Optimizing Medical Air Production Using Exergy and Process Cost Analysis

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Abstract: This work compared one new design of Air separation using Linde process for medical air production with existing plant using exergy and process cost analyses. Hyprotech System Simulator (HYSYS) software was used in simulating the process plants and Microsoft Excel was used for exergy, energy and process cost analyses. Annual profit was used as fiscal index for comparism with existing plant design. Exergy analysis of Linde air separation process showed that exergy efficiency of the existing plant (base case) was 3.23 kJ/h while that of the improved plant when the valve was replaced with a turbine (Case 1) was 11.65 kJ/h. Also, the process cost analysis showed that the annual profit for the base case was 48,818,463 **($/yr)** while that of the improved case was 50,485,051 **($/yr).** Replacing the valve with the turbine in the Linde air separation process could greatly give a better air separation process in terms of high purified medical air with greater annual venture profit.

Keywords: Medical air, exergy, Linde air separation, process cost analysis.

1. INTRODUCTION

Oxygen is a colourless and odourless gas which is vital for most life forms on earth. Medical oxygen is essential in hospital and clinical care for resuscitation. This odourless gas, which is potentially life-saving, is in limited supply in the developing world especially Sub-Saharan Africa, although the extent and nature of the problem are not well documented [1]. In the Gambia most health facilities have inadequate oxygen availability and that the factors that are important for ensuring oxygen supplies differ between countries and facilities [2].

Oxygen used in medical applications must be maintained at a purity of 99.2 mole percentage oxygen according to standards set by the Food and Drug Administration. Oxygen is produced on a commercial level through the liquefaction and distillation of ambient air at air separation plants. There are three methods of air separation commercially available: cryogenic distillation process, pressure swing adsorption process and membrane separation process [3]. Cryogenic air distillation is used when product high purity is needed especially in the healthcare industry. It is also advantageous when products are required in liquid form [4]. The basic requirement of cryogenic air separation process is air liquefaction and fractional distillation of liquid air. Efficiency of air separation process has been increased to some extent through equipment efficiency [5].

Exergy analysis is necessary when various forms of energy are used in a process, because it describes the quality of energy. Therefore, exergy analysis can reveal whether and by how much, it is possible to design more efficient energy systems [6]. Exergy analysis can assist in improving and optimizing designs [7].

In this present study, one design case which is an improvement over the existing design (base case) was performed and the exergy analysis done to determine their performance. Annual profit venture was used as fiscal indicator for comparism.

2. PROCESS DISCRIPTION

Air separation was done using Linde process which is illustrated in Figure **1**, the base case (Case 1) design. The air enters the compressor at 101 kpa and 300 k and after compression to 1907 kpa it is cooled to 376.6 K. The cooled air then enters the heat exchanger

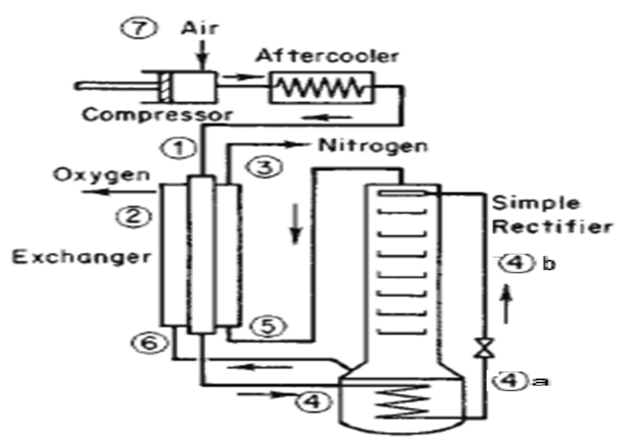

Figure 1: Flowchart of simple air separation (Case 1). Source: Perry and Green (1997) [9].

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at 1907 kpa and thereafter into a distiller at 101 kpa and 1289 K. The distill at the bottom goes back into the heat exchanger to give oxygen product at the rate of 294.96 K and 101 kpa. Some of the bottom products passes through the valve to the top of the distiller at 79.2K and 101 kpa before it passes through the heat exchanger to give nitrogen product at 295 K and 101 kpa. The surrounding temperature is assumed to be 300 K.

The Linde Air separation Process (LASP) for Case 2 was taken from Braimah M.N [8] and is shown in Figure **2**. It is a modification of the base case with the replacement of the valve with a turbine.

