THE LINDE GROUP

Linde

Floating LNG Production

Contents.

Introduction.

Natural gas will play a central role in meeting the world's mounting energy demand in the upcoming decades. It is readily available and the cleaner energy alternative compared to oil and coal. This is especially important in view of rising concerns about environmental pollution and nuclear power plant hazards. One possibility of trading natural gas is in the form of liquefied natural gas (LNG) which is currently representing almost 30% of the imported natural gas worldwide.

In many cases offshore gas reserves are considered to be stranded. As a consequence there is growing interest to unlock and monetize these reserves with floating facilities capable of liquefying and storing natural gas. Development of such floating LNG facilities is technically complex and challenging. Sound engineering with reputable partners is required to execute such an enterprise and to minimize the risk of this venture.

Calling on more than 125 years of experience as a cryogenic plant designer and having delivered more than 3.800 plants to clients all around the world Linde Engineering represents an ideal partner for the development and realisation of a floating LNG facility. In addition Linde has extensive cryogenic operational experience through the industrial gases division which owns and operates more than 400 plants for cryogenic gases production worldwide.

Competence in LNG.

Onshore

Linde Engineering has a strong history in the onshore LNG industry having developed, built and started-up over 20 LNG plants world-wide. Linde Engineering's range of experience includes small to mid scale natural gas liquefaction plants with annual LNG capacities of 50.000 to 500.000 tons as well as a world-scale LNG export plant with a capacity of more than 4 million tons per year.

The process portfolio includes single, dual and triple flow processes with a variety of mixed refrigerant options as well as expander type processes. Linde Engineering holds patents for a number of natural gas liquefaction processes such as the MFC® and the LIMUM® processes and is the only supplier offering both coil-wound and plate-fin heat exchangers, which are integral with the natural gas liquefaction process.

Linde Engineering is unique among EPC contractors in the LNG business in being able to offer its own proprietary processes, cryogenic key equipment as well as all EPC services to clients worldwide.

Offshore

Already in the mid 1970ies Linde Engineering started studying the feasibility of offshore natural gas liquefaction and storage platforms in a consortium with partners experienced in the offshore Oil & Gas industry.

Starting from 2002 extensive conceptual work for a LNG floating production, storage and offloading (FPSO) unit with capacities of 5 to 8 mtpa LNG have been performed for the Nnwa/Doro gas field together with the Nigerian government as well as several Oil & Gas majors.

Since early 2007 Linde Engineering has been working on a generic LNG FPSO concept together with SBM Offshore, a leading provider of solutions for the production, storage and offloading of hydrocarbons in offshore conditions. The generic concept was finalized end of 2008 after having spent more than 180.000 man hours together with SBM Offshore and prepared more than 1200 deliverables.

