THE MOORING BAY CONCEPT
FOR LNG LOADING IN HARSH AND ICE CONDITIONS

Sven Hoog*
IMPaC Offshore Engineering
Hamburg, Germany
Email: hoog@impac.de

Joachim Berger
IMPaC Offshore Engineering
Hamburg, Germany
Email: joe.berger@impac.de

Johannes Myland
IMPaC Offshore Engineering
Hamburg, Germany
Email: myland@impac.de

Günther F. Clauss
Naval Architecture & Ocean Eng.
Technical University of Berlin
Germany
Email: clauss@naoe.tu-berlin.de

Daniel Testa*
Naval Architecture & Ocean Eng.
Technical University of Berlin
Germany
Email: testa@naoe.tu-berlin.de

Florian Sprenger
Naval Architecture & Ocean Eng.
Technical University of Berlin
Germany
Email: f.sprenger@naoe.tu-berlin.de

ABSTRACT

The demand for natural gas from offshore fields is continuously increasing. Especially future production from Arctic waters comes into focus in context with global warming effects leading to the development of a dedicated technology. Relevant approaches work with floating turret moored production terminals (FLNG) receiving gas via flexible risers from subsea or onshore fields. These terminals provide on-board gas treatment and liquefaction facilities as well as huge storage capabilities for LNG (Liquefied Natural Gas), LPG (Liquefied Petrol Gases) and condensate. Products are transferred to periodically operating shuttle tankers for onshore supply reducing the need for local onshore processing plants providing increased production flexibility (future movability or adaptation of capacity). Nevertheless, in case of harsh environmental conditions or ice coverage the offshore transfer of cryogenic liquids between the terminal and the tankers becomes a major challenge. In the framework of the joint research project MPLS20 ([1]), an innovative offshore mooring and cargo transfer system has been developed and analyzed. MPLS20 is developed by the project partners Nexans ([2]) and Brugg ([3]), leading manufacturers of vacuum insulated, flexible cryogenic transfer pipes, IMPaC ([4]), an innovative engineering company that has been involved in many projects for the international oil and gas industry for more than 25 years and the Technical University (TU) Berlin, Department of Land-and Sea Transportation Systems (NAOE, [5]), with great expertise in numerical analyses and model tests. The overall system is based on IMPaC’s patented and certified offshore ‘Mooring Bay’ concept allowing mooring of the vessels in tandem configuration and simultaneous handling and operation of up to six flexible transfer pipes in full aerial mode. The concept is outlined to operate with flexible transfer lines with 16-inch inner diameter like the newly designed and certified corrugated pipes from Nexans and Brugg. The mooring concept and its major subsystems have proven their operability by means of extensive numerical analysis, model tests and a professional ship handling simulator resulting in an overall transfer solution suitable to be used especially under Arctic conditions like addressed by the EU joint research project ACCESS (http://access-eu.org/). The paper introduces the new offshore LNG transfer system and focuses especially on its safe and reliable operability in the Arctic - with ice coverage as well as in open water conditions.

INTRODUCTION

Gas transport by LNG tankers (Liquefied Natural Gas) can be an alternative to the use of pipelines. Each decision for a solution depends on several technical and economic factors with the distance to the client receiving facility being very relevant. In order to achieve economically reasonable transportation, the natural gas (mostly methane) is cooled down to -162 degrees C, whereby it is liquefied and reduced to 1/600th of its original volume.

State-of-the-art technology allows loading/offloading in benign seas by means of hard arm technology adapted from onshore technique. Nevertheless, the increasing loading capacity of LNG carriers (up to 266,000 m³) creates a new
market for fast and safe loading/unloading concepts — i.e. utilizing flexible pipes with inner diameter up to 16-inch and operations in rough seas and even in Arctic conditions.

Studies show that none of the ‘conventional’ vessel mooring configurations and transfer techniques can easily be adapted to meet the requirements of offshore LNG transfer, especially when dedicated for use in environmental conditions with significant wave heights up to e.g. 5.5 m at zero-up-crossing periods between 8 and 12 seconds or in ice conditions combined with significant wind and current loads and overall operation durations (incl. mooring, transfer and departure) of 18-24 hours.

The MPLS20 system employs flexible transfer pipes with ID 16-inch, newly developed by Nexans and Brugg (certified by DNV), providing a monitorable double containment system for the cryogenic cargo (refer [1]).

