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Review Article

Proposed Transformation Flow Sheet of a Single Column Cryogenic Air Separation Process Utilizing LNG Cold Energy

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Abstract: In this study a transformation flow sheet of a single column cryogenic air separation is proposed, the air separation process utilizes the LNG re-gasification cold energy, the transformation flow sheet shows the main actions happens in each unit operation in the process, these action are whether desired, undesired, corrective or transport transformation, this transformation flow sheet helps for better understanding of the process and also helps to investigate the weakness and improving the design.

Keywords: Transformation flow sheet; cryogenic air separation; LNG cold energy.

ABBREVIATIONS

DS	distillation system
LNG	liquefied natural gas
LTRS	LNG thermal recovery system
M-Com	main compressor
MHX	main heat exchanger
M-LHGHX	main LNG heat exchanger
N_2-Com	nitrogen compressor

1. INTRODUCTION

Air separation units are widely used industry, the pure oxygen and nitrogen produced have several uses, they are also used in many industries such as steel industry, semiconductor, aeronautical, food processing, medical industries and oil refinery, therefore air separation units are often combined with other processes, and from energy point of view some kind of integration should be found.

Liquefied natural gas (LNG) should be re-gasified before it used in the final destination, the LNG during re-gasification has a great potential for cold energy, and this cold energy can be used in various applications such as power generation, material freezing and sea water desalination.

As the temperatures required for the air separation process (-183.15 to -173.15 oC) are lower than the temperature of LNG (-163.15 oC), the cold energy of LNG can improve the air separation system efficiency (Mehdi Mehrpooya 2015), utilizing the LNG cold energy has an environmentally beneficial due to the large reduction of the number of electrically driven mechanical refrigerators. Additionally, the large amount of cold energy released from the LNG to gasify is greatly shortens the start-up time, also it has a remarkable affect on the production efficiency, exergy consumption, and operation cost.

There are two common scenarios for the utilization of the cryogenic energy of the LNG in the air separation processes, the first scenario is to find and way to transfer the cold air separation products “typically nitrogen as it an inert gas and it lowers hazard when contact with NG”, this generally enhance the process efficiency and produce liquid products as done by (Xiong YQ 2014), (Anselmini JP 1975) and (Ogata S 1980) .

The second scenario is to use the cold energy of the LNG for power production; this can be achieved either by using the LNG as the working fluid in natural gas direct expansion cycles, or by utilize the cold as the

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heat sink in closed Rankine cycles (Lee U 2014), Brayton cycles (Agazzani A 1999), Stirling cycles (Dong H 2013) and combined cycles that exploit more than one of these (P 1997).

In this study an air separation process utilizing the cold energy of LNG and flow the second scenario is analyzed with the aid of the transformation flow sheet (TFS). This helps improving the understanding of the various factors affecting each unit operation; TFS is a document that describes the chemical and physical changes that occur during conversion of raw materials into finished product. A TFS is generated during the process development or when new knowledge is gained about existing processes, it promotes a more fundamental understanding of what must occur as raw materials are converted to finished product, resulting in better and smarter process designs.

2. Transformation Flow Sheet

A transformation means any change which occurs in the unit operation, it describe the action happens, for example the transformation in the reactor is reaction and for mixture is mixing. This is known as the first level transformation, which is very general and not detail enough to define your process, but they may be adequate for a first cut TFS.

The second and the third level of transformation is to go deeper in the details of the actions accrue, as mentioned above the transformation of mixture of mixing in the first stage, and in the second level should be more detailed like liquid-liquid blending, dispersion of liquids, emulsification or solids wetting, the third level is further in the detailed such as Does solid hydrate or Does solid absorb liquid in a micro-capillary structure.

Table 1: Transformation Box

Transformation Type	Transformation Box
Desired to the process	Desired
Undesired to the process	Undesired
Corrective to the process	Corrective
Transport (no material change)	Transport

In general, the first level is too broad for thorough transformation understanding, the second level is sufficient to describe many transformations, and the third level may be required for new or complex transformation about which you have little knowledge which is not the case of this study.

The transformation are evaluated by identifying them to desirable, undesirable, corrective, and transport transformations with different forms of the transformation boxes as shown in Table 1.

