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Article

Oxygen Specific Power Consumption Comparison for Air Separation Units

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Abstract. Technologies life cycles became shorter than before as a result of globalization and open market, which derived organizations to update their dated technologies. Without technologies updating, which based on Technological Forecasting (TF), organizations can not be dominant leaders in the open market and eventually they will lose their business. The main objective of this paper was to evaluate the air separation units by calculating the oxygen specific power, to find the most cost effective unit. The oxygen specific power used as a Key Performance Indicator (KPI) for the selected Air Separation Unit (ASU) technologies. The KPI for the updated Air Separation Unit was reviewed and the latest value selected as theoretical benchmark, which was 0.28Kw/Nm^3. At the practical part, the data collected to three air separation units ASU-31, ASU-51 and ASU-71. The results showed that the specific power gaps that used as the KPI's of ASU-31, ASU-51 and ASU-71 are 0.464Kw/Nm^3, 0.639Kw/Nm^3 and 0.631Kw/Nm^3 respectively. The results showed that these gaps can be minimized by the recommendation suggested in this paper to reduce power consumption.

Keywords: Air separation unit, oxygen specific power, technological forecasting, key performance indicators.

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1. Introduction

Technology Forecasting (TF) used for the purpose of future identification. Betz in 2003 [1] highlighted that technological change was finiteness process and TF can be used as methodology to trace the technological progress. Technology forecasting needs to be implemented effectively through all the life cycle of technologies to enhance the accuracy of the decisions making. Forecasting generally defined as a prediction of unknown situation in the future; it was widely used in production and demand forecasting, forecasting deals with the characteristics of a technology, like speed of a military aircraft, fuel consumption by cars, and performance of a machine with respect to operating cost and production capacity in coming years. Technological forecasting developed in 1970's to predict a technical achievement within a specified period at a given level of support within a given confidence level, this view was not valid any more with the following years of that period. The scope of technology forecasting was changing from time to time with respect to capability and accuracy [2].

The rate of technologies development was not the same, technology life cycle became shorter than before because of the huge developments, that were taking place in a short time. For example, Information Technology was one of the technologies that were having short life cycle. Similarly, technologies used in defense sector also have short life cycle. All the technologies used for production, had relatively longer life cycles than other technologies. It was argued that an organization can only be as dominant leaders in the market if they have capability to forecast and implement the development on the technologies being used in their businesses, it was argued that manufacturing organizations were transformed from producing organization to a learning organization [3, 4].

All chemicals and petrochemicals companies used industrial gases like oxygen and nitrogen either as a feedstock or as utilities, therefore this paper is concerning comparison between the technological forecasting for air separation units of oxygen and nitrogen gases to forecasting the methods of less power consumption and cost effective. The three units available to this research were ASU-31, ASU-51, and ASU-71. Industrial gases processes classified into Non-Cryogenic Industrial Gas Process and Cryogenic Industrial Gas Process. The Non-Cryogenic Industrial gas processes operated at approximately ambient temperature and cannot produced oxygen and nitrogen in large scale; therefore in this paper Cryogenic Industrial Gas Process was considered, as the most efficient and cost effective process for production of large quantities of oxygen, nitrogen, and argon in gaseous or liquid forms, also with high purity.

2. Classification of Technological Forecasting Methods

Knowing the different TF methods and their capabilities enhances the proper selection of TF method and leads to an effective implementation for the selected TF. Armstrong in 1989 [5] and Slocum in 2001 [6] stated Technology Forecasting has evolved from being a methodology based on emotional responses to one predicated on data collection, moreover, the quantity and quality of available data required for TF are not the same for all the cases. The methodology of forecasting process in general classified in two main categories to *judgmental methods* and *statistical methods*, the judgmental methods are built on experience and expectation of people, where the statistical methods are built on data collection [7]. Mishra, et al in 2002 reviewed technological forecasting methods by classifying these methods to three categories [8]:

- Subjective assessment methods.
- Exploratory methods.
- Normative methods.

Porter, et al. In 2004 introduced an umbrella concept covering technological forecasting process with name of Technology Future Analysis (TFA), they classified the methods of TFA into two main categories: Qualitative which is built on empirical, numerical data and Quantitative as a Judgmental method based on knowledge [9].

Firat, et al. in 2008 stated that there are hundreds of TF methods that can be fit into 9 families; these are [10]:

- Expert Opinion.
- Trend Analysis.
- Monitoring and Intelligence Methods.
- Statistical Methods

- Modeling and Simulation
- Scenarios.
- Valuing/Decision/Economics Methods
- Descriptive and Matrices Methods.
- Creativity.

According to the above, the suitable method of technology forecasting selected in this paper was quantitative method based on historical data mining and theoretical information as a benchmark. The model specification establishment based on the performance of selected ASUs, represented by a mathematical correlation specified as oxygen specific power (Kw/Nm^3). This model was done to ensure that, the selected Key Performance Indicator (KPI) was representing the less power consumption and cost effective.

3. Air Separation Units

Fresh air is very essential for all living things; everybody can sense how air is important in his life. Air is not a single element but it is a mixture of chemicals in gases form, it may contain impurities like dust particles and water vapor as well as released gases known as pollutant. Table 1 shows the fresh air components and their percentage at the sea level [11].

Table 1. Fresh air components [11].

Component	Fraction of air	Component	Fraction of air
Nitrogen	78.09%	Methane	1-2 vppm
Oxygen	20.95%	Acetylene	<1 vppm
Argon	0.93%	Krypton	1.14 vppm
Carbon dioxide	350 vppm	Nitrous oxide	0.5 vppm
Carbon monoxide	3-5 vppm	Hydrogen	0.5 vppm
Neon	18 vppm	Ozone	0.4 vppm
helium	5.2 vppm	Xenon	0.086 vppm

Note: vppm: volume parts per million

From the table, Nitrogen gas (N_2) represented 78.09% of air, which was the largest percentage among air components, where Oxygen gas (O_2) represented 20.95% of air as the second highest percentage, the third element was Argon gas, which represented 0.93% of air. These are the main industrial gases produced in large scales for different applications [11].