The overall system is based on IMPaC’s patented offshore ‘Mooring Bay’ concept (certified by GL) allowing safe and reliable mooring of the shuttle carriers to the FLNG and simultaneous handling and operation of up to six transfer pipes in aerial mode.

SYSTEM SETUP
The new mooring concept utilizes a unique tandem configuration for the LNG terminal (the FLNG) and the shuttle carrier (LNGC, Figure 1). To meet the needs for Arctic application the initial design and the vessels have been adapted, resulting in icebreaking abilities, a new mooring concept for the barge and a modified concept for approach of the new I(ce)-LNGC to the mooring bay at the aft end of the new I(ce)-FLNG.

Mooring of the I-FLNG is realized by an internal turret mooring system using a submerged production buoy allowing coping with drifting ice. Up to sixteen segmented mooring lines are employed (depending on site specific environmental loads) to fix the buoy at location allowing weathervaning of the moored vessels in 360°.

Although the main focus of the development lies on the Mooring Bay and the cargo loading concept the hull design of both vessel types I-FLNG and I-LNGC is important for the concept, especially when it shall work in ice conditions.

To reduce the reacting forces of the mooring lines to ice loads the terminal barge bow has been modified to gain increased icebreaking capability. As result the bow shape of the I-FLNG can roughly be characterized as a flat spoon with abt. 30° stem angle and flared frames in the icebreaking zone allowing combining the required buoyancy and loading capacity with sufficient icebreaking ability (compare Ref. [7]). A wedge-shaped plough at the bow of the barge serves as an ice clearing system reducing the amount of ice reaching the turret mooring system below the hull bottom.

The I-LNGC is a double acting vessel with azipod drives which shall allow the ship to pass level ice with thickness up to 1.5 m in backward direction (comparable hull designs are approved and operating) and with optimized behavior in open water and reduced ice thickness in forward direction.

Relevant geometric parameters of the generic terminal barge and the carrier are listed in Table 1.

<table>
<thead>
<tr>
<th>Item</th>
<th>Terminal (I-FLNG)</th>
<th>Carrier (I-LNGC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length oa [m]</td>
<td>360 (+40 Mooring Bay)</td>
<td>282</td>
</tr>
<tr>
<td>Length pp [m]</td>
<td>347.7</td>
<td>257.4</td>
</tr>
<tr>
<td>Width [m]</td>
<td>65</td>
<td>42</td>
</tr>
<tr>
<td>Draught [m]</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Height [m]</td>
<td>33</td>
<td>26</td>
</tr>
<tr>
<td>Displacement [m³]</td>
<td>~253.000</td>
<td>~104.000</td>
</tr>
<tr>
<td>LNG loading capacity [m³]</td>
<td>250.000</td>
<td>138.000</td>
</tr>
</tbody>
</table>

Table 1: Main geometrical features of the LNG terminal and the LNG carrier

Offshore LNG Transfer Concept
The concept features the generic I-FLNG design with the so called Mooring Bay, double acting shuttle carriers and the handling system for a set of up to six flexible LNG/LPG transfer pipes (Figure 2). The I-FLNG is of barge type
providing a cargo loading capacity for LNG up to 250,000 m³ in five independent SPB tanks (Self-supporting, Prismatic, IMO Type B) which are sloshing-proof and provide a flat deck (refer [1]). By-products like LPG and condensate are stored in dedicated tanks with capacity up to 25,000 m³ each.

The employed I-LNGCs are ice going vessels with quasi standard dimensions and functionality but equipped with an additional receiving manifold at the bow deck space. This manifold completely enters the Mooring Bay when the carrier is pulled and moored to the cargo transfer position. The resulting distance between the loading flanges at the terminal and the receiving manifold at the carrier is thus minimized achieving a total length of less than 40 m for the transfer pipes.

The Mooring Bay is built of two so called ‘mooring wings’, which are structurally part of the terminal’s aft end at starboard and port side, respectively, reducing the risk of ice inflow between both vessels (Figure 2). For safety reasons any remaining ice in the Mooring Bay can be pushed out of way by means of dedicated thrusters at the aft end of the barge prior to the approach of carriers.

The mooring arrangement for the I-LNGC to the Mooring Bay results in a symmetrical arrangement of six moorings each operated by load adequate winches and heave compensation systems at the I-FLNG. This arrangement provides a unique solution to actively pull in and stop the incoming vessel in a controlled manner at the required position right below the loading bridge. The moorings are temporarily fixed to quick release hooks (QRH) which can be remotely activated for safety reasons.