3. Cryogenic Air Separation Process Utilizing LNG Cold Energy

Although cryogenic air separation is a quiet mature technology, but the cryogenic air separation processes utilizing LNG cold energy still need to be analyzed for deeper understanding, most of the studies present the general idea without giving detailed process configuration.

The process will be analyzed in this study is proposed in (Zheng Jieyu 2015), Zheng et al proposed a novel single-column air separation process with the implementation of heat pump technique and introduction of LNG cold energy, the main feature that the produced nitrogen was divided into three parts, the first part is compressed and re-cooled in the main heat exchanger to recycled as reflux to the column, the second part is used to exchange heat with LNG, where electric power is produced and the nitrogen is liquefied, the third part is stored as gas. The process is simplified to proceed the transformation flow sheet as shown in Figure 1.

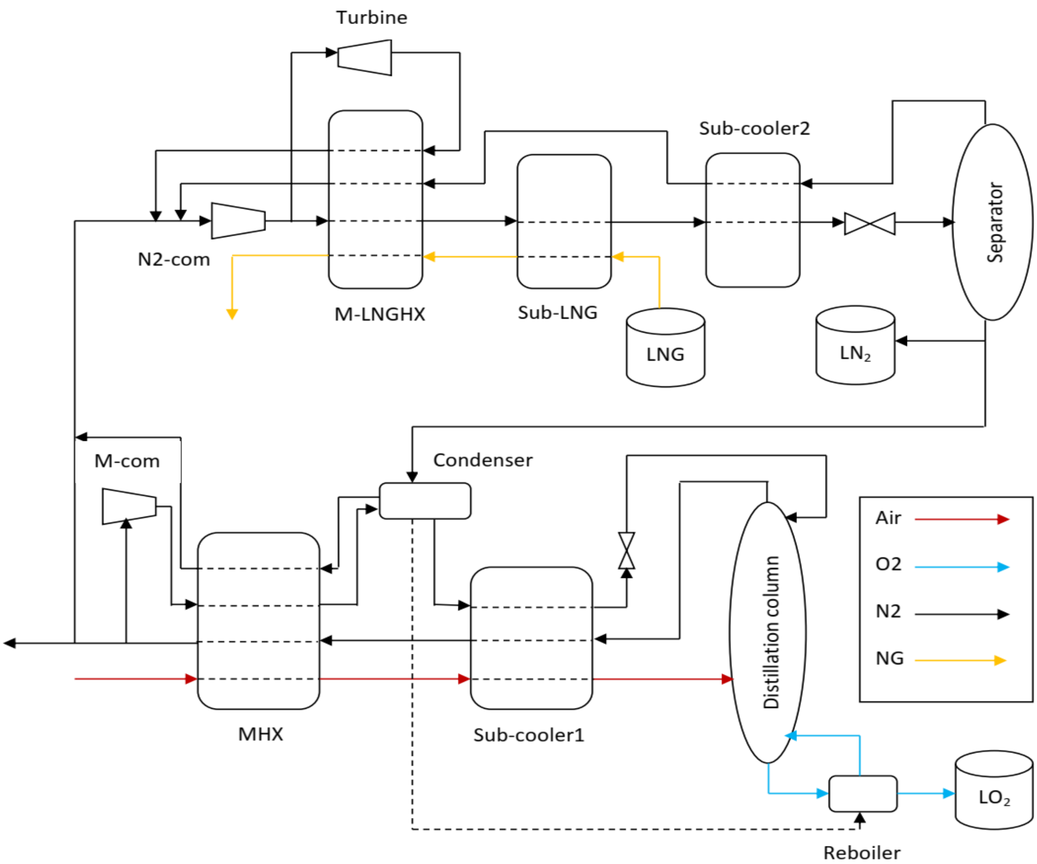


Figure 1: Single-column air separation process

4. Proposed Cryogenic Air Separation Transformation Flow Sheet

The cryogenic air separation processes utilizing LNG cold energy can be divided into two main systems, distillation system (DS), and LNG thermal recovery system (LTRS), it is also important to mention that the feed air pretreatment has been ignored. The DS section is the core of the process where air is separated to its components, on the other hand the LTRS is quite important where the cold energy of LGN is recovered and electrical power produced.

