POWER RECOVERY IN FLOATING LNG REGASIFICATION PLANTS

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ABSTRACT

Floating Storage Regasification Units, FSRU, Floating Production, Storage and Offloading Units, FPSO, 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 LNG [Appendix 1]. In those used for offloading the cargo to the destination in gaseous form, the LNG is vaporized in a regasification unit on board 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 paper proposes and describes a two-phase fluid Rankine Cycle to efficiently recover power from the floating regasification plant. The power recovery is achieved using field proven rotating and non-rotating equipment.

INTRODUCTION

The offshore regasification process is similar to the onshore process [1], although, the design of an offshore plant shows some significant differences. Every square meter of an offshore footprint is relatively expensive since it requires the support of an offshore structure. The design has to be compact to keep the surface area as small as possible. Due to the limited space, additional risk mitigation measures [2] and HAZOP assessments are required.

The continuous motion of the vessel 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 centre of gravity is as low as possible to increase the stability of the vessel.


Figure 1

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 pipe line 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.

Figure 1 and Figure 2 show the cryogenic high-pressure LNG pump for pressurizing the fluid up to the high pipe line pressure while it is still in the liquid state.

Figure 2

Typical dimensions for these pumps are 4 meters in height and 1 meter in diameter, with 12 centrifugal pump impeller stages each of 300 mm diameter.

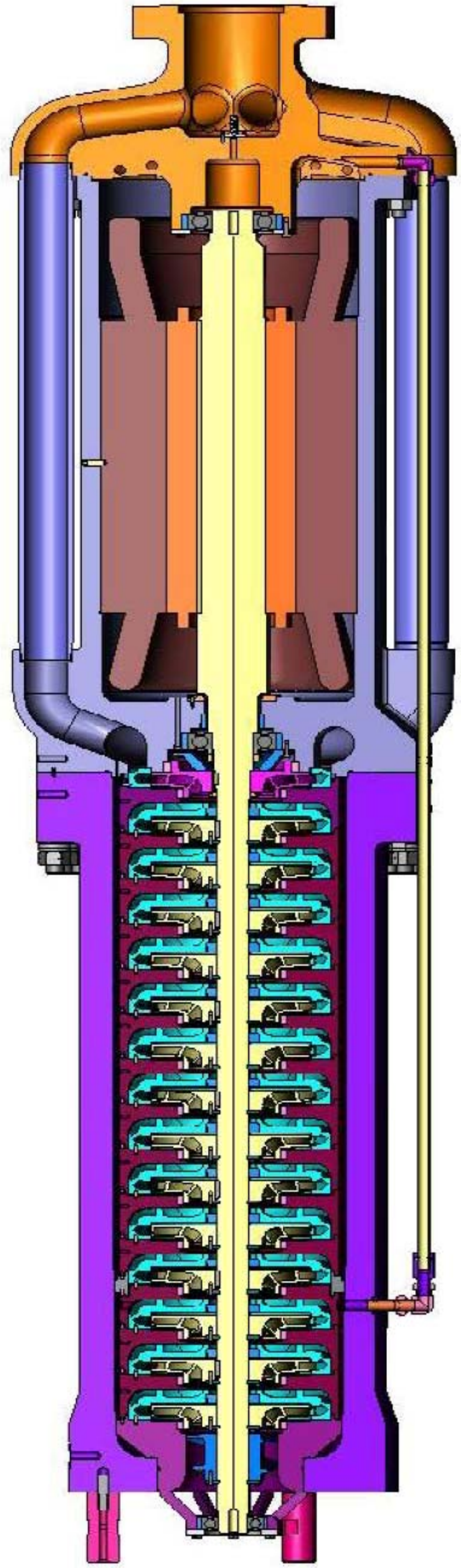

Figure 3

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

- The single piece rotating shaft with integrally mounted multi-stage pump hydraulics and electrical induction motor.
- The thrust balancing mechanism to eliminate high axial thrust forces on the bearings.
- The electrical induction motor is submerged in and cooled by LNG.
- The ball bearings are lubricated and cooled by LNG.

Figure 4 summarizes the general high-pressure pump design criteria.

