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Two-phase fluid cycle efficiently recovers power from FSRUs

Compact design is efficient and economical

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Floating storage regasification units (FSRUs); floating production, storage and offloading units (FPSOs); and floating drilling, production, storage and offloading units (FDPSO) are floating vessels used by the offshore industry for the drilling, processing, storage and transportation of liquefied natural gas (LNG) or oil. When offloading the LNG cargo in gaseous form, the LNG is vaporized in a regasification unit onboard the vessel, usually using ocean water as the heat source. Due to the large temperature difference between the LNG and the environment, a substantial power recovery is available. This article will describe a two-phase fluid Rankine cycle to efficiently recover power from floating regasification plants using field-proven rotating and nonrotating equipment.

The offshore regasification process is similar to the onshore process, although an offshore plant can have significant differences.[1] Every square meter of an offshore footprint is relatively expensive; it requires the support of an offshore structure. The design must be compact to keep the surface area small. Due to the limited space, additional risk mitigation measures and hazard and operability study (HAZOP) assessments are required.[2]

Impact of motion. The continuous vessel motion impacts the design of the process equipment for operation under these dynamic conditions. Rotating equipment has to be designed to withstand the additional gyroscopic forces caused by the vessel movements. The design of any equipment requires that the center of gravity is as low as possible to increase the vessel's stability.

The conventional regasification process for onshore and offshore plants incorporates two major elements:

- High-pressure send-out pumps to bring the LNG from storage pressure through the vaporizer to pipeline pressure
- The vaporizer to transform the LNG into gaseous natural gas.

The proposed regasification process incorporates a third element:

- The power recovery system to partially regain the input energy used in the overall process.

Figs. 1 and 2 show the cryogenic high-pressure LNG pump for pressurizing the fluid up to the high pipeline pressure while it is still in the liquid state. Typical dimensions for these pumps are 4 m in height and 1 m in diameter, with 12 centrifugal pump impeller stages, each with a 300-mm diameter.

There are particular design features shown in Fig. 3 for high-pressure centrifugal LNG pumps:

- The single-piece rotating shaft with integrally mounted multi-stage pump

FIG. 1 Nine-stage submersible LNG sendout pump, post-performance test.

FIG. 2 An LNG sendout pump upon removal from a performance test stand.

hydraulics and an electrical induction motor

- The thrust-balancing mechanism to eliminate high axial thrust forces on the bearings. The self adjusting mechanism allows the ball bearings to operate essentially at no load over the entire usable capacity range for pumping. This feature substantially increases the reliability of the bearings, and reduces maintenance costs. In addition, normal machine wear patterns are compensated by the self adjusting mechanism
- The thrust balancing mechanism responds within less than 20 milliseconds, to changes in the thrust force.
- The electrical induction motor is submerged in and cooled by LNG
- The ball bearings are lubricated and cooled by LNG.

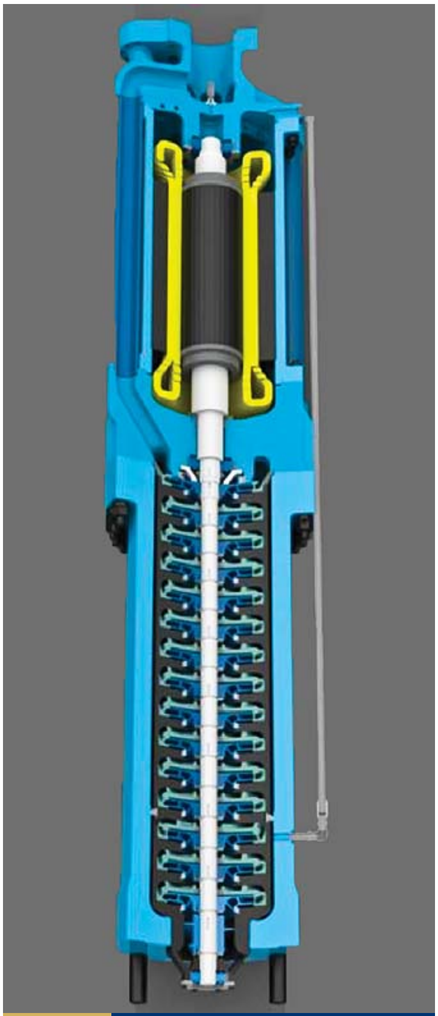

FIG. 3 Cross-sectional view of a high-pressure cryogenic LNG pump, 15 stages.