4.1 Distillation System

The transformation block diagram of the DS is shown in Figure 2, each block describes the main action happen in the each unit operation. The feed air and the recycled compressed nitrogen cooled by exchanging heat in the main heat exchanger against the produced nitrogen and cold nitrogen form the main condenser, they further cooled in sub-cooler1 against produced nitrogen, and then the compressed nitrogen is expanded before fed to column as a reflux.

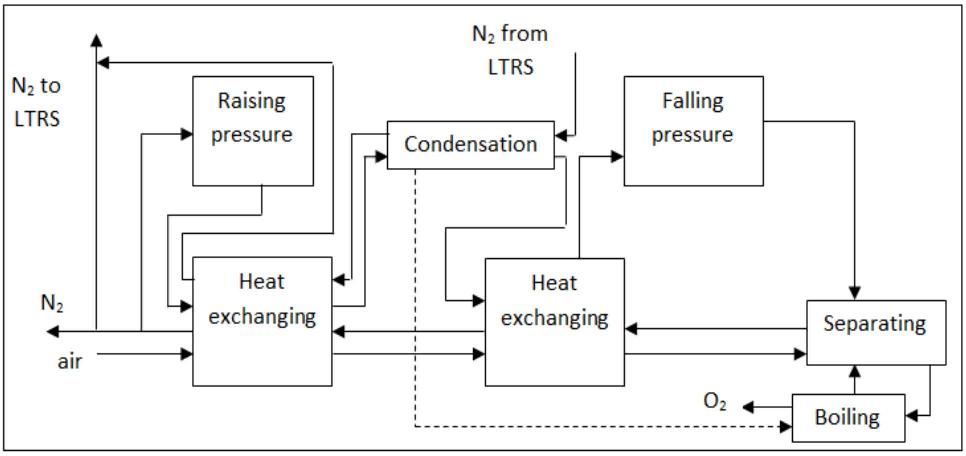


Figure 2: Transformation Block Diagram of the DS

The distillation column produced nitrogen from the top which is heated in the subcooler1 and the main heat exchanger, then divided into final nitrogen product, recycled compressed nitrogen and nitrogen to the LTRS, the LTRS nitrogen portion is liquefied and a part of liquid nitrogen is used in the main condenser to condense the recycled compressed nitrogen before fed the column, the other product from the column is the oxygen from the bottom, the detailed transformation of each unit in the DS is shown next.

4.1.1 Main heat exchanger and sub-cooler1

The heat exchanging is the transformation of the main heat exchanger (MHX) and sub-cooler1, and their detailed transformations are shown in figures (3a) and (3b) respectively, in the MHX there are two hot streams should be cooled (feed air and recycled N_2) and two cooled streams (N2 and N2 from LTRS), theses streams are same in the sub-cooler1 except the N_2 from LTRS, so cooling or heating these streams is a desired transformation.

On the other hand there are undesired transformations such as pressure falling of the compressed recycled N_2 due to friction, and the exergy losses due to temperature difference and friction, the exergy losses due temperature difference can be minimized by exchanging heat in more than one stage, and already the configuration of the MHX and the sub-cooler1 is in a series has which reduced some of the exergy losses due to temperature difference, but more staging will complicate the process, another commonly undesired transformation in sub-ambient processes is the cold energy losses to the surrounding which can be greatly minimized by well thermal isolation.