The Global industrial gas market was worth $29.2 billion in 2005 and $30.9 billion in 2006, Andrew in 2009 expected demand worth $40 billion in 2011 as shown in Fig. 1, this increment in the demand for industrial gases derived the developments in Air Separation Units for further improvements in production cost, production quality and minimizing the risk in production phase [12].

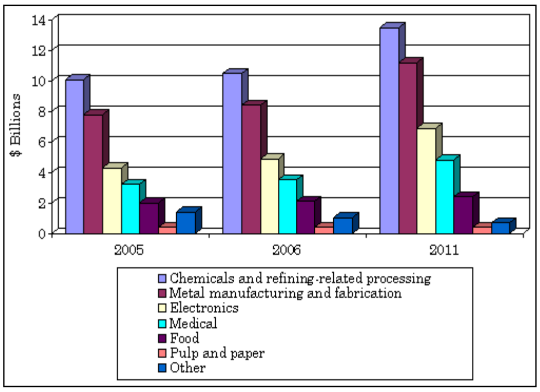

Fig.1. Global industrial gases market value [12].

Air Separation Units consist of five units operation; these are (see Fig. 2):

- Feed Air Compression unit.
- Feed Air Pre-Treatment unit (purification unit).
- Heat exchange and Liquefaction unit.
- Cryogenic separation unit.
- Product compression unit.

The air compression unit is located at the front end of this process, followed by air treatment unit, which is considered as the safe guard of the plant from the risk of hydrocarbons and water trace. Heat exchange and liquefaction is the core of ASU, where the heat of the feed air is transferred to liquid product and become gases, where the feed itself become liquid air, following to heat exchange step, cryogenic separation, where liquid air distilled to different products as oxygen and nitrogen, which are compressed in the compression unit to meet customer needs [13].

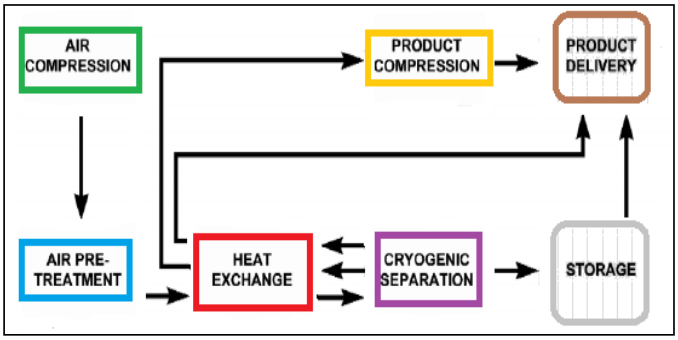

Fig. 2. Units operations for a cryogenic air separation process [13].

The process of industrial gases classified into two classes:

- Cryogenic industrial gas process.
- Non-Cryogenic industrial gas process.

Fig. 3 was sketched to show these classification and the sub technologies in each class [14].

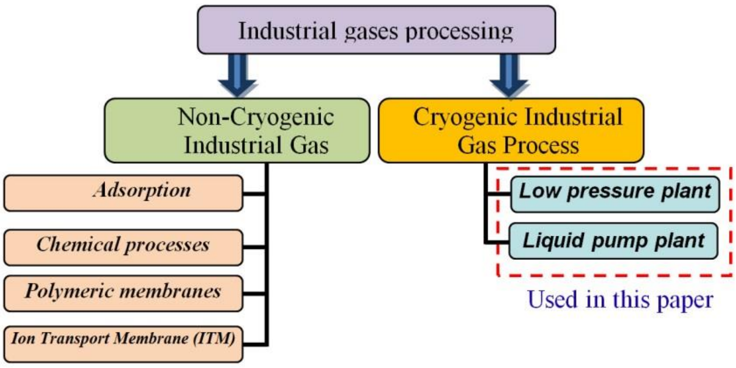

Fig. 3. Classification of industrial gases processing [14].

The *Cryogenic industrial gas process* consists from two technologies that were used in this paper. These two methods are:

- Low pressure plant with product compressors.
- Liquid pump plant (internal compression pump is used instead of compressors).

The *Non-cryogenic industrial gas* processes mainly classified into four classes:

- Adsorption.
- Chemical process.
- Polymeric membranes.
- Ion Transport Membrane (ITM)

The units that are used in this research are;

- Phase three air separation unit (ASU-31).

- Phase five air separation unit (ASU-51).
- Phase seven air separation unit (ASU-71).

These units equipped with gas purification systems, which had concerned to be very critical area, where the safety and quality started, these areas had been conceded to be area of improvement, where most of power consumption was took place and reflected in overall units performance.

Cryogenic Air Separation Unit (ASU) composed of compressors, heat exchangers, expander and distillation columns where air is separated into nitrogen and oxygen gases by distillation at very low temperatures, the design of cryogenic air separation unites ASU depended on the scale of production and the nature of the products required by customers. While basic principles were always the same, process flows for each plant can vary significantly since ASU's designed to meet specific customer's requirement.

For Low-pressure plant; Air at ambient temperature withdrawn by compressor via intake filter, where dust particles are removed, Compressed air passes to pre-cooling system, which composed of direct contact air cooler, Air passes to purification system composed of Molecular Sieve, Purified air cold down in high efficient heat exchanger, purified air compressed more in booster air compressor then subjected to expansion by turbine, which leads to a significant drop in air temperature to liquefaction point, air gas liquefied at very low temperature less than -185C°, which is the source of the coldness in ASU. Liquid air separated by distillation, where liquid production of oxygen, nitrogen and argon produced. Small amount of liquid product subjected to further cooling in sub-cooler, then transferred to liquid storage tanks as a backup for gas. Finally, these streams of liquid products gain and converted to gas and compressed in order to meet customers' needs.

Other cryogenic ASU technology used internal pump, where liquid oxygen is pumped with elevated pressure matching customer needs before it passed to main heat exchanger for vaporization. This unit normally equipped with nitrogen compressor to elevate nitrogen to customers need.

4. Key Performance Indicators for Air Separation Unit

There are 5 mains KPI's that can be used to monitor individual unit operation performance that can be summarized by the followings:

i. Individual air compressors specific powers.
ii. Individual oxygen compressors specific powers.
iii. Individual Nitrogen compressors specific powers.
iv. Molecular Sieve regeneration power.
v. Overall oxygen specific power, which is known as the ratio between the

(Total power consumption in Kw/hr) and (Total oxygen production in Nm^3 /hr).