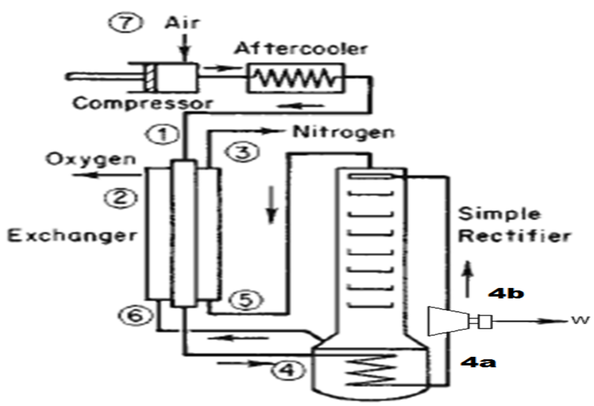

Figure 2: Flowchart of simple air separation (Case 2). Source: Braimah M.N (2011) [8].

3. MATERIALS AND METHOD

3.1. Simulations

Simulation of the LASP plant was done at specified operating conditions using HYSYS 3.2 process simulator software [10]. The lost work and exergy analyses were done using Microsoft EXCEL spreadsheet. HYSYS [10] simulation software was used to simulate the air separation plant process in order to generate the temperature, pressure, mass flow, molar flow, specific entropy, compositions and design parameters for different units. The simulation diagrams are as shown in Figures **3** and **4**.

3.2. Exergy Analysis

Three governing equations are normally used in energy-exergy analysis of open systems, they are; conservation of mass equation, conservation of energy equation and exergy balance equation [11-13]. When an open system is considered, the mass, energy and exergy balance equations over a control volume, respectively, are [14]:

$$\sum \dot{m}_i = \sum \dot{m}_o \quad (1)$$

$$\sum \dot{E}_I + \dot{Q}_{cv} = \sum \dot{E}_E + \dot{W}_{cv} \quad (2)$$

Where $_I$ is inlet, $_E$ is the exit, $\dot{E}$ is the energy rate (kJ/h), $\dot{Q}$ is the heat transfer rate (kJ/h), $\dot{W}$ is the work (kJ/h) and cv is the control volume. The mass and conservation of energy equations (1) and (2) was incorporated into HYSYS simulator package. The exergy losses and total exergy flow is expressed in equation (3).

$$\sum \dot{E}x_I + \sum_j \left(1 - \frac{T_o}{T_j}\right) \dot{Q}cv = \sum \dot{E}x_E + \dot{W}cv + \dot{I}xcv \quad (3)$$

The exergy efficiency is estimated using equation (4) as;

$$\text{Exergy Efficiency} = \frac{Ex_{sink}}{Ex_{source}} \times 100 \quad (4)$$

3.3. Process Cost Analysis

In improving the exergy efficiency of any process plant it is expected that the plant could require additional expenses from equipment procurement, maintenance and operation. In order to substantiate the choice of process scheme from the existing alternatives, equipment costing, cost of raw material, cost rate due to process operation and maintenance are evaluated, and annual venture profit are used as economic indicator.

There are two major cases in air separation;

Case 1: The process units in this case are; (Parameters gotten from Coulson and Richardson [15]). Details as shown in Appendix **A**

Compressor cost = Cost × (Power of the driver)^n

Cost of cooler = bare cost of cooler × pressure factor × type factor

Cost of LNG exchanger = bare cost LNG exchanger × pressure factor × type factor

Cost of distiller = bare cost of distiller × pressure factor × type factor

The total equipment cost = Cost of Compressor + Cost of Cooler + Cost of Heat Exchanger + Cost of Distiller

Total physical plant cost = 3.40 × Total equipment cost

Fixed capital = 1.45 × Total physical plant cost

Working capital = 0.1 × Fixed capital

Total investment = Fixed capital + Working capital

Case 2: The process units in this case are the same as that of case 1 with the addition of a turbine.

Turbine cost = Cost in Coulson and Richardson [15] × $(\text{Size})^n$

Utility cost is estimated from working capital.

The total cost = Equipment cost + Installation + Working capital

Revenue = Cost of final product – Cost of raw materials

The calculation for the cost of raw materials and that of final products are shown in Appendix **B**.

