Thermo-Fluid Dynamics and Design of Liquid-Vapour Two-Phase LNG Expanders

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ABSTRACT

Modern process plants for the liquefaction of natural gas operate at high pressure to improve the overall efficiency of the cryogenic process. Following the condensation of the refrigerated gas the pressurized Liquefied Natural Gas (LNG) is expanded to a lower pressure suitable for storage and transportation. The expansion process generates some vapour and cools the remaining liquid.

The aim of using an expander rather than a Joule-Thomson valve is to increase the amount of liquid and to decrease the amount of vapour at the outlet of the expander. By employing a two-phase expander with draft tube at the exit an increased amount of liquid is produced in a near-isentropic expansion process. The fluid dynamic operation and the thermodynamic performance of two-phase LNG expanders is presented and analyzed.

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INTRODUCTION

Conventional liquefaction processes for natural gas operate at high pressure through the condensation phase, after which the pressure of the liquefied natural gas LNG is reduced by expansion across a Joule Thomson (J-T) valve or liquid expander before rundown to storage at near atmospheric pressure.

When the condensed fluid is flashed across a J-T valve with constant enthalpy an undesirable amount of LNG is vaporised. When turbines are used, the hydraulic energy is converted into electrical energy to reduce the enthalpy of the liquefied gas and to recover energy [1].

In a typical modern LNG plant as shown in Figure 1, the LNG is expanded across a turbine, a compact device in which shaft power is generated from a near-isentropic expansion process. Due to the resultant reduction in enthalpy, the volume of flash gas can be reduced and / or increased production rates can be achieved for a given power input to the refrigeration cycle. Increased production is possible because less sub-cooling of the LNG is required in the liquefaction process.

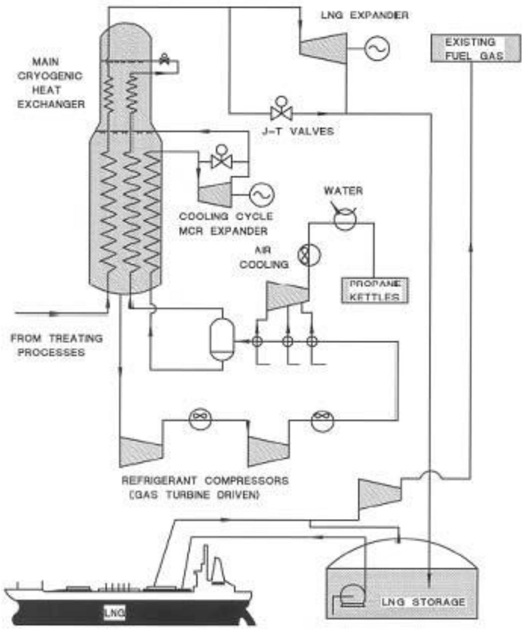

Fig 1 Typical LNG Liquefaction Process Scheme

However, the mechanical design of most expanders installed on LNG plants today is such that little if any vapour breakout inside the machine can be tolerated. These LNG expanders are operated with a backpressure up to around 5 bar above the liquid bubble point to ensure that the LNG remains in the liquid phase at the outlet of the expander. The final pressure letdown to storage is therefore adiabatic, representing a lost opportunity to produce further work.

The application of an expander in the LNG product stream suitable for two-phase flow at the outlet allows the expander outlet pressure to be reduced to a lower level by the near-isentropic expansion process, giving further reductions in enthalpy and resultant improvements in plant efficiency and production .

EULER TURBINE EQUATION

At the Academy of Science, Berlin in 1756, Leonhard Euler published his universal turbine equation under the title “A more complete theory of machines which are activated by their reaction to water” [2]. The Euler turbine equation applies to any type of turbine, but in the case of existing cryogenic liquid expanders in LNG service, the radial inflow turbine became the preferred design.