The most important parameter of KPI is the oxygen specific power, which is the total power consumption per normal cubic meter of oxygen, this parameter of KPI reflects the overall performance of the ASU, Individual specific power can be used for monitoring individual equipment performance, an example for this, is the air compressor specific power (Kw/Nm^3 of Air), but this will not reflect the overall ASU performance. Hence, comparison between different ASUs performance normally done by calculating the oxygen specific power since it is involved in the overall production cost.

The design bases for any ASU done according to capacity of oxygen production since oxygen considered as the main product of any ASU. The overall oxygen specific power was selected in this paper as KPI, which will be used as a tool for calculation and comparisons.

5. Air Separation Unit Theoretical Oxygen Specific Power

One of the technological forecasting studies done by Castle showed that the oxygen specific power for cryogenic air separation unit will be reduced to about $0.28\sim0.3 Kw/Nm^3$ in year 2010 [11], this technological forecasting was done by extrapolation method as shown in Fig. 4, the forecasted value was confirmed by Pfaff, and Kather, they mentioned that the specific power for up-to dates ASU is approximately $0.25\text{-}0.28 Kw/Nm^3$ [15], which is closed to the earlier forecasting done by Castle [11].

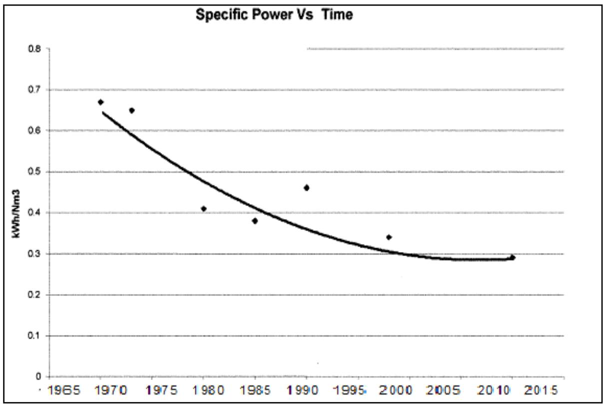

Fig. 4. Specific Power vs. Time [11].

The oxygen specific power value (0.28Kw/Nm³) will be used as the theoretical benchmark for current air separation used in this paper.

6. Air Separation Units

Three air separation units ASU-31, ASU-51 and ASU-71 used to collect data in calculating specific power that was used in comparison in this paper.

6.1. Air Separation Units ASU-31

The air separation unit ASU-31 is classified as a low pressure cryogenic plant as shown in Fig. 5, because it is operated with oxygen compressors. The production of this unit is 1200 metric ton/day, which is equivalent to 35000 Nm³/hr. The accuracy of the data collected for oxygen production was not representing the actual production quantity of oxygen gas, the data collected at three places as follows;

- P1: out of the column.
- P2: out of oxygen compressors.
- P3: plant Battery limit (BL).

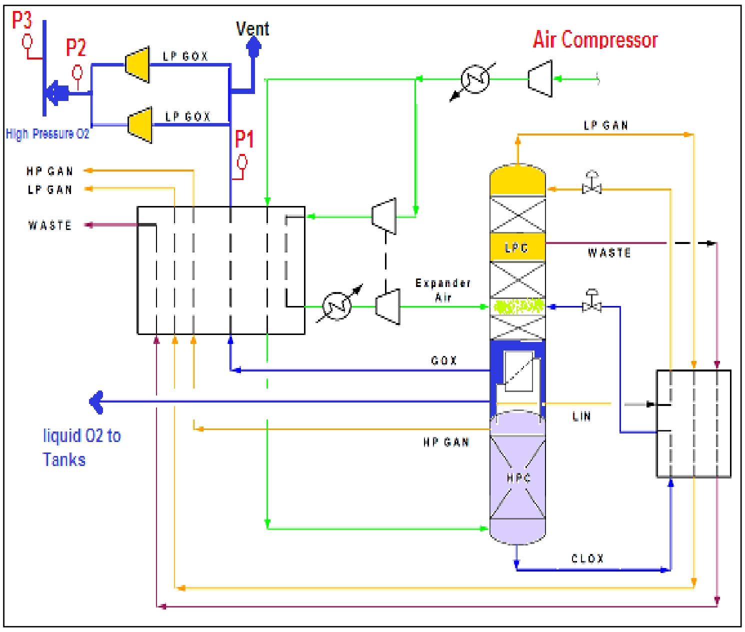

Fig. 5. Locations of O_2 production readings in ASU-31.

Note: *LP GOX: Low Pressure Gas OXygen*
HP GOX: High Pressure Gas Oxygen
HP GAN: High Pressure GAs Nitrogen

LP GAN: Low Pressure GAs Nitrogen
CLOX: Circulating Liquid OXygen
LIN: LIquid Nitrogen

Table 2 shows the gas oxygen production from the three places as P1, P2 and P3. The oxygen specific power was calculated by the following formula [11];

$$O_2 \text{ Specific Power in } (Kw/Nm^3) = \text{Total Power consumption in } (Kw/hr) / \text{Total } O_2 \text{ production in } (Nm^3/hr) \quad (1)$$

The oxygen specific power at (P1) represented all the production of oxygen out of the coldbox, where the oxygen specific power at (P2) represented the actual oxygen production compressed to the customers, (P1) did not effected when some of oxygen production vented to the atmosphere, where one compressor was in use. This happened when there was less demand, and this unit did not have the capability to produce the exact quantity of production that must be depended on demand.

Table 2. Power consumption, oxygen production and specific power for ASU-31.