TABLE 1. General pump design criteria

Liquid	LNG
Pump design pressure	133.4 bara
Lowest design temperature	–168°C
Operating temperature	–147°C
Rated flow	287 m^3/hr
Rated differential head	2,396 m
Rated density	417.417 kg/m^3
Maximum design density	451.00 kg/m^3

Table 1 summarizes the general high-pressure pump design criteria.

Power-recovery system. LNG regasification plants represent large heat sinks that necessitate large heat sources. The differences in temperature between the heat sources and the heat sinks are in the range of 170°C, providing the preconditions for an efficient recovery of power. The Rankine cycle is a thermodynamic cycle that converts heat into work. The heat is supplied externally to a closed loop with a particular working fluid, and also requires a heat sink. This cycle generates about 80% of all global electric power. The Rankine cycle is shown using a typical Mollier diagram with the pressure (p)

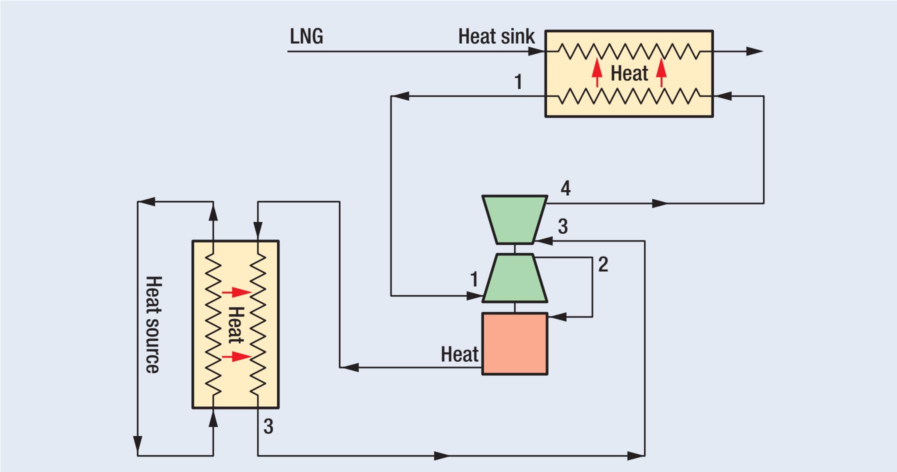

FIG. 6 Rankine cycle equipment schematic.

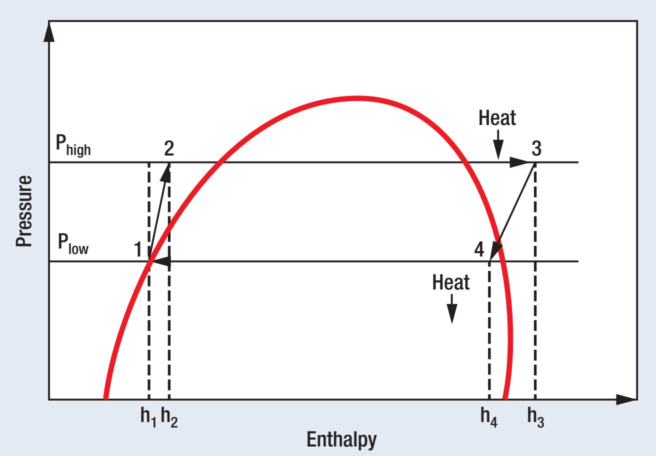

FIG. 4 Four steps of an ideal Rankine cycle.