The cargo transfer flanges are located in a sheltered position within the loading bridge structure high above the wings weather decks so that handling, draining and purging of the flexible pipes can be carried out in a safe, efficient and reliable way (Figure 3).

Figure 3: Safe and reliable handling of the flexible pipes for cargo transfer and in ESD situations

**Flexible LNG Transfer Pipes**

Vacuum insulated pipes are common in all kinds of cryogenic application. Nevertheless, the developments of Nexans and Brugg are based on their flexible vacuum insulated pipe system CRYOFLEX for offshore LNG loading applications considering EN1474-2, refer [9] for details.

These pipes provide a double containment system - the ‘Pipe in Pipe’ technology - having advantages in terms of leak detection and risk assessment of the installations with best thermal insulation properties.

A corrugated double wall pipe of stainless steel 316L is insulated by a super insulation and a vacuum space between these two pipes. A stainless steel braiding on the inner pipe bears the end cap load of the pipe. For mechanical protection an outer sheath of Polyethylene (PE) or Polyamide (PA) can be applied.

The vacuum does not need active pumping during operation for more than 15 years. The pipe structure offers leak detection in the vacuum space, giving a signal to the system if the vacuum degrades due to a leak in either the inner or the outer pipe. Nevertheless, in case of a problem the gas cannot escape to the environment because of the double containment system.

**Manuovering in Ice**

The approach of the I-LNGC follows several clearly defined steps (Figure 4): First is the far field approach of the carrier with ice breaking in backward drive. This step is characterized by the entering of the carrier into the terminals ice free wake (Phase I). One of the waiting tugs moors to the aft end of the carrier allowing controlling of the alignment of both vessels. The carrier proceeds driving with very slow speed in forward direction to the Mooring Bay until mooring lines are deployed from the terminal to the QRH at the carrier taking over speed control (Phase II). The final approach starts by the gentle and controlled pull-in of the carrier into the Mooring Bay until the receiving manifold has reached the exact position right under the loading bridge which is standby and ready for coupling of the header to the manifold (as shown in Figure 3 and Figure 4, Phase III).

Figure 4: Steps of approach and pull-in of the carrier to the Mooring Bay and cargo transfer in ice conditions
Connection of Transfer Lines

When the carrier/manifold is located in the right position two lines are released from the header and hooked-in in dedicated docking cones at the manifold. Active winches allow safe pull-in of these lines for the final approach of the header to the manifold (Figure 3). The header carries the complete set of up to six transfer pipes (max. 4 for LNG, max. 2 for vapor return) each equipped with its QCDC and ERC couplings. After touchdown of the header the QCDC couplings are closed and the cargo transfer, which alone can last up to 18 hours, can be started. According to international requirements the transfer capacity is outlined to reach at least 10,000 m³ per hour.

It is important to note that this concept provides a fully aerial solution which means that no cargo carrying component touches the sea surface (or sea ice) in any regular phase of operation or even in ESD situation.

After completion of the cargo transfer this sequence is followed vice-versa so that the header remains permanently under control until it has been fully retrieved from the carrier deck/manifold.

ESD situation

The handling of LNG transfer lines in emergency situations is a very critical part of related risk assessments. Here, the MPLS20 system has proven especially good performance as the developed aerial solution provides full control of every single step of operation. If for example a critical situation (e.g. loss of a mooring) results in excessive vessel relative motions and the reaching or exceeding of the pre-defined working envelope within the Mooring Bay, the cargo pumps are stopped (phase ESD 1) or even all ERCs are opened followed by the departure of the carrier from the Mooring Bay (phase ESD 2), respectively. This situation can be carried out in a safe and reliable way and without disturbances due to environmental constraints, which has been approved in principle (AiP) by Germanischer Lloyd (GL).

SYSTEM VERIFICATION

A number of system verifications have been carried out for the new Mooring Bay and the transfer pipe handling system. Also the new developed flexible pipe from Nexans and Brugg has been certified (‘fit for purpose’) by DNV. Beside the risk assessment (FMEA) by the GL extensive numerical analyses with two well established ‘competing’ Software systems (WAMIT and ANSYS AQWA) and model tests in the towing tank of the TU Berlin as well as simulations and animations at the professional ship handling simulator MSCW in Warnemünde (Germany) have been performed.

Motion Analysis

The numerical calculations are conducted by the two software systems WAMIT and ANSYS AQWA, both potential theory approaches.
While the specially adopted radiation-diffraction panel code WAMIT (Wave Analysis at Massachusetts Institute of Technology) is able to take inner free liquid surfaces into account (sloshing), ANSYS AQWA considers wind and current, providing results in frequency domain as well as time series for ship motions and mooring forces of the multi-body system.

