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REVIEW PAPER

Current trends for the floating liquefied natural gas (FLNG) technologies

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Abstract−Natural gas (NG) and liquefied NG (LNG), which is one trade type of NG, have attracted great attention because their use may alleviate rising concerns about environmental pollution produced by classical fossil fuels and nuclear power plants. However, when gas reserves are located in stranded areas and a portion of the offshore reserves is a significant amount of the total gas reserves, LNG is not suitable because (i) installation of pipelines for the transfer of NG to onshore LNG facilities is expensive and difficult, and (ii) it still has environmental and security problems. As a result, there are many efforts to excavate and monetize these stranded and offshore reserves with floating facilities where offshore liquefaction of NG is possible. Therefore, the development of floating LNG (FLNG) technology is becoming important. Although the FLNG technologies have advantages over conventional LNG technologies, there are still several roadblocks. To overcome the challenges, modular designs related to the main and typical stages of the FLNG process – gas pretreatment, liquefaction and regasification topsides, hulls, mooring, and transfer systems should be enhanced. Regarding FLNG ongoing operations and future plans, there are six nations (Argentina, Brazil, Kuwait, UAE, UK, and USA) operating FLNG, and a variety of FLNG liquefaction projects will be finished soon. Shell and Petrobras are making rapid strides to build FLNG facilities, and Flex LNG, Hoegh LNG, SBM Linde, MODEC, and Saipem are also building their FLNGs. In this review paper, we initially review the LNG concept and compare it with FLNG. In turn, new and typical FLNG technologies are introduced and the main challenges are also explained with insight into how these challenges are overcome. The main market drivers for FLNG industry are also considered.

Keywords: Liquefied Natural Gas, Floating Liquefied Natural Gas, Liquefaction Process, Hull and Mooring Process, Offloading Process

INTRODUCTION

Uncertainty and unbalance in the energy supply and consumption have become a bottleneck for continuous growth of the global economy. There are many suggestions for change in the paradigm of the conventional energy market. Such uncertainty and unbalance is mainly attributed to political, geographical, and economical crises like depletion of fossil fuels such as coal and crude oil, rapid increase of energy consumption in newly industrialized countries such as China and India, fortification of resource nationalism, and limitation of carbon emission by climatic change conventions such as the Kyoto protocol [1-6].

As mentioned above, the crises in energy security make stable procurement of the energy resources more difficult and, as a result, limited wars and excessive competition between countries have occurred frequently. In particular, excavating ‘easy oil’ that is often extracted by the national oil companies (NACs) of Middle Asia is becoming difficult work. To find new oil reserves and offset oil production decline, the NACs are moving to even harsher environments such as offshore, deepwater, and politically risky and geographically remote areas [5-8].

As another way to overcome these issues, many countries have made efforts to develop alternative energy, including new and renewable energies. In this regard, the role of natural gas (NG) is critical because capital expenditure (capex) of the NG is the lowest of all the energy resources, particularly in power plant fields which need large energy capacity [5]. Fig. 1 presents the capexes in different energy resources. The capex of NG is almost one-third of that of coal and one-sixth of that of wind offshore, indicating that NG is the most effective energy resource. Liquefied natural gas (LNG) pro-

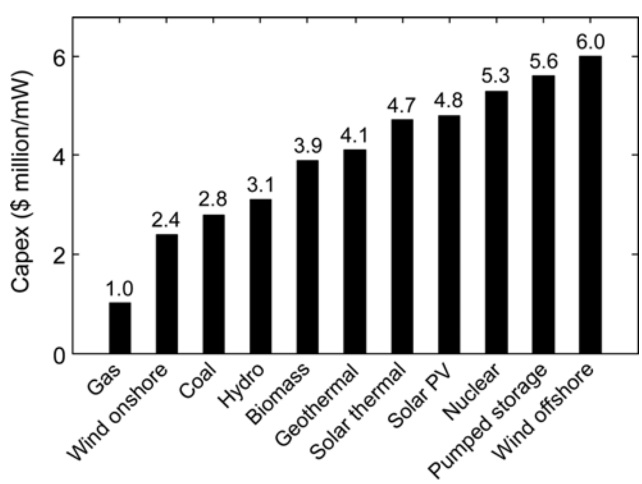

Fig. 1. The capexes in different energy resources like gas, wind onshore, coal, hydro, biomass, geothermal, solar thermal, solar PV, nuclear, pumped storage and wind offshore.

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duced when NG is cooled to the temperature of liquefaction has been considered one of the best options for reducing conflicts over energy initiative and security [6]. LNG has also been recognized as the most clean energy source and desirable alternative to curb greenhouse gas and to replace conventional fossil fuels [2].

Since the first commercial LNG terminal was built in Arzew, Algeria, in 1964, LNG production has continuously expanded [2]. According to published reports, global LNG consumption has increased rapidly [9,10]. In the USA, before 2005, its consumption increased 6.4% annually and between 2005 and 2010, it increased 12.6% annually, while even after 2010, 8.5% annual increase is expected. In Europe, especially in countries like England, France, Italy, and Spain, LNG consumption increased twice after 2010 compared with before 2010. In Asia, LNG consumption of conventional LNG importing countries like Korea, Japan, and Taiwan has rapidly increased. For the last 40 years, the LNG business has rapidly grown and accounts for more than 29% of global gas trade.

However, for more activation of the LNG industry, the significantly increased capital cost for developing LNG should be reduced. Also, many onshore LNG construction projects have been postponed. Due to these reasons, the floating liquefied natural gas (FLNG) industry has been considered, at least, a half-way solution for overcoming energy crises, and the FLNG business has been one of the dominant growth sectors [5,6]. The cost issue, combined with environmental and security problems, has made FLNG technology more intriguing as well. For the past several years, many studies related to the feasibility of FLNG have been published.

The FLNG concept started in the 1950s when an LNG plant was installed on a river barge in southern Louisiana [8]. To date, although a base-load liquefaction plant has not been installed offshore, it is expected that many oil companies will invest to realize FLNG business soon. For example, in 2005, an offshore import terminal dubbed regasification vessel (RV) was set up for operation and then floating storage and regasification units (FSRU) were deployed in Brazil in 2008 and 2009 [5].

FLNG consists of the following four main stages; (i) gas production and transportation to a liquefaction terminal; (ii) liquefaction, storage, and loading on LNG carriers; (iii) shipping; and (iv) unloading, storage, regasification, and distribution [11]. Among them, FLNG liquefaction based on an export terminal and FLNG regasification based on an import terminal should be the most important processes to be optimized. To date, the validity of the FLNG liquefaction has not been proven and, therefore, much focus has been placed on determining typical unit technologies, while FLNG regasification has been already been verified as viable [6]. Although FLNG technology has many benefits, there are still difficult obstacles to overcome like sloshing-resistant containment systems, optimal cryogenic offloading system, field specific topside modules, and multiple small/large scale vessels [5]. Regarding the capex for FLNG, the cost of hulls and a containment system is predicted to reach ~ 45% of the total global capex, whereas that of liquefaction and regasification will be ~28% [6]. Hence, many projects are being prepared to reduce the cost of construction of the hulls and a containment system. It is also expected that the total cost will reach $7.4 bn annually by 2016. The portions of each unit stage of FLNG are shown in Fig. 2 [6].

In brief, FLNG technologies are making progress and the FLNG industry plays a crucial role in the energy market. However, there is little information explaining the current status and future prospect of the FLNG industry and technology. It is for this reason that the present review paper is needed.