The Euler turbine equation states that the generated torque T of rotating turbine runners is equal to the difference of the angular momentum L at the inlet L1 and outlet L2.

$$T = L1 - L2 \qquad (1)$$

The angular momentum L is equal to the product of the tangential velocity c of the fluid, the radial distance r to the centre of rotation and the mass flow m per time.

$$L = c\ r\ m \qquad (2)$$

The angular momentum L is defined as positive if rotating in the same rotational direction with the runner, and negative if rotating in opposite direction. If the inlet and outlet angular momentum L1 and L2 are both positive then the maximum generated torque Tmax is equal to the inlet angular momentum L1 if the outlet momentum L2 is equal to zero (3).

$$T_{max} = L1 \ \text{ for } \ L2 = 0 \qquad (3)$$

The efficiency of the turbine reaches a maximum value if the outlet angular momentum is equal to zero, because the fluid exits the turbine runner with no rotational energy. If the outlet angular momentum has a remaining rotational energy that is not recovered then the overall turbine efficiency is reduced. This reduction in overall efficiency can be eliminated by converting the remaining outlet rotational energy into static energy in form of pressure by using diffuser type of flow straighteners [3].

Generation of an optimal torque Topt, larger than Tmax is feasible if the outlet angular momentum L2 is negative (4) giving a greater differential angular momentum between inlet angular momentum L1 and outlet momentum L2.

$$T_{opt} = L1 - (- L2) = L1 + L2 \ > \ T_{max} \qquad (4)$$

The overall turbine efficiency is increased if the remaining outlet rotational energy is converted into static pressure energy described above.

Figure 2 shows the general torque T as the difference of the inlet and outlet angular momentum L1 and L2 multiplied by the mass flow m. The torque T corresponds to the size of the hatched area, since the angular momentum is equal to the product of tangential velocity c and radial distance r. The mass flow m is a constant scaling value across the expander.

Figure 3 shows the maximum torque Tmax with the outlet angular momentum L2 equal to zero corresponding to the hatched area.

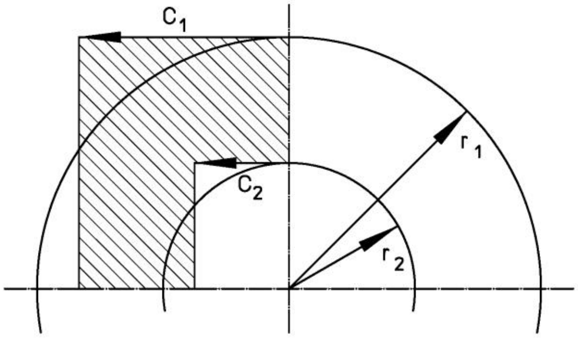

Fig 2: General Torque T

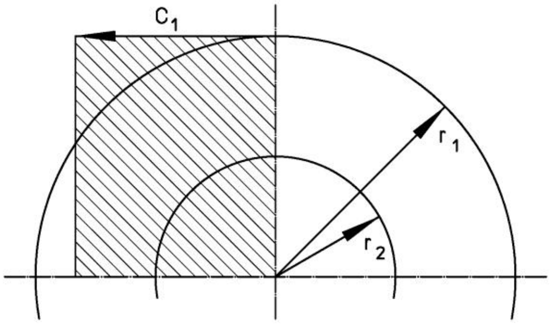

Fig 3: Maximum Torque Tmax

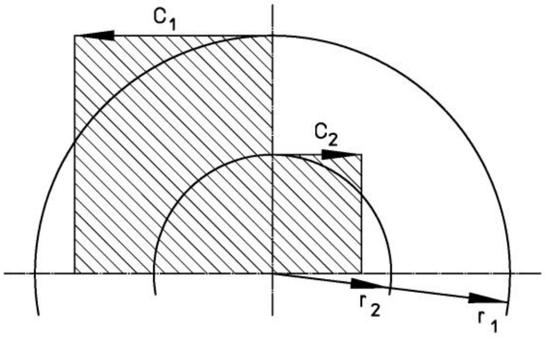

Fig 4: Optimal Torque Topt

Figure 4 shows the optimal torque Topt with positive inlet angular velocity generating a negative outlet angular momentum increasing the differential angular momentum.

The optimal torque is greater than the maximum torque. The fundamental Euler turbine equation with its possible variations of negative, positive and zero outlet angular momentum is appropriately applied in the design of the here presented liquid-vapour two-phase LNG expander.