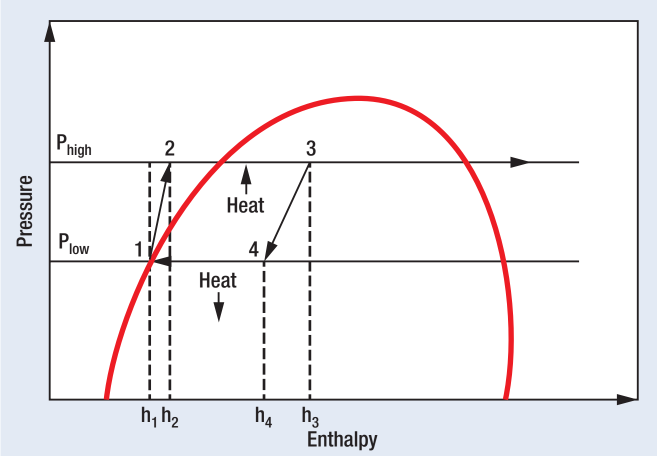

FIG. 5 Graphical representation of Rankine cycle with a liquid-vapor two-phase expansion.

over the enthalpy (h).

The ideal Rankine cycle with single-phase vapor expansion consists of the following four process steps (Fig. 4):[3]

- 1→2 Isentropic compression of the liquid fluid to a high pressure in a pump
- 2→3 Constant high-pressure heat addition in a boiler to completely vaporize the fluid
- 3→4 Isentropic expansion in a turbine gas expander to low pressure
- 4→1 Constant low-pressure heat rejection in a condenser to re-liquefy the fluid.

The two-phase fluid ideal Rankine cycle with liquid-vapor two-phase expansion (Fig. 5) consists basically of the same four steps, with the difference being that the pressurized liquid is only partially vaporized, thus remaining within the saturation dome and the isentropic expansion of the liquid-vapor mixture is achieved in a two-phase fluid expander.

The thermodynamic efficiency η_{therm} of the ideal Rankine power cycle is the ratio of the net power output w_{net} to the heat input q_{in}. The net power output w_{net} is the difference between the work output w_{out} from the expander and the work input w_{in} to the pump.

$$w_{out} = h_3 - h_4$$

$$w_{in} = h_2 - h_1$$

This is calculated by the enthalpies h_1, h_2, h_3, h_4, given by the four steps in the described process:

$$w_{net} = (h_3 - h_4) - (h_2 - h_1)$$

The heat input q_{in} is the enthalpy difference between steps 3 and 2.

$$q_{in} = h_3 - h_2$$

Two-phase Rankine power cycle. For power recovery using a two-phase fluid Rankine cycle in LNG regasification plants, several field-proven working fluids are available and are used in similar applications. To achieve a higher efficiency, the working fluid is passed through two heat exchangers and one pump two-phase expander generator (PTPXG), a compact assembly of a pump, a two-phase expander and an induction generator integrally mounted on one rotating shaft.

Fig. 6 presents the schematic of the equipment using the Rankine power cycle with two-phase expansion following the four described process steps:

- 1→2 With work input, the pump (P) pressurizes the liquid single-phase working fluid from low pressure to high pressure.
- 2→3 The pressurized single-phase working fluid is heated and partially vaporized by passing through the generator (G) and the heat exchanger with the heat provided by seawater or other heat sources,
- 3→4 The pressurized and heated two-phase saturated working fluid expands from high-pressure to low pressure across the two-phase expander (T) generating a work output.
- 4→1 The low-pressure two-phase saturated working fluid passes through a heat exchanger with the heat sink, the LNG for regasification. The working fluid condenses from a saturated liquid-vapor two-phase to a nonsaturated liquid single-phase.

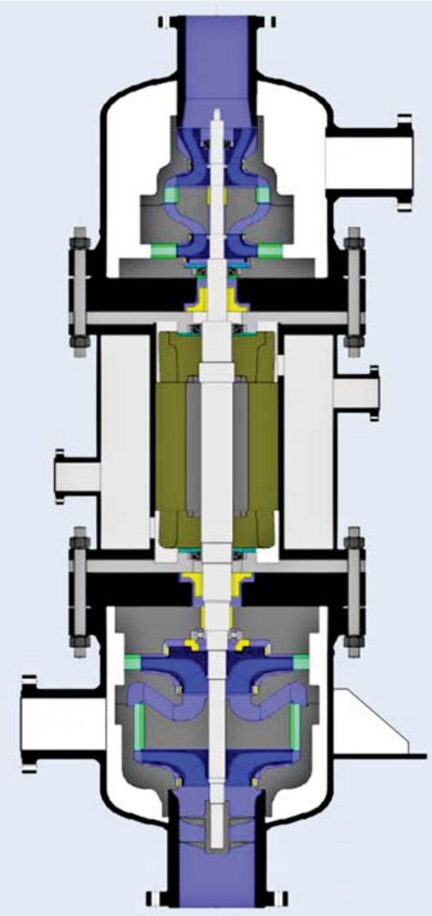

FIG. 7 Compact assembly of a pump two-phase expander (PTPXG) generator cooled by liquid nitrogen or a similar nonexplosive fluid.