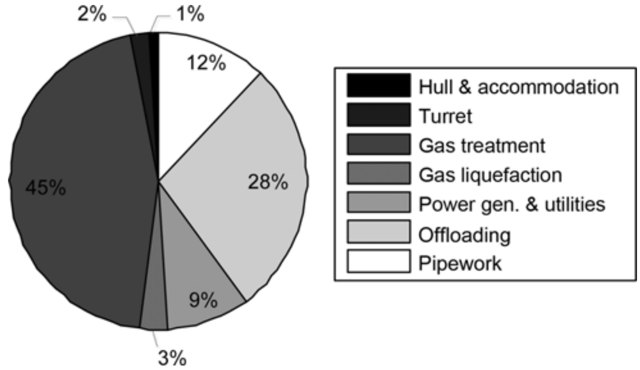


Fig. 2. The portions of all unit stages consisting of FLNG. As the main unit stages, hull and accommodation, turret, gas treatment, gas liquefaction, power generation and utilities, offloading and pipework are selected.

In this paper, we introduce conventional LNG processes and their extended application to FLNG, summarize the main FLNG unit technologies, and probe present and future FLNG market drivers and trends in the FLNG sector. Also, the main obstacles of FLNG are considered and their solutions pinpointed.

COMPARISON OF LNG AND FLNG

1. Supply Chains of the Main Processes of LNG and FLNG Technologies

LNG is produced when NG is cooled to –161 °C at 1 atm. When NG is liquefied, its volume is reduced to 1/600th [2,12,13]. Due to the reduced volume of NG, it has become feasible to deliver LNG to distant markets by specially designed tankers. Indeed, strong gas demand and the discovery of available large gas reservoirs have resulted in greater attention being paid to liquefaction of NG. Among various trade types of NG, FLNG has been a main growth sector in the LNG industry since its first installation in Gulf Gateway located in the US Gulf of Mexico in 2005 [5]. Now, there are seven terminals for the FLNG: one for Argentina, Kuwait, UAE, USA, and UK, and two for Brazil – one is being operated and the other is being delivered [5,6].

LNG mainly consists of methane, nitrogen, ethane, and propane. LNG itself is very clean and its combustion is cleaner than that of fossil fuels. In liquid state, LNG is lighter than water and odorless, non-corrosive, and non-toxic. As for possibility of leakage, LNG rapidly vaporizes as soon as it is exposed to ambient state; thus it cannot be explosive in an open environment [12].

Supply chain diagrams for both LNG and FLNG are shown in Fig. 3 [5]. Both LNG and FLNG technologies are made up of four main processes: (i) gas production and transportation to liquefaction terminal; (ii) liquefaction, storage, and loading on LNG carriers; (iii) transportation; and (iv) unloading, storage, regasification, and distribution [6]. The specific aspects of the main stages are as follows:

1-1. Stage 1 (Production)

Gas exists as a solution or is separated from oil as a formation

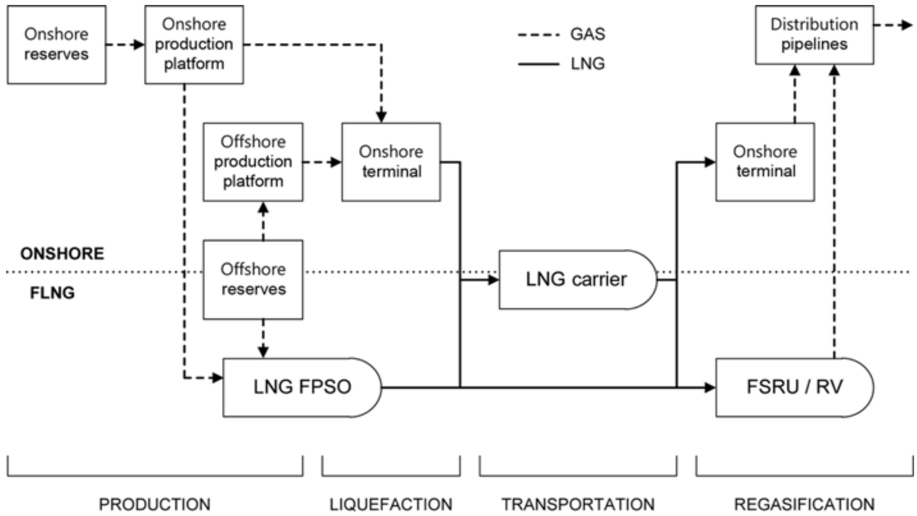


Fig. 3. Supply chain diagrams for both LNG and FLNG.

known as gas cap relying on the pressure. To deliver gas to onshore LNG terminals, it is transferred through pipelines from onshore/offshore production facilities. Conversely, gas delivery to FLNG terminals comes from offshore reserves.

1-2. Stage 2 (Liquefaction)

When NG is delivered to the liquefaction facilities, its contaminants are removed. In turn, the cycle runs to cool the NG to −161 °C. For the cooling process, several refrigerants circulating via a heat exchanger, compressor, and expansion valve are used. These cooling units are called trains. The LNG is transported to storage tanks and loaded to LNG carriers.

1-3. Stage 3 (Transportation)

LNG carriers need unique containment systems to hold LNG because the low temperature of liquid NG may damage even hard materials like steel pipes. For this purpose, An FeNi alloy is used with insulating materials. Although the cargo is insulated, a little gas is permitted to evaporate in order to hold the cargo at the constant temperature.

1-4. Stage 4 (Regasification)

When the LNG carrier arrives at its destination, the LNG is unloaded to a jetty and pipelined to an onshore facility to be regasified or to an offshore terminal with a vessel containing regasification equipment. In that terminal, the LNG passes through tubes and is heated by gas burner or seawater.

2. Prospect of NG Market and Cost Trends of LNG and FLNG Industries

When it comes to long-term gas demand, according to IEA's forecast, the utilization of NG will increase at the rate of 1.6% annually from 2006 to 2030, and account for 23% of the total global energy use by 2030 [6]. The expectation of increase in NG utilization is caused by continuously growing population, limited crude oil, and coal productions, as well as global consensus on discovering the optimal energy source for reduction of greenhouse gas emission. In particular, because CO_2 production of NG is a third that of crude oil and coal, use of NG as a fuel for power generation and a substitute for other fossil fuels will meet the CO_2 emission target [5].

Moreover, there have been many debates on the possibility of long-lasting production of crude oil. Several experts expect that crude oil production will be limited within the next 25 years. For instance, based on the figures of a recent study, the known yet-to-find reservoirs cannot satisfy even the present production level of 77 mmb/d (million barrels per day) in 2029 [5]. The further growth of the global economy will bring forward the peak year. According to EnergyFiles, which contains a chart showing the status of the global crude oil supply between 1930 and 2050, a peak in demand will come in 2016 when the crude oil production is expected to be 91 mmb/d [5,6].

Unlike crude oil, current and future production prospect for NG is very promising. According to EnergyFiles, Eastern Europe dominates NG supply, and will produce 14.7 mmb/d within the next two decades [6]. Also, Asia, Africa, the Middle East, and Latin America are expected to produce significantly NG, although the top three countries (Russia, Iran, and Qatar), which have huge NG reserves, are not willing to build any FLNG facilities in the near future. Russia prefers production and transportation of LNG using pipelines and has onshore plants in Sakhalin. Qatar, the world's biggest LNG exporter, has only large onshore plants in operation and under construction. Iran has been very slow developing LNG export facilities, and the USA especially has banned Iran's access to LNG technology and prevented foreign crude oil companies from investing in Iranian projects. In this regard, FLNG cannot be the technology to solve these problems in Iran because LNG FPSO is also one of the technologies under sanction [5].