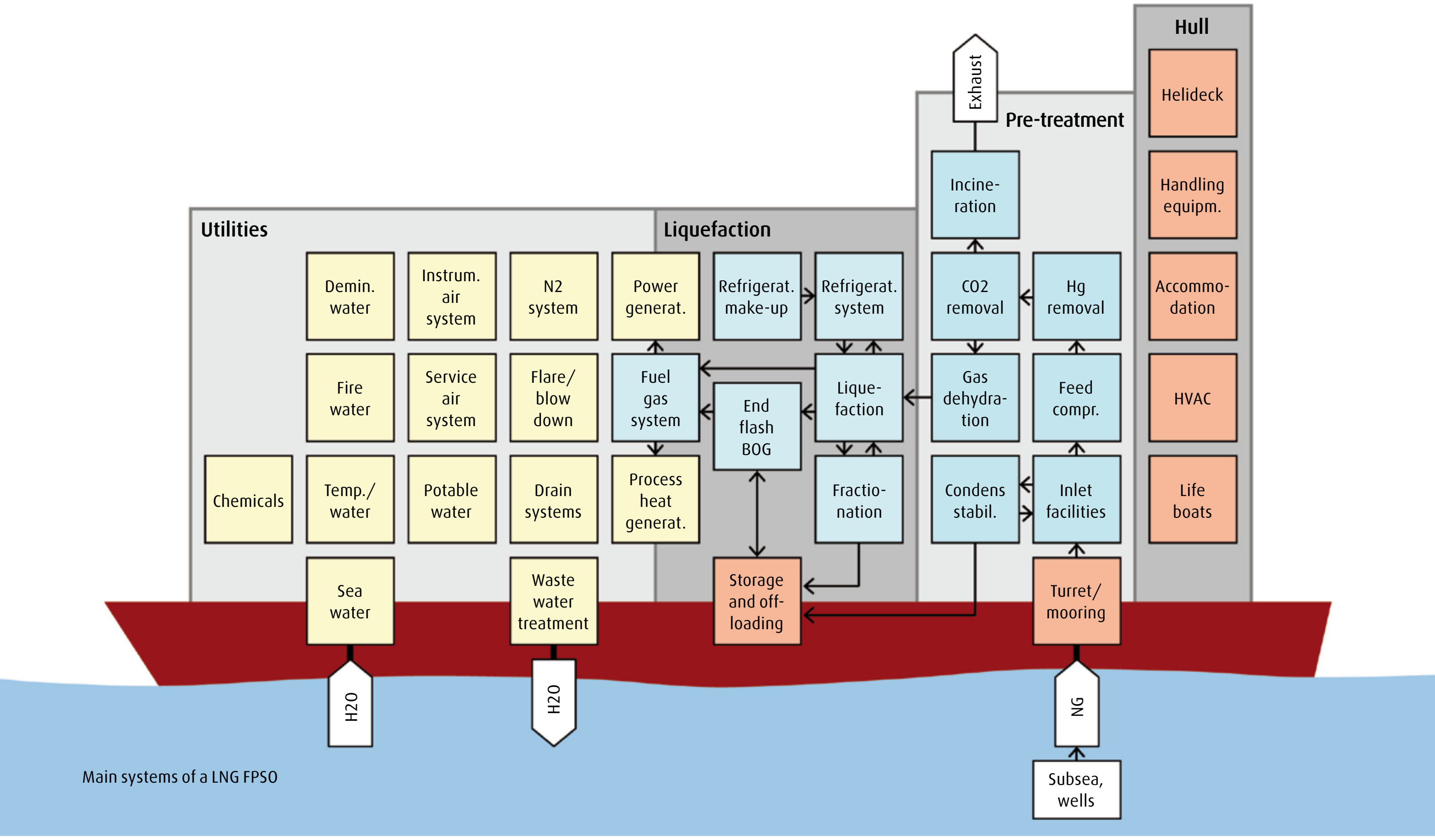
ABS granted an Approval in Principle (AIP) for the generic LNG FPSO concept, covering the review of over 400 documents including philosophies, layouts, P&IDs and the outcome of the safety studies.

Based on the generic concept sensitivity and feasibility studies have been and are currently being performed for different potential customers to tailor the generic concept to specific project requirements. This way Linde Engineering has gathered significant experience and competence in this application of LNG technology over the past years.

Modularisation

Linde has successfully delivered modular process plants including LNG plants like the base load plant in Hammerfest, Northern Norway. Due to limited available plot space and difficult construction conditions north of the polar cycle, the plant was modularised and pre-assembled to the highest possible extent. The heart of the plant is the largest ever built LNG plant module which was pre-fabricated in a Spanish yard and transported 2,700 nautical miles to Hammerfest.

Barge including main process units and power generation on the way to Hammerfest, Norway



Main systems of a LNG FPSO

LNG FPSO overview.

Coil-wound heat exchangers manufactured in Linde's own workshop in Schalchen, Germany

As stand-alone unit a LNG FPSO has to feature in principal all the systems of an onshore base-load LNG facility including an own power and heat generation unit and all other necessary utilities. The drawing on top shows an overview of the main systems of a LNG FPSO facility.