No.	DATE	Power Consumption (Kw/hr)	**P1** Total O_2 Production at Coldbox Outlet (Nm3/hr)	**P2** Total O_2 Production out of Compressors (Nm3/hr)	**P3** Total O_2 Production at Battery Limit (Nm3/hr)	**P1** O_2 Specific Power (Kw/Nm3) at Cold box	**P2** O_2 Specific Power (Kw/Nm3) at Compressors	**P3** O_2 Specific Power (Kw/Nm3) at BL
1.	08/09/2009	18386	35372	35790	25912	0.520	0.514[5]	0.710[2]
2.	09/09/2009	18424	35138	8666	19444	0.524	2.126[1]	0.948[2]
3.	10/09/2009	18212	35004	5910	20685	0.520	3.081[1]	0.880[2]
4.	11/09/2009	18091	34552	30680	28754	0.524	0.590	0.629
5.	12/09/2009	18120	34597	35995	29840	0.524	0.503	0.607
6.	13/09/2009	18150	34644	35058	29817	0.524	0.518	0.609
7.	14/09/2009	18189	34623	34982	29754	0.525	0.520	0.611
8.	15/09/2009	18257	34786	35076	29773	0.525	0.520	0.613
9.	16/09/2009	18185	34676	36013	29903	0.524	0.505	0.608
10.	17/09/2009	17925	34407	36078	30042	0.521	0.497	0.597
11.	18/09/2009	17399	33644	36215	29824	0.517	0.480	0.583
12.	19/09/2009	17295	33150	34766	29621	0.522	0.497	0.584
13.	20/09/2009	17411	33169	35642	29210	0.525	0.489	0.596
14.	21/09/2009	17330	33159	36883	29209	0.523	0.470	0.593
15.	22/09/2009	17555	33081	36742	29360	0.531	0.478	0.598
16.	23/09/2009	17376	33126	36561	29421	0.525	0.475	0.591
17.	24/09/2009	17281	32888	36400	29305	0.525	0.475	0.590
18.	25/09/2009	17225	32725	36504	29393	0.526	0.472	0.586
19.	26/09/2009	17210	32805	36300	29445	0.525	0.474	0.584
20.	27/09/2009	17589	33518	35939	29808	0.525	0.489	0.590
21.	28/09/2009	17596	33327	36015	29946	0.528	0.489	0.588
22.	29/09/2009	17625	33118	36167	29971	0.532	0.487	0.588
23.	30/09/2009	17448	33037	38060	29946	0.528	0.458	0.583
24.	01/10/2009	17435	33016	38267	29439	0.528	0.456	0.592
25.	02/10/2009	17315	32980	36768	29442	0.525	0.471	0.588
26.	03/10/2009	14816	2367	2843	28496	6.259[6]	5.211[1]	0.520
27.	04/10/2009	16553	22719	7146	27606	0.729	2.316[1]	0.600
28.	05/10/2009	17870	35165	4535	21614	0.508	3.941[1]	0.827[2]
29.	06/10/2009	18285	35877	10257	20168	0.510	1.783[1]	0.907[2]
30.	07/10/2009	18216	34829	29691	19433	0.523	0.614	0.937[2]
31.	08/10/2009	18295	34916	35971	19277	0.524	0.509	0.949[2]
32.	09/10/2009	18238	35220	35838	19294	0.518	0.509	0.945[2]
33.	10/10/2009	18187	35050	36185	19379	0.519	0.503	0.938[2]
34.	11/10/2009	18154	35054	35569	19284	0.518	0.510	0.941[2]
35.	12/10/2009	18253	35222	23291	19445	0.518	0.784	0.939
Unit Shutdown								
36.	17/12/2009	17730	35424	36743	28043	0.501	0.481	0.582
37.	18/12/2009	17712	35457	36599	28064	0.500	0.484	0.847
38.	19/12/2009	17808	35449	36641	28124	0.502	0.489	15.534[2]
39.	20/12/2009	17712	35510	36568	28023	0.499	0.485	14.406[2]
40.	21/12/2009	17681	35651	34939	27243	0.496	0.506	13.945[2]
41.	22/12/2009	17585	35488	34879	27352	0.496	0.503	2.728[2]
42.	23/12/2009	17326	34819	35903	27682	0.498	0.481	0.913
43.	24/12/2009	17685	35060	36200	28829	0.504	0.489	0.674
44.	25/12/2009	17822	35203	35800	29586	0.506	0.496	0.599
45.	26/12/2009	17771	35414	36596	29612	0.502	0.485	0.592
46.	27/12/2009	17788	35185	36456	30252	0.506	0.483	0.652
47.	28/12/2009	17754	35373	38046	30513	0.502	0.464[3]	0.704
48.	29/12/2009	17657	34810	38286	20839	0.507	0.464[3]	0.700
49.	30/12/2009	17453	34733	30035	1124	0.503	0.579	15.534[2]
50.	31/12/2009	17414	34352	22839	1209	0.507	0.763[4]	14.406[2]
51.	01/01/2010	17382	34351	22840	1246	0.506	0.764[4]	13.945[2]
52.	02/01/2010	17586	34736	33641	6446	0.506	0.525	2.728[2]
53.	03/01/2010	17797	35008	38204	19499	0.508	0.466	0.913
54.	04/01/2010	17729	35131	36431	26321	0.505	0.485	0.674
55.	05/01/2010	17975	35121	36442	30022	0.512	0.492	0.599
56.	06/01/2010	17812	35123	36485	30111	0.507	0.490	0.592
57.	07/01/2010	17999	35123	36430	27620	0.512	0.496	0.652
58.	08/01/2010	17973	35209	36457	25537	0.510	0.491	0.704
59.	09/01/2010	17968	35202	36460	25686	0.510	0.490	0.700
60.	10/01/2010	17844	35053	34322	25550	0.509	0.519	0.698
61.	11/01/2010	17841	35081	23064	25230	0.509	0.774	0.707

62.	12/01/2010	18169	35165	20240	24987	0.517	0.899	0.727
63.	13/01/2010	17690	33371	1221	24895	0.530	14.949[1]	0.711
64.	14/01/2010	17634	32958	13727	24662	0.535	1.285[1]	0.715
Average		**17721**	**33836**	**31176**	**25243**	**0.608**	**0.999**	**2.063**

Note: [1]*compressors unloaded, no demand*
[2]*not all product to P3*
[3]*lowest value, maximum production*
[4]*one compressor was running, less demand*
[5]*used as an example*
[6]*up normal*

The average of the power consumption is (17721Kw/hr) and the average of the total oxygen production at P1=33836Nm^3/hr, P2=31176Nm^3/hr and P3=25243Nm^3/hr. The averages of these values showed large deviation between the three averages; P1=0.608Kw/Nm^3, P2=0.999Kw/Nm^3 and P3=2.063Kw/Nm^3. The oxygen specific power calculated from the data of the battery limit P3 was the highest value compared with the results of O2 specific power at P2 and P1. The reason for that was withdrawing some of oxygen production out of ASU-31 through the tie-in piping located before P3. The oxygen specific power at P1 represents all production of oxygen out of the coldbox, where the oxygen specific power at P2 represents the actual oxygen production compressed to the customers,

The averages of oxygen production at P1= 33836Nm^3/hr, P2=31176Nm^3/hr, and P3=25243Nm^3/hr, these averages showed that there are approximately average loss of oxygen between (P1 and P3) =33836-25243=8593Nm^3/hr, and for specific power there are an extra loss of specific power between (P1 and P3) = 2.063-0.608= 1.455Kw/Nm^3. The losses need to be minimized by adding the capability of controlling the unit to produce gases according to demand to minimize loss of power.