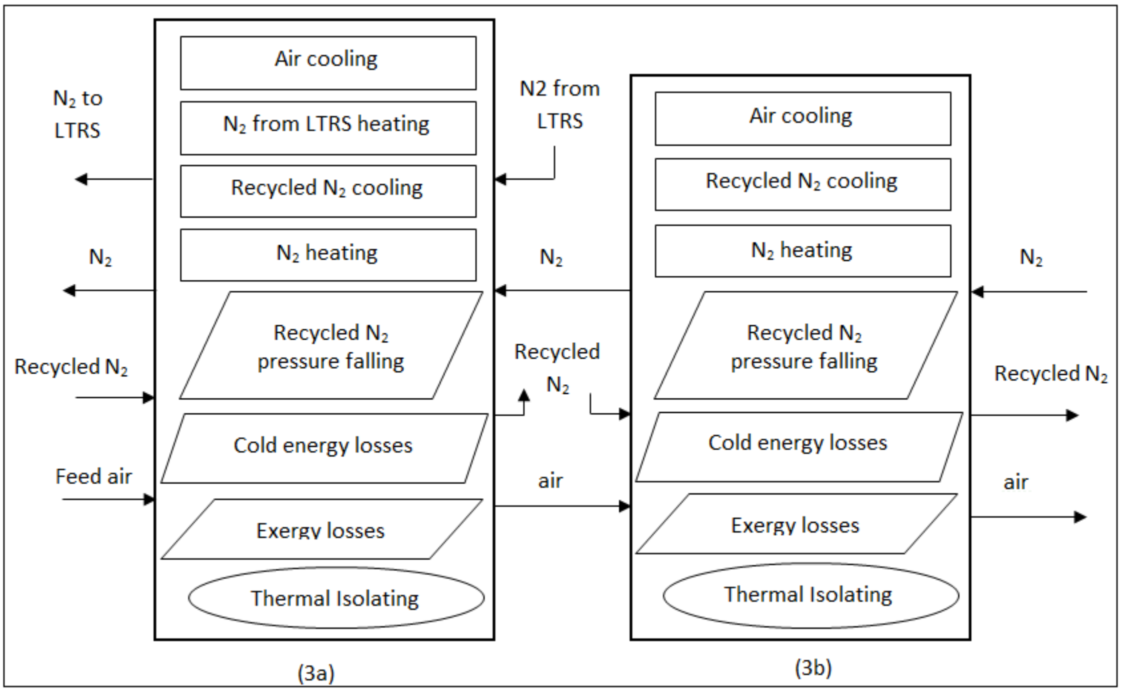


Figure 3: Transformation of the main heat exchanger (3a), and subcooler1 (3b)

4.1.2 Main Compressor and Valve

The main transformation of the main compressor (M-Com) is raising the pressure of the recycled N_2, and the main transformation of the valve which expanded the recycled N_2 before fed to the column is falling pressure, the detailed transformations of M-Com and valve are shown in Figure (4a) and (4b) respectively.

Compression - expansion technique is commonly used in low temperature processes, but it faced with the increase of temperature due to the direct proportion relation between temperature and pressure and in compression, this results in increasing the temperature of the compressed recycled N_2 which is undesired transformation, which it can corrected by inter cooling, the other undesired transformations in the compression is the exergy destruction and energy consumption, and both can be reduced by using a multistage compressor, but attention should be paid to the increasing of the capital investment of the process.

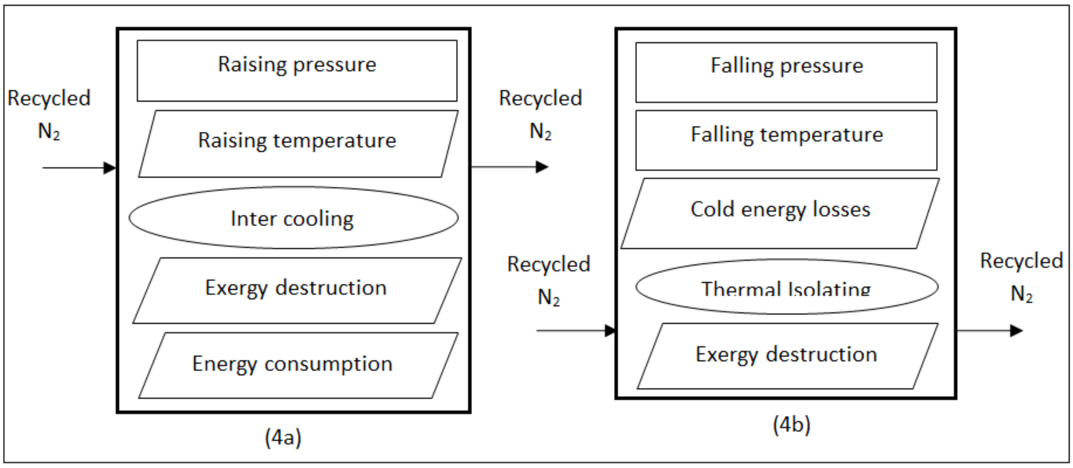


Figure 4: Transformation of the M-Com (4a), and valve prior to column (4b)

The bright side of the direct proportion relation between the pressure and temperature is clearly obvious in the pressure falling of recycled N_2 in the valve, the reduction of the temperature is highly desirable and it is the core of the compression - expansion technique, and also obtaining low temperature cause losing of cold energy to the surrounding and it can be corrected by thermal isolation also a small amount of exergy may be destroyed.