The pre-treatment and the liquefaction process units represent the predominant part of the top-sides facilities with regard to equipment count and space requirements. Linde Engineering has world-class experience in design and construction of the entire natural gas processing chain having built numerous natural gas treatment facilities (like LPG and NGL recovery plants) as well as LNG plants based on proprietary process know-how. Linde is therefore well positioned to offer all kind of technical as well as commercial services, including feasibility studies, pre-FEED, FEED and detail engineering up to turnkey delivery of process modules. More than 3,800 plants erected worldwide demonstrate Linde's competence and capabilities in project development, planning, execution and construction of all kind of gas processing plants.

Specialized and tailor made cryogenic key equipment like plate-fin and coil-wound heat exchangers are key elements of any natural gas liquefaction facility. Linde Engineering has undisputed experience in fabrication and delivery of plate-fin and coil-wound heat exchangers and also produces cryogenic expanders, pumps, turbines and compressors through Cryostar which belongs to the Linde Group as well. As a matter of fact Linde can ensure adequate integration into the overall process design which is vital to the success of any project, especially for LNG FPSO development where only limited experience is available up to know.

The generic LNG FPSO concept development.

Linde Engineering has developed a generic LNG FPSO concept together with SBM Offshore with the objective to design a safe, robust and economically viable floating facility using proven components to the greatest extent possible. Furthermore the design is considered to be flexible enough to enable a quick adjustment to different project specific requirements without changing the overall concept.

Design approach

Based on the analysis of a large number of gas compositions from different regions worldwide a gas composition design envelope was established as basis for the generic design. Subsequently layout, weight and other basic requirements have been designed for the most conservative scenario during the conceptual phase of the design study ensuring the flexibility to tailor the concept to specific field applications. As a consequence the principle results of the safety studies performed during the generic development can be applied in general and only require case specific adjustments. Furthermore key conceptual choices have been made, key philosophies developed and preliminary engineering work performed e.g. product definition, liquefaction technology comparison and selection, a driver selection study and power/steam generation philosophy, safety analyses, etc.

A Front End Engineering Design (FEED) package has been developed for the generic LNG FPSO concept, detailing significant design questions and providing a solid basis for further FPSO facility design. Approximately 1200 deliverables have been produced by spending around 180.000 man hours together with Linde Engineering's partner SBM Offshore. The deliverables included equipment specifications, P&ID's, process and mechanical data sheets, an overall 3D CAD model including topsides, power generation and marine systems (see picture below) as well as extensive safety studies, such as fire and explosion analyses, a detailed blast-effect study, gas dispersion analyses, a QRA, a HAZID, and a coarse HAZOP.

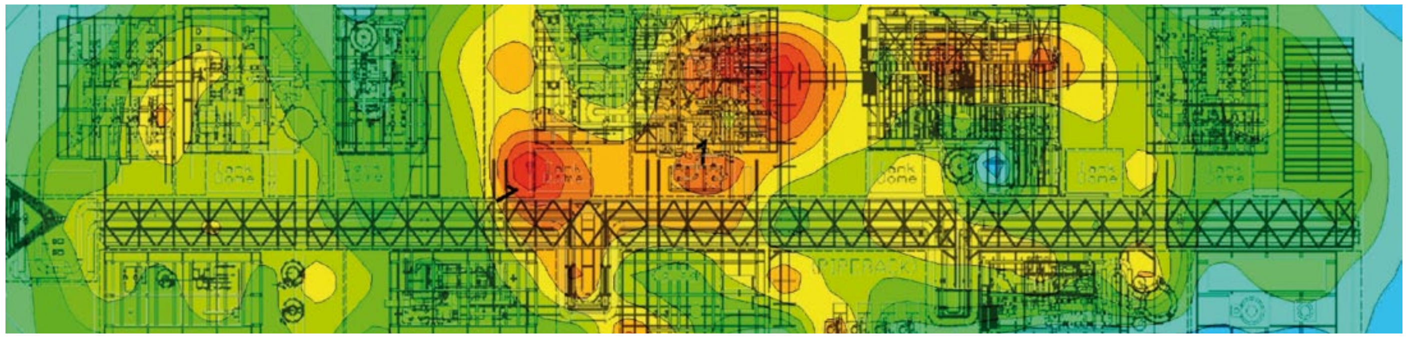
Structural design studies have also been performed to minimize the steel weight and to optimize the topsides load distribution and structural integration on the main deck of the hull.