6.2. Air Separation Units ASU-51

The air separation unit ASU-51 classified as a cryogenic Liquid pump plant as shown in Fig. 6, because it was equipped with Internal Compression pump (IC-Pump) instead of oxygen compressors, which were used in ASU-31. ASU-51 was designed to produce 2682metric ton/day of oxygen, which equivalent to 78225Nm^3/hr. Since there was only one measuring point for oxygen gas, data was collected for the total oxygen production by adding both gaseous oxygen at P4 and liquid oxygen. The total power consumption for ASU-51 was collected by adding all the power consumption of equipments, which were involved in oxygen production as follows:

- Power of air compressors.
- Power of regeneration heaters.
- Power of all pumps involved in production.

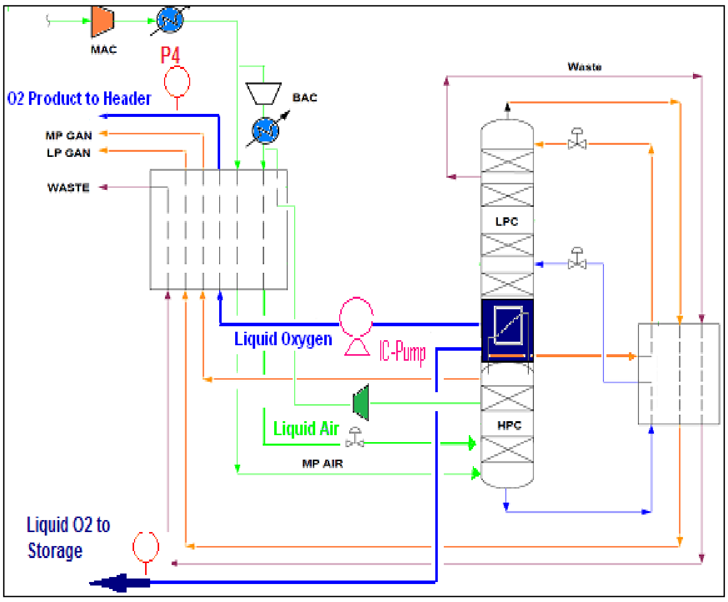

Fig. 6. Location of O2 production readings in ASU-51.

Note: *LP GOX: Low Pressure OXygen Gas*
HP GOX: High Pressure Gas OXygen
MP GAN: Medium Pressure GAs Nitrogen
LP GAN: Low Pressure GAs Nitrogen
MAC: Main Air Compressor
BAC: Booster Air Compressor
IC-Pump: Internal Compression pump

Table 3 shows the total oxygen production and total power consumption.

Table 3. Power consumption, oxygen production and specific power for ASU-51.

NO.	DATE	Total Power Consumption (Kw/hr)	**P4** Total O_2 Production (Nm^3/hr)	**P4** Specific Power (Kw/Nm^3)
1.	8/9/2009	48674	20652	2.357
2.	9/9/2009	51222	76161	0.673
3.	109/2009	50952	75285	0.677
4.	11/9/2009	50513	74861	0.675
5.	12/9/2009	50683	75193	0.674
6.	13/9/2009	50702	75294	0.673
7.	14/9/2009	50800	74936	0.678
8.	15/9/2009	50884	74450	0.683
9.	16/9/2009	50735	75058	0.676
10.	17/9/2009	50707	75012	0.676
11.	18/9/2009	50430	74230	0.679
12.	19/9/2009	49090	70886	0.693
13.	20/9/2009	48837	70445	0.693
14.	21/9/2009	48737	70451	0.692
15.	22/9/2009	48797	70466	0.692
16.	23/9/2009	48549	69946	0.694
17.	24/9/2009	48519	70130	0.692
18.	25/9/2009	48200	69494	0.694
19.	26/9/2009	47976	69419	0.691
20.	27/9/2009	48003	69948	0.686
21.	28/09/2009	48057	70426	0.682
22.	29/09/2009	47961	69928	0.686
23.	30/09/2009	48067	70054	0.686
24.	01/10/2009	48162	69305	0.695
25.	02/10/2009	48059	70164	0.685
26.	03/10/2009	49806	73180	0.681
27.	04/10/2009	50228	73703	0.681
28.	05/10/2009	48290	69930	0.691
29.	06/10/2009	46138	57397	0.804[1]
30.	07/10/2009	48751	70352	0.693
31.	08/10/2009	50623	74578	0.679
32.	09/10/2009	51734	77313	0.669
33.	10/10/2009	52897	79453	0.666
34.	11/10/2009	53017	79787	0.664
35.	12/10/2009	53046	79829	0.664
36.	13/10/2009	53034	79595	0.666
37.	14/10/2009	52938	79315	0.667
38.	15/10/2009	52995	79107	0.670
39.	16/10/2009	51921	77472	0.670
40.	17/10/2009	47081	67480	0.698
41.	18/10/2009	47030	68331	0.688
42.	19/10/2009	47152	68617	0.687
43.	20/10/2009	47443	68707	0.691
44.	21/10/2009	47082	68188	0.690
45.	22/10/2009	46880	67972	0.690
46.	23/10/2009	46977	67721	0.694
47.	24/10/2009	47005	67718	0.694
48.	25/10/2009	47075	67987	0.692
49.	26/10/2009	47051	67398	0.698
50.	27/10/2009	47120	67097	0.702 (Highest Value)
51.	28/10/2009	47020	67836	0.693
52.	29/10/2009	46839	68490	0.684
53.	30/10/2009	46716	67948	0.688
54.	31/10/2009	47218	67861	0.696
55.	01/11/2009	50941	74635	0.683
56.	02/11/2009	54025	79843	0.677
57.	03/11/2009	52920	77583	0.682
58.	04/11/2009	51990	77137	0.674
59.	05/11/2009	53949	80613	0.669
60.	06/11/2009	53807	80509	0.668
61.	07/11/2009	53762	80691	0.666
62.	08/11/2009	53774	80584	0.667
63.	09/11/2009	53653	80810	0.664
64.	10/11/2009	53574	80674	0.664
65.	11/11/2009	51549	76928	0.670
66.	12/11/2009	51419	76703	0.670
67.	13/11/2009	51189	76696	0.667
68.	14/11/2009	50277	75030	0.670
69.	15/11/2009	48894	72139	0.678
70.	16/11/2009	53552	80836	0.662
71.	17/11/2009	53776	81208	0.662
72.	18/11/2009	53838	81901	0.657