In a comparison of cost between onshore and offshore LNG plants, engineering procurement and construction (EPC) cost play an important role. Fig. 4 presents the total capexes of onshore and offshore liquefaction terminal constructions, respectively [6]. Over five years, the EPC cost for the onshore LNG terminal increased steadily because of contractor backlogs, cost increase of raw materials, and lack of proper labor. This meant that the remaining EPC cost for LNG was high [14,15]. In particular, much EPC cost is due to building an LNG plant that is located in isolated places where the workforce is flown in and needs to be accommodated in camps. Conversely, FLNG industries have very positive prospects. They can build a floating production unit in a well-configurated shipyard where a skilled workforce is always available. In turn, such a predictable

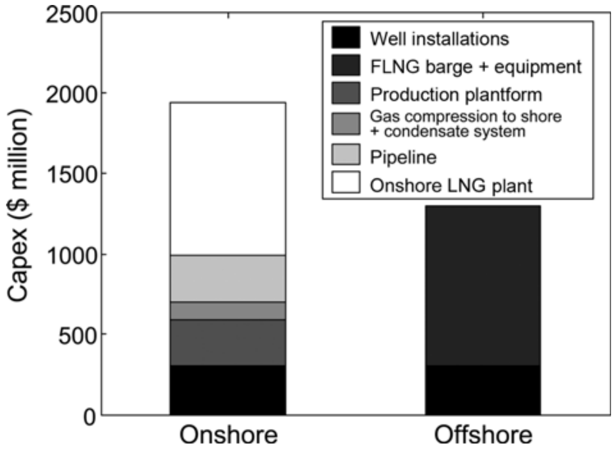


Fig. 4. The total capexes of onshore and offshore liquefaction terminal constructions.

work environment promotes shorter development and construction time schedules. Also, they can prepare for more optimal designs that relieve commissioning time. Thus, floating import terminals are often cheaper than onshore import terminals. However, in the case of larger import terminals that need great storage capacity, onshore terminals are cheaper to construct because they have larger space to build large storage tanks compared with the limited space of shipyards used for building storage tanks of floating import terminals [16,17].

Besides capexes related to the construction of terminals, other costs are considered and compared during the development of an LNG project. When a gas field is offshore, complicated facilities like offshore production platform, subsea wells, and subsea pipelines are required to build an onshore terminal. In comparison, when a floating offshore LNG terminal is used instead of the onshore terminal, an expensive production platform and subsea pipelines are not needed, meaning that the total capex cost can be saved [5].

Regarding liquefaction methods, there are two types of onshore liquefaction plants – peak-shave plant and base-load plant, depending on plant size and its role. The peak-shave plants produce a small amount of LNG (up to 100,000 tpy (tons per year)) and are aimed at minimizing distance mismatch between gas producing site and its consuming site. They store the surplus of NG for when demands are low and the NG is vaporized when demand reaches peak. Most peak-shave plants were built between 1970 and 1980 in Europe and the USA. Base-load facilities produce a large amount of LNG (2,000-3,000 tpd (tons per day)) and the LNGs are transferred using marine transportation. The number of base-load trains operating and under construction is now ~70 at 15 different sites. Now, maximum capacities are greater than 3 MM tpy. Recently, to save more cost, offshore liquefaction is becoming popular because it enables cost-effective use of remote fields and makes onshore connection possible by use of an economical single LNG train [12,14,15].

FLNG TECHNOLOGIES

1. Main FLNG Gas Pretreatment and Liquefaction Processes

The core of LNG FPSO is to optimize modular design for liquefaction process equipment. Modular design optimization makes installation and commissioning of the corresponding equipment more manageable. The major steps of the modular design are gas pretreatment and liquefaction. The processes are shown in Fig. 5 [5]. In Fig. 5, the white boxes represent unit steps of gas pretreatment processes, while the gray boxes show those of the liquefaction process.

During the gas pretreatment process, the quality of the NG fed to liquefaction terminal is not constant because there are differences in field characteristics and geographical location [2,5,17]. Besides methane, NG contains many heavy hydrocarbon components such as water, CO_2, hydrogen sulfide, and nitrogen and heavy metals like mercury as well as toxic acid gases. Therefore, eliminating non-methane component is instrumental to enhancing LNG purity prior to liquefaction of the NG. In particular, toxic hydrogen sulfide and CO_2 should be removed; the process for removing the toxic components is called “gas sweetening.” Mercury, acid gases, and heavy hydrocarbons included in the NG liquid (from ethane to more C containing components, particularly, C5+ components) should also be eliminated, because the mercury and acid gases corrode metal units such as an aluminum heat exchanger and the heavy hydrocarbons (C5+ components) are frozen during liquefaction process and damage the related equipment [12].

Following the gas pretreatment process, the liquefaction process is operated. When it comes to liquefaction technology, the liquefaction terminal consists of one or more parallel trains. Gas lique-

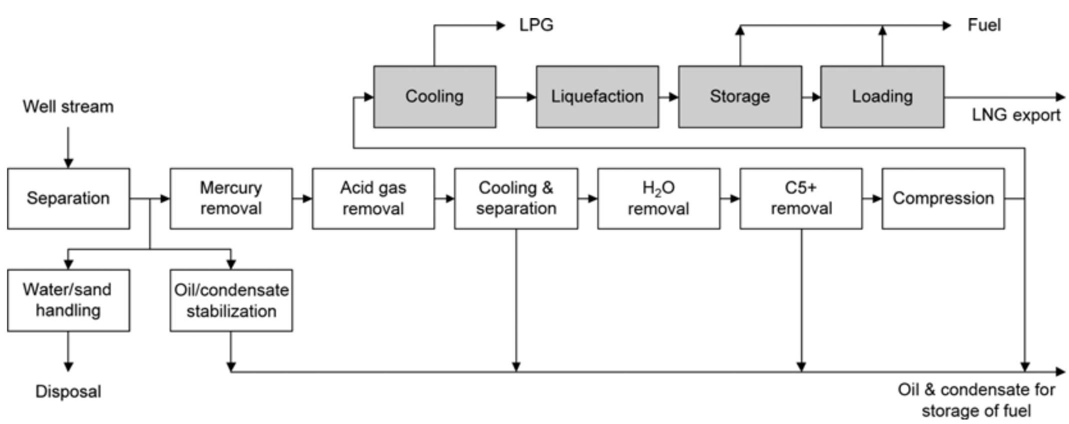


Fig. 5. The major steps of modular design that are determined for gas pretreatment and liquefaction.

fies at −161 °C using refrigerants circulating heat exchanger, compressor, and expansion valve. There are various commercial liquefactions including regasification processes for LNG and FLNG technology. We introduce the representative processes in this section.

1-1. Cascade Refrigerant Process

As shown in Fig. 6(a), the NG is cooled, condensed, and subcooled in heat exchangers with propane, ethylene, and methane consecutively [12]. The three refrigerant chambers usually have multiple refrigerant expansion and compression systems and each works at three evaporation temperatures. After compression, propane is condensed with cooling water, while ethylene is condensed with the evaporating propane and methane is condensed with the evaporating ethylene. The cascade cycle has the benefit of consuming a small amount of power because a low flow of refrigerant is needed while operating the cycle. The method is also very supple for a running process because the refrigerant chambers can be easily controlled. Fig. 6(b) shows the composite cooling and warming curves [12,18]. Mean temperature discrepancy between the curves is wider than that of the mixed refrigerant cycle. Thus, its heat exchanger surface area is small, saving cost for the heat exchange. In comparison, the capital cost of this method is high because it needs many refrigeration systems and each system should have its own compressor and refrigerant storage. Maintenance and spare equipment costs are also high due to the large number of machines. In terms of scale, the cascade cycle is selected for large train sizes because the low heat exchanger area and low power requirement relieve the burden in cost that is consumed operating multiple machines. Also, by selecting an optimal machine, the cascade cycle is compatible with the pre-cooled mixed refrigerant cycle that was dominant in base load mixed refrigerant plants. In brief, the cascade refrigerant cycle has relatively low power and low surface area, but it is relatively complicated due to complexity in machine configuration.