Pump General Design Criteria		
Liquid		LNG
Model		6ECC-1212
Pump Design Pressure	[bara]	133.4
Lowest Design Temperature	[°C]	-168
Operating Temperature	[°C]	-147
Rated Flow	[m³/hr]	287
Rated Differential Head	[m]	2396
Rated Density	[kg/m3]	417.417
Maximum Design Density	[kg/m3]	451.00

Figure 4

POWER RECOVERY

LNG regasification plants require 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° Celsius providing the preconditions for an efficient recovery of power.

The Rankine Cycle is a thermodynamic cycle which 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 over the enthalpy h.

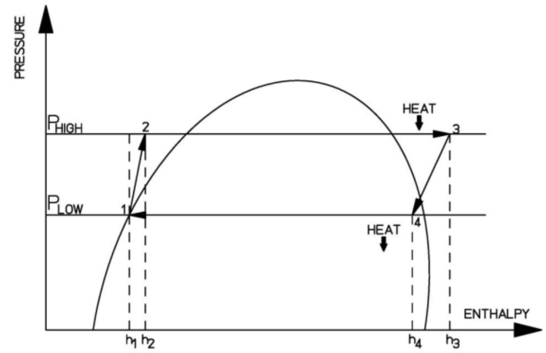

Figure 5

The ideal Rankine Cycle [3] with single phase vapour expansion consists of the following four process steps (Figure 5):

- 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-vapour two-phase expansion (Figure 6) consists basically of the same four steps, with the difference that the pressurized liquid is only partially vaporized thus remaining within the saturation dome and the isentropic

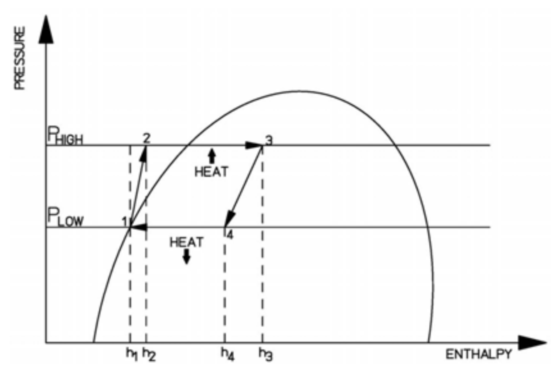

Figure 6

expansion of the liquid-vapour 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

$$w_{out} = h_3 - h_4$$
$$w_{in} = h_2 - h_1$$

and 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 step 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 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.
Figure 7 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 sea water 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 saturated liquid-vapour two-phase to non-saturated liquid single phase.

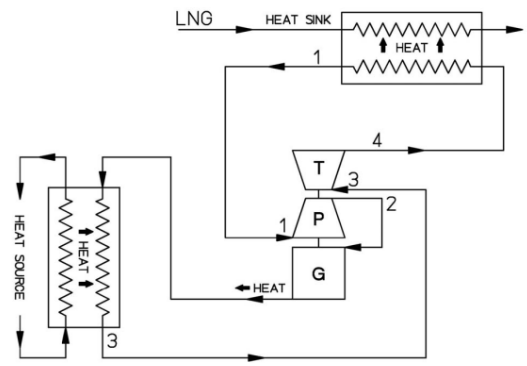

Figure 7

The compact assembly of a Pump Two-Phase Expander Generator (PTPXG) is demonstrated in Figure 8 and Figure 9 as two different designs of PTPXP. In Figure 8 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 Figure 9, 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 though the heat exchanger. In both design versions the leakage flow 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 advantages of the compact assembly PTPXG can be realised

- The expander work output is larger than the pump work input and the difference in work is converted by the generator into electrical energy.

