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Optimization of Natural Gas Liquefaction Processes for Offshore Floating Liquefied Natural Gas Plants

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Abstract- The production, liquefaction, storage and transfer of natural gas on a floating vessel can solve global energy issues and also be a profitable venture. Design and simulation of natural gas treatment and liquefaction processes for a small scale offshore facility was done for the Poly refrigerant integral cycle operation (PRICO) and nitrogen expander cycle with methane pre-cooling (NiChe). Optimizing both cycles produced specific power of 0.152kWh/kg of LNG and 0.332kWh/kg of LNG for the PRICO and NiChe models, respectively. Coefficient of performance for the optimized PRICO model was 1.93 while that of the optimized NiChe model was 0.59. Evaluation of a suitable natural gas liquefaction model was done based on thermal efficiency, safety, compactness and other parameters.

Keywords- *liquefied natural gas, floating plant, specific power*

I. Introduction

Natural gas (NG) is a mixture of hydrocarbon gases and impurities [9, 13]. Impurities like carbon dioxide, hydrogen sulphide, helium, mercury, nitrogen, and water vapor usually exist in NG in relatively trace amounts. Dry NG will practically contain no liquid components at standard pressure [15]. Wet NG has organic species like pentanes which exists in liquid phase at ambient conditions and heavier chemical species like water vapor and carbon dioxide and will require some processing to enhance its commercial value. The NG can be obtained from oil, condensate or gas reservoirs which can either exist in an onshore or offshore location. NG is an important fuel source for power generation and transportation as well as a major industrial feedstock for petrochemicals and fertilizers [11].

Much of the world's NG reserves are in offshore fields. This NG must be produced and liquefied as liquefied natural gas (LNG) to obtain energy necessary for domestic and industrial use, and tackle growing environmental stress. Reference [20] reveals that LNG is the most profitable way of transporting NG at distances greater than 4000km. Because LNG is a clean-burning and low-pollution fuel, there is a rising global demand for LNG for power generation [6].

Offshore floating liquefied natural gas (FLNG) production offers the potential to avoid flaring or reinjection of associated gas and to monetize smaller or remote fields of non-associated gas [1, 14]. The FLNG plant does not require land purchase, jetty facilities, harbor or break water developments and continuous dredging. It also reduces environmental impact by a gas treating facility. FLNG also provides maximum flexibility in developing a gas resource. Facilities may be easily moved to new fields and re-used once the existing field is depleted which will substantially reduce the risk associated with a stationary investment facility. A floating production unit can be built in a controlled shipyard environment using a skilled workforce [12].

The small and large scale FLNG development models are relevant to LNG's future growth. The small scale FLNG produces less than 3.5MTPA. It uses a ship-like hull and can store LNG up to 220,000m^3. Simpler liquefaction processes like the Single Mixed Refrigerant (SMR) processes, N_2 single and dual expander processes can be effectively employed in small scale FLNG. Accompanying challenges of equipment and process safety considerations, LNG capacity and storage, LNG product transfer and risk considerations must be addressed for FLNG.

In this research, the poly refrigerant integral cycle operation (PRICO) and double nitrogen expander cycles with methane precooling (NiChe) for offshore liquefaction are investigated on a small scale production capacity with an aim to minimize utility. Optimization is done using the specific power per kg of LNG as objective function and the product of the overall heat transfer coefficient and surface area (UA) of the LNG exchanger as equality constraints. AspenHYSYS 3.2 is used for the design and simulation. Cycles are optimized using the multivariable steady state optimizer tool of HYSYS; employing SQP minimization scheme. Selection of the most desirable liquefaction technology from proposed models is done and sound engineering techniques that will accommodate the technical challenges such as motion, flammable components, weight, space limits and plant compactness are also considered.

II. FLNG Facility

The FLNG facility has three parts: field specific, liquefaction and utility parts [8]. The field-specific part separates natural gas from condensate and stabilizes the condensate. The liquefaction part converts the natural gas to LNG. The utility part of the plant provides cooling water, nitrogen, power, and other necessary materials to the required specific and generic equipment. The liquefaction part is the heart of the FLNG. Reference [10] proposes a hull size of 440m x 65m x 35.5m, and top side weight of 55,000tons for a 2.5MTPA production capacity. Reference [2] states key dimensions of Shell's FLNG concept as approximately 450m x 75m, for a 3.5MTPA capacity.