1-2. Nitrogen Expander Process

The nitrogen expander liquefaction process is used for small-scale LNG facilities. A diagram showing its process flow is in Fig. 7 [5,19,20]. It can offer advantages like low weight/space requirement and good design flexibility. With that, designing a better floater and heat exchanger is possible. This process performs NG refrigeration by repetitive compression and expansion of gaseous refrigerant. In the main heat exchanger, the cycled gas is pre-cooled with returning cold gas. After the pre-cooling, the gas is fed to an expansion turbine to expand its volume and lower its temperature. The cold and pressurized gas is then returned to the main heat exchanger. Most closed-loop gas expander cycles take into consideration pure

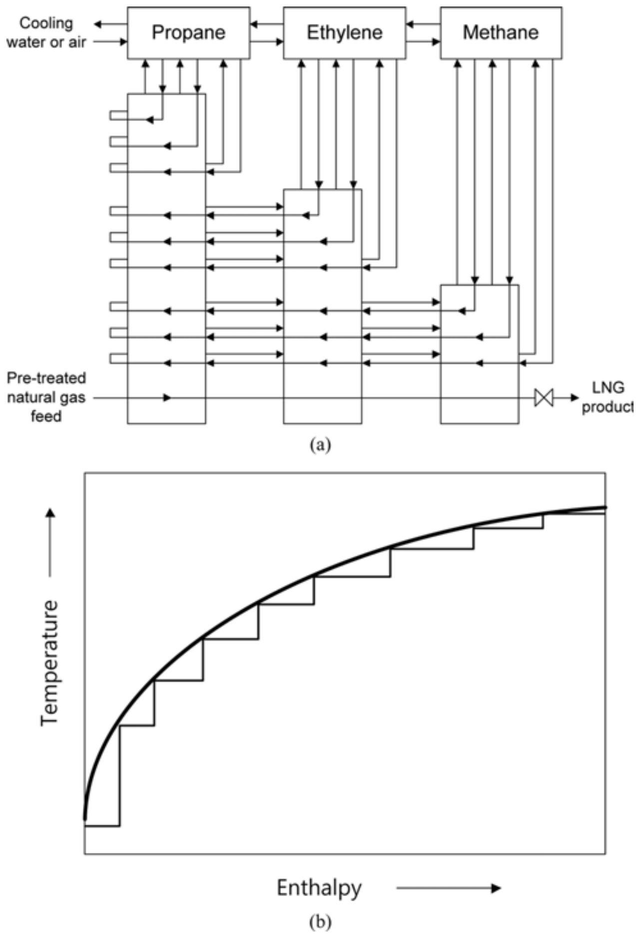


Fig. 6. (a) A schematic diagram showing process flow of cascade refrigerant process. (b) cooling and warming curve in cascade refrigerant process.

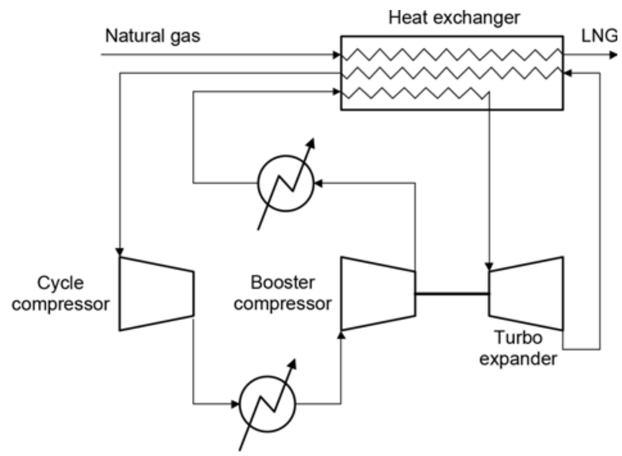


Fig. 7. A schematic diagram showing process flow of nitrogen expander liquefaction process.

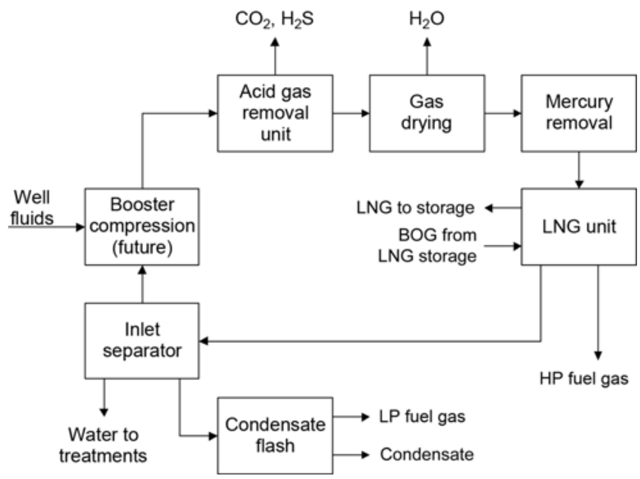


Fig. 8. A schematic diagram showing process flow of Proteus LNG process.

nitrogen as the cycle gas. Many companies like Gasol, Flex LNG, BW Offshore and Sevan Marine's FLNG apply this process. Kanfa Aragon that is owned by Sevan Marine used this technology to supply liquefaction topsides to Flex LNG for their first LNG FPSO [5].

1-3. Proteus LNG Process

Proteus LNG has developed a unique liquefaction technology for building an offshore plant. Its process diagram is given in Fig. 8 [5,21]. The liquefaction technology that is based on Gas Consult's turbo expander is designed for mid-sized vessels. Unlike other liquefaction processes, liquid hydrocarbon refrigerant is not needed for the Proteus LNG technology because the feed gas itself is used as the refrigerant. The process shows higher thermodynamic efficiency than nitrogen expander technology and its design is simpler than that of the mixed refrigerant liquefaction process. Currently, the company is installing a demonstration plant with the first commercial sized facilities.