Profit = Revenue – Total Cost

4. RESULTS AND DISCUSSION

4.1. Process simulation

The process flow diagrams generated by the simulation of base case and modified case are presented in Figures **3** and **4**. The simulation was validated by comparing the results obtained in the base case with the literature results and it is exciting to note that both the simulation and the literature results were the same for the base case [9].

4.2. Analysis of Air Separation

The result of the exergy analysis of the overall plant for the two cases of air separation are presented in Table **1**.When the valve in base case 1 was replaced with a turbine it gave a better efficiency which was case 2. Case 2 gave the best overall exergy efficiency with almost 3.6 times better than the base case 1.

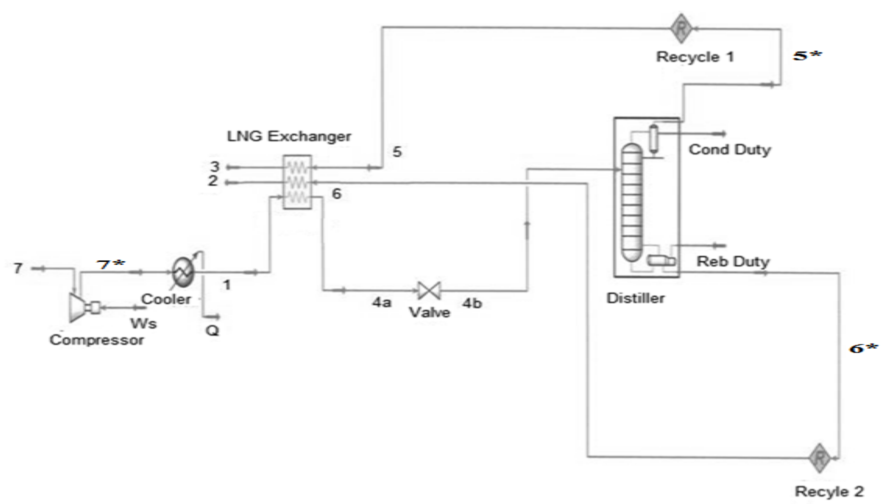

Figure 3: Case 1 (simulation diagram of the base case of air separation).

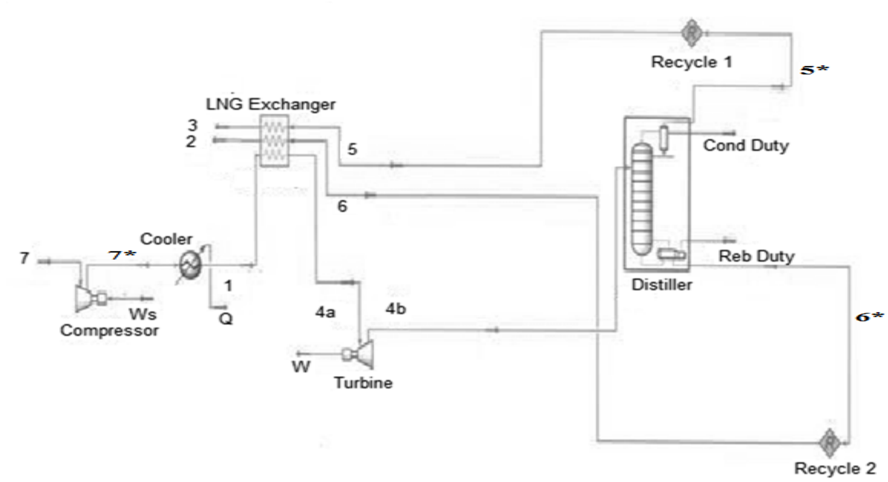

Figure 4: Case 2 (simulation diagram of the base case of air separation with the replacement of a valve with a turbine).

Table 1: Exergy Analysis of the Overall Plant for the Two Cases of Air Separation

Overall Plant	Energy loss (kJ/h)	Energy Efficiency (%)	Exergy Loss (kJ/h)	Exergy Efficiency (%)	Lost Work (kJ/h)	Irreversibility (%)
Case 1	0.00	100.0	19.47	3.23	19.79	2.6
Case 2	0.00	100.0	17.27	11.65	20.92	11.06

Table 2: Cost of Air Separation Process

Cases	Total Cost ($/yr)	Revenue ($/yr)	Profit ($/yr)
Case 1	474,116	49,292,579	48,818,463
Case 2	512,190	50,997,241	50,485,051

4.3. Analysis of Process Plants Cost

The cost analysis of air separation processes are presented in Table **2**.