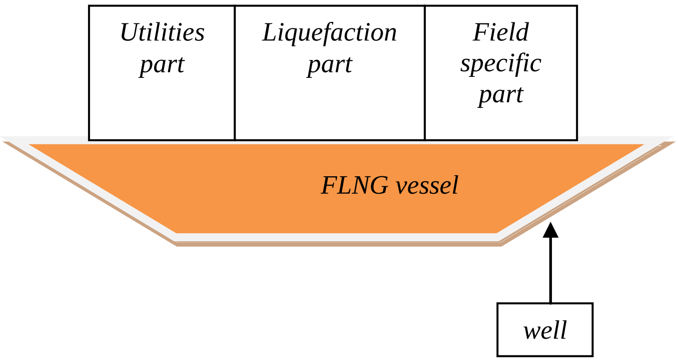

Figure 1. FLNG concept

The basic steps for the processing of NG for an FLNG plant are outlined as:

- Removal of impurities from NG
- Refrigeration of the gas until it liquefies
- Movement of the LNG to storage and finally into the tanker

Raw gas rises from subsea wells to the floating facility through some form of riser/swivel connected to a seabed template in the NG processing scheme [18]. The raw gas that reaches the process plant consists of three phases; gas, condensate and water which are separated and split into three streams in a slug catcher. Condensates or NGLs are removed from the raw gas in the pre-treatment step and sent to a stabilization unit. NGL would only need to be fractionated if separate components are needed as refrigerants or if need be to reinject into the LNG stream at a later point in order to adjust energy content and flammability characteristics of LNG. The NGL can also be exported as a C3/C4 mixture. LPG carriers would be required to handle the exports as the condensate is a valuable additive in motor fuel production at refineries and as a feed material at petrochemical plants.

Heavier impurities in the raw feed is removed from the bottom of the slug catcher and treated to remove solid particles, salts and most of the water. The water is treated before being discharged into the sea. Next, trace amounts of mercury found in NG that could damage metal equipment in other parts of the process is removed, still in the pre-treatment step. Sulphur compounds and acid gases are also removed from the NG largely because they could freeze and damage equipment during the cooling process as their freezing points is well above the temperature of the final LNG product. Scrubbing processes, using the amine method can be employed to remove CO_2. In cases were only minor amounts of sour gas is present, acid gas can be removed by adsorption along with the removal of water. The absorber and regeneration column is designed to accommodate motion, by increasing its size relative to a similar duty for a land-based plant [18]. Also, the absorber column is likely to be the tallest and heaviest vessel on the ship as it is designed for the feed gas pressure. The vessel is therefore positioned at a location close to the centre line of the FLNG. Heat recovered from the exhaust of the gas turbine generators is supplied for acid gas removal in the regeneration process. Water is removed by a dehydration process to dry the NG to less than 1ppm. Natural gas can be dried using molecular sieve. This is necessary to prevent the water turning to ice later in the process. The dry sweet NG is then cooled in the cryogenic heat exchanger to about -150^{o}C at 5000kPa and subcooled to a temperature of about -162^{o}C by a throttling process. After the liquefaction process, the LNG is pumped into a cryogenic storage tank in the hull of the vessel. The LNG has to be transferred to carrier ships with a strong focus on safety considerations. This is achieved with the side-by-side approach using conventional equipment [2, 18].

The FLNG process plant is self-sufficient in terms of power demand and there is minimal interface with the vessel support system. Boil-off gas (BOG) is inevitable in course of the process hence gas compression and use of BOG as well as end flash gas (EFG) as fuel for the propulsion system is done [7]. The plant and vessel electricity requirements can be met by up to six gas turbine generator sets that generate over 200MW of electricity for a 3MTPA plant [6]. A large part of power generated is used to service the compressors. Reference [6] also states that the gas turbine fuel requirement can reach 12% of the total natural gas feed rate. Seawater is used as cooling agent as it is conventional in offshore processing. An open loop seawater cooling system is employed.

A. *Safety concerns*

Mishap on the FLNG vessel can cause accidents thus control procedure is carried out to ensure that risk is as low as reasonably practical. LNG poses little danger as long as it is contained within storage tanks, piping, and equipment designed for use at cryogenic conditions. However, vapors from LNG due to an uncontrolled release can be hazardous if it is exposed to an ignition source. One worrisome phenomenon for LNG is Rapid Phase Transition (RPT) or flameless vapor explosion which occurs when cold LNG spills on water [21]. RPT can be prevented by ensuring that the LNG does not come into contact with water. As for concerns on a boiling liquid expanding vapor explosion (BLEVE), laboratory and open ocean combustion tests show that catastrophic release of LNG does not create BLEVE [16]. Blast pressure calculations can ensure that explosions can be easily contained. The escalations can be prevented by leaving open areas between modules or by inserting blast walls [5]. However, offshore systems will require similar safety systems employed for onshore liquefaction plants.