1-4. Mixed Refrigerant Process

Mixed refrigerant (MR) processes use a mixture of butane, ethane,

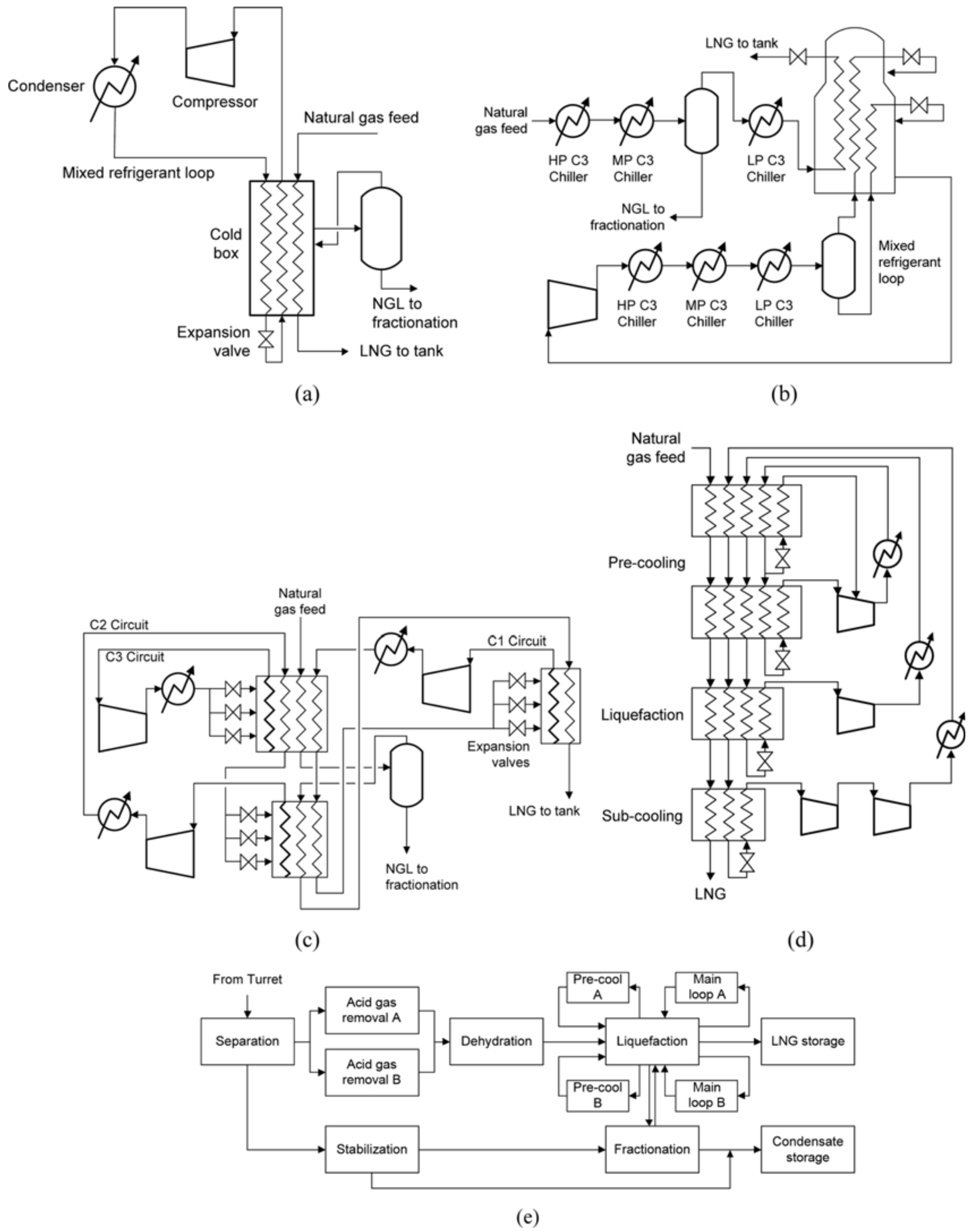


Fig. 9. Schematic diagrams showing process flows of mixed refrigerant (MR) processes; (a) sing mixed refrigerant (SMR) process, (b) pre-cooled mixed refrigerant (PMR) process, (c) pure refrigerant cascade (PRC) process, (d) mixed fluid cascade (MFC) process and (e) dual mixed refrigerant (DMR) process.

nitrogen and propane as refrigerants for cooling the NG [2,5,6,12]. The process is the most common liquefaction technology used for building LNG terminals. There are many different MR processes and most of them are used for installing large scale FLNGs due to their complexity. Shell and SBM reported that they were likely to use the MR process for building their LNG FPSOs. Especially, SBM is working with Linde for their FPSOs [6]. The MR cycle utilizes a single mixed refrigerant. The mixture composition is so specified that the liquid refrigerant is evaporated at the similar temperature range to evaporation of NG. A mixture of nitrogen and hydrocarbons is used as a refrigerant to get the optimal refrigeration characteristics such as close matching of composite in warming and cooling curves with small temperature gap at entire temperature range. The small temperature gap makes reversible operation possible, resulting in better thermodynamic efficiency, lower power requirement and smaller number of machines that need one compressor and small vessels for refrigerant separation. In spite of that, the MRC has lower efficiency than the cascade refrigerant cycle due to high flow of refrigerant. Of the variety of MR processes, there are five main processes to be introduced in this paper and Fig. 9 represents their process flows [5,12,22-30].

1-5. Single Mixed Refrigerant Process

Single mixed refrigerant (SMR) processes use MR consisting of nitrogen, methane, ethane, propane, butane and pentane [12,22,23]. Reversible operation is possible due to the small temperature gap, resulting in better thermodynamic efficiency, lower power requirement and smaller number of machines that need one compressor and small vessels for refrigerant separation. This process uses a single refrigeration loop to cool the NG. Black & Veatch Pritchard developed this technology dubbed as 'PRICO' that enables reduction in equipment and maintenance costs compared to more complex cascade processes [24]. In the process, the MR is compressed and partially condensed before entering into the cold box that contains efficient heat exchangers. In turn, the MR is condensed as it passes an open valve to drop pressure and temperature. The resulting cooled vapor returns to the cold box again where it condenses the MR stream and feed NG. The NG is first cooled to −35 °C. During the process, heavier components are eliminated in a separator and remaining components then go to the fractionation terminal, while light components such as methane passes to the cold box to cool their temperature to −161 °C. After that, the MR goes to compressor for recompression. Huge gas turbines produce a large amount of energy to compress the refrigerant. The SMR process is used for medium scale FLNG because its plant complexity is moderate [5,6].

1-6. Pre-cooled Mixed Refrigerant Process

Pre-cooled mixed refrigerant (PMR) process has been the most popular method to build onshore liquefaction plants. Air Products and Chemicals Inc. (APCI) has licenses for both PMR process and cryogenic heat exchanger that is main part of this PMR process [25]. APCI also takes on more than 80% of the world's current base load LNG capacity. This process uses only one refrigerant loop that contains a multi-component refrigerant. Although this concept is the same as that of the SMR process, unlike the SMR process, the PMR process uses a propane pre-cooler with a refrigerant of lower molecular weight consisting of nitrogen, methane, ethane and propane. In that process, the propane coolers partially condense the MR, while light and heavy components are separated and fed to the heat exchanger, respectively. The streams are cooled by passing a cold box and then flashed cross expansion valve. The resulting vapor is fed back to the heat exchanger and NG reaches its liquefaction temperature at the top of the heat exchanger [5].

1-7. Pure Refrigerant Cascade Process

The pure refrigerant cascade (PRC) process consists of three separate kits, and all of the kits contain a pure coolant like propane, ethylene and methane to cool the NG [5,26]. Each kit has an expansion valve, compressor, condenser and heat exchanger. In the expansion value, coolant is flashed to decrease its temperature. As soon as the NG enters into the system, it is fed to the heat exchanger of the propane kit and is cooled to −35 °C. In turn, the NG undergoes a fractionation stage where the heavier components are separated. Light NG passes to the second stage to reduce its temperature to −100 °C. The light NG that finished the second stage passes to the methane kit to liquefy the NG. The produced LNG is stored in the storage tank.

1-8. Mixed Fluid Cascade Process

The mixed fluid cascade (MFC) process shows better thermodynamic efficiency and operational flexibility than conventional cascade processes because it has mixed refrigerant cycles [5,26,27]. According to the process, purified NG is pre-cooled, liquefied and sub-cooled by three individual mixed refrigerant cycles. For that reason, this process enables larger single compressors to handle refrigerant at a wide range of temperature.

