STUDY OF CRYOGENIC SYSTEMS WITH ASPEN - HYSYS ANALYSYS

A PROJECT REPORT SUBMITTED IN PARTIAL FULFILLMENT
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By

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CERTIFICATE

This is to certify that the project work entitled "**Process design of Cryogenic systems with ASPEN-HYSYS Simulations**" by **Somadutta Sahoo** has been carried out under my supervision in partial fulfillment of the requirements for the degree of Bachelor of Technology during session 2009-10 in the Department of Mechanical Engineering, National Institute of Technology, Rourkela and this work has not been submitted elsewhere for a degree.

Place: Rourkela
Date:

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I would like to express my greatest gratitude and respect to my supervisor **Prof. SUNIL KUMAR SARANGI**, for his excellent guidance, valuable suggestions and endless support. He has not only been a wonderful supervisor but also a genuine person. I consider myself extremely lucky to be able to work under guidance of such a dynamic personality. Actually he is one of such genuine person for whom my words will not be enough to express.

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I would like to express my thanks to all my classmates, all staffs and faculty members of mechanical engineering department for making my stay in N.I.T. Rourkela a pleasant and memorable experience and also giving me absolute working environment where I unlashed ,my potential .

SOMADUTTA SAHOO
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ABSTRACT

The thermodynamic efficiency of any process is dependant upon following factors:

(a) The efficiency of independent components used.

(b) Operating condition i.e. variation of input parameter(like temperature, Pressure etc)

To improve the efficiency of any process, efficiency of component is fixed (it is dependant upon level of technology available and cost of equipment), thus we are left with optimizing operating condition which is under our control. This paper presents analysis of thermodynamic cycle commonly used for liquefaction of Nitrogen (N2) under given set of operating condition and efficiencies. The liquefying temperature of Nitrogen being 77.36K is taken into consideration. The cycles considered are:

(a) Simple LINDE-HAMPSON cycle

(b) CLAUDE cycle

Computer-aided process design programs, often referred to as process simulators, flow sheet simulators, or flow sheeting packages, are widely used in process design. Aspen HYSYS by Aspen Technology is one of the major process simulators that are widely used in chemical and thermodynamic process industries today. It specializes on steadystate analysis. System simulation is the calculation of operating variables such as pressure, temperature and flow rates of energy and fluids in a thermal system operating in a steady state. The equations for performance characteristics of the components and thermodynamic properties along with energy and mass balance form a set of simultaneous equations relating the operating variables. The mathematical description of system simulation is that of solving these set of simultaneous equations which may be non-linear in nature.
Cryogenics is the branch of engineering that is applied to very low temperature refrigeration applications such as in liquefaction of gases and in the study of physical phenomenon at temperature of absolute zero. The various cryogenic cycles as LINDE cycle, CLAUDE cycle etc govern the liquefaction of various industrial gases as Nitrogen, Helium etc. The following work aims to simulate the cryogenic cycles with the help of the simulation tool ASPEN HYSYS where all calculations are done at steady state and the results hence obtained.

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CHAPTER- 1

PREVIEW OF CRYOGENICS

INTRODUCTION

The word **cryogenics** means production of icy cold, but today it is synonym for low temperatures. On temperature scale there is no clear distinction where ordinary refrigeration range ends and cryogenics begins. However the **National Bureau of Standards** at Boulder, Colorado consider temperature below 123K as cryogenic operating temperature. This can be accepted because boiling temperature of permanent gases like helium (He), hydrogen (H), neon (Ne) etc are below 123K.

Cryogenic engineering deals with development and improvement of low temperature techniques, processes and equipment. It deals with utilization of low temperature phenomena. In general **cryogenic system** refers to interacting group of components involving low temperature. Examples are: Air liquefaction plant, helium refrigerators etc.

There are many textbook available regarding cryogenic systems. I have referred to **cryogenic systems** by **Barrons (2).**

Principle of Liquefaction:

Liquefaction of gases is always accomplished by refrigerating the gas to some temperature below its critical temperature so that liquid can be formed at some suitable pressure below the critical pressure. Thus gas liquefaction is a special case of gas refrigeration and cannot be separated from it. In both cases, the gas is first compressed to an elevated pressure in an ambient temperature compressor. This high-pressure gas is passed through a countercurrent recuperative heat exchanger to a throttling valve or expansion engine. Upon expanding to the lower pressure, cooling may take place, and some liquid may be formed. The cool, low-pressure gas returns to the compressor inlet to repeat the cycle. The purpose of the countercurrent heat exchanger is to warm the low-pressure gas prior to recompression and simultaneously to cool the high-pressure gas to the lowest temperature possible prior to expansion. Both refrigerators and liquefiers operate on this basic principle. In a continuous refrigeration process, there is no accumulation of refrigerant in any part of the system. This contrasts with a gas liquefying system, where liquid accumulates and is withdrawn. Thus, in a liquefying system, the total mass of gas that is warmed in the countercurrent heat exchanger is less than that of the gas to be cooled by the amount liquefied, creating an imbalance mass flow in the heat exchanger. In a refrigerator the warm and cool gas flows are equal in the heat exchanger. This results in what is usually referred to as a "balanced flow condition" in a refrigerator heat exchanger. The thermodynamic principles of refrigeration and liquefaction are identical. However the analysis and design of the two systems are quite different because of the condition of balanced flow in the refrigerator and unbalanced flow in liquefier systems.

The Joule-Thomson coefficient is a property of each specific gas. It is a function of temperature and pressure, and may he positive, negative, or zero. For instance, hydrogen, helium, and neon have negative J-T coefficients at ambient temperature. Consequently, to be used as refrigerants in a throttling process they must first be cooled either by a separate pre coolant liquid. Only then will throttling cause a further cooling rather than a heating of these gases.

Another method of producing low temperatures is the adiabatic expansion of the gas through a work-producing device such as an expansion engine. In the ideal case, the expansion would be reversible and adiabatic and therefore isentropic. In this case, we can define the isentropic expansion coefficient which expresses the temperature change due to a pressure change at constant entropy. An isentropic expansion through an expander always results in a temperature decrease. Whereas an expansion through an expansion valve may or may not result in a temperature decrease. The isentropic expansion process removes energy from the gas in the form of external work, so this method of low-temperature production is sometimes called the external work method.

HISTORICAL BACKGROUND

Till 1870s no significant developments were made in the field of field of cryogenics. It was in 1877 when Louis Paul Cailletet, a French mining engineer produced fogs of liquid oxygen droplets. In April 1883 Wroblewski and Olszewski obtained liquefied nitrogen and oxygen at the Cracow University laboratory in Poland.

In 1892 Dewar developed a vacuum insulated vessel for cryogenic fluid storage. In 1907 Linde installed the first air liquefaction plant in America. In 1908 Onnes liquefied helium. In 1916 first commercial production of Argon was made. In 1917 and 1922 first commercial production of helium and neon were made respectively. In 1933 magnetic cooling was first used to attain temperature below 1K. In the year 1937 evacuated powdered insulation was first used on a commercial scale in cryogenic fluid storage vessels.

In 1952 National bureau of Standards Cryogenic Engineering Laboratory was established. In 1958 high efficiency multilayer cryogenic insulation was developed. In 1966 dilution refrigerator using He^3-He^4 mixtures was developed. In 1975 record high super high transition temperature (23K) was first achieved.

CHAPTER- 2

GAS LIQUEFACTION SYSTEMS

INTRODUCTION:

The choice of thermodynamic cycle is made by considering the following factors:

(1) The size of the plant.

(2) Level of technology available to the manufacturer.

(3) Cost of the equipment.

(4) The cycle efficiency.

The efficiency of a process is determined by thermodynamic efficiency of the cycle at given operating condition and the performance of the components used. The latter is largely determined by level of technology available and the cost of equipment. The designer can choose optimum operating condition to maximize overall efficiency of the plant (1).

GENERAL METHODOLOGY

The general methodology of analyzing liquefaction process consists of the following steps:

(1) Identification of input (equipment and operating) and output (performance) parameters;

(2) Derivation of system equations based on conservation of mass and energy and definition of equipment efficiencies;

(3) Computation of performance (output) parameters with varying specifications of operating parameters; and

(4) Optimization of operating parameters for maximum yield or minimum specific power consumption.

The output or performance parameters are:

(1) Thermodynamic states of the working fluid at different state points on the flow chart.

(2) The liquid yield.

(3) Work of compression per unit mass of gas compressed.

(4) Specific work requirement, i.e. net work expended per unit mass of liquid output.

(5) Figure of merit (Ratio of work per unit mass liquefied to work requirement per unit mass compressed).

System performance parameters:

The following three payoff functions indicate performance of liquefaction system:

(1) Work required per unit mass of gas compressed.

(2) Work required per unit mass of gas liquefied.

(3) Fraction of total flow of gas that is liquefied.

These payoff functions are different for different gases, so we define another performance parameter as a basis of comparison of same system using different fluids. The **Figure of merit (FOM)** is such a parameter defined as theoretical minimum work requirement divided by actual work requirement for the system. It varies between 0 and 1. It measures how closely a system can approach ideal system performance.

Thermodynamically ideal system:

A system may be ideal in thermodynamic sense but not so as far as practical systems are concerned. Carnot cycle is considered to be perfect cycle in thermodynamics. Its first two processes involve: reversible isothermal compression followed by reversible isentropic expansion. Liquefaction is an open system process.

The gas to be liquefied is compressed reversibly and isothermally from ambient condition to some high pressure. Upon reversible expansion through expander, the high pressure gas becomes saturated liquid. For this high pressure must be carefully selected. The final condition is taken at same pressure as the initial pressure. For nitrogen final pressure after isothermal compression is as high as 70 GPa. It is highly impractical to attain such high temperature, so they are not considered as ideal process for practical system.

Joule-Thompson effect:

Applying first law of steady flow to expansion valve, we find zero heat and work transfer and for negligible potential and kinetic changes, we find $h_1=h_2$. But the interesting thing is flow within the valve is irreversible and not isenthalpic, but the inlet and outlet enthalpy states lie on same curve. In isenthalpic curve there is a region where we can note rise in temperature with fall in pressure and another region where net decrease in temperature results. Curve separating these two regions is an **inversion curve**.

The effect of change in temperature with an isenthalpic change in pressure is represented by **Joule-Thompson coefficient**. It is defined as derivative interpreted as the change in temperature due to change in pressure at constant enthalpy. It is the slope of isenthalpic lines. It is zero along the inversion curve. For a temperature increase during expansion it is negative and positive for decrease in temperature.

Adiabatic expansion:

This is the second method of producing low temperatures through a work producing device. In ideal case expansion is reversible and adiabatic, hence isentropic. The **isentropic expansion coefficient** expresses the temperature change due to pressure change at constant entropy.

Isentropic expansion through an expander results in temperature decrease, but through an expansion valve it may or may not result in temperature decrease. During isentropic process, energy is removed as external work; this method of low temperature production is called **external work method**. Expansion through expansion valve do not remove energy but move the molecule farther apart under influence of intermolecular forces. This is called **internal-work method**.

CHAPTER- 3

Process Design Using Aspen Hysys

Introduction to Aspen Hysys

Aspen Hysys is a process simulation environment designed to serve many processing industries especially Oil, Gas and Refining. With Aspen Hysys one can create rigorous steady state and dynamic state models for plant design, performance monitoring, troubleshooting, operational improvement, business planning, and asset management. Through completely interactive Aspen Hysys interface, one can easily manipulate process variables and unit operation topology, as well as fully customize simulation using its customization and extensibility capabilities. The process simulation capabilities of Aspen Hysys enable engineers to predict the behavior of a process using basic engineering relationships such as mass and energy balance, phase and chemical equilibrium, and reaction kinetics. With reliable thermodynamic data, realistic operating conditions and the rigorous Aspen Hysys equipment models, they can simulate actual plant behavior. Some of the important Aspen Hysys features are listed below:

I have taken the contents of introduction to Aspenhysys from hysys tutorial (4, 5).

(1) **Windows Interoperability:** Interface contains a process flow sheet view for graphical layout, data browser view for entering data, the patented Next expert guidance system to guide the user through a complete and consistent definition of the process flow sheet.