Key features of the generic LNG FPSO concept

The generic LNG FPSO concept consists of the following key features which ensure a robust, safe and reliable design of the facility:

- Linde's proprietary LIMUM® process (single mixed refrigerant cycle) which represents a liquefaction technology with a considerable track record.
- Single train medium-scale liquefaction unit (2.5 mtpa) minimizing complexity and yielding a simple overall design based on proven components.
- Linde's proprietary cryogenic coil-wound heat exchanger (CWHE), which is less sensitive to thermal stresses occurring during plant operation than plate fin heat exchangers.
- Steam turbines as reliable refrigerant compressor drives, which make the electric power plant smaller and more stable. As an alternative also gas turbines can be used as mechanical drive.
- Topsides layout with open spaces between the topsides modules to prevent excessive explosion pressures and escalation to other areas.
- Storage of mixed refrigerants under-deck.
- Stand-alone system including pre-treatment facilities able to handle untreated well fluids including slugs, eliminating the need for new pipelines, platforms etc. If desired, sequestration of CO_2 can be incorporated into the design.

Generic LNG FPSO developed by Linde Engineering and SBM Offshore



Overpressure contours at hull deck from fire
and explosion analysis performed by ARCADIS VECTRA

Safety first.

"No harm to People and the Environment."
This clear mission statement is the basis of all work performed within The Linde Group. Safeguarding of personnel's health and environmental protection is therefore a fundamental principle of any plant design performed by Linde. This has been broken down to the LNG FPSO development to ensure safe and reliable operation of the LNG FPSO facility as well as of involved LNG carriers.

Safety studies

Several safety studies have been performed during the concept development. A HAZID (Hazard Identification) study was carried out and facilitated by DNV (Det Norske Veritas, service provider for risk management). Subsequently at the end of the conceptual phase a first preliminary QRA (Quantitative Risk Analysis) was performed by DNV.

A much more detailed QRA has been performed later by ARCADIS Vectra as part of the generic FEED study. The detailed QRA was based on P&IDs and a respective 3D-CAD-model for the generic LNG FPSO covering the following studies:

- Gas dispersion analysis
- Cryogenic spill protection
- Fire and explosion analysis (see drawing)
- Smoke and gas ingress analysis
- Escape, evacuation and rescue analysis
- Emergency systems survivability
- Dropped object study
- Ship collision study
- Design accidental loads

The objective of the QRA was to produce an integrated model of the risks associated with the operation of the LNG FPSO concentrating, in particular, on those risks associated with hydrocarbon release events. Other risks such as those arising from ship collisions and occupational and transportation accidents were also assessed.

Layout considerations

In order to prevent the occurrence of explosion overpressures that exceed critical limits, empty spaces between modules should be introduced. These "safety gaps" lead to decelerating flame speed and consequently pressure decrease, when the flame front is passing through areas that are not congested. Based on this, some sensitivity calculations have been performed in order to define the required size of "safety gaps" in order to prevent the explosion overpressure to exceed critical limits.

Space is limited on a FPSO facility. Linde Engineering has studied means of reducing explosion overpressure in congested areas with the aim to reduce "safety gap" distances, e.g. installation of pressure relief panels between critical modules in order to reduce the maximum size of flammable gas clouds or area deluge system, initiated upon gas detection.

The reasonable application of such measures needs to be assessed from case to case on the basis of a plot plan considering the general safety concept for the FPSO facility.

Environmental Studies

Possible applicable international environmental protection standards have been screened resulting in FPSO design requirements. Noise control requirements have also been determined. Of course, a final assessment always needs to be performed for client and country specific requirements as well as project related boundary conditions, but Linde Engineering has prepared a sound basis for such an assessment.