1-9. Dual Mixed Refrigerant Process

The dual mixed refrigerant (DMR) process utilizes two mixed refrigerant kits. This process was invented by Shell. The kits are used for pre-cooling and liquefaction, [5,28-30]. This process has two compressor strings, each consisting of a parallel arrangement of compressors. The reason for using two compressor strings is to prevent the train operation from being stopped. The first application of this technology in a base-load LNG terminal was at the Russian Sakhalin II project. Shell also plans to apply its Dual Mixed Refrigerant technology to building LNG FPSOs.

After the liquefaction process for LNG production is completed, the LNG formed is transformed into gaseous state prior to going to consumers. Regasification is required for changing the phase of LNG from liquid state to gas state. This process is mainly run in the LNG import terminal consisting of LNG receiving carrier, LNG unloading, LNG storage, metering and send-out, etc. Regasification converts LNG to gas by raising the temperature. Regarding the phase transformation, there are two types of LNG vaporization methods – open rack vaporizer and submerged combustion vaporizer. The LNG is initially pumped from storage tanks to vaporizer and then passed through tubes that consist of fins to maximize the heating area. The tubes are immersed in seawater that flows around the tubes and LNG is heated as it passes through. In the submerged combustion vaporizer, water is used to burn the boil-off gas. This vaporization is considered a secondary or back-up unit to the main seawater vaporizer as it is more expensive and the design permits rapid start up of the unit. Both vaporizers are shown in Fig. 10 [5,6]. As the main FLNG market drivers for the regasification process, companies like Shell, Flex LNG, Hoegh LNG, Petrobras, SBM Linde, MODEC, and Saipem are making rapid progress.

2. Main FLNG Hull and Mooring Systems

There are several notable prerequisites to installing an LNG termi-

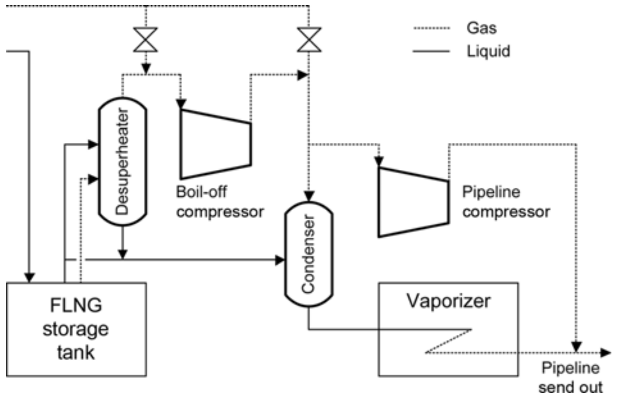


Fig. 10. A schematic diagram showing process flow of vaporizer that is required for LNG vaporization during regasification process.

nal offshore. The most important is to build an appropriate platform that is large enough to accommodate the relevant topsides. The next requirement is a containment system that offers a flat deck area. An attractive aspect of the current FLNG design is the steel-hulled vessels that are simple in design for LNG carriers and well-adapted to either liquefy or regasify NG. These vessels can move LNG easily between fields whenever needed, compared with other types of floating platforms. To install an LNG terminal offshore, the following parts should be constructed: floating production, storage and offloading (FPSO) vessel, liquefaction barge, and floating storage and regasification unit (FSRU) [6].

2-1. FPSO Vessel

FPSO is a ship-like vessel deployed to produce and store hydrocarbons from wells placed on the subsea wall or on an offshore platform [5,31,32]. Unlike conventional oil-producing FPSOs, LNG FPSO vessels contain LNG liquefaction facilities onboard. To date, there have been no LNG FPSOs under operation, and only four units are under construction. The key components of LNG FPSO are: (i) the vessel itself, which is categorized as a new LNG carrier, (ii) a mooring system that is built on a turret mounted inside the hull, (iii) specific topsides like liquefaction facilities, and (iv) a containment system for preventing sloshing damage.

2-2. Liquefaction Barge

The liquefaction barge system consists of a floating pretreatment and liquefaction barge. Also, two storage vessels are moored at a protected jetty [6,33]. The fixed element gets the untreated gas by pipeline. All of the utilities, instrumentation, and loading arms are positioned on the fixed platform. Gasol, Teekay, and Mustang are developing a Near-Shore LNG Production System for use in the Gulf of Guinea.

2-3. FSRU

FSRU is a ship-shaped vessel that gains the liquefied gas from carriers and then regasifies it onboard before offloading by either jetty or buoy [5,34]. This has enough capacity to store LNG onboard unlike RVs. RVs and FSRU are similar in design and are classified as being similar. So far, there is only one operational FSRU – Golar LNG's converted LNG carrier in Brazil – while there are several RVs in operation in Argentina, UK, and the USA.

FLNG terminals should be operated even in severe weather conditions. To ensure safe and effective operation of the terminal, maintaining reliability of the mooring systems that enable the terminal to remain on station is important. The mooring depth of vessels including the FLNG terminal and the type of environmental conditions encountered at its field location are the main parameters determining complexity and cost of the mooring system. For instance, in mild conditions with directionality in prevailing weather patterns, a simple low cost system is possible. Conversely, in severe circumstances like icy and typhoon-prone weather, the mooring system may not be connected well and the vessels should be moved into safer places at greater cost. Fig. 11 shows the representative FPSO [35] and FSRU that were used for installing an LNG terminal offshore [36].

Mooring systems are generally installed by anchor-handling tugs and other offshore support vessels before the arrival of a floater. As soon as the floater arrives at the field location, the vessels can be rapidly hooked up and moved to a safe place. The mooring system is made up of the following four segments: spread mooring systems, differential compliance anchoring systems (DICAS), dynamic positioning, and turret mooring systems [5].

2-4. Spread Mooring System

The mooring lines are hung in catenary configurations in spread

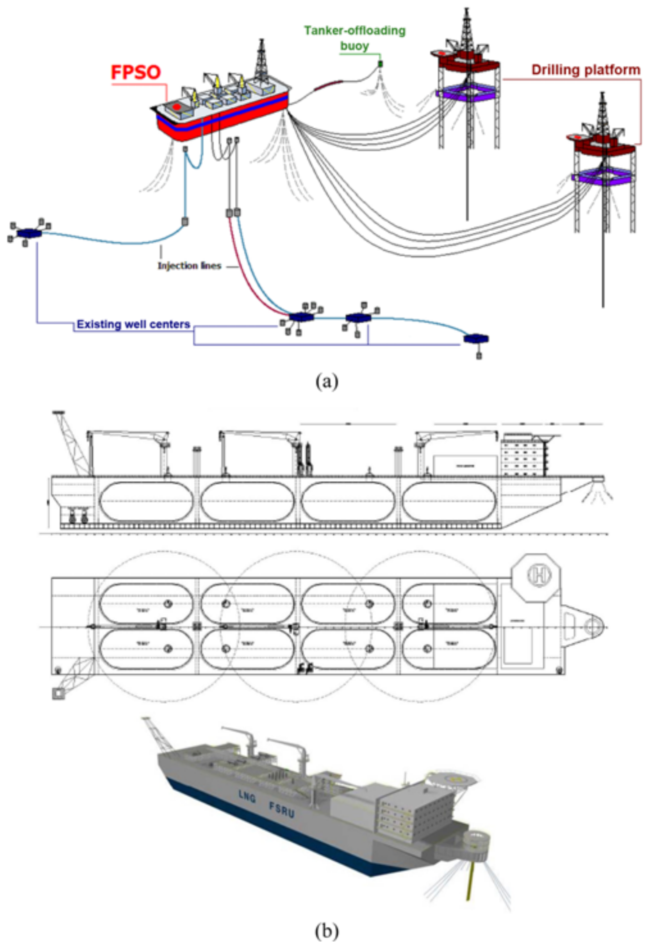


Fig. 11. (a) A schematic diagram showing floating production, storage and offloading (FPSO) system and (b) top view and cross-section view of representative floating storage and regasification unit (FSRU) vessel structure and 3 dimensional schematics.

mooring systems and arranged in symmetrical pattern. The system ties up the vessel on a fixed heading [37,38]. This system can offer advantages such as wide applicability in terms of vessel type and water depth, usability of cheap mooring equipment, and suitability for a wide range of mooring lines. The mooring lines are hung on the bow and stern with risers and control umbilicals brought in riser porches located along the side of the vessel. The arrangement provides ample room to accommodate a large number of risers and umbilicals. Because spread moorings make the vessel point in a fixed direction, they can be used in locations where the prevailing weather is directional (good weather conditions).