(2) **Plot Wizard:** Hysys enables the user to easily create plots of simulation results.

(3) **Flowsheet Hierarchy and Templates:** Collaborative engineering is supported through hierarchy blocks that allow sub-flowsheets of greater detail to be encapsulated in a single high-level block. These hierarchy blocks can be saved as flowsheet templates in libraries.

(4) **Equation-Oriented Modeling:** Advanced specification management for equation oriented model configuration and sensitivity analysis of the whole simulation or specific parts of it. The unique combination of Sequential Modular and Equation Oriented solution technology allows the user to simulate highly nested processes encountered typically in the chemical industry.

(5) **Thermo physical Properties:** Physical property models and data are keys to generating accurate simulation results that can be used with confidence. Aspen Hysys uses the extensive and proven physical property models, data and estimation methods available in Aspen Properties™, which covers a wide range of processes from simple ideal behavior to strongly non-ideal mixtures and electrolytes. The built-in database contains parameters for more than 8,500 components, covering organic, inorganic, aqueous, and salt species and more than 37,000 sets of binary interaction parameters for 4,000 binary mixtures.

(6) **Convergence Analysis:** to automatically analyze and suggest optimal tear streams, flowsheet convergence method and solution sequence for even the largest flowsheets with multiple stream and information recycles.

(7) **Sensitivity Analysis:** to conveniently generate tables and plots showing how process performance varies with changes to selected equipment specifications and operating conditions.

(8) **Design Specification:** capabilities to automatically calculate operating conditions or equipment parameters to meet specified performance targets.

(9) **Data-Fit:** to fit process model to actual plant data and ensure an accurate, validated representation of the actual plant.

(10) Determine Plant Operating Conditions that will maximize any objective function specified, including process yields, energy usage, stream purities and process economics.

(11) **Simulation Basic Manager**: This feature available in Aspen Hysys for using different fluids like nitrogen, air, acetylene as per requirement. Also several fluid packages like BWRS, MWRS, and ASME are provided to calculate properties at different states.

Procedure of Process Design in Aspen Hysys:

To create a new case, From the File menu, select New. In the sub-menu, select Case. The Simulation Basis Manager window will appear.

The Simulation Basis Manager is the main property view of the Simulation environment. One of the important concepts that HYSYS is based upon is Environments. The Simulation Basis environment allows you to input or access information within the Simulation Basis manager while the other areas of HYSYS are put on hold avoiding unnecessary Flowsheet calculations. Once you enter the Simulation environment, all changes that were made in the Simulation Basis environment will take effect at the same time. Conversely, all thermodynamic data is fixed and will not be changed as manipulations to the Flowsheet take place in the Simulation environment. The minimum information required before leaving the Simulation Basis manager is atleast one installed Fluid Package with an attached Property Package and At least one component in the Fluid Package.

The Components Manager is located on the Components tab of the Simulation Basis Manager. This tab provides a location where sets of chemical components being modeled may be retrieved and manipulated. These component sets are stored in the form of Component Lists that may be a collection of library pure components or hypothetical components. The Components Manager always contains a Master Component List that cannot be deleted. This master list contains every component available from "all" component lists. If you add components to any other component list, they automatically get added to the Master Component List. Also, if you delete a component from the master, it also gets deleted from any other component list that is using that component.

In HYSYS, all necessary information pertaining to pure component flash and physical property calculations is contained within the Fluid Package. This approach allows you to define all the required information inside a single entity. There are four key advantages to this approach:

(1) All associated information is defined in a single location, allowing for easy creation and modification of the information.
(2) Fluid Packages can be exported and imported as completely defined packages for use in any simulation.
(3) Fluid Packages can be cloned, which simplifies the task of making small changes to a complex Fluid Package.
(4) Multiple Fluid Packages can be used in the same simulation.

The Fluid Package Manager is located on the Fluid Packages tab of the Simulation Basis Manager. This tab provides a location where multiple fluid packages can be created and manipulated. Each fluid package available to your simulation is listed in the Current Fluid packages group with the following information: name, number of components attached to the fluid package, and property package attached to the fluid package. From the Fluid Packages tab of the Simulation Basis Manager click either the View or Add button to open the Fluid Package property view. Make sure you select the proper fluid package when using the view option. Click on the Set Up tab. From the Component List Selection drop-down list, select the components you want to use in your fluid package.

Here modified Benedict-Webb-Rubin (MBWR) fluid package was used. This model is commonly used for compression applications and studies. It is specifically used for gas phase components that handle the complex thermodynamics that occur during compression, and is useful in both upstream and downstream industries.

After selecting fluid packages and components, a process flowsheet window will appear on which the unit operations can be installed. There are a number of ways to install unit operations into your flowsheet. Many unit operations are available in the flowsheet palette. All information concerning a unit operation can be found on the tabs and pages of its property view. Each tab in the property view contains pages, which pertain to a certain aspect of the operation, such as its stream connections, physical parameters (for example, pressure drop and energy input), or dynamic parameters such as vessel rating and valve information. In steady state analysis recycler unit operations can be used to calculate the unknown parameters in the process flow diagram.

The process flow diagram (PFD) provides the best representation of the flowsheet as a whole. Using the PFD gives you immediate reference to the progress of the simulation currently being built, such as what streams and operations are installed, flowsheet connectivity, and the status of objects. In addition to graphical representation, you can build your flowsheet within the PFD using the mouse to install and connect objects. A full set of manipulation tools is available so you can reposition streams and operations, resize icons, or reroute streams. All of these tools are designed to simplify the development of a clear and concise graphical process representation. The PFD also possesses analytical capabilities. You can access property views for streams or operations directly from the PFD, or install custom Material Balance Tables for any or all objects. Complete Workbook pages can also be displayed on the PFD and information is automatically updated when changes are made to the process.

CHAPTER- 4

SIMPLE LINDE HAMPSON CYCLE

Assumptions:

(1) No irreversible pressure drops (except the expansion valve).

(2) No heat inleaks from ambient i.e. all the equipments are adequately thermally insulated.

(3) 100% effective heat exchanger is considered.

Components Used

COMPRESSOR: - It is a device used to reduce the volume of gaseous air and increase the pressure. Generally for cryogenic application compressor with high compression ratio are used. To achieve high stage compression ratio a number of compressor are used in series rather using a single compressor. It also reduces work consumption. For present work isothermal compression process is used.

HEAT EXCHANGER: - Heat exchangers are devices which transfer heat from hot fluid stream to cold fluid stream. In heat exchanger hot fluid temperature decreases and there is increase in temperature of cold fluid. By losing heat hot fluid is prepared for throttling process and similarly by gaining heat cold fluid heated up for compression process.

VALVE: - A throttling valve is used to reduce the pressure of the compressed air so that liquid air can be produced and stored. The process is assumed to be isenthalpic expansion.

SEPARATOR/DISTILLATION COLUMN: - In this chamber air is separated into desired components like liquid N2, liquid O2 etc and the gaseous part is again recirculated.

MIXER: - It is a device helps to maintain a constant flow rate of air into the compressor. The extra amount of air is added into incoming stream from separator. The process is assumed to be isobaric.

A basic differentiation between the various refrigeration cycles lies in the expansion device. This may be either an expansion engine like expansion turbine or reciprocating expansion engine or a throttling valve. The expansion engine approaches an isentropic process and the valve an isenthalpic process. Isentropic expansion implies an adiabatic reversible process while isenthalpic expansions are irreversible. In the Linde's system, the basic principle of isenthalpic expansion is also incorporated where as in Claude's cycle involves both isentropic and isenthalpic expansion procedure

Working:

(1) The gas is first compressed from ambient condition reversibly and isothermally, but in reality it is actually two processes: an irreversible adiabatic or polytropic compression followed by an aftercooling to lower gas temperature within a few degrees of ambient temperature.

(2) The gas then passes through a constant pressure heat exchanger where it exchanges energy with the outgoing low pressure stream.

(3) The gases then expand through expansion valve and send to two phase separator.

(4) Some of the gas stream is in the liquid state (are in saturated liquid condition and removed from bottom of separator) and the rest of the gas leaves the liquid receiver at saturated vapour condition.

(5) This cold gas is finally warmed to initial temperature by absorbing energy at constant pressure from incoming high pressure stream.

(6) This completes one cycle and the gas enters the compressor with some make-up gas and the cycle continues.

Applying first law for steady flow to the combined heat exchanger, expansion valve, and liquid receiver, we obtain:

$$0= (m-m_f)*h_1+m_fh_f-mh_2$$

As there is no heat or work transfer to or from surroundings for these components. Solving for the fraction of the gas flow that is liquefied,

$$m_f/m= y= (h_1-h_2)/(h_1-h_f)$$

the fraction of gas liquefied(the liquid yield) thus depends upon the pressure and temperature at ambient conditions, which fixes h_1 and h_f, and the after isothermal compression, which determines h_2 because the temperature at state point 2 is specified by the temperature at point 1.

Reversible isothermal work transfer is given by:

$$-W/m= T_1*(s_1-s_2)-(h_1-h_2)$$

Work transfer per unit mass of gas liquefied:

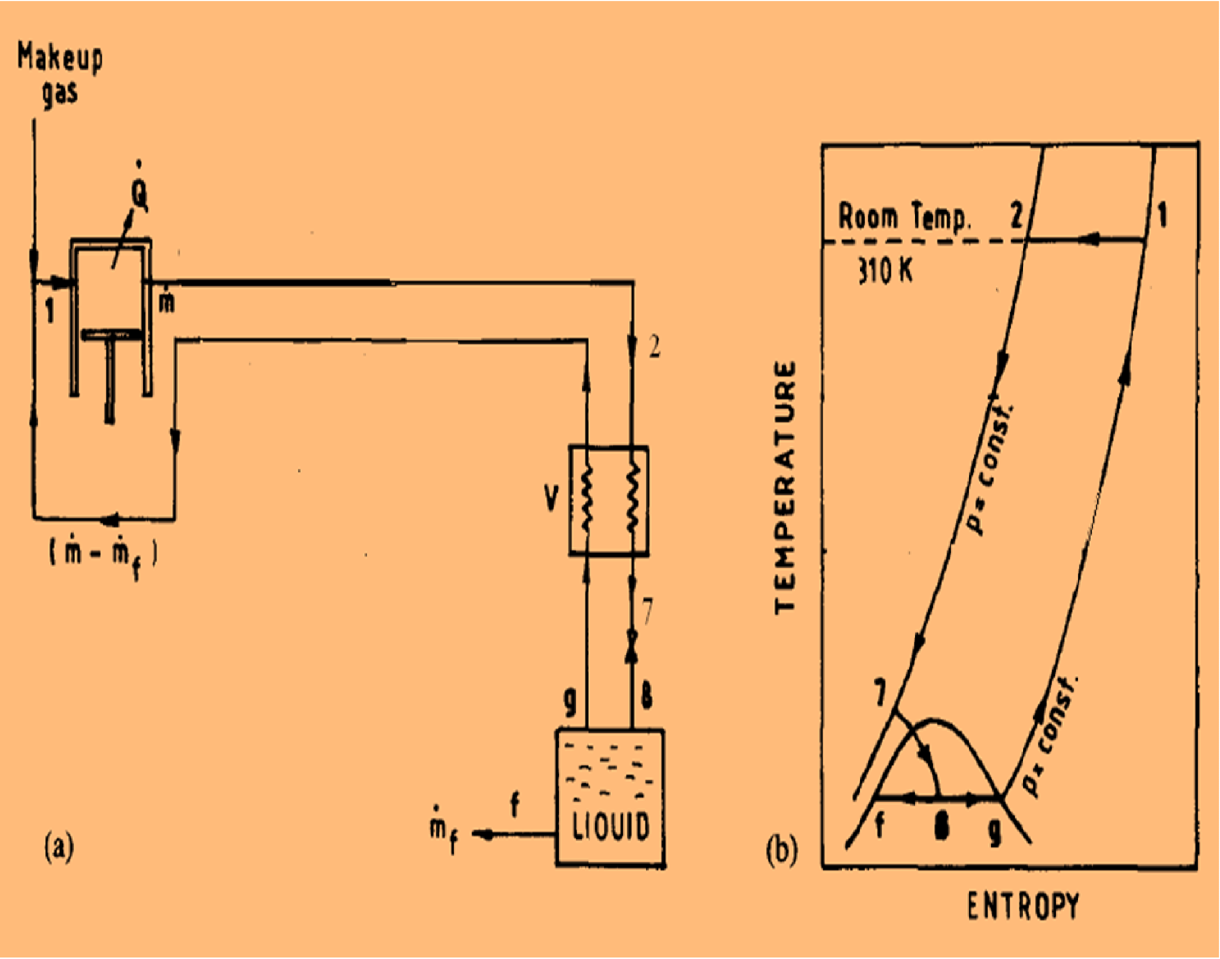
$$-W/m_f=-W/m*y= ((h_1-h_f) / (h_1-h_2))*(T_1*(s_1-s_2)-(h_1-h_2))$$

The simple Linde-Hampson system does work for gases like neon, hydrogen, helium because of following two reasons:

(1) System would never get started because maximum inversion temperature for these gases is below room temperature. There would be no heat exchange and points 2 and 3 would coincide. Expansion through expansion valve at ambient temperature fro point 3 to 4 would result in increase in temperature so that as operation is progressed, gas entering would continuously warmed rather than cooled. Therefore they would never produce lower temperature.