DESIGN OF LIQUID-VAPOUR TWO-PHASE LNG EXPANDERS

The design of two-phase LNG expanders essentially follows existing turbine and expander technology. The hydraulic energy of the pressurized fluid is first transformed into kinetic energy and then into mechanical shaft power, which is converted to electric energy by an electrical generator.

Figure 5 shows the LNG expander assembly mounted with vertical rotational axis on the head plate, inside the pressure vessel. The pressurized LNG enters through the horizontal inlet nozzle at the lower vessel part and flows upwards between vessel and expander, enters the expander at the red coloured nozzle ring and exits the expander and the vessel at the top through the vertical outlet nozzle. The pressure vessel is manufactured from a stainless steel cryogenic alloy and certified according to pressure vessel codes. The expander is manufactured from a cryogenic aluminium alloy. The main purpose of the pressure vessel is to protect the expander against mechanical damage and fire accidents since LNG is a flammable liquid and aluminium is a flammable metal. The special stainless steel alloy withstands flames, pressure and corrosion and carries also the thermal insulation between cryogenic temperature and the environment.
The expander itself consists of three main parts, the housing, the hydraulic assembly and the electric generator. The hydraulic assembly shown in the colours red, yellow, green and silver blue is mounted together on one rotating shaft with the electric generator shown in colour brown.

By following the Euler turbine equation, the hydraulic assembly transforms the fluid energy into rotating shaft power driving the electric generator, which converts the shaft power into electrical power transmitted by cryogenic electrical power cables to the outside of the vessel, and then connected directly or via a variable frequency drive to the general power net. Thus the original pressure energy of the LNG is converted into electrical energy and removed from the LNG stream. The enthalpy of the low pressure LNG is reduced correspondingly, reducing the evolution of flash gas, giving increased LNG production.

Figure 6 shows the hydraulic assembly transforming static pressure energy into shaft torque. The function of the hydraulic assembly is here described in detail.

Figure 7 shows the static, non-rotating, red coloured nozzle ring mounted on the expander housing.

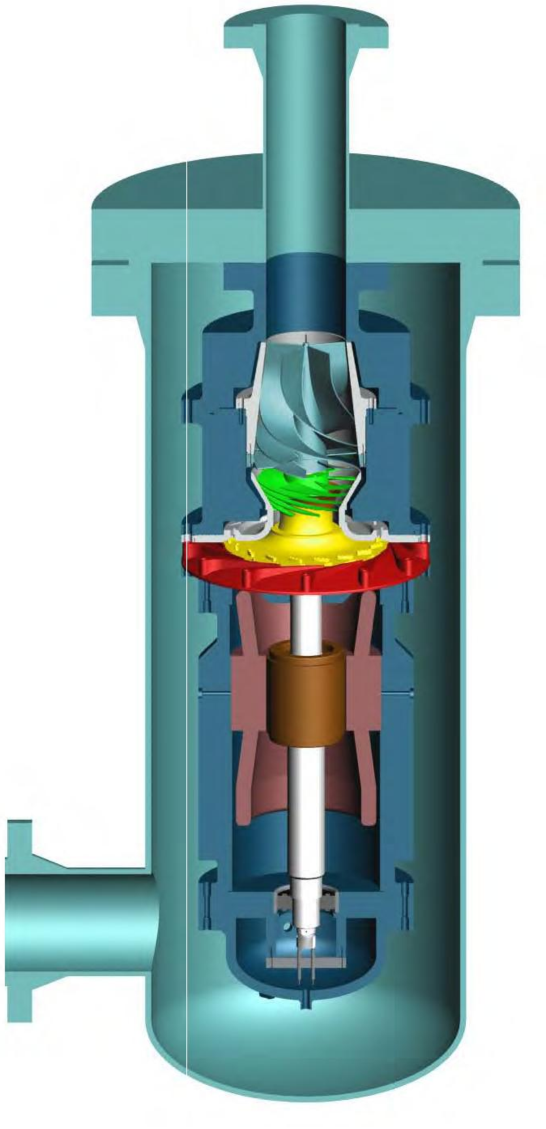

Fig 5: LNG Expander Assembly

The nozzle ring converts the pressure energy of the fluid into kinetic energy generating the important inlet angular momentum described by the Euler turbine equation. This energy transformation is achieved with high efficiency due to the specific design of the nozzle ring. The cross section of the fluid passage between the nozzle vanes is reduced in vertical and horizontal direction. This three dimensional nozzle ring design, producing an efficient angular Euler momentum with minimal losses, is most influential in the turbine and expander performance.