For validation purposes results of both numerical methods were compared with model test results (refer [1]). Figure 5 and Figure 6 show the ratio of the motions of both single vessels (LNGC and FLNG, selected degrees of freedom) for a specific excitation frequency to the height of the exciting wave, the so-called Response Amplitude Operator (RAO), plotted against the frequency of the exciting wave for identical inputs, i.e. solid filling in head seas.

During the cargo transfer period free fluid surfaces occur in the cargo tanks of the LNGC. This leads to a significant decrease of the initial intact stability and altered motion behavior (refer [9]). While the FLNG unit is equipped with sloshing-proof SPB tanks, the LNGC selected for the investigations features standard prismatic tanks without internal partitions. This type of tank is prone to resonant free surface motions that are induced by the ship moving in waves.

The sloshing analysis has been carried out in frequency domain with WAMIT. Calculations with water in the tanks have been carried out and compared with model tests in order to validate the numerical setup (refer [9]). Subsequent calculations with LNG tank filling provide the real motion behavior of the system with partially filled tanks.

Figure 7: Comparison of the solid filling case and 30% water filling for the LNGC’s surge (β=180°) and roll (β=90°) RAO

Figure 7 shows a comparison between the LNGC surge (β=180°) and roll (β=90°) RAOS for the solid filling case (please note that the model is not equipped with bilge keels) and tanks with 30% filling height. It can be deduced, that the low-frequency peak of the roll motion (ω=0.2 rad/s) is related to the hull resonance, since no fluid motions inside the tanks can be observed, i.e. the ship is rolling and the fluid surface remains in a horizontal plane parallel to the water surface in the basin. In contrast to this, the high-frequency roll motion peak (ω=0.86 rad/s) is clearly related to strong transverse sloshing inside the tanks. The same applies to the surge motion peak (ω=0.74 rad/s), which is related to moderate longitudinal sloshing inside the tanks. Peak height and resonance frequency depend on the filling level.

One of the main goals of the numerical analysis was to ensure that the maximum allowable bending radius of the transfer pipes will not be exceeded in order to ensure a safe loading/unloading operation. Therefore relative motions between the transfer pipe coupling points have been calculated, refer [1]. It has been shown that LNG can be transferred safely in wave heights up to Hs=5.5 m.

Ice Load Analysis

Numerical calculations have been carried out to determine specific loads from drifting ice to the moored multi-body system. For this purpose the above described generic I-FLNG hull with ice breaking capabilities has been analyzed with the software ANSYS AQWA. Two different mooring configurations (Figure 8) with 1) equidistant attachment of the lines around the circumference of the mooring buoy and 2) a 4 times 3 lines configuration (centered each 90°) have been considered and the resulting equilibrium positions and load in the lines are calculated. It should be noted that the mooring line assemblies are the same for both configuration very basic designs in order to achieve suitable solutions. They have to be subject of detailed investigations for each discrete development and location.

Figure 8: The analyzed mooring line configurations: 12x1 (left), and 4x3, with angle of attack 180° at each

Waves with significant height Hs=5.5 m, wind with max. velocity 15 m/s, current with velocity 1.0 m/s and two different ice coverages at the I-FLNG bottom (A=70% coverage and B=30% coverage due the wedge-shaped plough) have been considered.

The results show good performance and load distribution for the analyzed mooring configurations 12x1 and 4x3, with light advantages for the 12x1 configuration when a tidewater induced changing of the angle of attack for the environmental loads is likely to occur (Figure 9 to Figure 11).

The comparisons show differences in percentages of the load distributions and horizontal displacements for varying
external loads based on the initial ‘MPLS20-configuration’ (4x3). It can be seen that a ship shape modification like the wedge-shaped plough significantly helps to reduce the ice induced effects on the coupled multi-body system.

Figure 9: Comparison of tensions in the mooring lines – 12x1 configuration, 180° angle of attack (4x3, 180° open water case = 100%)

Figure 10: Comparison of tensions in the mooring lines – 4x3 configuration, 180° angle of attack (4x3, 180° open water case = 100%)

Figure 11: Comparison of horizontal turret displacements due to external loads (4x3, 180° open water case = 100%)

Tank Tests
In order to ensure the trustworthiness of the numerical approach, model tests are performed with the LNGC and FLNG hull at a scale of 1:100 (see Figure 12). All tests are carried out in the seakeeping basin of Technical University Berlin, where the models are soft-moored and equipped with wireless, individually pulsed infrared sensors. The body motions in six degrees of freedom are precisely tracked by five cameras mounted on a carriage above the basin with a tracking range of $8 \times 10$ m.