(2) The liquid yield would be negative as long as h1 is smaller than h2. This implies that, even if we could attain lower temperature with this system, the expansion through expansion valve at lower temperature would completely pass through vapour zone, and no gas would be liquefied.

DIAGRAM OF LINDE CYCLE:



ASPEN HYSYS SIMULATIONS

For the present study an attempt has made to simulate LINDE Cycle for liquefaction of Air and CLAUDE Cycle for liquefaction of Nitrogen. The details of two cycles are discussed below.

Example:

To represent LINDE cycle as shown in figure 2.1 using ASPEN HYSYS for the following given condition and calculate amount of liquid air is separated in the separator.

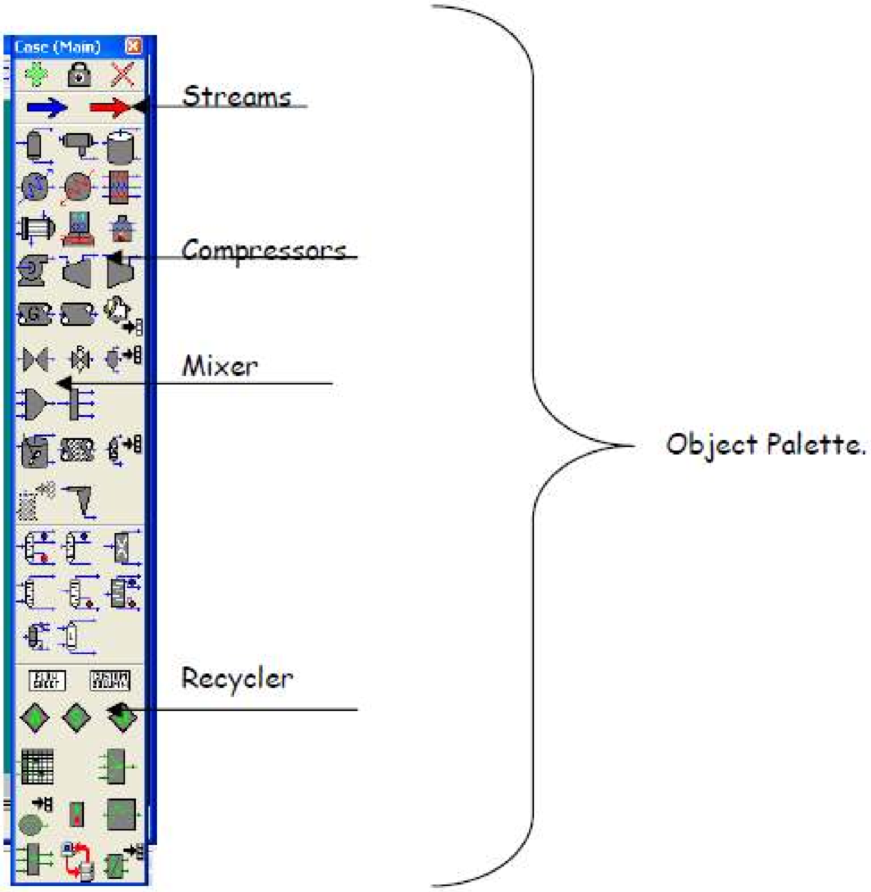
(1) Mass flow rate of air 1 kg/hr at 1 bar pressure.
(2) Compression Ratio 250:1.
(3) Inlet temperature of air 270C
(4) After throttling valve pressure drops to 1.2 bars.
(5) Isothermal compression process in compressor.
(6) Isenthalpic throttling in Valve.

Process Flow Diagram

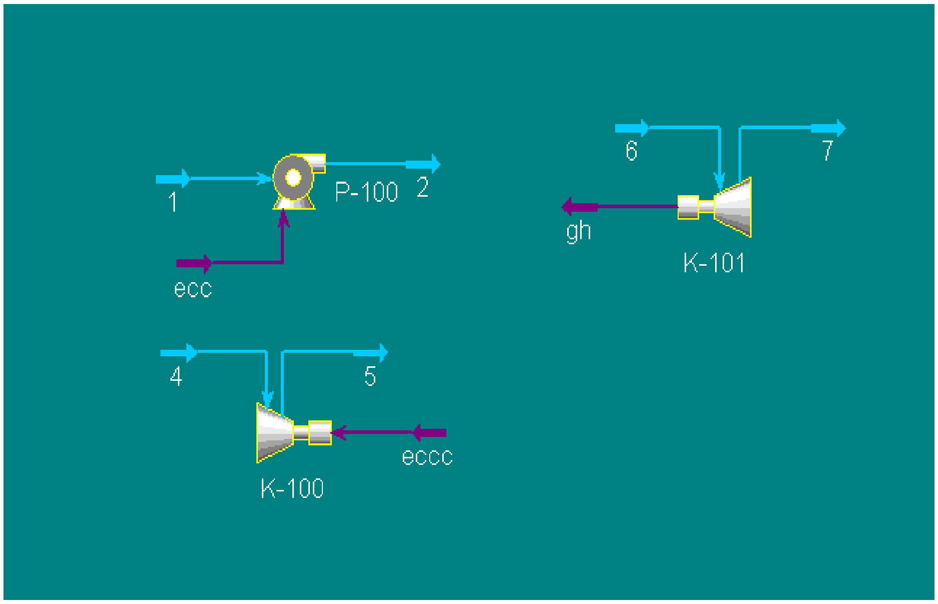
To represent above LINDE cycle in Aspen Hysys the first step is to make a process flow diagram (PFD). In Simulation Basic Manager a fluid package is to be selected along with the fluid which is to be cycled in the process. For the present work air is selected as fluid and MBWR as fluid package. Now using an option “Enter to simulation Environment” PFD screen is started. An object palette will appear at right hand side of the screen.

In the object palette a number of components available some are given below.

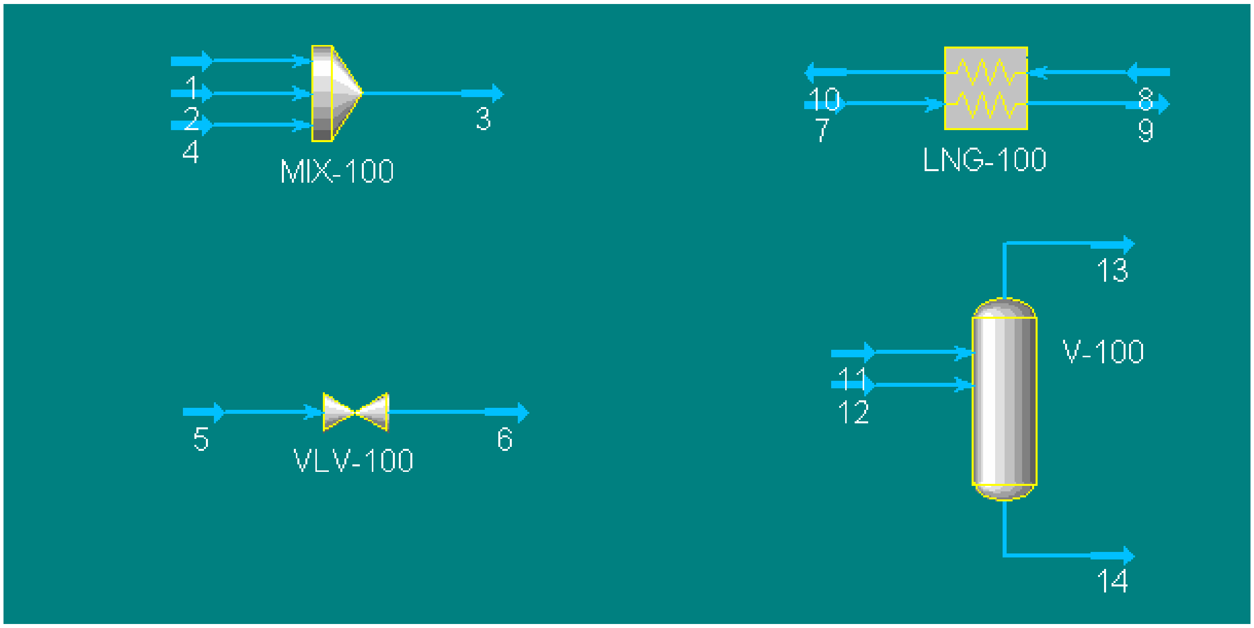
i. Streams (Material/Energy streams)
ii. Vessels (Separator and Tanks)
iii. Heat Transfer Equipments (Heat exchanger, Valves)
iv. Rotating Equipments.
v. Piping Equipments.
vi. Solid Handling.
vii. Reactor.
viii. Logical.
ix. Sub Flow sheet.
x. Short Cut Column.



Some of the components used.



Where
P-100 is a centrifugal pump.
K-100 is a compressor.
K-101 is an expander.



Where

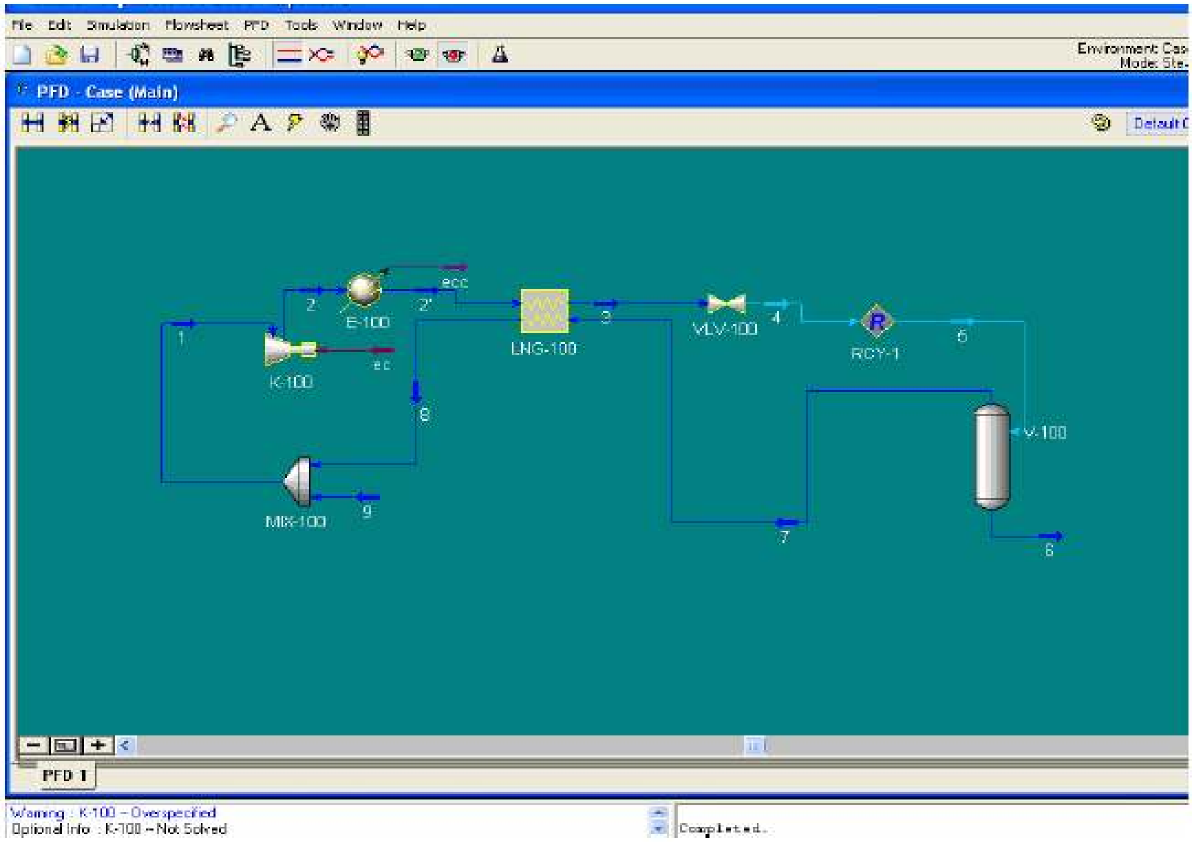
MIX-100 is a mixer.	LNG-100 is a LNG heat exchanger.
VLV-100 is a valve.	V-100 is a 3-phase separator.