Sea condition can cause sloshing effects and also affect the operation of process equipment especially process equipment with a liquid-liquid interface. Moss and SPB LNG containment systems are very robust and are specially designed for use on floating vessels to prevent sloshing. The movement of liquids in process vessels can be minimized by designing special topside module structures and vessel internals for sea operations. Topside modules can be supported on stools. This concept has been used on many new built FPSOs AKPO, and AGBAMI. Each stool is able to sustain a maximum vertical load of up to 2000ton.

B. Refrigerant considerations

With respect to safety, nitrogen refrigerant has a lot of advantages over the MR working fluid. Nitrogen is a non-combustible and non-toxic cooling medium [19]. It also works as a single component with no splitting streams unlike the MR and can operate on optimum design over a wide range of feed gas properties. Nitrogen is maintained in the gaseous phase at all points of the refrigeration cycle, so distribution in the heat exchangers is not a concern, unlike other refrigeration cycles [6]. As a result, plant performance is much less sensitive to vessel movement. MRs are flammable hydrocarbons and their storage and use on the FLNG plant presents a significant challenge as MR storage requires a significant amount of deck space [6]. More particularly, propane is discouraged for FLNG plants due to its high flammability as it poses a great risk of causing fire outbreak [3].

C. FLNG Layout Based On Safety Criteria

The layout of the FLNG plant should follow the conventional practice of locating hazardous processes away from the accommodation of personnel and the safer utility systems closer. Reference [10] suggests that living quarters should be located up-wind of the process plant and the flare and vents should be located at the stern, down-wind of all process facilities. Also, Turret mooring with thruster capability to increase ventilation and enhance the safety of offloading operations should be employed. Tandem LNG offloading should be at the FLNG stern. A hull design that will not give rise to “green water” (sea water) coming up over the deck in any weather condition is desirable. Reference [18] suggests that equipment sensitive to motion should be located where the movements due to sea conditions are least. To keep the centre of gravity low and ensure overall stability, large and heavy columns should be located on the centre line of the vessel.

D. Storage and Transfer

Reference [10] proposes LNG storage of membranes 245,000m^3 in 2x4 tanks for a 2.5MTPA production capacity. The storage tank for FLNG plants is expected to be partially filled thus the motion of the floating facility can cause sloshing of LNG in the tank. Spherical storage tanks designed by Moss are more robust and resistant to sloshing effects of LNG [4, 6]. For LNG transfer to carrier ships, flexible loading arms between the production vessel and the tanker such as the soft yoke mooring and offloading (SYMO) system can be used [1].

E. Compactness Considerations For FLNG

For simultaneous production and liquefaction operation on an offshore vessel, a good layout of all major equipment ensures that space is effectively utilized. Modular construction of equipment is done to reduce the amount of work and number of people required for installation and start-up. The FLNG for small scale production can have a usable deck area of about 15,000m^2 [18]. To settle on the overall configuration layout considering the position of the gas inlet turret, accommodation, flare and unloading, the Mobil square ‘doughnut’ approach can be employed [18].

III. LIQUEFACTION PROCESS

A. Process design and simulation basis

The liquefaction process for NG is for a plant with nominal design capacity of 25MMSCFD. Treated NG after dehydration is fed to the LNG exchanger. It is expected to be cooled to -150^{o}C at about 5000kPa. A Joule-Thompson (JT) expansion valve is used to further reduce the temperature of LNG to -162^{o}C from where it is sent to an end flash separator and the LNG storage tank at 100kPa. For the simulation, minimum temperature approach is 5^{o}C, temperature of working fluid at condenser outlets is 30^{o}C and adiabatic efficiency of centrifugal compressor is 75%.

B. The PRICO cycle

The PRICO cycle used a mixed refrigerant with 38% methane, 43% ethane, 11% propane and 8% nitrogen in mole percent. The MR which flows in a closed cycle is sent to the LNG exchanger as heat sink at a temperature below -150^{o}C. The working fluid contacts the NG stream thermally and cools it. At refrigerant outlet of the LNG exchanger, hot refrigerant flows into the compressor. Compression work raises the pressure of the MR that exits the LNG exchanger which also causes a rise in temperature. An aftercooler reduces the temperature of the MR before it enters the LNG exchanger. The MR is cooled to below -150^{o}C by a JT expansion valve.

Using the SQP scheme of the optimization tool in HYSYS, the minimum specific power requirement for the liquefaction process is obtained. The UA of LNG exchanger is set as an equality constraint.