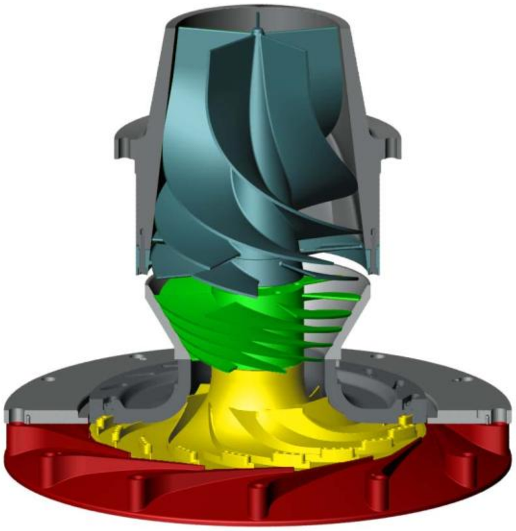

Fig 6: Hydraulic Assembly

Fig 7: Inlet Nozzle Ring

Figure 8 presents the rotating turbine runner of the expander mounted on the shaft and consisting of the grey coloured shroud and the yellow coloured hub with guide vanes. The rotating fluid enters the runner in angular and radial direction and passes through the fluid passages formed by the guide vanes and exits the runner in axial and vertical direction. The design of the runner as a radial inflow turbine is such that the outlet angular Euler momentum is zero with no remaining rotational fluid energy at the exit of the runner and the entrance of the jet exducer.

Mounted on top of the runner is the jet exducer rotating together with the runner. Figure 9 displays the exducer consisting of the green coloured hub with guide vanes and the grey coloured shroud. The jet exducer is a radial outflow turbine, also known as Hero's turbine, with no inlet angular momentum. The purpose of the exducer is to generate a negative outlet angular momentum.

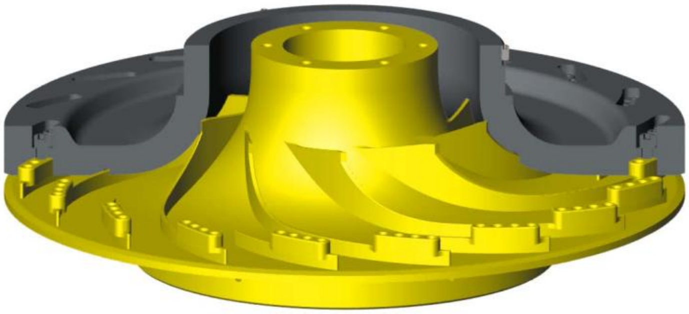

Fig 8: Runner Assembly

As described above, a negative outlet angular momentum increases the differential angular Euler momentum resulting in an increased shaft torque and shaft power. The guide vanes for the fluid flow through the exducer are helically wrapped around the shaft with cross sections increasing in size.

The saturated LNG begins to vaporize at the inlet of the exducer forming a liquid-vapour two-phase fluid flow. The volume of the

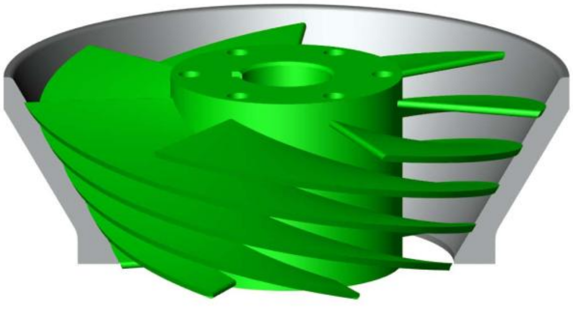

Fig 9: Exducer

vaporizing LNG is increasing and passing through the helical guide vanes the velocity of the fluid is increasing. The increase in fluid velocity causes a drop in the pressure due to Newton's Conservation of Energy Law. The drop in pressure increases the LNG vaporization at any location inside the guide vanes due to the thermodynamic properties. Increased vaporization increases the volume and the fluid velocity, causing further pressure drop in the fluid. The described vaporization-volume-velocity-pressure cycle is effective at any location within the helical guide vanes and repeats itself until the liquid-vapour mixture exits the exducer with a high fluid velocity.