Also, the foremost and sternmost tanks of the LNGC are placed on six-component force sensors to measure the forces and moments occurring between the tanks and the hull (Figure 13). A ship-fixed camera located at the stern of the vessel records the interior fluid motions in the tanks. Test series with filling levels of 10%, 20% and 30% water in all four tanks as well as the solid filling case have been conducted at a constant draught of 12 m and a water depth of 100 m (full scale).

Figure 12: The coupled LNGC and FLNG models (scale 1:100) in the seakeeping basin at Technical University Berlin (top right: a tracking camera’s view, bottom right: view into the tanks)

Figure 13: Illustration of the onboard tank load measuring equipment at the LNGC

The tank tests confirmed the results obtained by WAMIT and ANSYS AQWA.

Ship Handling Simulations
Professional ship handling simulators are employed to carry out training with nautical personnel. In addition the MSCW, as part of the University of Wismar, supports performing of applied research. The simulator has two fully equipped ship handling bridges with up to 360° visualization
abilities. The FLNG and LNGC vessels have been transferred to the system and their realistic motion and mooring behavior has been simulated and projected onto the screens. An experienced tanker captain commanded the bridge and instructed the ‘virtual’ tugs like in reality (Figure 14).

The simulated procedure included the approach of the carrier to the Mooring Bay in heavy sea state and the mooring to the terminal – all assisted by tugs like planned. It turned out that the tankers can be steered as required and that the overall concept is feasible to work in reality and in harsh environments.

![Figure 14: Nautical simulations carried out at the test center MSCW allow verifying the overall concept](image)

CONCLUSIONS

A new offshore LNG transfer system has been introduced developed to work in harsh environments and especially in ice conditions. The system allows cargo transfer between a permanently turret moored FLNG and LNG shuttle carriers with ice breaking abilities in a certified and patented tandem mooring configuration.

New developed and certified flexible transfer pipes provide increased safety features by means of a monitorable double containment structure. Simultaneous handling of up to six pipes in aerial configuration guarantees transfer rates of at least 10,000 m³ per hour and related vapor return to the tanks.

The successive loading of the carrier tanks in offshore conditions can result in severe and unwanted motions of the carrier induced by the partially filled LNG loadings. This phenomenon has been studied by means of numerical and tank tests and recommendations for designs have been derived.

All procedural and safety features required by current rules like EN 1474-1 to -3 are met and no ‘show stoppers’ have been identified. A risk assessment (FMEA), extensive numerical and tank tests as well as tests in a professional ship handling simulator prove that load transfer can be performed in harsh environments and even ice conditions without leaving the safe working envelope. Please visit the project web site for further information ([1]).

PERSPECTIVES

The project MPLS20 was especially successful as it led to the development of a completely new mooring concept for large vessels and a handling and approach system for a bundle of flexible transfer pipes in aerial mode. Nevertheless, the following general tasks are required to complete the verification for its use in ice conditions:

- Verification of application in (specific) ice conditions
- Verification of appropriate barge hull form (tank tests)
- Concept for winterization e.g. of the transfer system
- Application of the transfer system in snow/iced conditions
- Rescue and evacuation concept for application in Arctic conditions

A further approach to the demanding field of offshore transfer of cryogenic liquids has been taken by the project partners of MPLS20. The project Sideways Offshore Loading of LNG and LPG (SOTLL), funded by the German Federal Ministry of Economics and Technology (BMWi), started late 2011 and aims at the development of a new concept for cargo offloading in Side-by-Side configuration and in moderate environments (and no ice) as it is also required by the industry. The project is scheduled to deliver results in 2013.

ACKNOWLEDGMENTS

The authors want to express their gratitude to the German Federal Ministry of Economics and Technology (BMWi) for funding the project 'MPLS20 — Maritime Pipe Loading System 20' (FKZ 03SX240).

The authors from IMPaC want to express their gratitude to the European Commission (EC), 7th Framework Program, for funding the joint research project ACCESS (Arctic Climate Change, Economy and Society, contract no. 265863) in which the ice related research activities were carried out.

The authors want to acknowledge the contribution of all project involved colleagues from Nexans, Brugg, IMPaC and the Technical University of Berlin.

REFERENCES