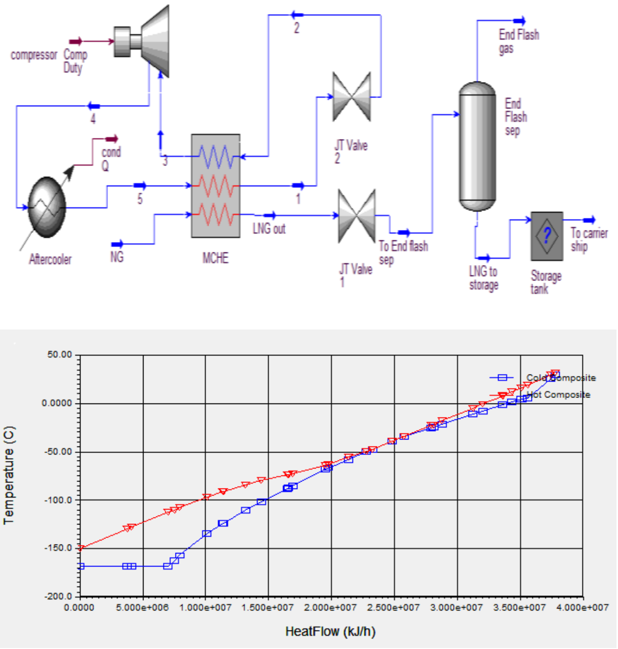

Figure 2. PRICO cycle and MCHE temperature vs heat flow

The temperature profile for the PRICO model shows the proximity of the MR cooling curve to the NG cooling curve. This represents the efficiency of the system. The gaps in the curve show where there is a loss in efficiency.

TABLE I. PRICO MODEL SIMULATION RESULTS

PRICO Case	**Base Case**	**Optimized Case**
Compression ratio	6.28	6.28
Compressor power, kW	5549	2774
Compressor heat flow, kJ/h	1.998×10^{7}	9.988×10^{6}
Condenser heat flow	3.853×10^{7}	1.926×10^{7}
Mass flow of LNG, kg/h	1.821×10^{4}	1.821×10^{4}
COP	0.93	1.93
Specific power, kWh/kg of LNG	0.305	0.152

C. The NiChe cycle

The NiChe used for the simulation has 0.98 and 0.02 composition for N_2 and O_2 respectively. The N_2 working fluid flows in a closed cycle and enters the LNG exchanger from an expander, as heat sink at a temperature lower than -150°C. The cold N_2 refrigerant contact the hot NG stream thermally in the LNG exchanger and cools it. At N_2 refrigerant outlet of LNG exchanger, the hot stream is compressed and cooled using an intercooler. The hot N_2 refrigerant is further compressed and cooled before it is sent through the LNG exchanger to the expander. A methane precooling stream reduces workload on the N_2 refrigerant cycle.

Using the SQP scheme of the optimization tool in HYSYS, the minimum specific power requirement for the liquefaction process is obtained. The UA of LNG exchanger is set as an equality constraint.

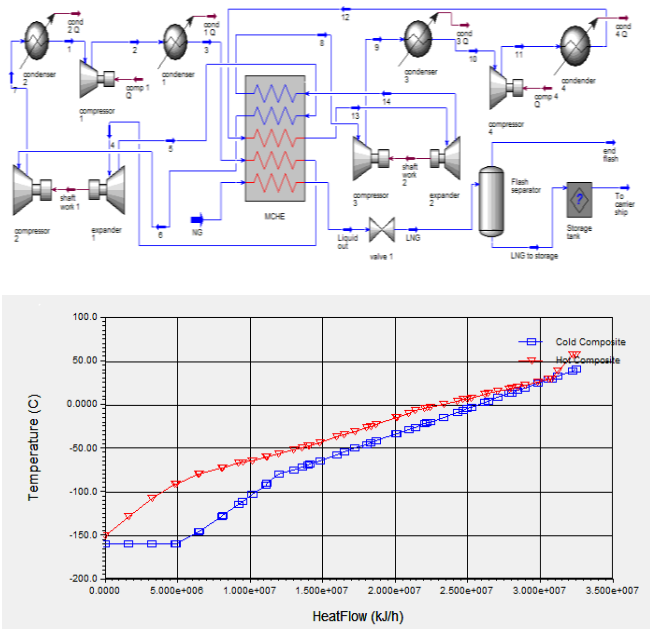

Figure 3. NiChe cycle and MCHE temperature vs heat flow

TABLE II. NICHE MODEL SIMULATION RESULTS

NiChe Case	**Base Case**	**Optimized Case**
Compression ratio	3.14	3.14
Total compressor power, kW	12082	6040
Total compressor heat flow, kJ/h	4.350×10^{7}	2.174×10^{7}
Total condenser heat flow	6.891×10^{7}	3.456×10^{7}
Mass flow of LNG, kg/h	1.821×10^{4}	1.821×10^{4}
COP	0.58	0.59
Specific power, kWh/kg of LNG	0.663	0.332