For every component certain inputs are supplied as constraints for the component operation. Some of the specifications are:

(1) For streams mass flow rate, temperature, and pressure.

(2) For Compressor compression ratio, inlet and outlet streams, duty factor, adiabatic efficiency.

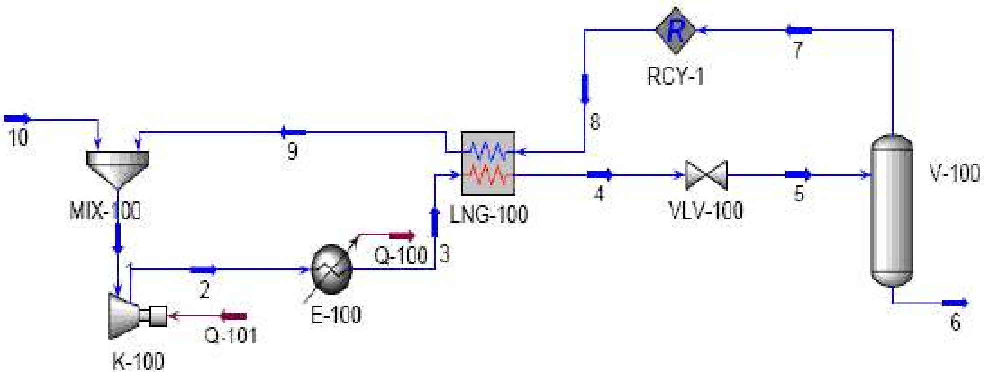
(3) For Expander adiabatic efficiency, inlet and outlet streams, and work outputs. After constraining every component properly the specific window gives a green signal and then Simulation is started. Following figure shows a partially solved process.



Warning : K-100 – Overspecified
Optional Info : K-100 – Not Solved

Completed.

Shows partially solved LINDE cycle.



Flowsheet for LINDE cycle created in Aspen Hysys.

Basic description of the flowsheet

The above flowsheet in Aspen Hysys shows the various components and the material streams needed to bring about the liquefaction of the air. It consists of a mixer, an isentropic compressor, a cooler, a shell and tube countercurrent heat exchanger, an isenthalpic J-T valve, a separator which performs flash operations and a splitter which takes care of the mass convergence problems. These components or the equipments are termed as the blocks in the language of Aspen Hysys.

The components or the blocks or the equipments

The description of the various components and the conditions at which they operate are described subsequently.

A. **Mixer (**MIX-100**)**

The outlet and the inlet pressure to be the same = 1.0 bar inside the mixture whose main purpose is to mix two incoming streams and send the outlet stream at some intermediate and equilibrium state. We consider a fresh feed stream of Air entering the mixer at 300 K and 1.0 Bar at the rate of 1 Kg/hr and also the final recycle stream entering into it at the same pressure. These two streams mix and the output stream 1 goes to the compressor. The temperature estimate is roughly given a guess of 300 K.

B. Compressor (K-100)

The compressor is modeled to be isentropic with an isentropic efficiency of 85%. The discharge pressure is 250 bars and hence a pressure ratio of 250/1.0 is considered.

C. After Cooler(E-100)

The pressurized stream that comes out of the compressor is too hot to enter into the tube side of the heat exchanger and hence an after cooler with a flash specification of 300 K temperature and 250 bars is considered. There are no pressure drops inside it.

D. Heat exchanger(LNG-100)

The heat exchanger as used in the simulation is a countercurrent shell and tube heat exchanger where the hot fluid flows through the tube side and the cold fluid through the shell side. A pressure drop of 1 bar is occurring during the flow in hot stream and 0.2 bar in cold stream. The exchanger duty is given an initial guess a minimum temperature approach of 10 K is estimated.

E. J-T Valve(VLV-100)

An isentropic J-T valve is used in LINDE cycle which works at a constant enthalpy and is such that with decrease in pressure an appreciable drop in temperature is brought about. The specification given is with a calculation type of adiabatic flash for specified outlet pressure and a pressure drop of 247.8 bars. The valid phases are vapor liquid mixture.

F. Phase separator(V-100)

For the purpose of flashing the vapor liquid mixture that comes out of the J-T valve, a phase separator is used with the flash specifications given with pressure =1.2 bar and a temperature of 90K which is just a guess value to start the iterative technique.

G. Recycler(RCY-1)

It is used for checking the convergence criteria. Generally at the place of under-constraint situation this is used to restrict the degree of freedom. After the convergence input and output conditions are with in the tolerance limit. The inputs for the various blocks were given systematically including the guess values so that all the minimum information was available and the simulation was ready to run.

Input values in hysys:

From simulation basis manager the component pure nitrogen was taken as material stream and MBWR as fluid package. Then the simulation environment was entered. There all unit operations are arranged in order and linked by material streams. For each unit operations

Following input values are entered.

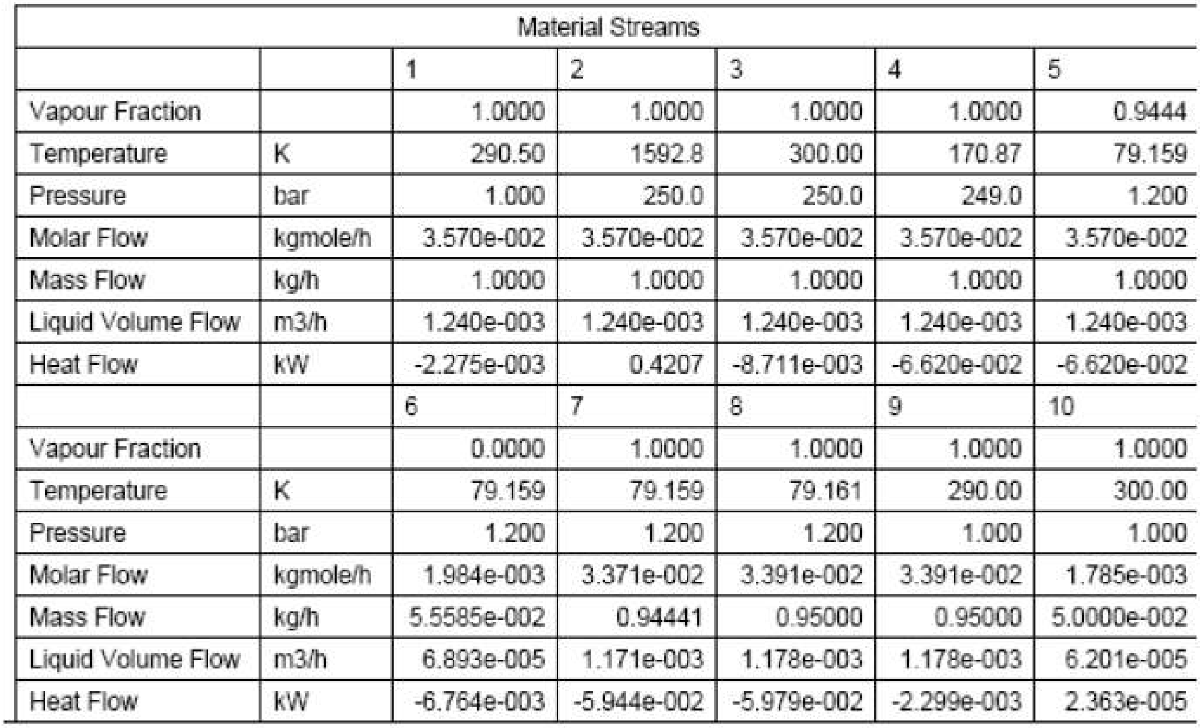
(1) **Mixer(MIX-100)**
Temperature: 300K
Pressure: 1bar

(2) **Compressor(K-100)**
Inlet pressure: 1bar
Outlet pressure: 250bar

(3) **Chiller(E-100)**
Outlet temperature: 300K
Outlet pressure: 250bar

(4) **Heat exchanger(LNG-100)**
Minimum approach: 10K
Pressure difference at hot stream: 100KPa
Pressure difference in cold stream: 20KPa

(5) **J-T valve(VLV-100)**
Outlet pressure: 120KPa



Material Streams						
		1	2	3	4	5
Vapour Fraction		1.0000	1.0000	1.0000	1.0000	0.9444
Temperature	K	290.50	1592.8	300.00	170.87	79.159
Pressure	bar	1.000	250.0	250.0	249.0	1.200
Molar Flow	kgmole/h	3.570e-002	3.570e-002	3.570e-002	3.570e-002	3.570e-002
Mass Flow	kg/h	1.0000	1.0000	1.0000	1.0000	1.0000
Liquid Volume Flow	m3/h	1.240e-003	1.240e-003	1.240e-003	1.240e-003	1.240e-003
Heat Flow	kW	-2.275e-003	0.4207	-8.711e-003	-6.620e-002	-6.620e-002
		6	7	8	9	10
Vapour Fraction		0.0000	1.0000	1.0000	1.0000	1.0000
Temperature	K	79.159	79.159	79.161	290.00	300.00
Pressure	bar	1.200	1.200	1.200	1.000	1.000
Molar Flow	kgmole/h	1.984e-003	3.371e-002	3.391e-002	3.391e-002	1.785e-003
Mass Flow	kg/h	5.5585e-002	0.94441	0.95000	0.95000	5.0000e-002
Liquid Volume Flow	m3/h	6.893e-005	1.171e-003	1.178e-003	1.178e-003	6.201e-005
Heat Flow	kW	-6.764e-003	-5.944e-002	-5.979e-002	-2.299e-003	2.363e-005

Table showing results of Linde cycle as obtained from Aspen Hysys.

***From above table amount of liquid air produced is given by column 6*.**

Mass flow rate of Liquid air: 5.558e-2 Kg/hr.

Pressure: 1.2 Bar.