The LIMUM® process.
(Linde Multistage Mixed Refrigerant)

Selection of the liquefaction process

Several natural gas liquefaction processes have been considered for application in the generic LNG FPSO concept by Linde Engineering. Due to the targeted liquefaction capacity of around 2.5 mtpa typical base load plant technologies e.g. C3MR, DMR, MFC® were disregarded early during the selection process due to the high equipment count and the resulting complexity of operation and large space requirement. As a consequence the short listed liquefaction technologies have been either based on a single mixed refrigerant (SMR) or on expander based processes. A comparison of Linde Engineering's LIMUM® process (Linde Multistage Mixed Refrigerant, SMR) against a double N_2 expander process with CO_2 pre-cooling is given in the following table.

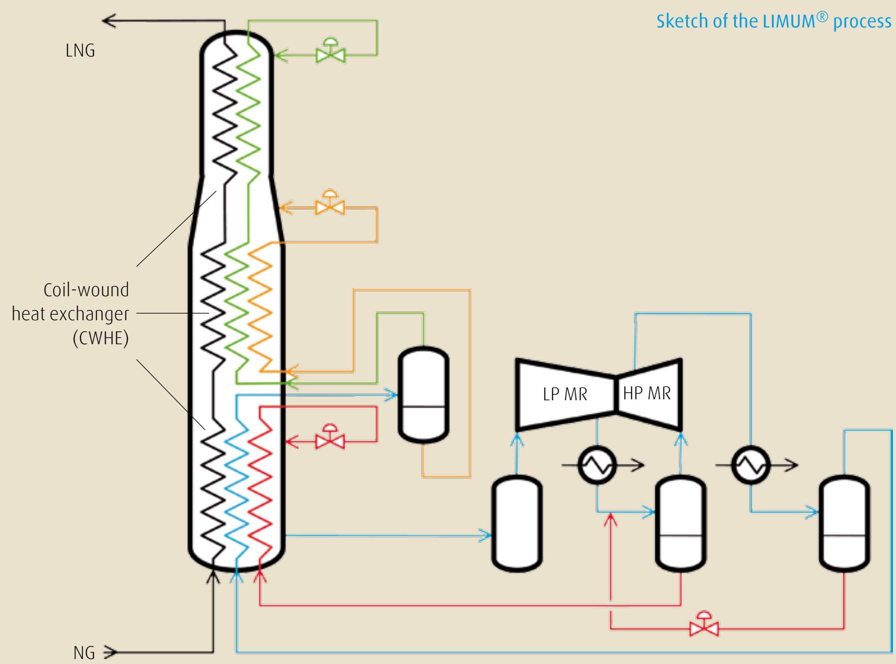
Notwithstanding the selected generic driver concept the comparison is based on the assumption of using 3 aeroderrivative gas turbines as drivers for the refrigerant compressors and a resulting plant capacity of around 2 MTPA. For most of the given selection criteria the LIMUM® process shows clear superiority .

	Double N_2 expander (with CO_2 pre-cooling)	LIMUM®
Suitability	At the upper limit	Good fit
Energy consumption	127 %	100 %
Reference situation	Several, but low capacity < 0.08 MTPA	Several, with medium capacity < 0.5 MTPA
Saftey (only wrt the refrigeration unit)	Inherently safe	"Safety gaps" required
Equipment count (machinery, 3 parallel compressor trains have been assumed)	1 x CO_2 compressor, 3 x N_2 compressors 3 x warm expander, 3 x cold expander	3 x compressors (parallel)
Plot space requirement	High	Medium
Offshore suitability	Aluminium PFHE, sensitive regarding fatigue	CWHE out of SS, higher weight and complex phase distribution
Operation/start-up	Simple process, high rotating equipment count	Relative simple process, two phase flow

Process description

A sketch of the LIMUM® natural gas liquefaction process is shown below. The process consists of a single mixed refrigerant cycle (MR) which is separated into two refrigerant streams of different molecular weights by 2-stage refrigerant cycle compression and partial condensation downstream the compressor stages. The heavier hydrocarbon fraction (red line) is used for pre-cooling of natural gas, the lighter one (blue line from separation vessel downstream of high pressure MR compressor stage) is first pre-cooled and then separated into two fractions from which the heavy one (yellow line) is used for liquefaction and the light one for sub-cooling (green line) of the natural gas.