73.	19/11/2009	53277	80902	0.659
74.	20/11/2009	47912	69666	0.688
75.	21/11/2009	20697	19904	1.040[1]
76.	22/11/2009	35290	9238	3.820[1]
77.	23/11/2009	46484	64280	0.723[1]
78.	24/11/2009	46444	68695	0.676
79.	25/11/2009	47526	70751	0.672
80.	26/11/2009	48897	72713	0.672
81.	27/11/2009	53100	80673	0.658
82.	28/11/2009	53695	81008	0.663
83.	29/11/2009	53389	81129	0.658
84.	30/11/2009	53040	81049	0.654
85.	01/12/2009	53129	81136	0.655
86.	02/12/2009	52977	81246	0.652
87.	03/12/2009	53081	81322	0.653
88.	04/12/2009	53279	81401	0.655
89.	05/12/2009	53235	81959	0.650
90.	06/12/2009	53700	83169	0.646
91.	07/12/2009	53870	83169	0.648
92.	08/12/2009	53583	83292	0.643
93.	09/12/2009	53607	83221	0.644
94.	10/12/2009	53567	83266	0.643
95.	11/12/2009	53202	83294	0.639 (Lowest Value)
96.	12/12/2009	53465	82927	0.645
97.	13/12/2009	52893	81923	0.646
98.	14/12/2009	48943	73118	0.669
99.	15/12/2009	50805	75349	0.674
100.	16/12/2009	52074	78666	0.662
101.	17/12/2009	53207	80731	0.659
102.	18/12/2009	53105	80568	0.659
103.	19/12/2009	53578	81354	0.659
104.	20/12/2009	53312	81282	0.656
105.	21/12/2009	53140	81567	0.651
106.	22/12/2009	53136	81499	0.652
107.	23/12/2009	53436	81511	0.656
108.	24/12/2009	53546	81300	0.659
109.	25/12/2009	54706	83278	0.657
Average		**50345**	**73841**	**0.772 (Kw/ Nm3)**

Note: [1]unit upset.

The average of the total power consumption is (50345Kw/hr) and the average of the total oxygen production at P4 is (73841Nm^3/hr), this production near to the designed production value of (78225Nm^3/hr), which means the production, was 5.6% less than the designed production.

The oxygen specific power of air separation of this unit was ranged between 0.639Kw/Nm^3 and 0.702Kw/Nm^3, where the total oxygen production was ranged between 67096Nm^3/hr and 83293Nm^3/hr. The maximum oxygen specific power was 0.702Kw/Nm^3 during plant turndown mode (less demand by customer).

6.3. Air Separation Unit ASU-71

This air separation unit was designed to produce 3000 metric ton/day of oxygen which equivalent to 87500Nm^3/hr. It is operated with Internal Compression pump (IC-Pump), this unit was classified as liquid pump plant, where IC-pump is used instead of oxygen compressors as shown in Fig. 7.

Table 4. Power consumption, oxygen production and specific power for ASU-71.

NO.	DATE	Total Power Consumption (Kw/hr)	**P5** Total O_2 Production (Nm^3/hr)	**P5** Specific Power (Kw/Nm^3)
1.	8/9/2009	61553.48	97979	0.628
2.	9/9/2009	48503.48	73285	0.662
3.	109/2009	48494.05	74515	0.651
4.	11/9/2009	52888.52	83425	0.634
5.	12/9/2009	49559.92	77507	0.639
6.	13/9/2009	49828.07	78086	0.638
7.	14/9/2009	49085.51	76435	0.642
8.	15/9/2009	49906.02	77426	0.645
9.	16/9/2009	49596.62	77436	0.640
10.	17/9/2009	49871.22	78646	0.634
11.	18/9/2009	50427.75	78499	0.642
12.	19/9/2009	49552.70	72318	0.685
13.	20/9/2009	49007.01	71933	0.681
14.	21/9/2009	48446.87	71655	0.676
15.	22/9/2009	48033.62	69840	0.688
16.	23/9/2009	48987.58	73070	0.670
17.	24/9/2009	49795.11	74968	0.664
18.	25/9/2009	49033.87	74192	0.661
19.	26/9/2009	50835.77	77045	0.660
20.	27/9/2009	49581.63	74474	0.666
21.	28/09/2009	48965.46	73722	0.664
22.	29/09/2009	48944.99	73047	0.670
23.	30/09/2009	49170.98	74207	0.663
24.	01/10/2009	49171.73	73697	0.667