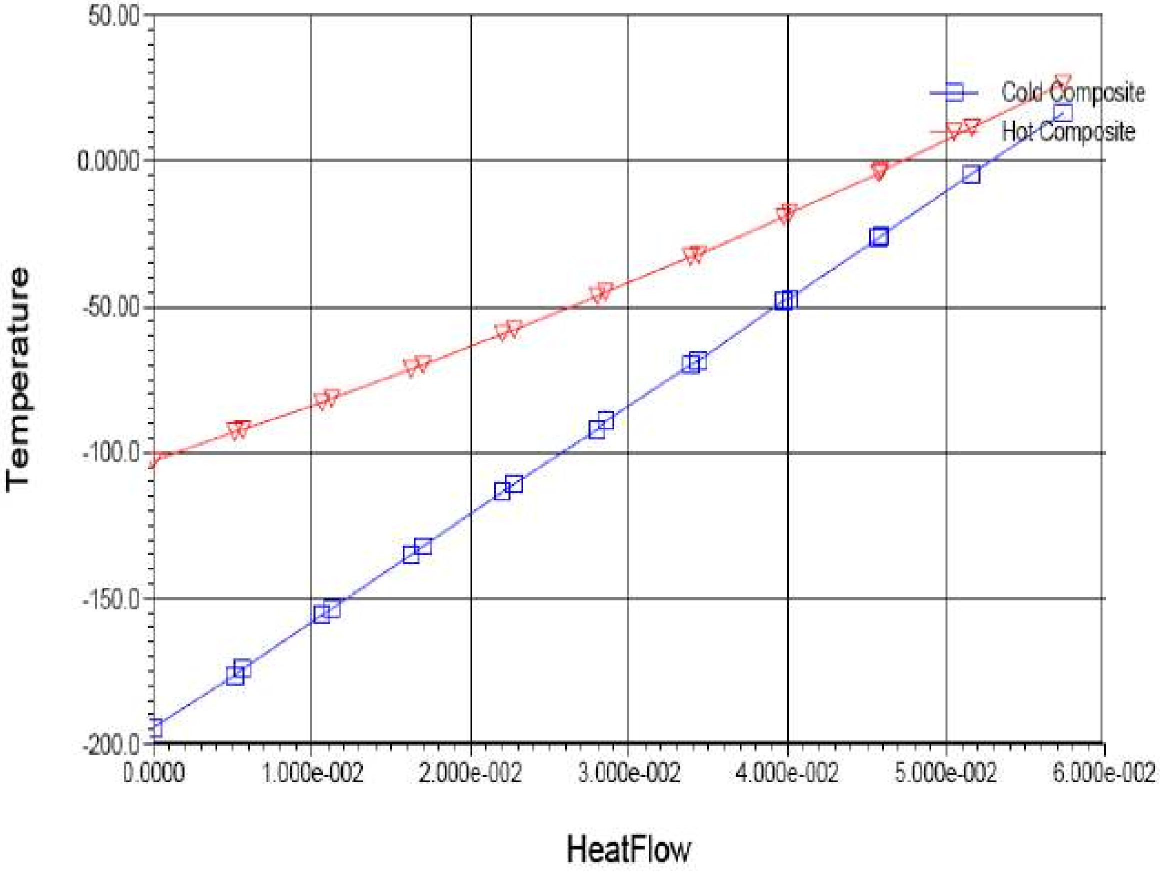
Temperature: 79.159 K.

Vapor Fraction: 0.0

Mass flow rate of Liquid air = (0.05/1.0);

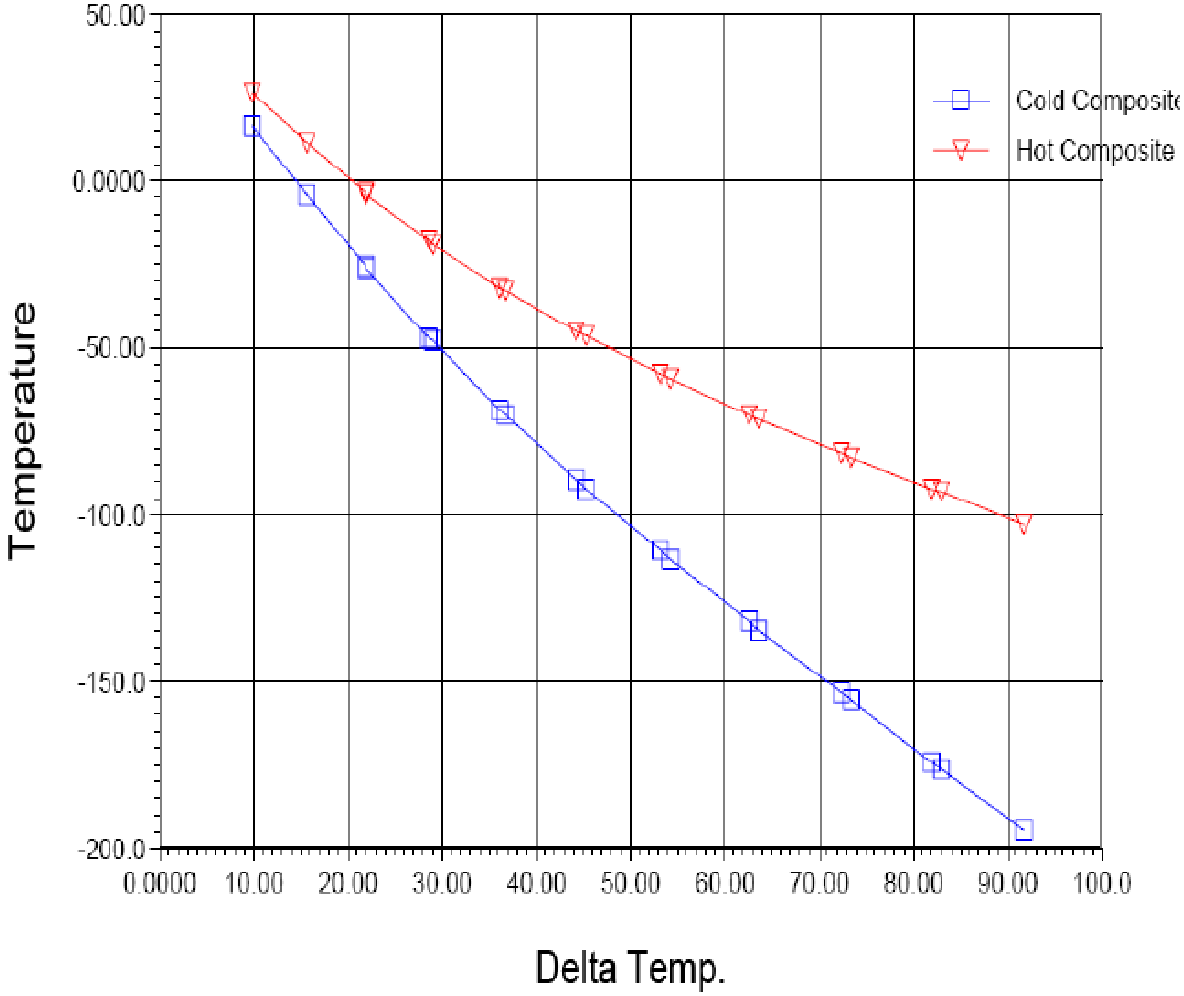
Total Mass flow rate= **5 % Liquefaction**.

(Temperature Vs Heat flow)



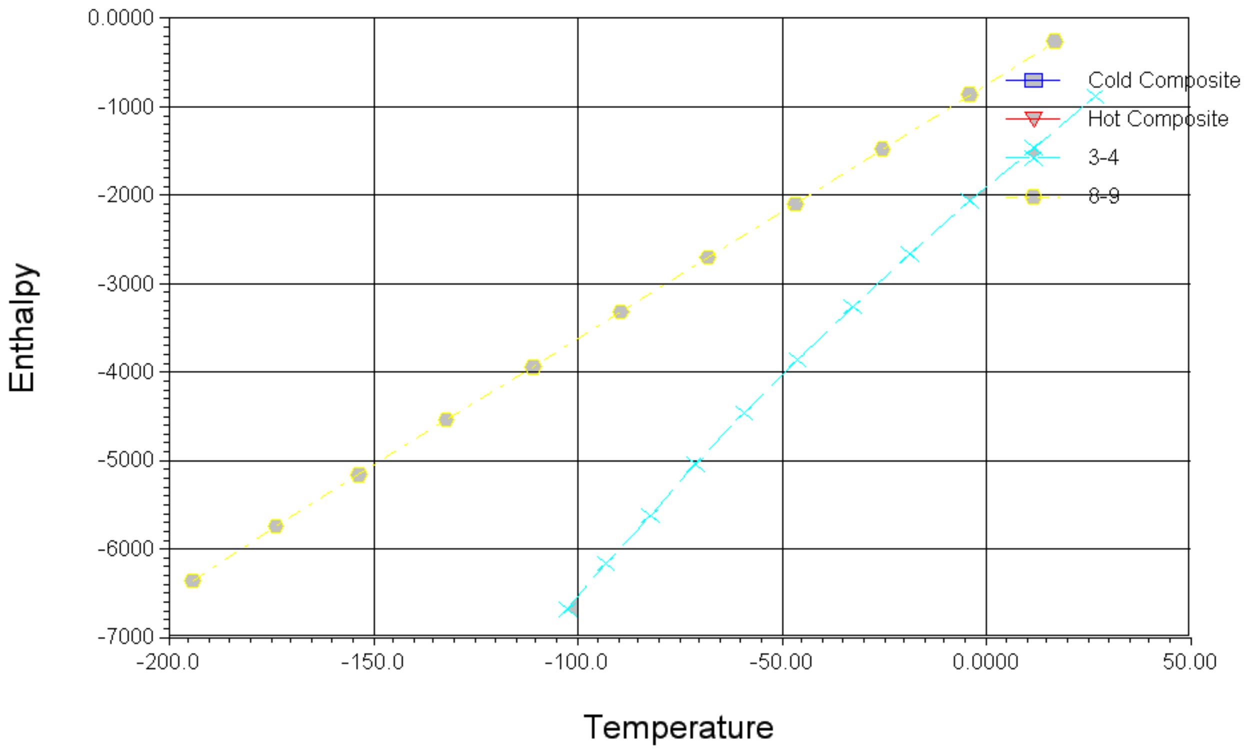
Plot showing Temp v/s Heat flow rate for Heat Exchanger.

(Temperature Vs Delta T)



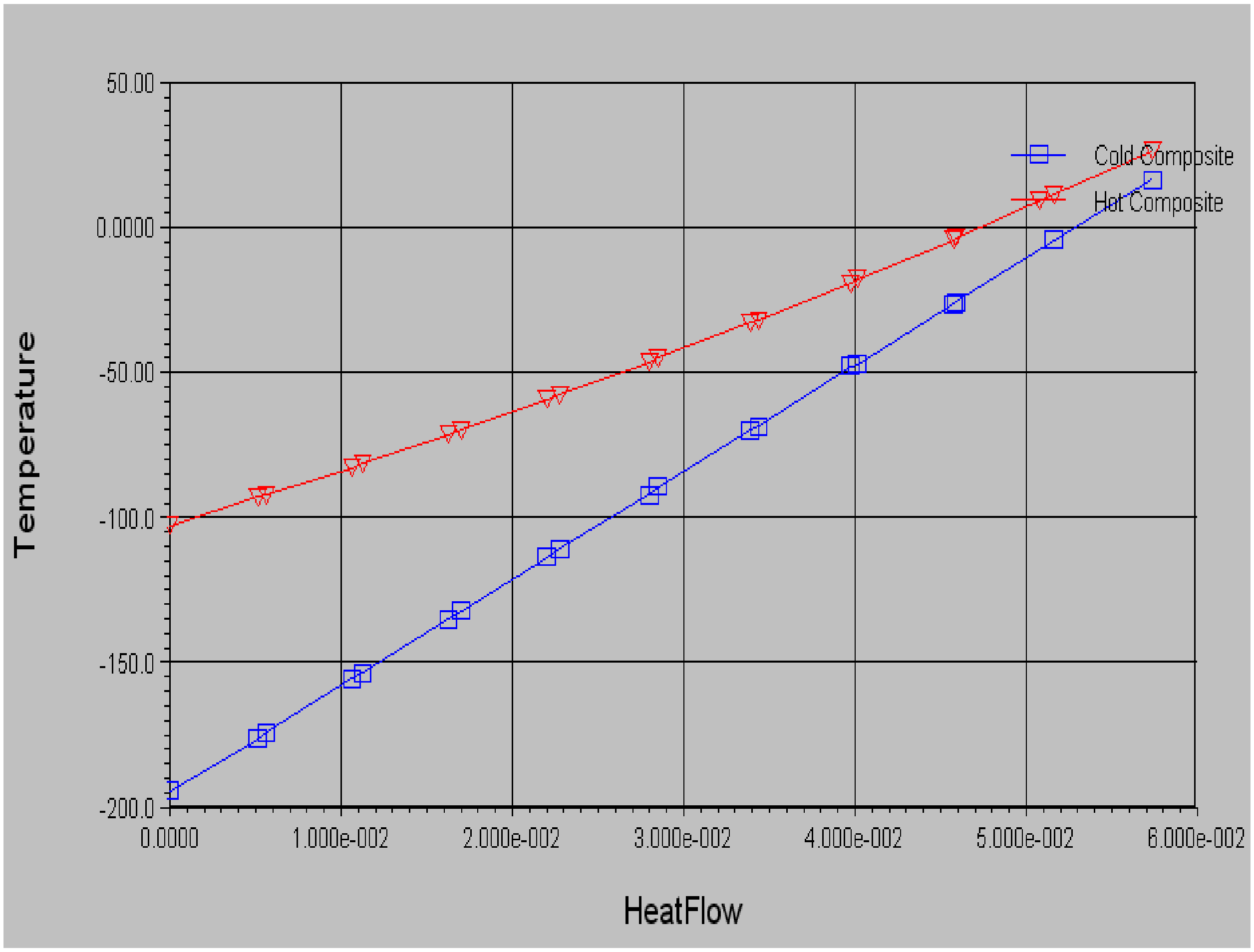
Plot showing Temp v/s Delta Temp for Heat Exchanger.