The high rotational exit velocity generates a large negative outlet momentum increasing the differential angular Euler momentum. The design of the jet exducer is applicable to liquid-vapour two-phase fluids of any ratio between vapour and liquid, including single-phase fluids as liquid or as vapour. Operating the LNG expander with variable rotational speed enables the expansion of single and two-phase fluids with smooth and uninterrupted transition across all phase ratios.

The large negative outlet angular momentum increases the shaft torque but also causes the fluid to exit the jet exducer with a remaining rotational kinetic energy. To recover this rotational kinetic energy by converting it into static pressure energy, the fluid passes through a so called condensation cone designed like a turbine draft tube with flow straightener [3] as shown in Figures 10 and 13. The non rotating silver blue coloured condensation cone is mounted on the expander housing. The guide vanes are helically shaped with changing pitch. The pitch of the helical vanes at the inlet is small and increases continuously in an upward direction until the vanes are parallel to the shaft axis. The helical vanes are attached to the conically shaped centre piece. The condensation cone reduces the fluid velocity to the necessary axial fluid velocity at the outlet nozzle of the pressure vessel. Thus the rotational fluid energy is converted into pressure energy due to Newton's Conservation of Energy Law transforming kinetic energy into static energy.

The two-phase LNG expander design presented performs the thermodynamic expansion of liquefied gases with optimal process efficiency, complying in an advanced form with the fundamental Euler turbine equation. The theory of thermo-fluid dynamics describes the two-phase expansion process in detail across the LNG expander.

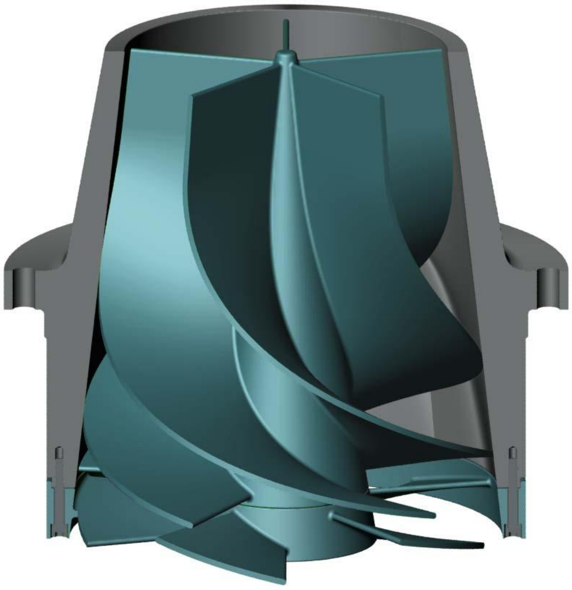

Fig 10: Condensation Cone

THERMO-FLUID DYNAMICS OF TWO-PHASE LNG EXPANDERS

The power generated by turbine expanders can be calculated by applying Newton's mass, momentum and energy conservation laws. In the case of turbines driven by ideal incompressible non-viscous liquids, the generated theoretical maximum power P is equal to the product of volumetric flow Q and pressure difference Δp between turbine inlet and outlet.

$$P = Q \Delta p \qquad (5)$$

In case of compressible non-viscous fluids or vapour gases the volumetric flow changes at any point across the turbine. The generated power has to be expressed in a differential term dP for a small differential pressure dp. The volumetric flow Q changes with the extracted generated power P and the pressure p

$$dP = Q[P,p] \, dp \qquad (6)$$

Two-phase fluids are mixtures of liquid and vapour and their thermo-physical properties are described by thermal-fluid sciences [4],[5].

The following thermodynamic quantities are necessary for calculating a two-phase expansion process.

Internal Energy U

is defined as the energy associated with the random, disordered motion of molecules.

Enthalpy H

is the sum of the internal energy of the system plus the product of the fluid pressure and its volume.

Entropy S

represents the amount of energy in a system that is no longer available for doing mechanical work.

Volume V

is defined as the three-dimensional space the fluid occupies.