In Table **2**, when the costs of each process plants were compared, the profit is better if case 2 is adopted. The profit is 1.03 times the profit of the base case. This shows that the base case actually needs improvement and when the profit was used as economic index the replacement of the valve with a turbine will give a better design option in the production of medical gas.

CONCLUSION

It was concluded from exergy and process cost analyses of Linde Air separation Process that there is need for improvement in the existing plant. Additionally, replacing the valve with the turbine could greatly give a better air separation process in terms of high purified medical air. Future research should focus on the effect of the size of the turbine and process parameters on the overall efficiency of air separation plant.

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APPENDIX A

Case 1: The process units in this case are;

1. Compressor: the type of compressor, driver power and index number are considered in the calculation.

   Compressor cost = Cost in Coulson and Richardson × (Power of the driver)^n

2. Cooler: the inlet coolant, outlet coolant, saturation temperature of the vapour, heat capacity (Q), Overall coefficient (U), heat transfer area, the material of construction were estimated from the graph in Coulson and Richardson to get the bare cost.

   Cost of cooler = bare cost of cooler × pressure factor × type factor

3. LNG Exchanger: is a special type of heat exchanger. The heat transfer area, the material of construction were estimated from Coulson and Richardson to get the bare cost.

   Cost of LNG exchanger = bare cost LNG exchanger × pressure factor × type factor

4. Distiller: the diameter, height, tray/packed space, number of trays used and material of construction are considered to get the estimate of the bare cost from Coulson and Richardson.

   Cost of distiller = bare cost of distiller × pressure factor × type factor

The total equipment cost = Cost of Compressor + Cost of Cooler +Cost of Heat Exchanger + Cost of Distiller

Estimation of fixed capital cost, reference Coulson and Richardson, for fluids processing plant.

Total physical plant cost = 3.40 × Total equipment cost

Fixed capital = 1.45 × Total physical plant cost

Working capital is estimated as a percentage of the fixed capital, 10-20%. Assuming the working capital is 10% of the fixed capital.

Working capital = 0.1 × Fixed capital

Total investment = Fixed capital + Working capital

The cost values used are based on mid-1998 and we have to convert to 2015 using equation 3.229.

Case 2: The process units in this case are the same as that of case 1 with the addition of a turbine.

1. Turbine: index number is considered in the calculation.

Turbine cost = Cost in Coulson and Richardson × $(\text{Size})^n$

The total equipment cost = Cost of Compressor + Cost of Cooler +Cost of Heat Exchanger + Cost of Distiller

Estimation of fixed capital cost, reference Coulson and Richardson, for fluids processing plant.

Total physical plant cost = 3.40 × Total equipment cost

Fixed capital = 1.45 × Total physical plant cost

Working capital is estimated as a percentage of the fixed capital, 10-20%. Assuming the working capital is 10% of the fixed capital.

Working capital = 0.1 × Fixed capital

Total investment = Fixed capital + Working capital

The cost values used are based on mid-1998 and we have to convert to 2015 using equation the equation below;

To estimate the present cost $\left(\text{Cost in year A} = \text{Cost in year B} \times \frac{\text{Cost index in year A}}{\text{Cost index in year B}}\right)$

Utility cost is estimated from working capital.

The total cost = Equipment cost + Installation + Working capital

Revenue = Cost of final product – Cost of raw materials

The calculation for the cost of raw materials and that of final products are shown in Appendix B.

Profit = Revenue – Total Cost

APPENDIX B

Air Separation Process

Basis: 10,000kg/hr of air feed.

Stream Data:

Case 1:	8300 kg/hr of nitrogen
	1700 kg/hr of oxygen
Case 2:	8650 kg/hr of nitrogen
	1350 kg/hr of oxygen

Cost Data:

Nitrogen: $ 1/liter

Oxygen: $ 0.176/liter

Density Data:

Oxygen = 1.4290 kg/m^3

Nitrogen = 1.2506 kg/m^3

Annual Cost of Materials:

Case 1:	Nitrogen $47,785,063/yr
	Oxygen $1,507,516/yr

Total: $49,292,579/yr

Case 2:	Nitrogen $49,800,096/yr
	Oxygen $1,197,145/yr

Total: $50,997,241/yr

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