310	301.820	0.419	0.069	175.416
HE5	187.290	67.020	120.270	0.358	0.028	77.232
MHE	1380.180	1331.890	48.290	0.965	0.011	1.690
DC1	−1894.980	−3023.760	1128.780	0.627	0.258	421.377
DC2	−661.470	−670.070	8.600	0.987	0.002	0.110
ASC	−417.600	−458.110	40.510	0.912	0.009	3.582
APC	−21.090	−446.360	425.270	0.047	0.097	405.176
AC	1600	721.13	878.875	0.451	0.201	482.763
RC	510.000	71.710	438.290	0.141	0.100	376.663
C1	125.000	90.830	34.170	0.727	0.008	9.341
C2	125.000	90.170	34.830	0.721	0.008	9.705
ET1	−7.750	−25.760	18.010	0.301	0.004	12.589
ET2	−12.710	−23.610	10.900	0.538	0.002	5.036
WP1	20.000	18.340	1.660	0.917	0.001	0.138
WP2	15.000	13.670	1.330	0.911	0.001	0.118
WP3	25.000	22.480	2.520	0.899	0.001	0.254

Energy loss rate shows decrement of heat or work from the system. Exergy destruction rate represents to work dissipation because of the irreversibilities in the system. Entropy generation is a measure of the irreversibility in the system. The higher the entropy production, the higher the irreversibility of the system which negatively affects the efficiency of the system according to the first and second laws. Energy efficiency shows how energy is used effectively and exergy efficiency indicates how the considered system is close to a reversible system. Other parameters investigated in the study are relative energy and exergy loss along with energetic and exergetic development potentials. The relative rates of both energy loss and exergy loss are important evaluation parameters to find the parameters of the most influence for the total losses. Energetic and exergetic development potential indicates the maximum energy and exergy to be achieved with the improvement of the system.

The energy and exergy efficiencies of the plant were found to be 45.3% and 13.1% respectively. The exergy efficiency of the system was lower than of some plants reported in the literature (1, 2, 6). The energy and exergy values of both the entire plant and its components and other evaluation parameters can be viewed in detail in Tables 2-5.

An air separation plant investigated in this study was examined and analyzed in detail according to the first and second laws of thermodynamics. The efficiency values of energy and exergy, the values of energy loss and exergy destruction, the EIP, ExIP, and the production of entropy values were found to be 0.453, 0.79, 4368.475 kW, 10535.875 kW, 2391.535 kW, 3800.485 kW, and 35.347 kW/K, respectively.

Some important results obtained for the system components in terms of energy analysis can be listed as follows:

- Energy efficiencies of only eight of the twenty four components are less than 0.5.
- Energy loss of nine components are bigger than 100 kW.
- Similarly, the relative energy loss of only four components have greater values than 0.1.
- Energetic improvement potential of the most of the components, thirteen of twenty four, are low.

According to the results above, the system has good thermodynamic parameters in terms of energy analysis. However, its energetic improvement potential is restricted except nine

TABLE 4
Parameters related to exergy for components

Component	Exergy input (kW)	Exergy output (kW)	Exergy destruction (kW)	ψ	α	σ (kW/K)	ExIP (kW)
SC1	5.187	2.39	2.797	0.461	0.000	0.009	1.508
SC2	10693.27	10516.35	176.920	0.983	0.015	0.593	2.927
MS1	148.120	119.860	28.260	0.809	0.002	0.095	5.392
MS2	10516.350	8415.250	2101.100	0.800	0.183	7.047	419.786
B	154.600	148.120	6.480	0.958	0.001	0.022	0.272
HE1	743.019	637.710	105.309	0.858	0.009	0.353	14.926
HE2	824.719	816.540	8.179	0.990	0.001	0.027	0.081
HE3	729.74	718.693	11.047	0.985	0.001	0.037	0.167
HE4	2011.497	1308.474	703.023	0.650	0.061	2.358	245.708
HE5	2792.650	1992.281	800.369	0.713	0.070	2.684	229.384
MHE	9855.558	5634.119	4221.439	0.572	0.368	14.159	1808.172
DC1	5984.670	4828.151	1156.519	0.807	0.101	3.879	223.494
DC2	1324.654	1304.580	20.074	0.985	0.002	0.067	0.304
ASC	1998.614	1885.178	113.436	0.943	0.010	0.380	6.438
APC	811.484	35.443	776.041	0.044	0.068	2.603	742.146
AC	2478.875	1505.750	973.125	0.607	0.085	3.264	382.017
RC	510.000	489.284	20.716	0.959	0.002	0.069	0.841
C1	159.17	76.490	82.680	0.481	0.007	0.277	42.948
C2	159.83	93.180	66.650	0.583	0.006	0.224	27.793
ET1	64.386	48.358	16.028	0.751	0.001	0.054	3.990
ET2	88.160	61.502	26.658	0.698	0.002	0.089	8.061
WP1	20.000	14.350	5.650	0.718	0.000	0.019	1.596
WP2	15.000	2.643	12.357	0.176	0.001	0.041	10.180
WP3	25.000	2.310	22.690	0.092	0.002	0.076	20.593