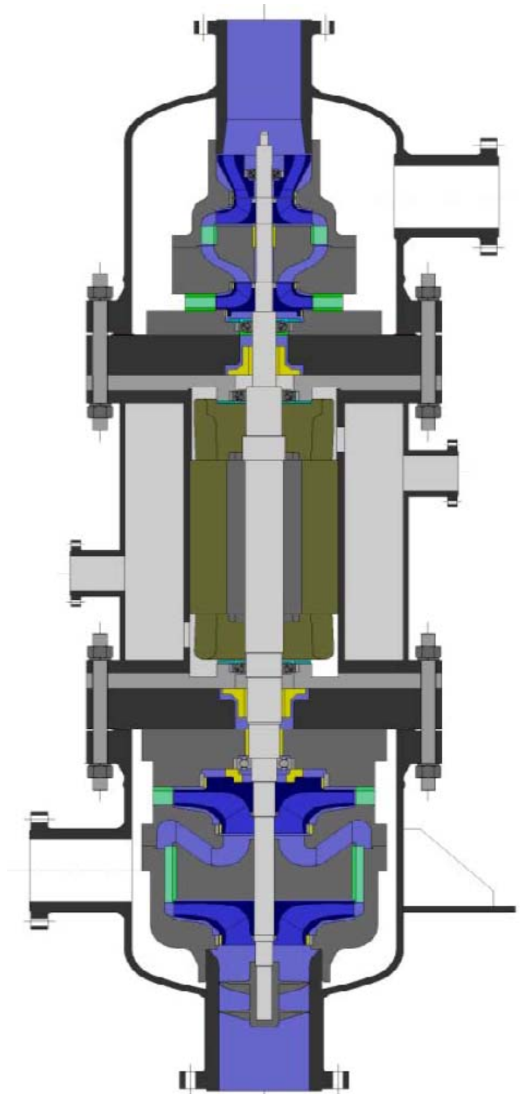

Figure 8

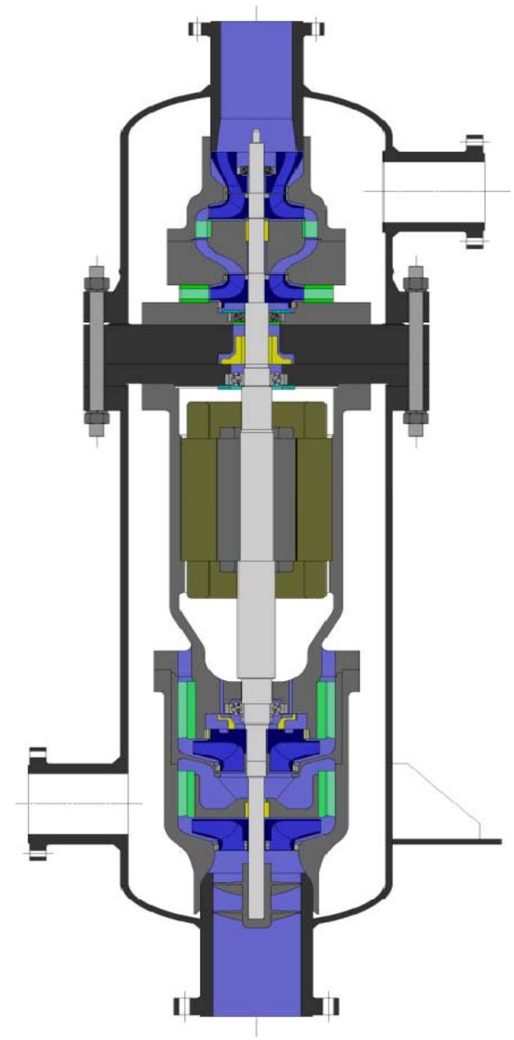

Figure 9

- The losses of a separate pump motor are eliminated.
- The losses of the induction generator are recovered and used as heat source to heat the working fluid in addition to the heat from sea water and other heat sources.
- Any leakage of the working fluid is within a closed loop and occurs only between 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 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 [4] generates the power within the compact assembly of the Pump Two-Phase Expander Generator (PTPXG). Figure 10 shows the cross section of the installed expander inside the pressurized containment vessel with lower inlet and upper outlet nozzle. Figure 11 presents the two-phase hydraulic assembly with the non-rotating 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 non-rotating two-phase draft tube.