By the described separation of the refrigerant into fractions of different molecular weights the efficiency of the liquefaction process can be optimized. The MR cycle is composed of the following components: methane, ethane (or ethylene, depending on availability on the market), butane and nitrogen. The composition of the MR cycle can be varied and therefore optimized in case of changing feed gas composition. A coil-wound heat exchanger (CWHE) is used for pre-cooling and liquefaction of natural gas as well as sub-cooling of LNG. A potential concern with this main cryogenic heat exchanger is its sensitivity to motions and acceleration. However, extensive theoretical investigations as well as model testing has been conducted in Linde Engineering's laboratory to prove the satisfactory performance under motion conditions (see page 10).



Sketch of the LIMUM® process

Key success factors

One of the major arguments for the selection of the LIMUM® process is the existing track record. The following table lists selected references for onshore application of the LIMUM® process.

Special attention should be directed to the plant reference in Stavanger, Norway (see picture). This plant was built using a CWHE made of stainless steel instead of aluminum. Manufacturing and operating experience for a stainless steel CWHE in LNG service is therefore available. This is especially important for floating applications due to the fact that stainless steel is the preferred material offshore to withstand fatigue. Furthermore the CWHE in Stavanger is equipped with a fibre optic temperature measurement system which provides sufficient data for compilation of complete 3D temperature profiles inside the CWHE.

Customer and location	Liquefaction capacity	Linde Engineering's scope of work	Date of start-up
Xinjiang Ji Munai Guanghui Liquefied Natural Gas Development Co. Ltd. Jimunai, Xinjing, P.R. China	400,000 tpa	Engineering, procurement of main equipment, construction, supervision, start-up supervision	2011
Lyse Gass AS Stavanger, Norway	300,000 tpa	Engineering, procurement, construction, start-up supervision	2010
Wesfarmers Gas Limited Kwinana, WA, Australia	63,000 tpa	Engineering, procurement, construction, start-up supervision	2008
Xinjiang Guanghui Industry and Commerce Group Co. Ltd. Tuha oil field, Shan Shan, Xinjiang, P.R. China	430,000 tpa	Engineering, procurement, construction, supervision, start-up supervision	2004

Besides the existing track record the key success factors of applying the LIMUM® process for a LNG FPSO facility are the following:

- Reliability due to proven components and low equipment count
- Robust and easy to operate process including robust and proven key cryogenic equipment (coil-wound heat exchangers)
- High efficiency compared to nitrogen expander based process technology (about 20 to 40 % better)
- Higher LNG capacity in case of fixed driver power for the main refrigerant compressors (as a consequence of higher efficiency)
- Relative simplicity of the process compared to typical base load plant technologies e.g. C3MR, DMR etc.
- Easy start-up
- Tolerance of variations in feed gas composition by change of refrigerant compositions

LNG plant in Stavanger, Norway

Marinization of cryogenic key equipment.

CWHE vs. PFHE in offshore application
Linde Engineering is manufacturer of coil-wound heat exchangers (CWHE) and plate-fin heat exchangers (PFHE), which both can be applied as main cryogenic heat exchanger for LNG processes. For floating LNG applications and LNG capacities over 1 mtpa Linde Engineering recommends to use coil-wound heat exchangers for the following reasons:

- For the achievement of 1 mtpa LNG plant capacity installation of about 8 to 10 parallel PFHEs or two CWHEs in series is required. Maldistribution due to sea motion can be avoided better with application of CWHEs.
- CWHEs can be manufactured in stainless steel. This material is much more forgiving to cyclic forces than aluminium. PFHEs can be manufactured in aluminum only and are therefore much more exposed to fatigue on a FPSO.