Dividing these thermodynamic quantities by the mass introduces

the specific energy u
the specific enthalpy h
the specific entropy s
the specific volume v

The volumetric flow Q is the volume V per time unit passing across the turbine expander. The specific volume v per time unit is the Volume V per time unit divided by the mass.

The extracted generated differential power dP is equal to the differential specific enthalpy dh per time unit. The thermo-physical properties state that the specific volume v is a function of the enthalpy h and pressure p, symbolized as

$$v = v[h,p] \qquad (7)$$

The theoretical maximum differential power generated by the expansion of two-phase fluids is described by the following non-linear differential equation

$$dh = v\,[h,p]\,dp \qquad (8)$$

The specific volume v is a two variable function of the specific enthalpy h and the pressure p and listed in thermo-physical properties tables, and also expressed as two variable polynomial functions. The expansion of two-phase LNG can be approximated with acceptable accuracy by a linear function for the specific volume

$$v\,[h,p] = a+bh+cp \qquad (9)$$

transforming the non-linear differential equation (8) into a linear differential equation (10)

$$dh =(a+bh+cp)\,dp \qquad (10)$$

with an analytical solution (11)

$$h[p] = b^{-2}\,((c+b(a-bh_1+cp_1))\,e^{b(p-p_1)} - (c+b(a+cp))) \qquad (11)$$

The initial conditions for the expansion are h_1 and p_1 at the beginning of the expansion. The theoretical maximum mechanical power P_{max} generated by the expansion of two-phase fluids from pressure p_1 to p is equal to the change of specific enthalpy Δh multiplied by the mass flow m_t per time.

$$P_{max} = \Delta h\, m_t = (h[p] - h_1)\, m_t \qquad (12)$$

In the case of two-phase LNG expanders, the specific internal Energy u is constant and does not contribute to the generated power.

The actual generated mechanical power P_{act} is smaller than the maximum theoretical power due to friction losses and leakage flow. The hydraulic efficiency η is the ratio between P_{act} and P_{max}

$$\eta = P_{act} / P_{max} \qquad (13)$$

$$\eta = P_{act} / ((h[p] - h_1)\, m_t) \qquad (14)$$

Efficiencies are defined as the ratio between the actual value achieved and the theoretical maximum value possible. Equation (14) complies with this general efficiency definition.

FIELD EXPERIENCE WITH TWO-PHASE LNG EXPANDERS

Two-phase expanders of this design, Fig 11 & Fig 12, were installed in January 2003 at PGNiG, KRIO, Odalanów, a Nitrogen Rejection Unit in Poland [6] and have been operating successfully since. Two-phase expanders were initially installed for pressure reduction of the rich liquid feed to the upper column [9] and more recently additional two-phase expanders have been installed in the feed to the lower column. The operator worked closely with TGE to accomplish the upgrade and has reported significant benefit in efficiency and production with the process being highly flexible [7] [8]. The plant was constructed by Costain in the 1970's and with the increased cold generation provided by the installation of the two-phase expanders now has the ability to produce an LNG by-product.

Fig 11: Two-Phase Expanders

Fig 12: Two-Phase Expander After Testing

Fig 13: Condensation Cone

CONCLUSIONS

The utilisation of two-phase LNG expanders is an advanced and novel approach which enables a further decrease in enthalpy across the pressure reduction process and increase in power generation through application of the fundamental Euler turbine equation and Newton's conservation laws.

The benefits of two-phase LNG expanders can be realised through further reduction in flash gas evolution or by reducing the sub-cooling required in the liquefaction process, resulting in lower power requirements or increased production capacity.

Since various liquefaction processes have different specific energy consumption for each degree of cooling as the LNG outlet temperature changes, the potential increased production rates and improved plant efficiencies due to the resulting lower product sub-cooling requirements will vary depending on the liquefaction process.

The two-phase LNG expanders described are designed to expand LNG into the two-phase region, but may also be operated with single-phase outlet by the application of backpressure from a downstream valve. Application of variable speed technology allows flexible operation of the expander across a range of process conditions in single-phase or two-phase to maximise benefit to plant performance.

Several two-phase cryogenic liquid expanders are operating continuously in LNG service and are field proven for several years.

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