4.1.3 Single distillation column

The distillation column is the core unit in the air separation process, the separation accrue when there is a well contact between vapor and liquid phase, therefore the liquid-vapor contact can be considered as the most important transformation, as a result of this N_2 species in the liquid phase vaporized, and simultaneously O_2 species in the vapor phase condensed, so the vapor N_2 drawn from the top and liquid O_2 from the bottom and re-boiled O_2 is fed back to the column, all these above mentioned action are desired transformations in the distillation columns.

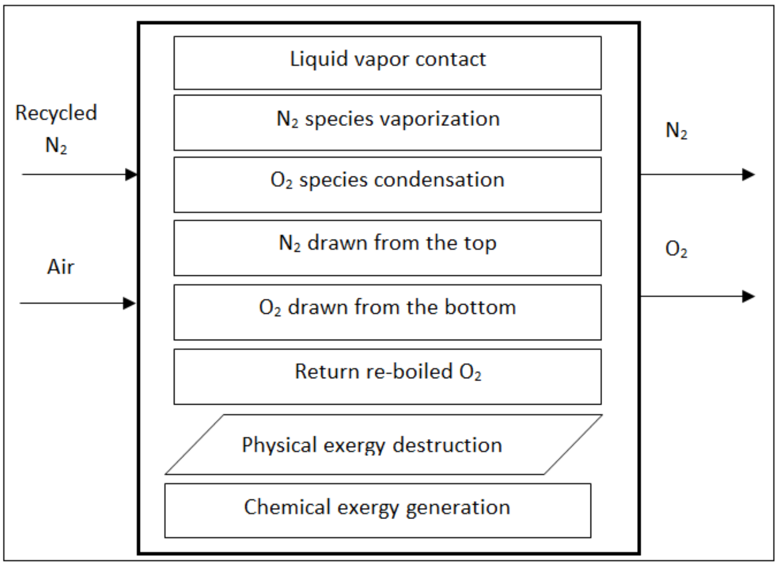


Figure 5: Transformation of the single distillation column

In the unit operations which involve changing in the component such as separator and reactor, exergy should be consider as physical and chemical exergy, so the physical exergy in the distillation column is slightly destroyed due to the pressure drop and cold temperature losses to the surrounding, but on the other hand chemical exergy of the products streams (O_2 and N_2) is higher than the feed air which is greatly desired transformation.

4.1.4 Boiler and Condenser

For any process with a distillation column, always there is a need to liquid reflux and vapor boil-up to have the liquid vapor contact, the liquid reflux to the distillation column in this study is the recycled N_2 which is condensed in the condenser against liquid N_2 from LTRS, and also heat is drawn from the condenser to the partial re-boiler, the boil-up is fed back to the column where the liquid O_2 is stored as a final product.

The condenser and boiler transformations are shown in figure (6a) and (6b) respectively.

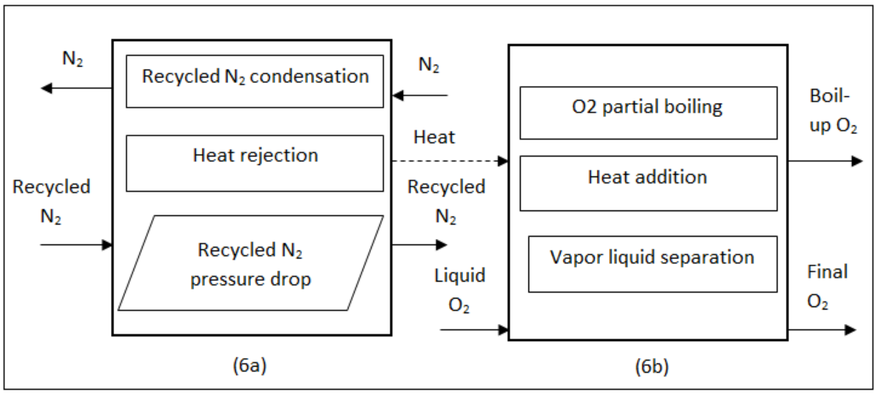


Figure 6: transformation of the condenser (6a), and re-boiler (6b)

