Intense research efforts are being invested for producing LNG in the offshore locations on top of FPSO (Floating Production, Storage and Offloading) and GBS (Gravitation Based Structure). These are aimed at monetising stranded gas reserves at the world vast offshore locations. An offshore LNG process utilizing the feed gas pressure to reduce energy consumption for LNG production is very attractive. One key step in the offshore high-pressure gas liquefaction process is the application of liquid expanders in the super-critical region of the produced natural gas. The process requirement and development of a super-critical natural gas (SNG) expander for this application are presented in this paper. The benefit of letting down the pressure by a super-critical expander is compared with using a J-T valve for a constant enthalpy expansion. The mechanical design challenges of a super-critical expander are examined in light of processing requirements. Safety, compactness and operational flexibility are among the key requirements.
Chen-Hwa Chiu [6] described a liquefaction process for high-pressure natural gas. The natural gas is expanded through a turbo-expander to reduce pressure and thereby cool it. The natural gas is then passed through a demethanizer to remove heavier components from it. Before substantial warming occurs, the natural gas is pre-cooled by heat exchange with a C₂ hydrocarbon refrigerant, either ethane or ethylene, contained in a single refrigerant system. The pre-cooled natural gas is liquefied by heat exchange with a mixed refrigerant contained in a mixed refrigerant system. The mixed refrigerant consists essentially of nitrogen, methane, and either ethane or ethylene. Contained in the mixed refrigerant system, the mixed refrigerant is cooled by heat exchange with the C₂ hydrocarbon refrigerant contained in the single refrigerant system.

S. Shu and F. Christiano [7] presented a process for producing LNG from the methane that is produced during natural gas liquid extraction. The process includes distilling the feed to extract methane, then cooling and expanding the methane to produce LNG and cold methane vapour. The cold methane vapour is employed as a coolant to pre-cool the feed and to cool the methane before expansion, and is then recompressed for reinjection into the well formation. The bottoms from the methane distillation may be further distilled to extract ethane, which may be cooled with the cold methane vapour and combined with the LNG product. A portion of the recompressed methane may be diverted from the compressor train, cooled and expanded to produce additional LNG and cold methane vapour.

C. Christiansen et al. [1] proposed a feasible concept for the process of high-pressure natural gas liquefaction. There are two major challenges to be observed: The pre-treatment of the process feed with an available high-pressure gas-cleaning technology and the application of liquid expanders for supercritical natural gas (SNG).

Subject of this paper is to present a conceptual design of a liquid expander for supercritical natural gas and to describe the technical features and operational aspects of the SNG expander and its application in the liquefaction process.

BRAYTON CYCLE LIQUEFACTION PROCESS
The goal of high-pressure natural gas liquefaction process is to maximize reliability and safety as well as to minimize space requirements and energy consumption in upcoming offshore production of LNG. The main aspects for the process are safety, compactness, simplicity and high-pressure utilization. The proposed process [1] utilizes the pressure in the dense supercritical phase of the feed gas to liquefy natural gas during the expansion across a liquid expander designed as a multistage radial inflow reaction turbine. It is necessary to cool down the supercritical natural gas (SNG) before entering the expander to receive 100% liquid at the outlet of the expander.

Figure 1: Natural gas expansion from supercritical to liquid phase in T-S-diagram
Figure 1 illustrates the expansion path directly from the supercritical dense phase to the liquid phase. To avoid two-phase conditions at the expander inlet, the SNG has to be pre-cooled dependent on the natural gas feed pressure. Process calculations suggest that pre-cooling of approximately 2°C per 100 bar pressure will be sufficient to avoid two-phase inlet conditions. The proposed refrigeration process is a Brayton cycle with nitrogen refrigerant. The Brayton cycle is a compact cooling cycle that is inherent in any refrigeration scheme using one or more expanders. Figure 2 shows the high-pressure liquefaction process with nitrogen Brayton cycle pre-cooling [1].

![NG precooling and liquefaction](image)

**Figure 2: High-pressure natural gas liquefaction process**

The clean high-pressure natural gas feed enters a gas/gas heat exchanger HX, where it is cooled with nitrogen vapour to its required pre-cooling temperature. The supercritical natural gas is then expanded to liquid natural gas at 1 bar across a liquid expander NGEx, designed as a cryogenic multistage Francis turbine [8]. The pre-cooling loop is a standard Brayton cycle. Hot nitrogen gas is compressed across compressor C and cooled with water in the lower heat exchanger HX. The nitrogen stream is then expanded and cooled in the turbo gas expander Ex. The cold nitrogen is used to cool the natural gas in the upper heat exchanger HX and returned to the compressor C. The presented Brayton cycle can easily adapt to different feed pressure levels by adjusting the cooling effect on the nitrogen pre-cooling cycle.

**CURRENT LNG EXPANDERS**

Liquefied gas expanders convert the hydraulic energy of the cryogenic fluid stream into electric energy, thus reducing the thermodynamic enthalpy of the liquefied gas and increasing the efficiency and productivity of the gas liquefaction process. All recently built LNG plants are equipped with LNG expanders reliably operating in Malaysia and Oman [9][10].
Figure 3 shows a cross-sectional drawing of the current design of LNG expanders, which makes use of the well-established features of hydroelectric Francis turbines. Named after the developer of this turbine type, Francis turbines are radial inflow turbines, which generate shaft torque by changing the angular momentum of the rotating fluid. Although the same principle is used to generate shaft torque in hydroelectric and cryogenic Francis turbines, there are distinctly different features in the overall turbine design due to certain operational requirements.