(Enthalpy v/s temperature)



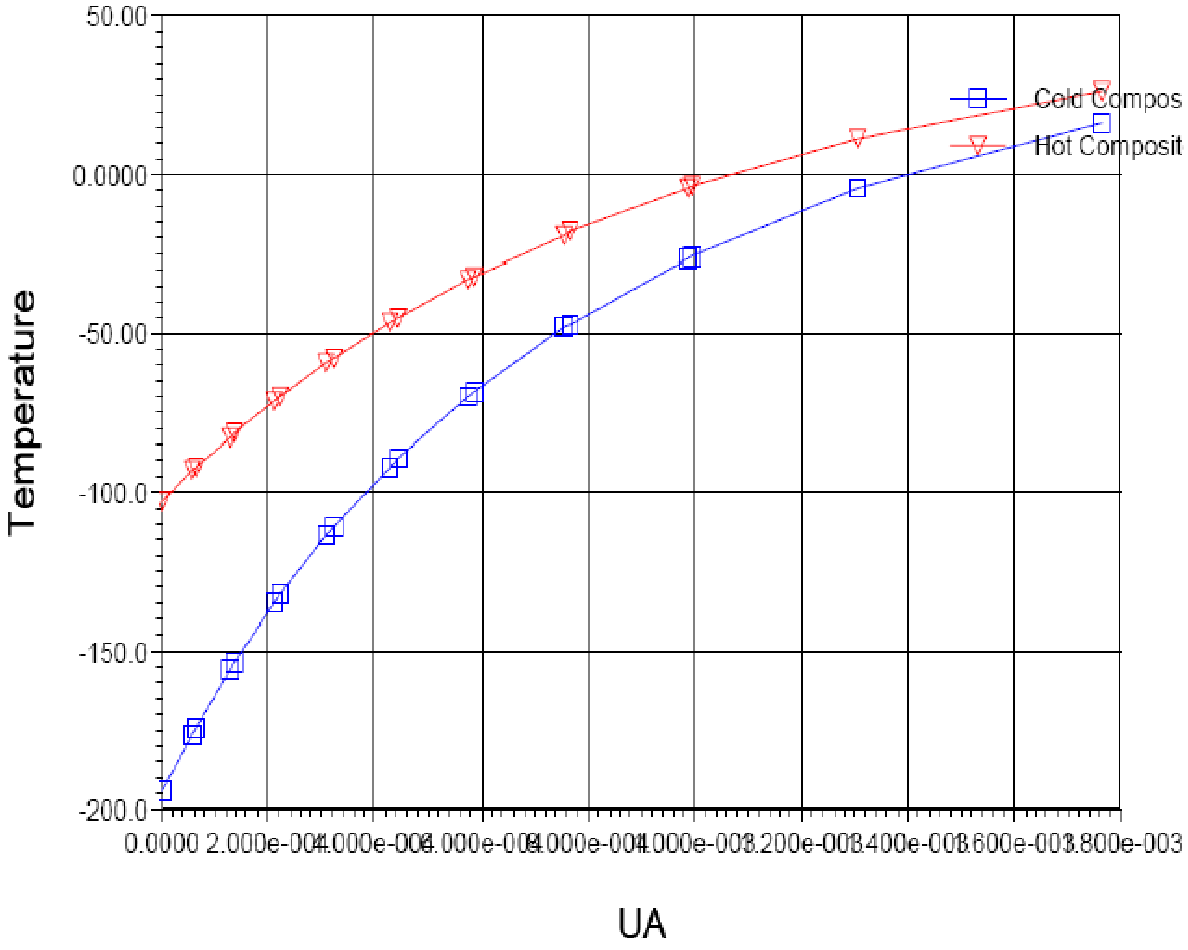
Plot showing enthalpy v/s temperature

(Temperature v/s heat flow)



Graph between temperature and heat flow

(Temperature Vs UA)



Plot showing Temp v/s Overall Conductance for Heat Exchanger.

We should always try to reduce the gap between hot air and cold air temperature. Lesser the temperature difference indicates lesser irreversibility showing increased efficiency.

At 3-8(i.e. hot air in, cold air out) efficiency is less due to larger gap between hot air and cold air and efficiency gradually increases towards the other end

Increased temperature difference also indicates increased entropy (measure of degree of randomness). Thus 3-8 has larger entropy than 4-7.

We also know that, for equilibrium energy lost by hot air is equal to energy gained by cold air

$$m_h*c_h*dT_h=m_c*c_c*dT_c$$

since $m_c<m_h$(as some gas gets converted to liquid) and assuming $c_h=c_c$, we conclude that

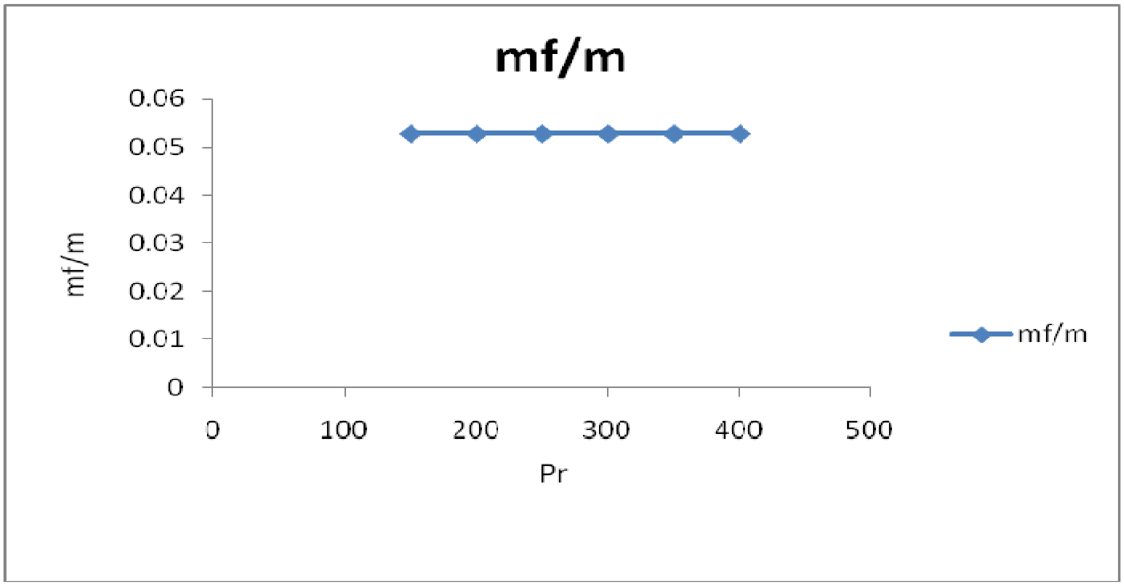
$$dT_h > dT_c,$$

which is also indicated by graph.

Enthalpy difference for hot fluid is greater than cold fluid, indicating heat loss by hot fluid is greater than heat gained by cold fluid. This is because heat exchanger is not 100% efficiency. Here the efficiency of heat exchanger is taken as 75%.

I have referred to heat and mass transfer by P.K.Nag for this explanation.

Pr	**m_f/m**
150	0.05275
200	0.05275
250	0.05275
300	0.05275
350	0.05275
400	0.05275



Energy/ mass imbalance:

Unit op name	status	mass flow(kg/hr)	Energy flow(kg/hr)	Volume flow
E-100	OK	7.200e-007	7.200e-007	7.200e-007
K-100	OK	3.600e-007	3.600e-007	3.600e-007
LNG-100	OK	1.080e-006	1.080e-006	1.080e-006
MIX-100	OK	0.0000	0.0000	-1.906e-019
RCY-1	OK	5.587e-003	-1.264	9.086e-006
V-100	OK	1.800e-006	1.800e-006	1.800e-006
VLV-100	OK	1.440e-006	1.440e-006	1.440e-006

Total flow of inlet stream: .05 kg/hr

Total flow of outlet stream: .0556 kg/hr

Imbalance: (total flow of outlet stream)-(total flow of inlet stream)=.00585 kg/hr

Relative imbalance: imbalance/(total flow of inlet stream)*100%=11.17%

CHAPTER- 5

CLAUDE CYCLE

The components or the blocks or the equipments

The description of the various components and the conditions at which they operate are described subsequently (4, 5).

(1) Mixer (MIX-1, MIX-2**):**

The outlet and the inlet pressure to be the same = 1.0 bar inside the mixture (MIX-1) whose main purpose is to mix two incoming streams and send the outlet stream at some intermediate and equilibrium state. A fresh feed stream of N2 entering the mixer at 300 K and 1.0 Bar at the rate of 0.1 Kg/s and also the final recycle stream entering into it at the same pressure. These two streams mix and the output stream 1 goes to the compressor. The temperature estimate is roughly given a guess of 300 K. In the other mixture (MIX-2) the streams coming from expander and third heat exchanger mixes.

(2) Compressor(COMPRESSOR):

The compressor is modeled to be isentropic with an isentropic efficiency of 85%. The discharge pressure is 40 bars and hence a pressure ratio of 40/1.0 is considered.

(3) After Cooler (CHILLER):

The pressurized stream that comes out of the compressor is too hot to enter into the tube side of the heat exchanger and hence an after cooler with a flash specification of 300 K temperature and 40 bars is considered. There are no pressure drops inside it.

(4) Heat exchanger (HX-1, HX-2, HX-3**):**

The heat exchanger as used in the simulation is a countercurrent shell and tube heat exchanger where the hot fluid flows through the tube side and the cold fluid through the shell side. A pressure drop of 0.1 bars occurring during the flow in each stream. The exchanger duty is given an initial guess a minimum temperature approach of 10 K is estimated.

(5) **Splitter** (TEE-100):

Stream 3 coming from HX-1 is passed through splitter which separates a definite fraction of (0.6 to 0.8) fluid from main stream and allowed to bled later stage. The remaining portion of the fluid moves through other heat exchangers. This separation helps to achieve lower temperature and desired output conditions.

(6) J-T Valve (VALVE):

An isentropic J-T valve is used in CLAUDE cycle which works at a constant enthalpy and is such that with decrease in pressure an appreciable drop in temperature is brought about. The specification given is with a calculation type of adiabatic flash for specified outlet pressure and a pressure drop of 38.4 bars. The valid phases are vapor liquid mixture.

(7) Phase separator (tank)

For the purpose of flashing the vapor liquid mixture that comes out of the J-T valve, a phase separator is used with the flash specifications given with pressure =1.3 bar and a temperature of 90K which is just a guess value to start the iterative technique.

(8) Expander (turbine):

It a rotating device used for expansion of separated fluid in the splitter. The expansion process is assumed to be isentropic. Adiabatic efficiency of expander is varied from 0.4 to 0.6 for different case studies.

(9) Recycler (RCY-1, RCY-2, RCY-3, RCY-4, RCY-5**)**

It is used for checking the convergence criteria. Generally at the place of under-constraint situation this is used to restrict the degree of freedom. After the convergence input and output conditions are with in the tolerance limit. The inputs for the various blocks were given systematically including the guess values so that all the minimum information was available and the simulation was ready to run.

Working of CLAUDE CYCLE:

(1) Gas is first compressed to pressure of the order of 4MPa.

(2) It is then passed through first heat exchanger.