2-5. DICAS

DICAS was developed from Petrobras' PROCAP 2000 R&D initiative [39]. It is a form of spread mooring system for vessels that allows partial weather vaning by establishing difference compliance in the mooring lines at the vessel's bow and stern. The differential compliance holds the bow secure but leaves the stern free to move within certain limits, enabling the vessel to align itself with the direction of the prevailing weather.

2-6. Dynamic Positioning

Dynamic positioning enables vessels to take up position in any water depth because they use their own power to remain on a station [5,12]. The vessels are fitted with azimuth thrusters positioned fore and aft that work to keep the vessel at fixed coordinates. The level of accuracy is within two meters of the specified locations. These reference systems may be used with underwater acoustic or satellite positioning signals or with both. Dynamic positioning vessels can be of further benefit like greater load capacity and larger deck space than conventionally moored vessels. Under bad weather conditions, such as storms and heavy snow, the dynamic positioning system contains automatic break-away equipment that disconnects the unit from the risers and moves the vessel away from the area in order to overcome the bad weather conditions. The capex related to the dynamic positioning system is likely to be more expensive than that of the traditional passive mooring system. Hence, the dynamic positioning system is best fitted with vessels like deepwater rigs and drill ships than floating terminals. There is potential to use dynamic positioning on the Early Production System (EPS) like Petrobas' Seillean FPSO.

2-7. Turret Mooring System

The turret mooring system is designed for floaters operating in harsh environments where spread mooring systems are not desirable [40-42]. They are more complicated and expensive than the catenary spread mooring system. The turret mooring systems make it possible for a vessel to weathervane easily, in order to align with the prevailing weather and to be operated as normal even in moderate to extreme sea conditions. The turret system houses the vessel's risers for production, export, gas lift and water injection, and umbilicals delivering electrical and hydraulic control signals and chemicals. For the latter purpose, the main component of the turret mooring system is the swivel, an example of which is pictured. This enables the transfer of gas and chemicals to continue uninterrupted in spite of the vessel's movements as it pivots around the geostationary turret. The systems produce a niche market within the floating production sector and a wide range of designs has been developed. As suppliers of this system, SBM, Bluewater, and Sofec (FMC's subsidiary) are well known. Also, nowadays, Advanced Production and Loading (APL), a former Statoil subsidiary, is rising in the market. Fig. 12 represents schematics of spread mooring and turret mooring, which are the most popular mooring methods [43].

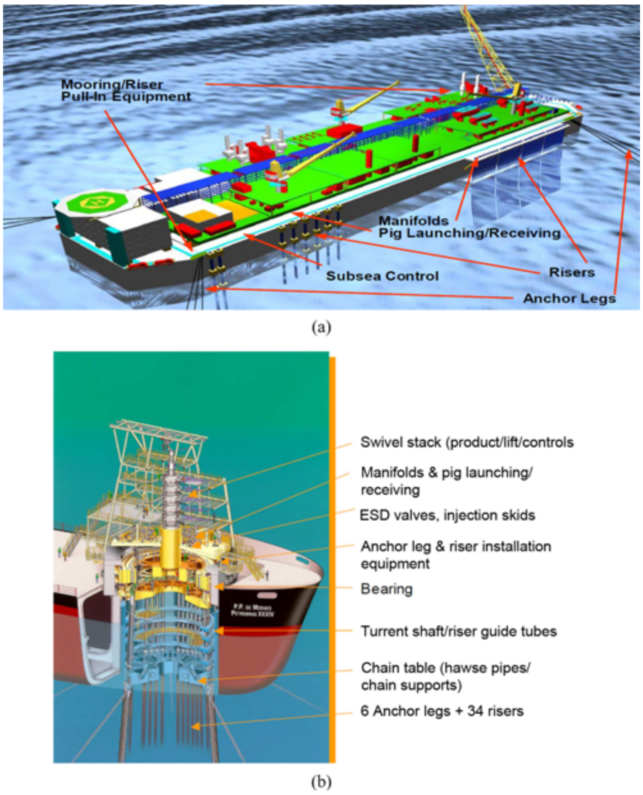


Fig. 12. Representative schematic diagrams showing (a) spread mooring system and (b) turret mooring system.

3. Main FLNG Offloading Systems

The offloading of LNG and gas between two vessels in the sea is also a challenging operation and difficult in harsh weather conditions. Specific equipment that provides safe and efficient offloading is therefore important to operators. It is one of the most unproven technologies in the FLNG industry. There are many types of offloading equipment and offloading methods. We introduce two main offloading equipment (loading arms and cryogenic hoses) and two main offloading methods (side by side transfer and tandem offloading) [5,44,45].

3-1. Loading Arm

The loading arms that are attached to the side of a ship or at the bow are needed for the offloading of LNG and NG. Companies like FMC, Aker Solutions, and SBM offer loading arms for side by side, tandem or ship to shore offloading. Marine loading arms have several components like base riser, inboard arm, and outboard arm. FMC technologies currently offer two special marine loading systems for the LNG operations – the rotary counterweight marine arms (RCMA-S) and double counterweight marine arms (DCMA-S) [5,6].

3-2. Cryogenic Hose

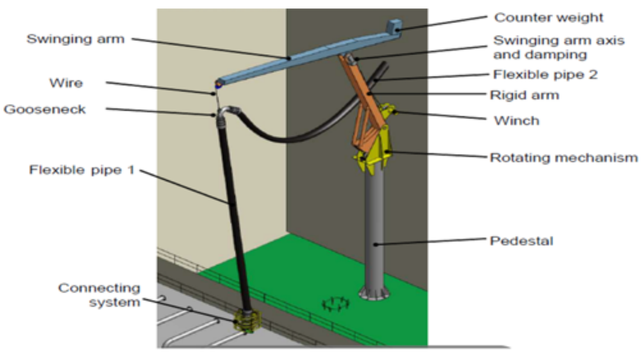
As an alternative to loading arms, cryogenic hoses are thermally isolated hoses which transfer both LNG and NG between FLNG vessels and LNG carriers. Hoses are used in hostile sea conditions where a close contact between vessels is difficult. These floating cryogenic hoses are used in tandem offloading arrangement where there is no bow manifold. The first transfer of LNG between two vessels using cryogenic hoses took place at the Teesside Gas Port in 2007 [5,6].

3-3. Side by Side Transfer

Moored side by side operation is an important option for offloading on LNG FPSO, FSRUs, and RVs [5,46]. The most important during the operation are the loads in mooring lines between two vessels and the loads in floating fenders. These are determined by weather conditions such as wave and wind, besides also the loads on the two vessels. Thus, this side by side mooring is only valid in benign environments. The side by side offloading is operated by using both loading arms and cryogenic hoses that are placed on the side of a ship. Side by side offloading via loading arms was used for crude oil and LPG for a long time and its effective role was proven between two LNG carriers, although offloading has not yet been proven between LNG FPSO and LNG carrier [47].