IV. DISCUSSION

The small scale FLNG has a wide range of concepts. Reference [22] states that for a production rate of between 0.5

to 3MTPA, a storage capacity of 14000m^3 to 150000m^3 can be employed. The PRICO as well as expander cycles can be employed for liquefaction in mild or harsh environments. The hull size of the vessel can range from 100m to 500m in length with topside weight of 5,000ton to nearly 100,000ton. Power consumption can range from 30MW to 300MW depending on liquefaction model choice, number of compressor stages and utility energy demand. Power generation can either be gas turbine or steam turbine depending on choice. Vapor compression which is characteristic of liquefaction processes require a high amount of driver power which can be applied directly to serve the compressors or indirectly using electric motors. A typical nitrogen cycle will use 2 gas turbine drivers while for the simple SMR system like the PRICO model, a single driver, can be used [17].

A. Selection of Liquefaction Cycle

The selection process between the PRICO and NiChe is based on the evaluation of characteristic parameters that largely determine the feasibility and operating costs. Such parameters have been previously investigated for offshore liquefaction plants and reliable information is used. Comparison of specific power per kilogram of LNG is a necessary criterion for evaluating liquefaction cycles. The optimized case for the PRICO and NiChe cycles had 0.152kWh/kg of LNG and 0.332kWh/kg of LNG respectively. PRICO cycle showed a lower specific power requirement compared to the NiChe. However, because methane is used as source of fuel for gas turbines on the facility, specific power is not a very strong criterion for selection. In terms of safety, the PRICO cycle has a comparatively lower rating due to the MR used which has high flammability unlike the N_2 cycle which is less susceptible to fire accident.

Factors that bother on availability of deck space, equipment weight and height limitations, and the robustness of equipment in the offshore environment must be taken into account. Based on equipment count, the PRICO has a fewer number of process units. This reduces demand for equipment space on the floating vessel. While a PRICO train can involve 7 major process units for its liquefaction cycle, the NiChe has 14 process units for its train. However, for a PRICO liquefaction plant, a NGL fractionation train must also be setup to guarantee supply of hydrocarbon refrigerants. The NiChe can be modularized and is moderately compact. Although the PRICO cycle is simple, MR composition poses a challenge during start-up. The MR used for the PRICO cycle hampers the flexibility of the cycle unlike for the NiChe which uses pure refrigerants. The NiChe is more robust with respect to hull movements, as its refrigerants operate in the gas phase. NiChe process also has the benefit of operating at higher pressures, resulting in smaller pipes and valves than PRICO cycle at near ambient pressure. For NiChe, the precooling refrigerant and the nitrogen both remain in gaseous phase, which eliminates the problem of two phase flow distribution. This also addresses the need for liquid refrigerant storages, drums and separators. The PRICO uses a SWHE whereas the NiChe uses a PFHE. The PFHE occupies a lesser space and is less expensive compared to the SWHE.

Selecting a liquefaction model is a challenging exercise for the PRICO and NiChe cycles based on the criteria considered. However, safety poses a strong concern in most process plants. Because the fuel for compression duty is not much of a problem and both systems are generally compact, the NiChe model is a better option for liquefaction of NG on a floating vessel.

V. CONCLUSION

The NiChe and PRICO cycles are suitable candidates for FLNG because they offer minimal equipment count, require smaller space, and can be modularized. Reducing the total operating cost of the FLNG plant can be achieved by optimization. This is done by adjusting primary variables in the liquefaction system which minimizes the specific power required to liquefy 1kg of LNG. Parameters like the COP and the temperature vs heat flow profile of the LNG exchanger can be used to appraise the liquefaction system. Factors like safety, compactness, equipment count, thermal efficiency, flexibility, modularity, and refrigerant storage must also be considered in FLNG plant selection and design. The NiChe is preferred to the PRICO for an FLNG plant based on parameters evaluated. By employing a suitable liquefaction technology to process NG offshore, energy firms will be able to meet rising global energy demand, address environmental issues and make profit.

VI. ACKNOWLEDGMENT

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