4.2 LNG Thermal Recovery System

In the LTRS the cold energy of LNG re-gasification is utilized by exchanging the LNG with portion of nitrogen produced from the DS, therefore a set of heat exchanging is used with compressors and turbine, this is beside a liquid vapor separation vessel to collect the liquid nitrogen from the bottom as a final product and recycle the vapor nitrogen. Figure (7) shows the transformation block diagram for the LTRS.

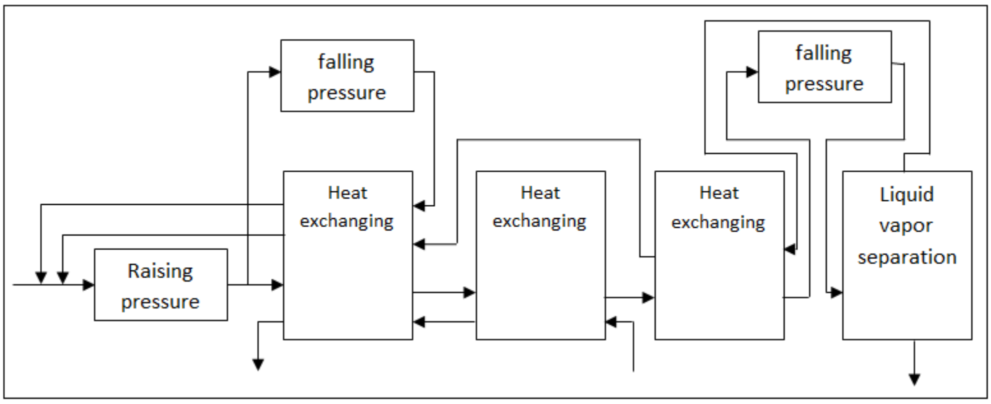
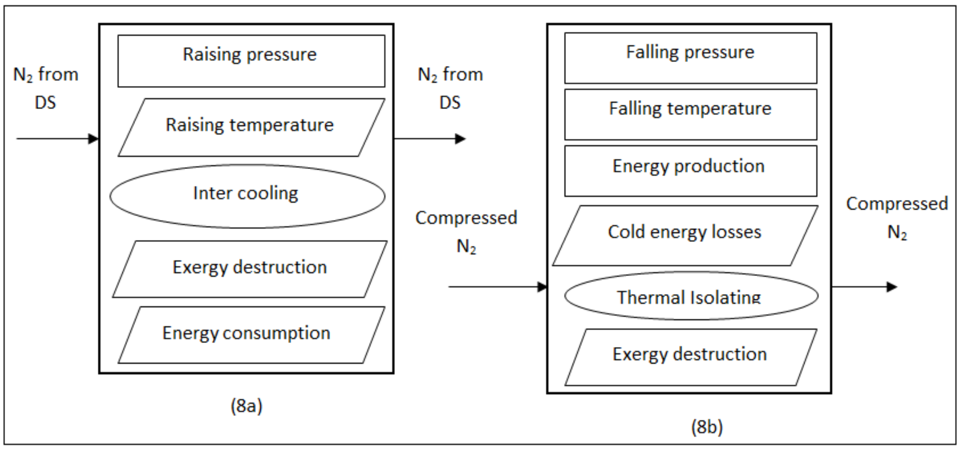


Figure 7: Transformation Block Diagram of the LTRS

4.2.1 Nitrogen Compressor, Turbine and Valve

The nitrogen compressor (N_2-com) and valve in the LTRS almost have the same transformation of m-com and valve in the DS, the difference in the existence of the turbine as a pressure change device in the LTRS, the main transformation in turbine is the falling the pressure, but unlike the valve there is an energy production from the turbine, but still there are many reasons of using the valve instead of turbine and losing the advantages of energy production.