25.	02/10/2009	49061.09	73818	0.665
26.	03/10/2009	52013.87	79180	0.657
27.	04/10/2009	51486.85	77954	0.660
28.	05/10/2009	47823.42	69903	0.684
29.	06/10/2009	49074.80	71365	0.688
30.	07/10/2009	50959.87	74416	0.685
31.	08/10/2009	53414.57	81632	0.654
32.	09/10/2009	55579.89	84251	0.660
33.	10/10/2009	55036.42	83255	0.661
34.	11/10/2009	55366.59	82917	0.668
35.	12/10/2009	55594.15	83561	0.665
36.	13/10/2009	55597.73	83462	0.666
37.	14/10/2009	54565.96	82505	0.661
38.	15/10/2009	53336.40	79810	0.668
39.	16/10/2009	51569.68	76159	0.677
40.	17/10/2009	48586.53	72446	0.671
41.	18/10/2009	47836.63	70208	0.681
42.	19/10/2009	47894.30	70042	0.684
43.	20/10/2009	47753.41	70146	0.681
44.	21/10/2009	47483.85	68765	0.691
45.	22/10/2009	48385.68	72356	0.669
46.	23/10/2009	48124.81	71478	0.673
47.	24/10/2009	47968.27	70784	0.678
48.	25/10/2009	47104.68	67703	0.696
49.	26/10/2009	47280.46	68045	0.695
50.	27/10/2009	47621.45	68226	0.698 (highest value)
51.	28/10/2009	47469.86	68813	0.690
52.	29/10/2009	47840.63	70676	0.677
53.	30/10/2009	47457.07	69757	0.680
54.	31/10/2009	50120.48	74175	0.676
55.	01/11/2009	56709.54	85259	0.665
56.	02/11/2009	59618.29	90636	0.658
57.	03/11/2009	60649.04	93351	0.650
58.	04/11/2009	61278.64	95473	0.642
59.	05/11/2009	60377.52	93675	0.645
60.	06/11/2009	59372.13	91086	0.652
61.	07/11/2009	54401.71	79118	0.688
62.	08/11/2009	50566.41	75300	0.672
63.	09/11/2009	60688.41	94554	0.642
64.	10/11/2009	54822.22	83555	0.656
65.	11/11/2009	48713.58	73441	0.663
66.	12/11/2009	51119.94	78079	0.655
67.	13/11/2009	50827.04	77151	0.659
68.	14/11/2009	48732.20	73885	0.660
69.	15/11/2009	48998.62	73201	0.669
70.	16/11/2009	60752.65	94099	0.646
71.	17/11/2009	57690.81	87672	0.658
72.	18/11/2009	51762.23	76864	0.673
73.	19/11/2009	49401.73	73108	0.676
74.	20/11/2009	48009.40	72535	0.662
75.	21/11/2009	55327.40	82021	0.675
76.	22/11/2009	59999.95	89358	0.671
77.	23/11/2009	48191.85	69838	0.690
78.	24/11/2009	47762.22	69583	0.686
79.	25/11/2009	47845.47	69841	0.685
80.	26/11/2009	52256.61	76383	0.684
81.	27/11/2009	58310.56	88397	0.660
82.	28/11/2009	58571.63	87884	0.666
83.	29/11/2009	59032.65	88778	0.665
84.	30/11/2009	59029.89	89146	0.662
85.	01/12/2009	59471.78	90706	0.656
86.	02/12/2009	59514.50	90662	0.656
87.	03/12/2009	59407.32	90642	0.655
88.	04/12/2009	58678.67	89242	0.658
89.	05/12/2009	59329.67	92197	0.644
90.	06/12/2009	59464.45	92195	0.645
91.	07/12/2009	59871.93	93330	0.642
92.	08/12/2009	59661.31	93161	0.640
93.	09/12/2009	59557.14	93367	0.638
94.	10/12/2009	59115.09	92736	0.637
95.	11/12/2009	58287.61	90291	0.646
96.	12/12/2009	52041.38	77694	0.670
97.	13/12/2009	53082.93	80928	0.656
98.	14/12/2009	51241.40	77946	0.657
99.	15/12/2009	48201.86	71663	0.673
100.	16/12/2009	54248.18	81723	0.664
101.	17/12/2009	58847.59	87622	0.672
102.	18/12/2009	59383.57	89458	0.664
103.	19/12/2009	60351.45	93656	0.644
104.	20/12/2009	60238.71	94520	0.637
105.	21/12/2009	60290.36	94549	0.638
106.	22/12/2009	60792.06	93984	0.647
107.	23/12/2009	60049.63	94565	0.635
108.	24/12/2009	60192.81	95412	0.631 (lowest value)
109.	25/12/2009	60147.39	95053	0.633
Average		**53220**	**80512**	**0.662**

The average of the total power consumption was 53220Kw/hr and the average of the total oxygen production at P5 was 80512Nm3/hr, this production near to the designed production value of 87500Nm^3/hr, which means production of this unit, was 7.9% less than the designed production. The oxygen specific power was ranged between 0.631Kw/Nm³ and 0.698Kw/Nm³, where the total oxygen production was ranged between 67703Nm³/hr and 95412Nm³/hr.

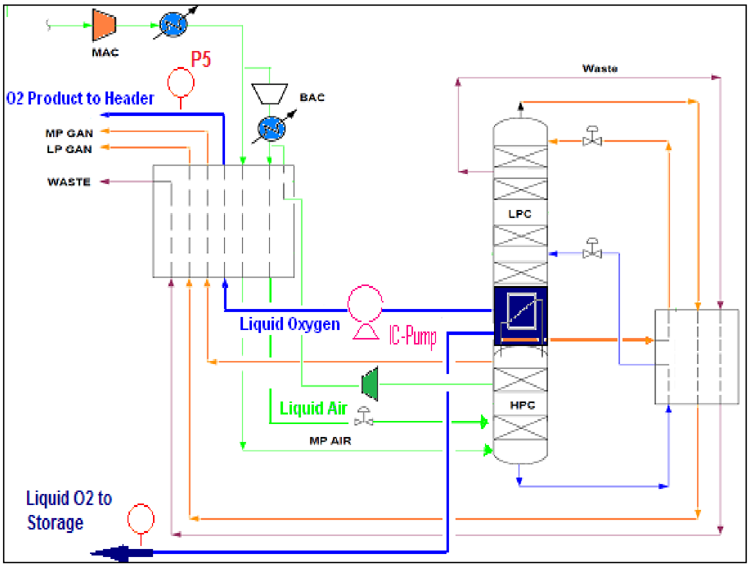

Fig. 7. Locations of O_2 production readings in ASU-71.