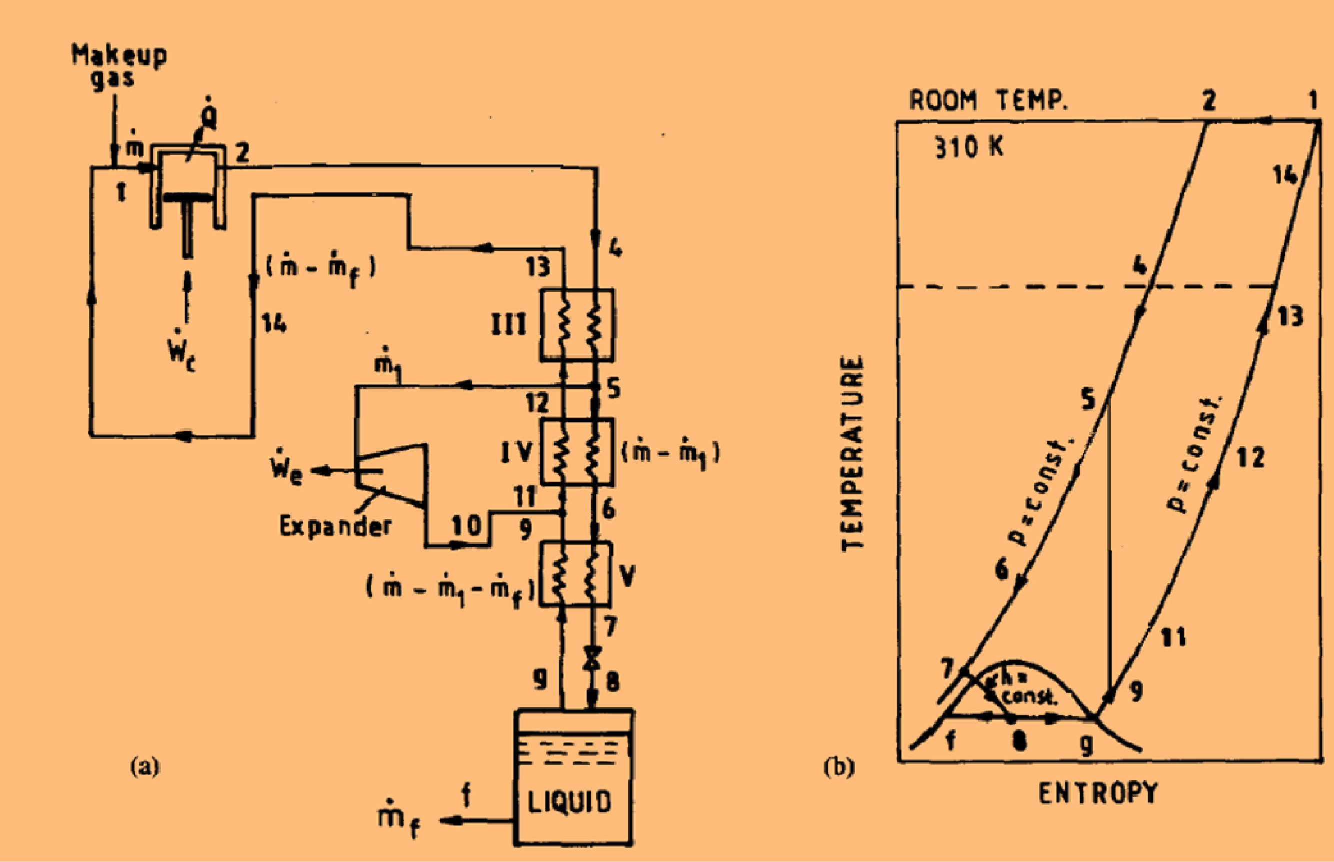
(3) Between 60-80% of gas is then diverted from mainstream, expanded through an expander and then reunited with the return stream below second heat exchanger.

(4) The stream to be liquefied continues through second and third heat exchanger.

(5) The stream is finally expanded through an expansion valve to the liquid receiver.

(6) The cold vapor from the liquid receiver is returned through the heat exchanger to cool the incoming gas.

DIAGRAM OF CLAUDE CYCLE



Applying first law of steady flow to heat exchangers, the expansion valve, and the liquid receiver as a unit, for no external heat transfer (3),

$$0= (m-m_f)*h_1+m_f*h_f+ m_e*h_e-m*h_2-m_e*h_3$$

Where

m= mass of fluid through compressor

m_f= mass of liquid obtained at two phase separator

h_1= enthalpy at the inlet of compressor

h_2= enthalpy of fluid at the outlet of chiller

h_3= enthalpy of fluid at the outlet of hot stream of first heat exchanger (HX-1)

h_e = enthalpy at the outlet of turbine

h_f = enthalpy of liquid at the outlet of two phase separator

The liquid yield is then obtained as

$$y= m_f/m= (h_1-h_2) / (h_1-h_f) + x*(h_3-h_e) / (h_1-h_f)$$

Where

$$x=m_e/m$$

If expander work does not help in help in compression then net work is same as that of Linde-Hampson system, else, it is given by

$$-W/m= (T_1*(s_1-s_2)-(h_1-h_2))-x*(h_3-h_e)$$

Example:

The inputs for the various blocks were given systematically including the guess values so that all the minimum information was available and the simulation was ready to run.

The following data are available with us:

1: Temperature of feed=300 K
2: LP=1.0 bar in the CLAUDE cycle
3: HP=90, 80 bar in the CLAUDE cycle

4: Mass flow rate of the compressor= 1 Kg/hr
5: Fraction of fluid separated = 0.4, 0.5, 0.6, 0.7, 0.8 etc.

Simulation using Aspenhysys:

(1) Mixer(MIX-1):

Feed temperature: 300K

Mass flow at outlet: 1 kg/hr

(2) Compressor(COMPRESSOR):

Inlet pressure: 100KPa

Outlet pressure: 9000KPa

(3) Chiller(CHILLER):

Outlet temperature: 300K

(4) Heat exchanger(HX-1):

Inlet temperature of cold stream: -163.8^{0}C

(5) Heat exchanger(HX-2):

Enthalpy of cold stream: -7062KJ/kgmoleK

Molar flow: 0.02945 kgmole/hr

(6) Heat exchanger(HX-3):

Inlet temperature of cold stream: -195.5^{0}C

Inlet mass flow of cold stream: 0.02492kg/hr

(7) Valve(VALVE):

Outlet pressure: 100KPa

(8) Split(SPLIT):

Dynamic split of stream:

Through turbine: .8kg/hr

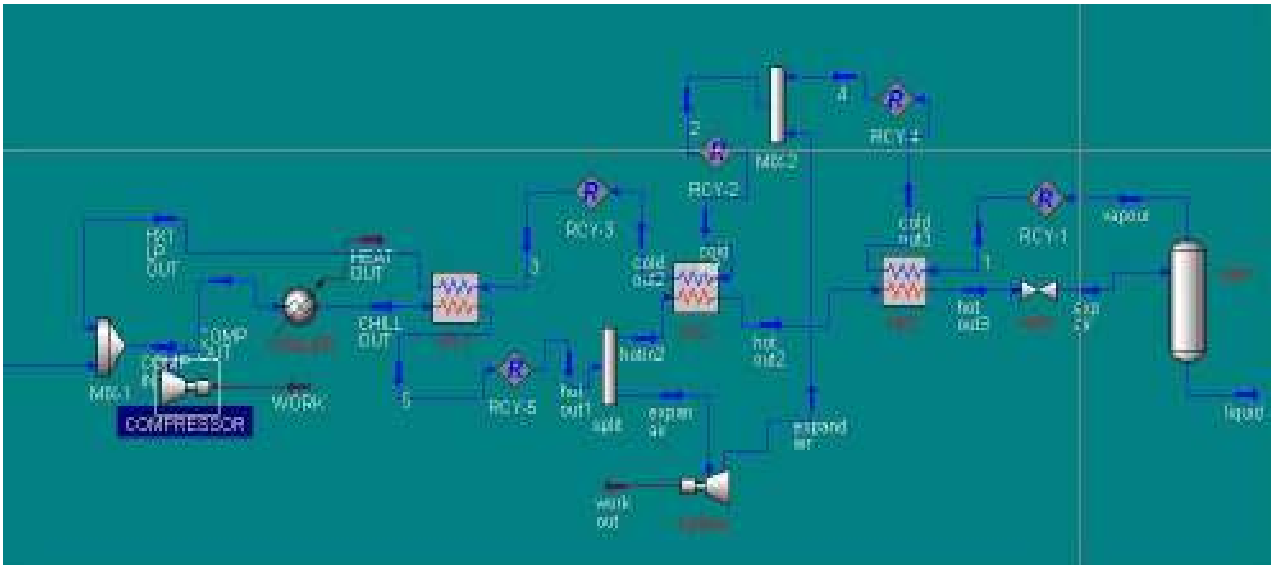
(9) Turbine(TURBINE):

Outlet stream pressure: 100KPa

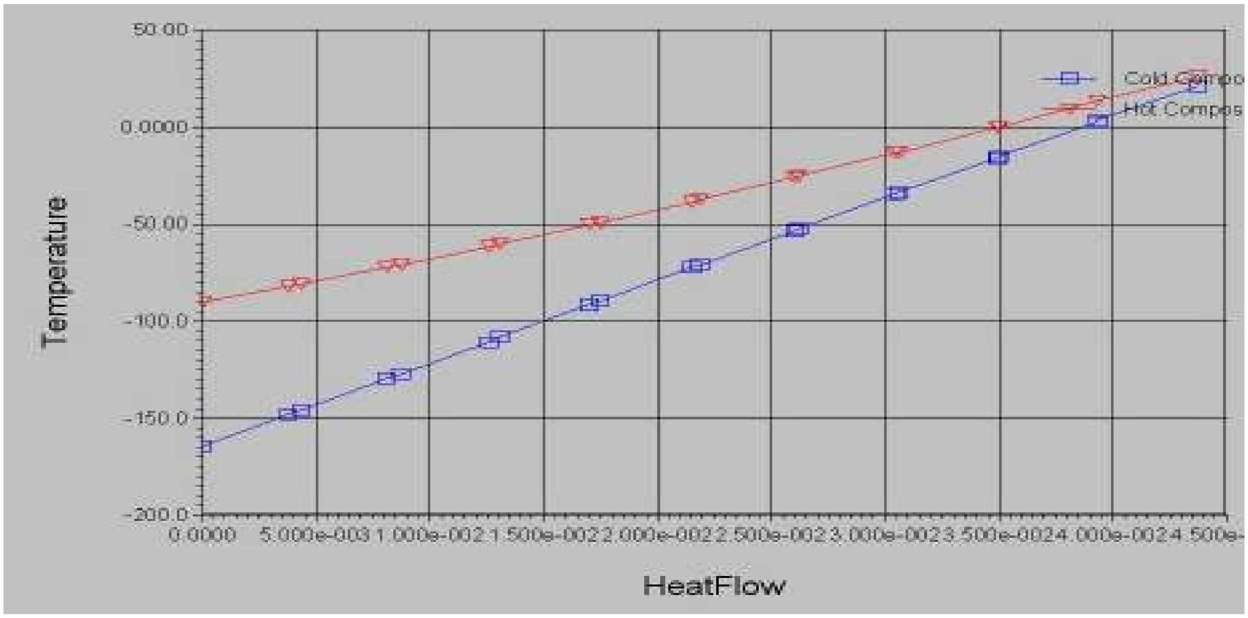
(10) Mixer(MIX-2):