The two most important operational requirements are the cryogenic temperatures and flammable properties of hydrocarbon fluids. Both requirements suggest designs to insulate and separate the machine from the environment. Current LNG expander design features a radial inflow reaction turbine with an induction generator mounted on an integral shaft. The entire unit, including the electric generator is totally submerged in the cryogenic fluid. The turbine generator has no dynamic shaft seal and no coupling between turbine and generator.
The only connections to the environment are the electric power cables and the inlet and outlet piping system. All three connections are sealed with reliable cryogenic static seals.

Figure 3 demonstrates an LNG expander with three turbine stages, induction generator, rotating shaft, housing, power cables and containment vessel with inlet and outlet piping. The ball bearings are submerged and lubricated by the cryogenic fluid and a special thrust-equalizing mechanism (TEM) is mounted between turbine and generator.

The hydraulic pressure of the fluid stream is used to balance any axial thrust hence increasing the life of the ball bearings lubricated by the liquefied hydrocarbon. The LNG expander is controlled through the power cables by use of a variable frequency device. This solution allows expander control without any dynamic seals. The usual control mechanism for hydroelectric turbines, the variable geometry nozzle vanes, would require dynamic seals [8][11].

Oman LNG is one of the largest engineering and construction projects in the world. The complex consists of two LNG trains with a total annual capacity up to 6.6 megatons of liquefied natural gas. The process is based on seawater cooling with Propane and Mixed Refrigerant cooling cycle. Each LNG train is equipped with two liquid expanders, one for LNG and one for Mixed Heavy Refrigerant (MHR).

The LNG expander is located downstream of the Main Heat Exchanger (MHE) and the MHR expander is installed in the Cooling Cycle parallel to the MHE. The treated natural gas is condensed and subcooled under pressure in the Main Cryogenic Heat Exchanger and expanded before it is transferred to large atmospheric pressure storage tanks. This pressure letdown is achieved through cryogenic liquid expanders for MHR and LNG operating at variable speed.

The composition of the feed gas and the type of cooling selected are the main parameters in the design and operation of LNG plants. The various operating cases of the plant are determined by these parameters and to obtain maximum plant capacity at lowest costs the efficiency of equipment and in particular liquid expanders is essential. Variable speed liquid expanders comply optimally with this requirement.

SUPERCRITICAL NATURAL GAS EXPANDER

Current LNG expanders are designed for medium range pressures, but the reliable operation and the experience gained in the field suggest the same conceptual design to be applied for high pressure supercritical natural gas expanders. Figure 4 shows the conceptual design of a supercritical natural gas expander based on the design of current LNG expanders.

Using the experience of existing LNG expanders, SNG expanders have several common design features with LNG expanders, also the particular dimensions and material selections may differ: The hydraulic energy of SNG is converted into shaft power by multistage radial inflow reaction turbines of the Francis type. The number of stages is larger than five and depends on the pressure difference, the rotational speed and the turbine runner diameter.

The rotational speed is variable and controlled by an electronic frequency converter. The mechanical shaft power is converted into electrical power by an induction generator mounted together with the turbine runners on one shaft and completely submerged in SNG, eliminating the dynamic shaft seal and its inherent leakage problems. The dimensions of the cryogenically cooled generator are substantially smaller than dimensions of standard generators and rotational speeds above 3600 rpm are acceptable to reduce the total amount of stages.

Design features of the SNG expander that differ from the LNG expander are the upward flow direction during the expansion process and the elimination of the containment vessel. The upward flow direction makes use of the density change and the convective forces support the main fluid flow through the turbine passage. The housing material of the SNG expanders is stainless steel compared to aluminium for LNG expanders.

Figure 5 shows the design of the thrust-equalizing mechanism for SNG expanders being modelled on existing LNG expanders. The design allows small axial movements of the rotor and consists of a fixed and a variable orifice.

The opening of the variable orifice depends on the momentary axial position of the rotor. The graph in Figure 5 illustrates the pressure distribution of the fluid flow for the two extreme positions of the variable orifice. The left side demonstrates the variable orifice in the closed position generating a downstream thrust. The right side shows the variable orifice in the open position, producing an upstream thrust. Between these two extreme positions exists a certain position with no thrust on the rotor. The thrust-equalizing mechanism is self-adjusting and balances the thrust within a wide range of differential pressures.
Figure 4: Supercritical Natural Gas Expander Conceptual Design
CONCLUDING REMARKS
Offshore LNG production could open for exploitation of remote gas reservoirs. The natural gas liquefaction process proposed by C. Christiansen et al. [1] utilizes the feed gas pressure to reduce energy consumption and requires a reliable expansion turbine for supercritical natural gas.

The presented design concept for a supercritical natural gas expander is based on the existing design of LNG expanders operating in medium pressure range in Oman and Malaysia. Using the experience of existing LNG expanders, SNG expanders have several common design features with LNG expanders, also the particular dimensions and material selections may differ.

ABBREVIATIONS AND TERMINOLOGY
C  Compressor
Ex  Turbo-Gas Expander
FPSO  Floating Production, Storage and Offloading
GBS  Gravitation Based Structure
HX  Heat Exchanger
J-T  Joule-Thomson
LNG  Liquefied Natural Gas
NGEx  Liquid Expander
SNG  Supercritical Natural Gas
TEM  Thrust-Equalizing Mechanism
T-S  Temperature-Entropy
REFERENCES