Fig. 1: CWHE test rig

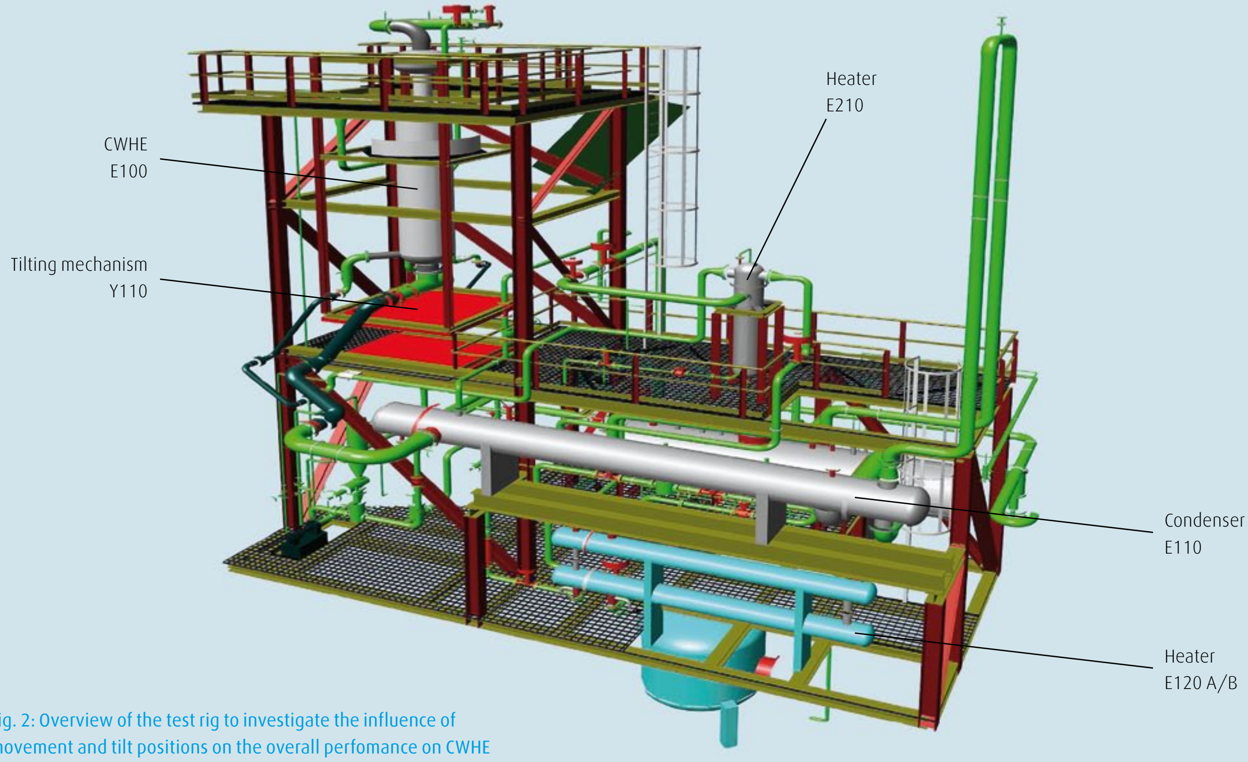


Fig. 2: Overview of the test rig to investigate the influence of movement and tilt positions on the overall perfomance on CWHE

Marinization of key equipment

In order to qualify CWHE for the application in a floating environment extensive large scale model testing has been conducted by Linde Engineering. The test results proved the satisfactory performance under motion conditions. In the testing program dynamic operational conditions were imposed on a coil-wound heat exchanger through a motion simulator that used a condensing hydrocarbon fluid on the shell side against water as coolant in the tubes. A picture of the test rig to investigate the influence of movement and tilt positions on the overall performance on CWHE is given in Fig. 1 and 2.

In addition to the test programme described above a qualification program was performed using the FMEA (Failure Mode and Effects Analysis) method to identify potential failure modes, classify their severity and determine the failure's effect on the system. Furthermore HAZAN studies have been performed for investigation of special operating conditions.