Inlet temperature from heat exchanger: -193.5^{0}C

Schematics of CLAUDE cycle using HYSYS simulation

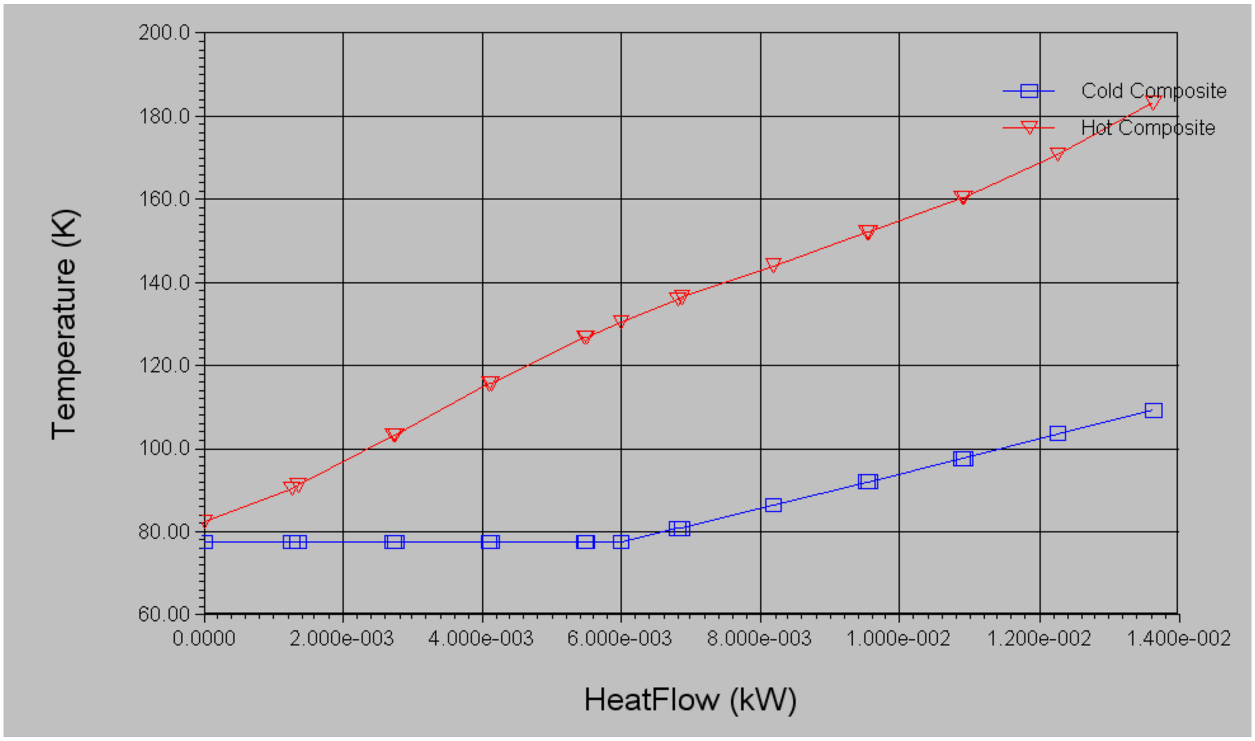


(Temperature v/s heat flow)

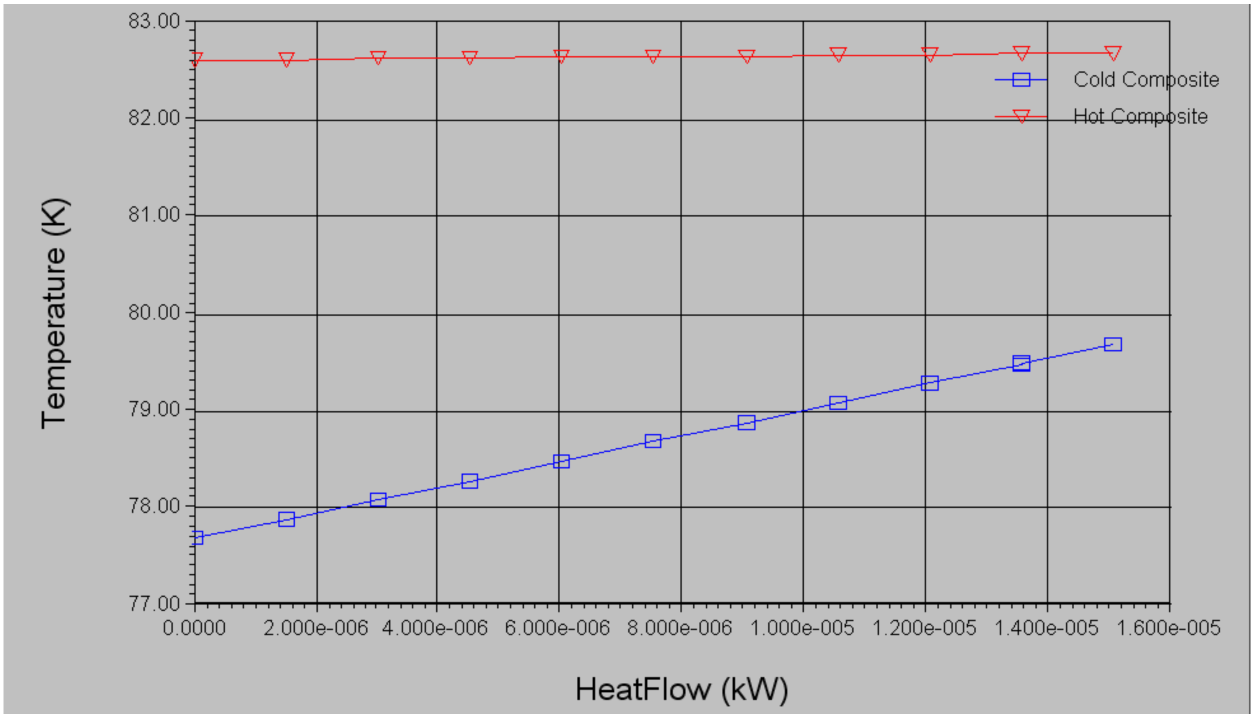


(1) **Graph between temperature and heat flow for first heat exchanger (HX-1)**

(Temperature v/s heat flow)



(2) Graph between temperature and heat flow for second heat exchanger (HX-2)



(3) Graph between temperature and heat flow for third heat exchanger (HX-3)

Table showing relation between work input per unit mass of fluid obtained per cycle and fraction of gas going through turbine

Pr	T1	h1	s1	T2	h2	s2	x	h3	he	hf	mf/m	-w/m	-w/mf
90	295.88	-72.68	186.4	300	-433	147.8	0.8	-4710	-7011	-12460	0.1758	11060.65	62916.09
	296.13	-65.28	186.4	300	-433	147.8	0.7	-2437	-5816	-12460	0.2127	11062.9	52011.74
	296.63	-50.69	186.4	300	-433	147.8	0.6	-1308	-5278	-12460	0.2064	11067.61	53622.13
	297.13	-36.1	186.5	300	-433	147.8	0.5	-462.7	-4907	-12460	0.1875	11102.03	59210.83
	295.82	-74.32	186.3	300	-433	147.8	0.4	-1097	-5193	-12460	0.1593	11030.39	69242.88
80	295.88	-72.68	186.4	300	-387.4	148.9	0.8	-4665	-6940	-12470	0.1764	10780.78	61115.53
	296.25	-61.35	186.4	300	-387.4	148.9	0.7	-2260	-5658	-12460	0.2021	10783.33	53356.38
	296.03	-68.31	186.4	300	-387.4	148.9	0.6	-2023	-5560	-12460	0.1984	10782.04	54344.93
	295.73	-76.93	186.3	300	-387.4	148.9	0.4	-1225	-5181	-12460	0.1527	10749.83	70398.38

Where:

Pr = pressure ratio between outlet and inlet pressure of compressor

T1 = temperature at the inlet of compressor

h1 = enthalpy at the inlet of compressor

s1 = entropy at the inlet of compressor

T2 = temperature at the outlet of chiller

h2 = enthalpy at the outlet of chiller

s2 = entropy at the outlet of chiller

x = fraction of total flow that passes through expander

h_3= enthalpy of fluid at the outlet of hot stream of first heat exchanger (HX-1)

h_e = enthalpy at the outlet of turbine

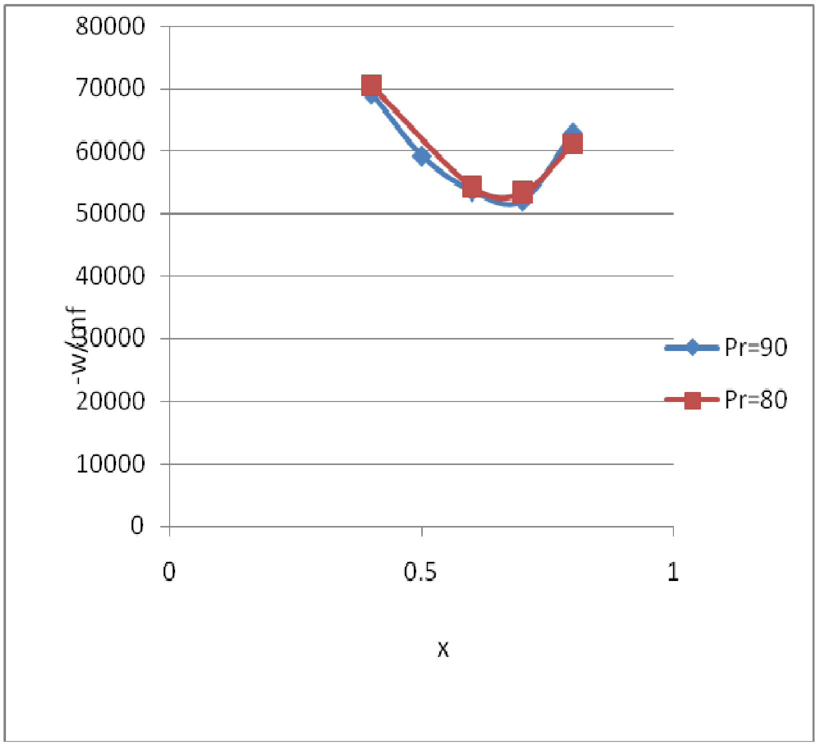
h_f = enthalpy of liquid at the outlet of two phase separator

mf/m = liquid yield

-W/m = net work done on the system

-W/mf = net work done per unit liquid yield

Graph between work input per unit mass of fluid obtained per cycle and fraction of gas going through turbine



Mass flow rate of liquid N2 : 0.1758kg/hr.
Liquid temperature : -195.5^{0}C
Vapor fraction : 0.0
Pressure : 100KPa

<u>Mass flow rate of liquid N2</u> = (0.1758/ 0.2)
(Total Mass flow rate of liquid N2
in expander stream after separation)

= 22 % of liquefaction

DISCUSSION

(1) An expansion valve is required in CLAUDE SYSTEM in addition to expander. Expander cannot tolerate much liquid. The liquid has much lower compressibility than gas, therefore if liquid were formed in the cylinder of an expansion engine, high momentary stress would result. Now some turbines (rotary type) have been developed that are able to tolerate as high as15% liquid by weight without damage to the turbine.

(2) The simple LINDE-HAMPSON cycle does not work for gases like Neon (N), Hydrogen (H) and Helium (He) because system would never start as maximum inversion temperature for these gases is below room temperature.

(3) In actual system, irreversibilities in the heat exchangers, expander and compressor would reduce figure of merit (FOM) considerably.

(4) As mentioned earlier, in some CLAUDE cycle, energy output of the expander is used help in the compression of gas in compressor. In most systems, energy is dissipated in brake or blower. Wastage of energy does not affect the liquid yield, but it increases the compression work requirement when expander is not used.

(5) Efficiency of various systems is calculated in terms of work input per unit of liquid separated and not in terms of only liquid yield only.

CONCLUSION

(1) The work requirement per unit mass in CLAUDE CYCLE is exactly the same as that of the LINDE-HAMPSON system if the expander work is not utilized to help in compression.

(2) If the high pressure in CLAUDE CYCLE is increased, the minimum work requirement per unit mass liquefied decreases.

(3) Figure of merit (FOM) of CLAUDE SYSTEM is much higher than LINDE SYSTEM implying that CLAUDE CYCLE is a better liquefaction system.

(4) Percentage liquefaction of LINDE CYCLE is the found to be 5% while that of CLAUDE CYCLE is found to be 22%, suggesting that the latter is a better cycle.

SCOPES AHEAD

Efficiency of cryogenic systems are much less. Work input per unit mass of gas liquefied is still very high. A huge scope lies in the improvement of efficiency of cryogenic cycles. User friendly ASPENHYSYS can be used for the optimization and simulation of these cycles. The main problem with these cycles is energy exchange with the surroundings (ambient condition). Though much advancement have been made in the field of design of heat insulators.

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(9) Thesis on *Process design of cryogenic systems using Aspenhysys simulations* by Sunil Manohar Dash