TABLE 5
Parameters related to energy and exergy for overall air separation system

System data			Performance parameters		
Data	Unit	Value	Parameter	Unit	Value
Energy input	kW	1808.23	η	–	0.453
Energy output	kW	−2560.165	**EIP**	kW	2391.535
Energy Loss	kW	4368.475	ψ	–	0.131
Exergy input	kW	52114.553	σ	kW/K	38.429
Exergy output	kW	40657.010	**ExIP**	kW	9956.608
Exergy destruction	kW	11457.547			

components. Maximum and minimum values for the energetic parameters can be listed as follows:

- The highest energy efficiency was 0.991 in HE 1 (heat exchanger 1) and HE 3 (heat exchanger 3) while the lowest value 0.047 in APC (argon distillation column).
- The lowest relative energy loss was just about 0.001 in HE 2 (heat exchenger 2), HE 3, WP 1 (water pump 1), WP 2 (water pump 2), and WP 3 (water pump 3), while the highest value was 0.258 in DC 1 (distillation column 1).
- The highest EIP value was 482.763 kW in AC, while the lowest one was 0.002 kW in B (battery).
- The highest energy loss was 1128.78 kW in DC1 (distillation column 1), while the lowest loss was 0.25 kW in HE 3.

Important results for the system components in terms of exergy analysis can be aligned as follows:

- Exergy efficiency of only four of the twenty four components are less than 0.5.
- Exergy destruction rate of ten components are bigger than 100 kW.
- Similarly, in relative exergy loss only three components have greater values than 0.1.
- Exergetic improvement potential of most of the components, eighteen of twenty-four, are low.

Similar to energetic parameters, the system has good thermodynamic parameters in terms of exergy analysis. However, its exergetic improvement potential is restricted except six components. Maximum and minimum values for the exergetic parameters can be listed as follows:

- The highest exergy efficiency was 0.990 in HE 2, while the lowest one was 0.044 in APC.
- The lowest relative exergy loss was just about 0.001 in SC 1 (spray cooler 1), B, HE 2, HE 3, WP 1, and WP 2, while the highest value was 0.368 in MHE (main heat exchanger).
- The highest ExIP value was 1808.172 kW in MHE, while the lowest one was 0.081 kW in HE 2.
- The exergy destruction rate was 4221.439 kW in MHE, while the lowest loss was 2.797 kW in SC 1.
- The highest and the lowest entropy productions were 14.159 kW/K and 0.009 kW/K for MHE and SC 1, respectively.

CONCLUSIONS

Consequently, by taking into account the results listed above, it is possible to identify the necessary components to be developed and to make the system more efficient. Energy and exergy parameters have good values for the system generally. In addition, energetic and exergetic improvement potentials of the components is relatively low. Although it is hard to make large changes in an air separation plant, insulation can be made where necessary or some changeable components such as compressors, turbines, pumps, or heat exchangers can be changed with the most efficient ones. Another option is to design more efficient air separation plants by utilizing this and similar studies. It is recommended for future work that advanced exergy based analyses should be conducted besides the conventional thermodynamic analyses.

NOMENCLATURE

$\dot{E}$: energy rate (kW)
$\dot{E}x$: exergy rate (kW)
$\dot{E}IP$: energetic improvement potential rate (kW)
$\dot{E}xIP$: exergetic improvement potential rate (kW)
h: enthalpy (kJ/kgK)
$\dot{m}$: mass rate (kg/s)
P: pressure (kPa)
R: gas constant (kJ/kgK)
$\dot{Q}$: heat (kW)
s: entropy (kW/K)
T: temperature (K)
$\dot{W}$: work (kW)

Abbrevations

AC: air compressor
ATM: atmosphere
ASC: argon separation column
APC: argon distillation column
B: battery
C: compressor
DC: distillation column
EH: electrical heater
ET: expansion turbine
GAN: gaseous nitrogen tank
HE: heat exchanger
LAR: liquid argon tank
LIN: liquid nitrogen tank
LOX: liquid oxygen tank
MHE: main heat exchanger
MS: molecular sieve
RC: recycle compressor
SC: spray cooler
WP: water pump
WT: water tank

Subscripts

ch: chemical
cold: cold side
D: destruction
e: energetic
ex: exergetic
g: gaseous
HE: heat exchanger
hot: hot side
i: inputs
j: j'th component
k: boundary of system
L: loss
o: outputs
ph: physical
pump: pump
$\dot{Q}$: heat
T: Temperature
$\dot{W}$: work

Greek Letters

α: relative exergy loss ratio (%)
β: relative energy loss ratio (%)
η: first law (energy) efficiency (%)
ψ: second law (exergy) efficiency (%)
σ: entropy generation ($\mathrm{kWK^{-1}}$)

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