In order to minimize fatigue issues and to keep the weight of the coil-wound heat exchangers as low as possible, one recommendation of the study was to split the CWHE into a pre-cooling and a liquefaction/subcooling vessel. This way the height of each CWHE is not exceeding 40 m.

Based on information about offshore LPG fractionation available to Linde Engineering, motions do not affect the performance of distillation towers negatively even up to roll angles well in excess of 5 degrees. However, care should be taken that the column does not have a permanent inclination. Motion studies and scale model tests have been carried out on a column test rig (see Fig. 3). Random motions were tested to reproduce North Sea environment. Packing has proved to be suitable for installation on floating structures.

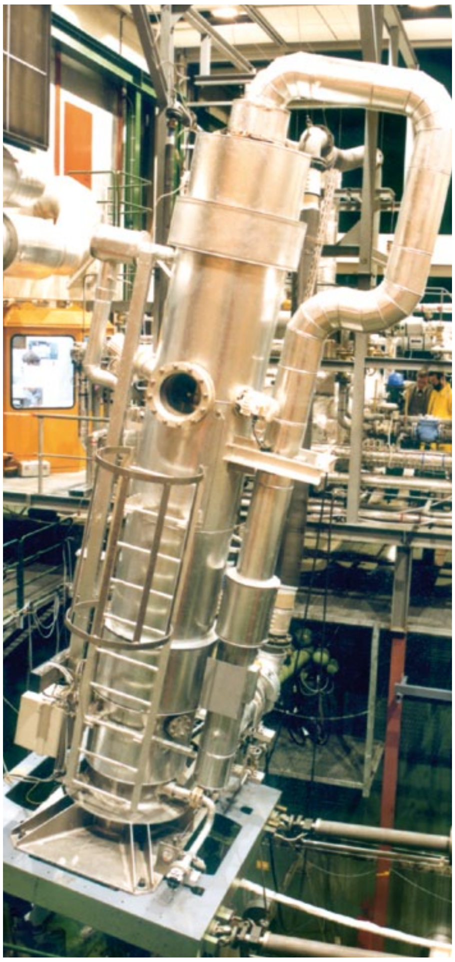


Fig. 3: Column test rig

LNG FPSO development is a fascinating and quickly evolving enterprise. Linde Engineering has accumulated comprehensive know how and experience for this technology.

Collaborate. Innovate. Deliver.

Linde's Engineering Division is a leading player in the international plant engineering business. Across the globe, we have delivered more than 4,000 plants and cover every step in the design, project management and construction of turnkey industrial facilities. Our proven process and technology know-how plays an indispensable role in the success of our customers across multiple industries – from crude oil, natural gas extraction and refining to chemical and metal processing.

At Linde, we value trusted, lasting business relationships with our customers. We listen carefully and collaborate closely with you to meet your needs. This connection inspires us to develop innovative process technologies and equipment at our high-tech R&D centres, labs and pilot plants – designed in close collaboration with our strategic partners and delivered with passion by our employees working in more than 100 countries worldwide.

From the desert to the Arctic, from small- to world-scale, from standardised to customised builds, our specialists develop plant solutions that operate reliably and cost-effectively under all conditions.
You can always rely on us to deliver the solutions and services that best fit your needs – anywhere in the world.

Discover how we can contribute to your success at www.linde-engineering.com

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Core competencies at a glance

Plant engineering
- Air separation plants
- LNG and natural gas processing plants
- Petrochemical plants
- Hydrogen and synthesis gas plants
- Adsorption plants
- Cryogenic plants
- Carbon capture and utilisation plants
- Furnaces, fired heaters, incinerators

Component manufacturing
- Coldboxes and modules
- Coil-wound heat exchangers
- Plate-fin heat exchangers
- Cryogenic columns
- Cryogenic storage tanks
- Liquefied helium tanks and containers
- Air-heated vaporisers
- Water bath vaporisers
- Spiral-welded aluminium pipes

Services
- Revamps and plant modifications
- Plant relocations
- Spare parts
- Operational support, troubleshooting and immediate repairs
- Long-term service contracts
- Expert reviews for plants, operations and spare part inventory
- Operator training

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