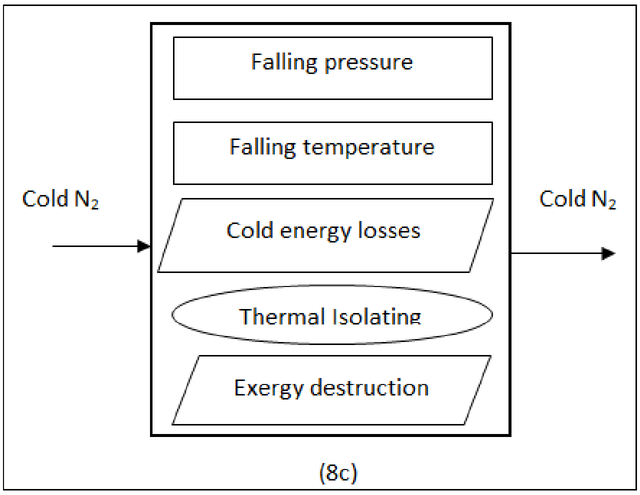


Figure 8: Transformation of the N_2-Com (8a), turbine (8b) and valve (8c)

As shown if Figure (1) the turbine working condition is in the ambient temperature, portion of the compressed nitrogen is expanded in the turbine and its temperature subsequently decreased the fed back to the M-LNG heat exchanger as a cold stream and then back to the compressor, but in sub-ambient conditions heat is more valuable than work, and the effect of isenthalpic sudden expansion is preferred than power production so valves are commonly used, and also the turbine should work in condition far from the wet zone, furthermore valve is a simple device while turbine is rotating component needs periodic maintenance, in addition to the increase to the investment cost. The transformation of the N_2-com, turbine and valve are shown in figure (8a), (8b), and (8c) respectively.