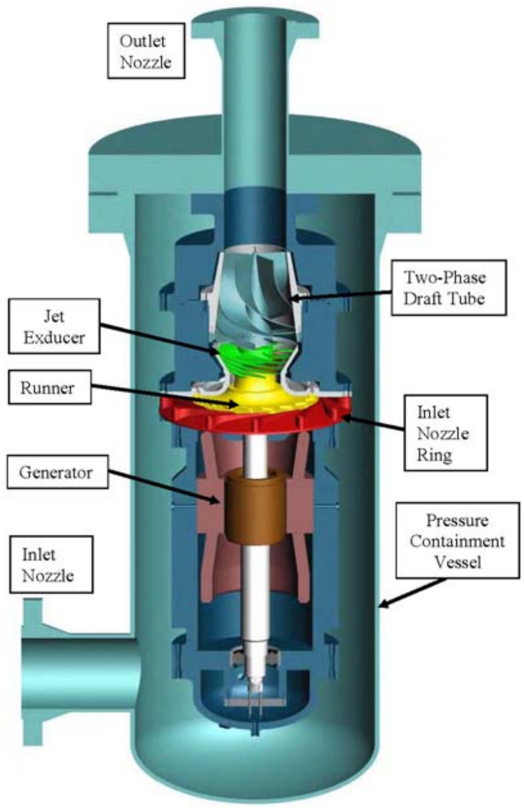

Figure 10

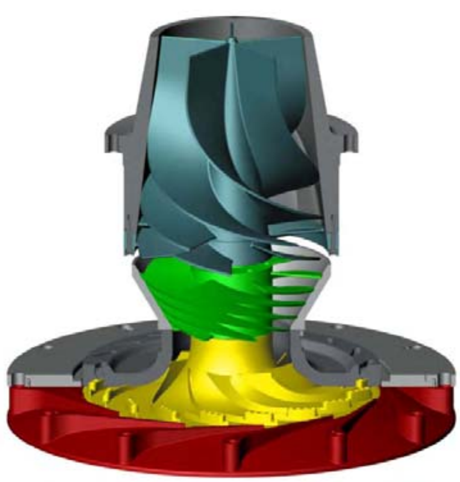

Figure 11

Figure 12 shows the nozzle ring with converging nozzles to generate a high-velocity vortex flow, and Figure 13 shows the radial inflow reaction turbine runner converting the angular fluid momentum of the vortex flow into shaft torque.

Figure 12

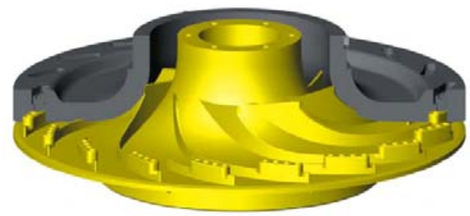

Figure 13

The jet exducer shown in Figure 14 is a radial outflow turbine mounted on top of the runner generating additional shaft torque by an angular fluid momentum in opposite direction of the nozzle ring angular momentum with a near isentropic two-phase expansion to the lower pressure.

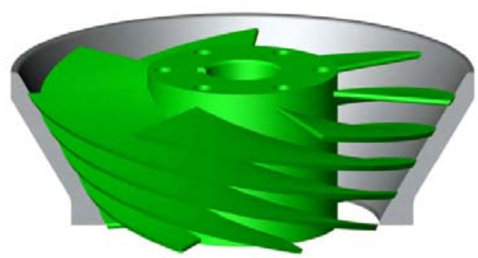

Figure 14

The two-phase draft tube displayed in Figure 15 recovers energy by converting the remaining rotational kinetic energy into static pressure energy.

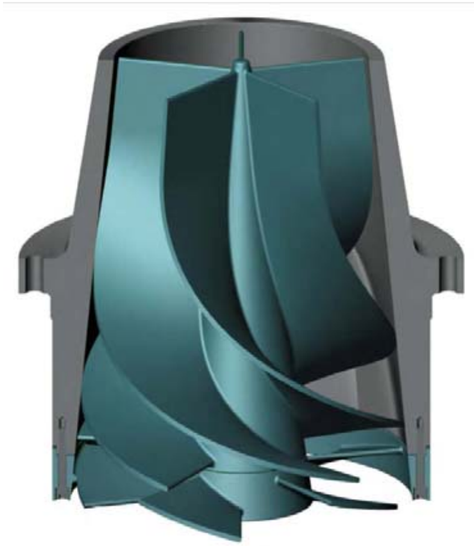

Figure 15

Figure 16

During start-up 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.

CONCLUSIONS

Liquid-vapour two-phase expander generators have been successfully operating in at PGNiG, Odalanów, Poland since 2003. Figure 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.

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Appendix 1 - Examples of Floating LNG Units

World First FDPSO "Azurite"
Floating Drilling, Production, Storage and Offloading Vessel

FPSO "Espirito Santo"
Floating Production and Offloading Vessel for Petrobras, Brazil

FSRU "Golar Winter"
Floating Storage and Regasification Unit for Golar LNG, Norway