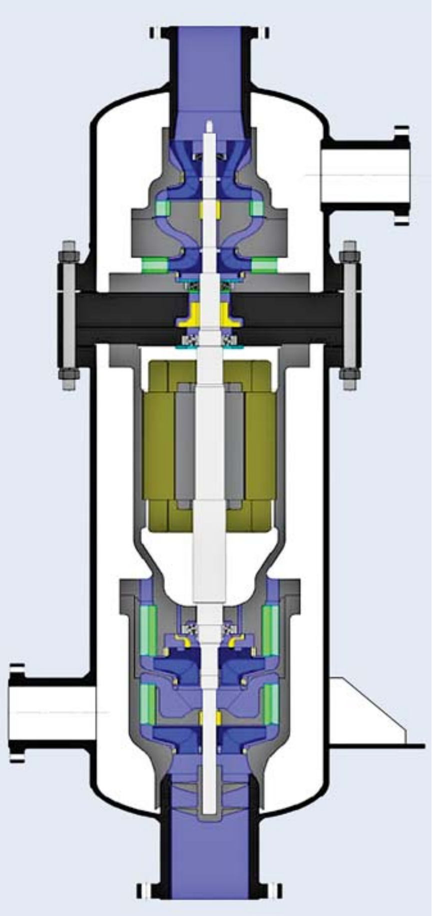

FIG. 8 Compact assembly of a pump two-phase expander (PTPXG) generator cooled by propane or a similar explosive fluid.

FIG. 9 Cross-section of a two-phase expander assembly.

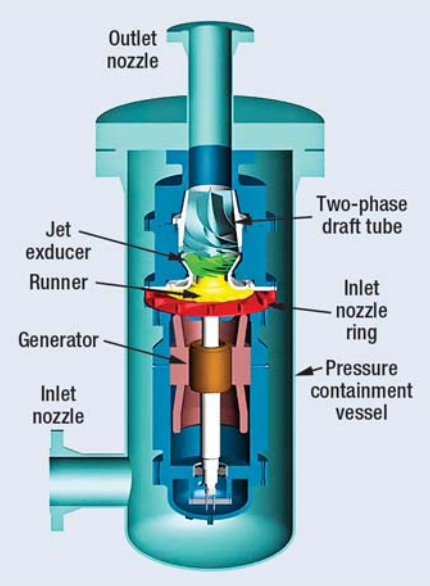

FIG. 10 Cross-section of a two-phase expander assembly inside a pressurized containment vessel.

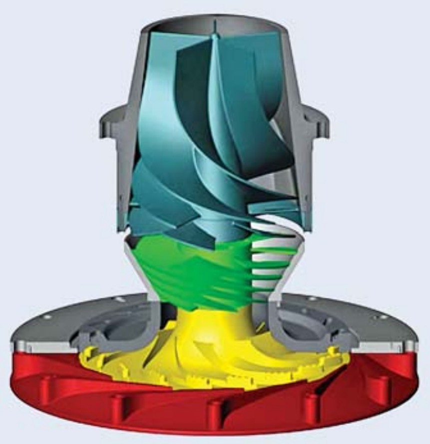

FIG. 11 Two-phase hydraulic assembly.

FIG. 12 Two-phase nozzle ring.

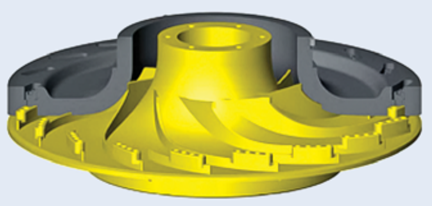

FIG. 13 Radial inflow turbine runner.

FIG. 14 Jet exducer.