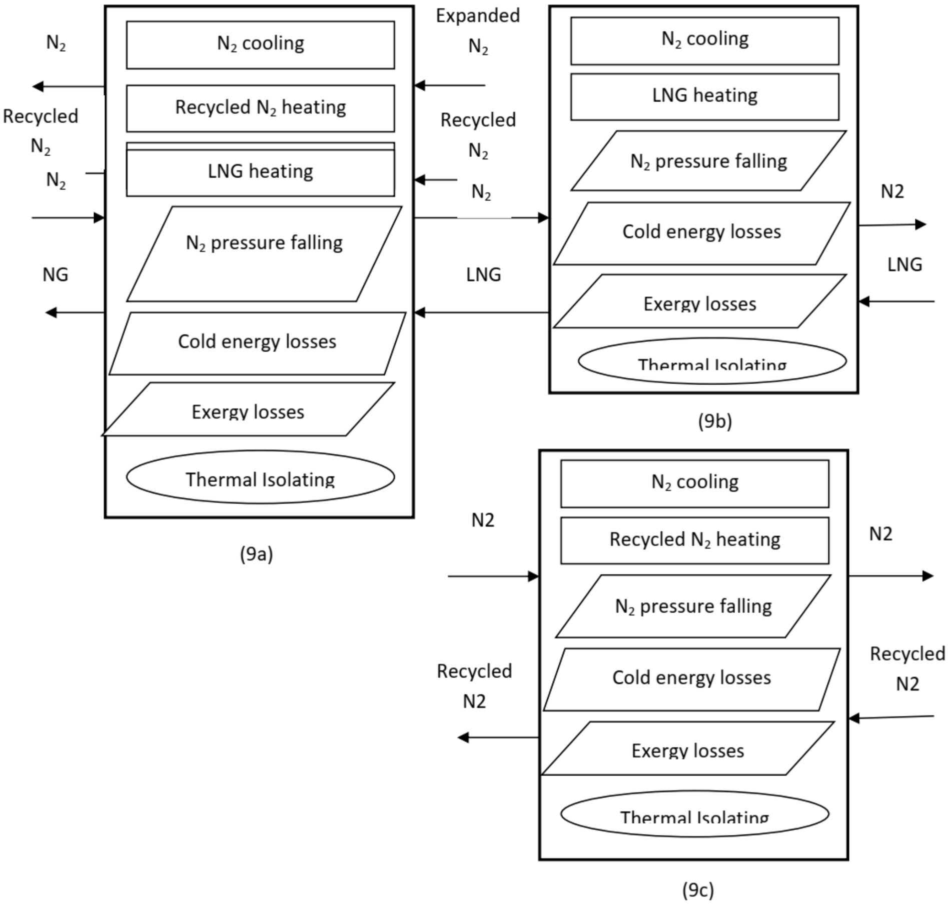


Figure 9: Transformation of the M-LNG (9a), sub-LNG (9b) and sub-cooler2 (9c)

4.2.2 Main LNG Heat Exchanger, sub-LNG and sub-cooler 2

Heat exchangers are vital devices in the LTRS, main LNG heat exchanger (M-LNGHX) is used to cool the nitrogen from DS against LNG and recycled N2, where the sub-LNG cool the nitrogen against LNG only, this series decrease the temperature difference in the heat exchanger which results in a reduction in exergy losses, finally the sub-cooler2 cool the nitrogen to the least temperature against the recycled vapor nitrogen from the separator. The transformation of the M-LNGHX, sub-LNG and subcooler2 are shown in figure (9a), (9b) and (9c) respectively.

4.2.3 Separator

The cold compressed nitrogen out of the valve is fed to the separator where liquid nitrogen drawn from the bottom and the uncondensed nitrogen collected from the top of the separator and recycled back to the process. The main transportation is the liquid vapor separation, the separation used the difference in the density between liquid and vapor, transformations of the separator are shown in Figure 10.

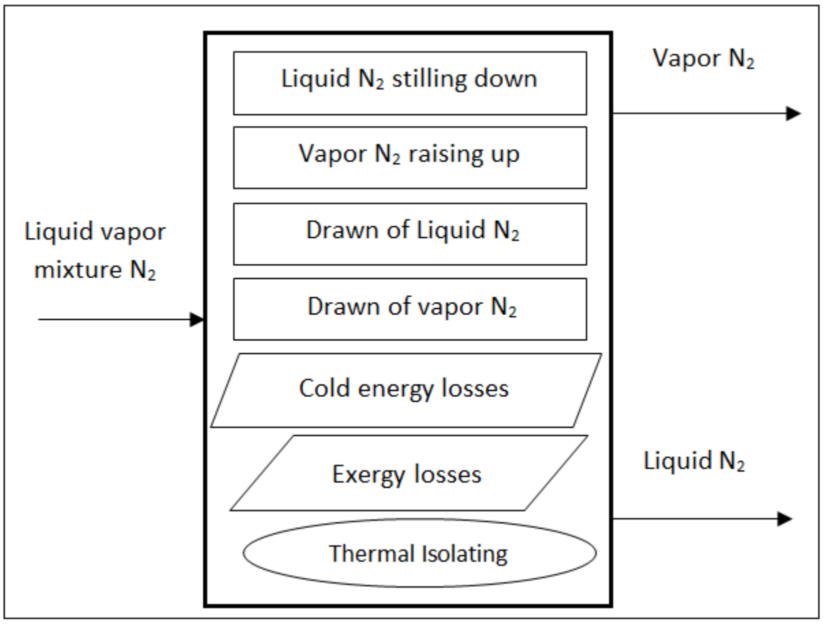


Figure 10: Transformation of the separator

5. CONCLUSIONS

The transformation flow sheet of the single column cryogenic air separation process with LNG cold energy utilization aids to conclude the flowing:

- From the second law of thermodynamic there is always an entropy generation in the real process, so each unit in the process involves exergy losses.
- The cryogenic air separation processes consider as sub-ambient process, so the cold energy is valuable and attention should be on the well isolation of the units.
- Compression – expanding technique is used to produce cold energy, and the multi stage compression will reduce the energy and exergy losses, also valves are preferred in sub-ambient conditions where turbines are more often used in above ambient conditions.
- Staging the heat exchanging by arrange the heat exchangers in series will reduces the exergy losses due the temperature difference.
- In exergy the distillation column should be considered as chemical and physical exergy.

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