3-4. Tandem Offloading

Tandem offloading is useful where ship by ship offloading of FLNG vessels is not possible [48,49]. Owing to the short distance between the bow and stern of two vessels and unstable wave/wind conditions, this is a very complicated operation. Tandem offloading may use aerial cryogenic hoses, floating cryogenic hoses or loading arms. Many companies are developing tandem offloading solutions. BW offshore and APL have developed a tandem offloading system based on their oil transfer BLS and SDS systems, while SBM began using its flexible cryogenic hoses for both aerial and floating tandem arrangements in 2010 [50]. Fig. 13 shows schematics of side by side transfer and tandem offloading that are mainly used as FLNG offloading systems [51].



(a)

(b)

Fig. 13. Representative schematic diagrams showing (a) side by side transfer and (b) tandem offloading.

CHALLENGES OF FLNG TECHNOLOGIES

The most technical challenge of FLNG is how to convert LNG production to offshore setting, which depends on the marine weather environment [1,15]. For instance, wave motion may influence the performance of process equipment units that include distillation and separation columns needed for condensate stabilization, LPG extraction and acid gas elimination in feed gas pretreatment before the liquefaction process. As possible solutions for the challenge, options such as structuring tower packing, liquid redistributors, and dividing column configurations have been considered. With these methods, liquids in columns built in the FPSO can be uniformly distributed. Also, LNG containment systems are important. They should prevent damage happening due to sloshing in filled tanks, which is attributed to irregular sea wave and current motions, while LNG transfers should withstand strong wind, waves, and currents in open seas.

IHI's containment system and GTT's tank configurations system represent commercial options that use the process equipment units in order to reduce and withstand wave impacts expected from sloshing and to provide the flat deck required to accommodate the floating plant [15]. Old LNG loading arms have also been adapted to make LNG transfer possible in open sea, whereas hose-based solutions for side-by-side transfers in mild sea conditions and tandem transfers in harsh conditions are used.

Space limitation of floating vessels is also a challengeable problem to overcome. Due to this reason, the amount of feed gas that can be reserved for floating liquefaction is restricted. Units for gas pretreatment operation are supposed to occupy about 50% of the available deck space of a floating production facility, although this relies on the impurity level in the feed gas stream [5,15]. This indicates that FLNG is more suited to feed gas streams including low levels of inert gases and impurities. CO_2, hydrogen sulfide, nitrogen, mercury, and acid gases are the main impurities determining the amount of feed gas.

FLNG is also confined in the level of condensates and liquid propane gases (LPGs) that can be directly handled aboard the vessels. While these liquids have brought valuable additional revenues for onshore LPG development, in FLNG their revenue profits are cancelled out due to expensive offshore settings due to increased processing and storage obligations that are imposed on the floating facility [6,15]. The complexity of offshore production operation that is already the most complicated results in unstable safety as well.

As FLNG development has become more advanced, concerns about the economical prospects have increased. There are many economic, financial, and legal considerations to alleviate the risk of FLNG technology before offshore LNG production becomes an actual solution for gas treatment. However, ultimately, it is predicted that FLNG will be economical. Although we are now at the early stage of development, the cost being pitched by LNG FPSO promoters is compatible with that of base-load LNG and oil prices. According to capital cost analysis, a small scale LNG facility has been constructed at a cost of between $600 and $1200 tpa, and a large scale LNG facility has been constructed for about $800 tpa. The recent economic downturn resulted in the drop of potential development and construction costs by 20-30%. However, this cost is still competitive compared with oil price [5,6,15].

The reliability of FLNG remains uncertain. FLNG's marine environment, LNG's stringent feed gas pretreatment requirements, and the application of new technologies will retard the maturity of FLNG, and it may take more time to reach normalization of process and stabilization of operational cost [6]. Related to reliability issues, depletion of reserves can also be a main concern for FLNG development. Many investments, especially in drilling and compression processes, are ongoing and it means that the FLNG industry should keep going forward because FLNG's high investments may not tolerate long and fast depletion of gas reserves.

The relocation of a floating liquefaction between different fields may be a problem because the operational situations of all gas fields are not the same. Thus, for example, in a second location, condensate processing and gas pretreatment process may be very expensive and new processing units are required for the operation. The degree of additional costs of the relocation of a floating liquefaction is dependent on parameters like timing of the move within the facility's economic life and whether gas monetization is suitable for the overall economics of the field development. The relocation may also produce misalignment between upstream gas supplier and liquefaction plant operator as the LNG operator may want to surrender a field and move into a new place earlier in the depletion curve than the field owner would like to surrender. For this reason, an optimal strategy can be suggested.

While FLNG is a growing sector of the LNG industry, over time its pace of development is affected by current economic trends [5,6]. Lower oil prices and falling LNG demand are further factors affecting FLNG development. Financing sources for technology development have diminished, making it more difficult for developer-led initiatives to finance later development stages. However, oil company piggybacked projects have been less affected due to their conservative economic assumptions and their sponsors' strong balance sheets. Falling material cost, weak shipping order books, and increasing cancellations may lead to a pause in development.

Unlike the challenges of FLNG, it is evident that other industry pressures ensure that FLNG development is maintained. The growing relevance of stranded gas reserves to the growth of international gas trade combined with LNG's ability to monetize reserves at tradable prices may increase FLNG revenues. Additionally, greenhouse gas effect and its regulations have increased FLNG's attractiveness as a source of low emission fuel and a means to reduce flaring of associated gas.

CONCLUSIONS

NG is likely to be the bridge between the end of the crude oil era and future energy solutions. The LNG industry, which is a dominant business model of NG trade, is paid attention due to the high price and confined reservation of the most conventional energy resource, crude oil, and the associated pollution issue of CO_2 emission. Furthermore, nuclear power plants, a notable substitute, are risky as a main energy source due to the threat of natural disaster like earthquakes and tsunamis. However, for greater activation of the LNG industry, a cheaper, more eco-friendly and more secure business model is needed. FLNG, which is operated in offshore liquefaction, can be an appropriate alternative to the LNG.

Regarding import terminals, the FLNG import terminal shows cheaper cost and faster lead time than the LNG import terminal. In comparison with liquefaction terminals, FLNG has lower upstream and EPC costs than its counterpart because the FLNG liquefaction terminal does not need to construct pipelines for the transfer of NG and has lower capex per t/y. It is also useful when an onshore plant cannot be built properly due to security issues and topography.

In terms of FLNG operation, six nations (Argentina, Brazil, Kuwait, UAE, UK, and USA) operate FLNG and several ongoing FLNG liquefaction projects. For instance, Shell's 3.6 mmtpa was approved and will be in operation from 2017, and Petrobras is building its offshore liquefaction facility in Brazil. Flex LNG, Hoegh LNG, SBM Linde, MODEC, and Saipem are also building their FLNG facilities. In terms of its market, Australia and Asia will dominate and Latin America and Africa will follow. Of all the FLNG processes, business especially associated with the construction of liquefaction and regasification terminals is expected to be the most interesting. However, in spite of the many advantages of the FLNG process, there are still difficulties in stabilizing its main stages. To address the challenges, the optimization of modular design related to the main and typical stages of FLNG is needed.

In this review paper, we considered the LNG concept and compared it with the FLNG concept. Following this, typical FLNG technologies such as offshore liquefaction and regasification topsides, hulls and containment systems, mooring and transfer systems were introduced and explained. The main market drivers for the FLNG industry were also examined. It is anticipated that the FLNG industry will be a very promising business model that acts as a connector between past energy solutions and future energy solutions.

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