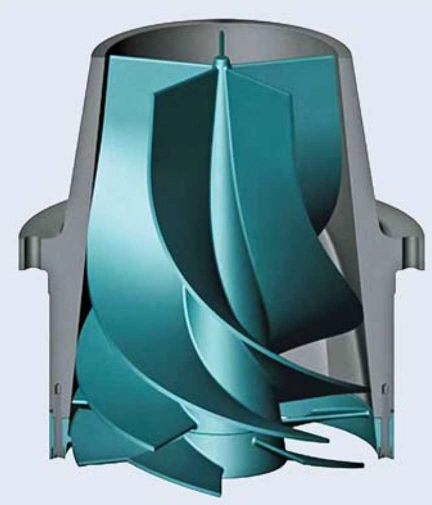

FIG. 15 Two-phase draft tube.

FIG. 16 Two-phase expander post performance test.

FIG. 17 The Golar Winter, FSRU for Golar LNG, Norway. (Photo courtesy of Keppel Offshore & Marine Ltd.)

The compact assembly of a PTPXG is demonstrated in Figs. 7 and 8 as two different designs of PTPXP. In Fig. 7, the working fluid enters the pump at the lower inlet nozzle, exits the pump to the side and passes through the generator housing cooling the generator, thus recovering the heat losses of the generator. After passing through the heat exchanger with the heat source, the saturated working fluid expands across the two-phase expander generating work, driving the pump and the induction generator.

In the modified design shown in Fig. 8, the pressurized single-phase fluid passes directly from the pump through the generator housing, thus cooling the generator, and then exits to the side to pass through the heat exchanger. In both design versions the leakage flows through the seal and the axial thrust is minimized due to equal pressure on both sides of the seal and opposing directions of the axial thrust forces.

The following are advantages of the compact assembly PTPXG:

- The expander work output is larger than the pump work input, and the difference in work is converted by the generator into electrical energy.
- The losses of a separate pump motor are eliminated.
- The losses of the induction generator are recovered and used as a heat source to heat the working fluid in addition to the heat from seawater and other heat sources.
- Any leakage of the working fluid is within a closed loop and occurs only between the pump and expander.
- Any leakage of the working fluid is minimized due to equal pressure on both sides of the seal, and small leakages are within a closed loop and occur only between the pump, expander and generator.
- The axial thrust is minimized due to opposing directions of the thrust forces decreasing the bearing load and increasing the bearing life.

Two-phase expander generator. The two-phase expander generator produces the power within the compact assembly of the PTPXG.^{4} Fig. 9 shows the cross-section of the expander, and Fig. 10 presents the expander inside the pressurized containment vessel with the lower-inlet and upper-outlet nozzle. Fig. 11 illustrates the two-phase hydraulic assembly with the nonrotating nozzle ring on the bottom, followed by the rotating turbine runner with the jet exducer mounted on top of the runner, and, on top, the nonrotating two-phase draft tube.[5] Fig. 12 shows the nozzle ring with converging nozzles to generate a high-velocity vortex flow, and Fig. 13 shows the radial inflow reaction turbine runner converting the angular fluid momentum of the vortex flow into shaft torque. The jet exducer shown in Fig. 14 is a radial outflow turbine mounted on top of the runner generating additional shaft torque by an angular fluid momentum in the opposite direction of the nozzle ring angular momentum with a near isentropic two-phase expansion to the lower pressure. The two-phase draft tube displayed in Fig. 15 recovers energy by converting the remaining rotational kinetic energy into static-pressure energy.

During startup of the compact assembly, the induction generator operates as an induction motor below the synchronous speed. When the shaft power of the expander is greater than the shaft power of the pump, then the induction motor operates in the generator mode above the synchronous speed.

Summary. Liquid-vapor two-phase expander generators have been successfully operating at PGNiG in Odalanów, Poland, since 2003. Fig. 16 shows one of the two-phase LNG expanders on the LNG test stand in Nevada. The presented Rankine power cycle, incorporating a compact design—consisting of a pump, a two-phase liquefied gas expander and an induction generator integrally mounted on one single rotating shaft—offers efficient and economical power recovery for floating LNG regasification units. An example of a current floating unit, Fig. 17 shows the FSRU Golar Winter for Golar LNG, Norway. Future FSRUs will be equipped with power-recovery systems. **HP**

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