Note: *LP GOX: Low Pressure Gas OXygen*
HP GOX: High Pressure Gas Oxygen
HP GAN: High Pressure Gas Nitrogen
LP GAN: Low Pressure Gas Nitrogen
MAC: Main Air Compressor
BAC: Boster Air Compressor

The air separation units ASU-51 and ASU-71 are identical and they have same technology of cryogenic liquid pump plant. Since there was only one measuring point for oxygen gas, data was collected for the total oxygen production by adding both gaseous oxygen and liquid oxygen quantities at P5.

The total power consumption for this unit represented by adding all the power consumption of equipments which were involved in oxygen production as follows;

- Power of air compressors; MAC and BAC.
- Power of regeneration heaters.
- Power of all pumps involved in production.

Table 4 shows the total oxygen production and the total power consumption.

7. Comparison between Gas Air Separation Units and Benchmark

The oxygen specific power for ASU-31 was ranged between 0.464Kw/Nm³ and 0.764Kw/Nm³ in normal operation with minimum value was 0.464Kw/Nm³, which will be used as the benchmark of ASU-31. The oxygen specific power for ASU-51 was ranged between 0.639Kw/Nm³ and 0.702Kw/Nm³ with average of 0.672Kw/Nm³, where the minimum value was 0.639Kw/Nm³, which will be used as the benchmark of ASU-51. The oxygen specific power of ASU-71 was ranged between 0.631Kw/Nm³ and 0.698 Kw/Nm³ with average of 0.662Kw/Nm³, with minimum value was 0.631Kw/Nm³, which will be used as the benchmark of ASU-71. The specific power comparison for ASU-31, ASU-51 and ASU-71 showed a big difference on oxygen specific powers compared with the theoretical benchmark values which is 0.28Kw/Nm³. Fig. 8 shows the comparison of the three units compared with the benchmark.

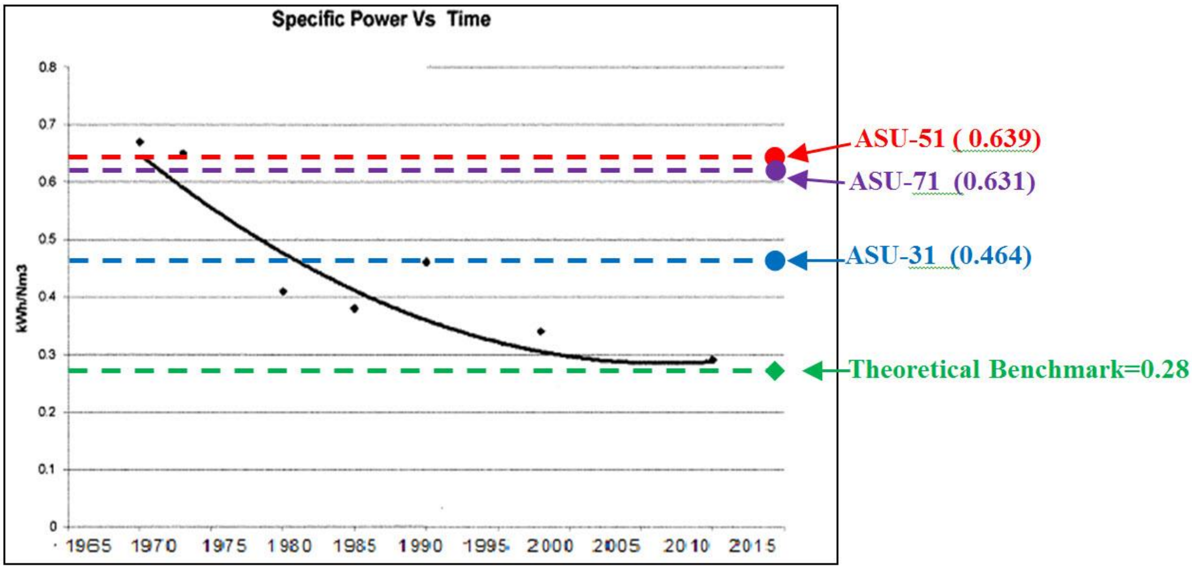

Fig. 8. Benchmarking for O2 specific power of Air Separation Units.

ASU-31 had the lowest oxygen specific power among other operated ASU's, since it was 0.464Kw/Nm³. The Figure shows also that both ASU-51 and ASU71 with oxygen specific power 0.639Kw/Nm³ and 0.631Kw/Nm³ respectively. The air separation units ASU-31 is the most effective unit compared with ASU-51 and ASU71 but still it's specific power is higher than the theoretical benchmark by 0.184Kw/Nm³, the reason behind this is the difference of technology been used on ASU-31, since it is a low pressure plant ASU technology compared with ASU-51 and ASU-71. The oxygen specific power of ASU-51 was higher than the theoretical benchmark by 0.359Kw/Nm³, where the oxygen specific power of ASU-71 was higher than the theoretical benchmark by 0.351Kw/Nm³. ASU-51 performance was very close to ASU-71, these two units have the same technology, which is liquid pump plant. The overall performance showed the needs for adoption of forecasted developments in ASUs units, where power consumption can be reduced in the future.

The ASU-31 is the most cost effective unit in three air separation units since it had the lowest oxygen specific power; this unit was classified as low pressure ASU, where oxygen compressors used in the process, while the other units ASU-51 and ASU-71 are classified as Liquid pump plant, since it was equipped with IC-Pumps.

8. Conclusion

Cryogenic air separation units were considered to be the most cost effective technologies used for industrial gases production for large quantities and high purity.

The oxygen specific power comparison between the three units of air separation units ASU-31, ASU-51 and ASU-71, showed that ASU-31 is the most cost effective unit. The comparison of the three units of air separation units with the theoretical benchmark of oxygen specific power (0.28Kw/Nm3) showed there is a difference of 0.184Kw/Nm3 for ASU-31, 0.359Kw/Nm3 for ASU-51 and 0.351Kw/Nm3 for ASU-71. Forecasting of the oxygen specific power can be reduced toward the benchmark which is (0.28 ~ 0.3 Kw/Nm3) using one of the followings suggested technologies;

i. Minimize oxygen losses with nitrogen waste, by increasing the capability of operating the units according to gasses demand.
ii. Adoption of New generation of adsorption beds, that can be regenerated with low temperature less power consumption.
iii. Adoption of the new generation of magnetic bearing, seals if applicable will reduce the frication and eventually reduce the power consumption.

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