TURBO-EXPANDER TECHNOLOGY DEVELOPMENT FOR LNG PLANTS

DEVELOPPEMENT DE LA TECHNOLOGIE DES TURBO-EXPANSEURS POUR LES CENTRALES DE GNL

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ABSTRACT

Turbo-expander technology plays an important role in cost savings for baseload LNG plants. Gas expansion turbines have been used in LNG peak-shaving plants and natural gas plants, and their applications for future LNG plants are discussed. These expanders could be used with advantages in either the high pressure feed gas streams or in the refrigerant system. Potential advantages especially for future offshore LNG plant applications are highlighted. In conventional liquefaction processes high pressure LNG or liquid refrigerant stream is reduced in pressure by expansion across a Joule-Thomson valve.

Recent technological advancement in cryogenic liquid expansion turbines has enabled the replacement of the Joule-Thomson expansion valve with a cryogenic power recovery turbine. Cost savings by reducing specific liquefaction power or increasing LNG production are discussed.

Cryogenic liquid expansion turbines of the first generation, operating at constant speed with an external generator, and the new generation of submerged cryogenic turbine generators, using variable speed operation, have been applied to recent baseload LNG plants. Both operational characteristics and equipment designs are very different. These different expansion turbines are compared, and future technological developments are also discussed.

RESUME

La technologie des turbo-expanseurs joue un rôle important dans la réduction des coûts pour les centrales de GNL de base. Des turbines à expansion de gaz ont été utilisées dans les centrales de pointe de GNL et les centrales de gaz naturel. Leurs applications dans les centrales futures de GNL sont discutées. Ces expanseurs pourraient être utilisés d’une manière avantageuse dans les circuits de gaz de charge de haute pression ou dans le système de réfrigération. Les avantages éventuels, notamment en ce qui concerne les applications futures dans les centrales marines de GNL, sont soulignées.

Dans les procédés conventionnels de liquéfaction, la pression des réfrigérants liquides ou GNL de haute pression en circulation est réduite par expansion à travers une soupape Joule-Thomson. Les progrès récents de la technologie des turbines à expansion de liquides cryogéniques ont permis de remplacer la soupape Joule-Thomson par une turbine de récupération d’énergie cryogénique. Les réductions des coûts réalisées par la réduction de l'énergie spécifique de liquéfaction ou l'augmentation de la production de GNL sont discutées.

Des turbines à expansion de liquides de la première génération, fonctionnant à une vitesse constante avec un générateur externe, et la nouvelle génération de turbines avec générateurs cryogéniques immergés, fonctionnant à un régime variable, ont été appliquées aux centrales récentes de GNL de base. Les caractéristiques de fonctionnement et conceptions des équipements sont très différentes. Ces différentes turbines à expansion seront comparées. Les développements futurs de la technologie sont également discutés.

INTRODUCTION

Turbo-expander technology plays an important role in cost savings for baseload LNG plants. Gas expansion turbines have been used in LNG peak-shaving plants and natural gas plants. The use of the gas expander in air separation plants has been extended to natural gas plants and the LNG peak shaving plants. It is expected that the gas expander will be applied in baseload LNG plants application the in the future to take advantage of high feed gas pressures, especially at offshore floating production, storage, and offloading (FPSO) LNG plant applications. Although developed at a later stage, liquid expansion turbines have already been applied in the baseload LNG plants with success. Liquid expansion turbine technology has evolved from a constant speed type to a variable speed type. Liquid expander has been used in several newer LNG plants, and has in general increased LNG production by several percent. Further developments have also advanced the optimal control of the LNG process.

GAS EXPANDER

Gas Expander for the Feed Gas

Gas expanders can be applied in either the high pressure feed gas streams or in the refrigerant system. In the feed gas system for a baseload LNG plant, the gas expander could be used in association with the scrub column to save on requirements of refrigeration and to facilitate separation of heavy components.

Since it is more efficient to liquefy natural gas at a higher pressure, one way of achieving the separation of heavy component at a lower pressure and also liquefy the feed gas at a higher pressure is to use a combination of an expander-booster compressor arrangement. The feed gas would enter a gas expander to reduce its pressure before entering the scrub column for the separation of heavy components. The overhead gas stream of the scrub column is then recompressed before entering the liquefaction heat exchanger. If the separations of heavy components are not required, the feed gas could be liquefied at a pressure above the critical pressure. Since separation by distillation can only be performed at a pressure below the critical pressure, it is necessary to reduce the feed pressure below the critical pressure by a valve or a gas expander. In order to liquefy the feed gas at a higher pressure after the heavy removal using the scrub column, the gas expander can be connected to a booster compressor to boost the feed gas pressure. This approach is very similar to the technology currently used in natural gas expander plants.

In general the feed gas expander can be better applied at temperatures lower than ambient, preferably after some precooling and removal of the sensible heat of the feed gas.

As a result the isentropic expansion through a gas expander is more beneficial in lowering the feed gas temperature than the isenthalpic expansion through a Joule-Thomson expansion valve.

A new development has indicated the benefits can be gained not only in the application of a gas phase expander for isentropic expansion in the feed gas circuit for the liquefaction of LNG, but also in the recycle gas circuit, where the same gas expander-compressor setup can be utilized to enhance the production of LNG. As indicated in a recent development, the three-dimensional design of a gas phase turbo expander wheel will promise a higher isentropic efficiency to greater than 90%, which will further improve the thermal efficiency of the liquefaction process utilizing gas phase turbo expanders.

Gas Expander for the Refrigerant

In a recent development of floating LNG plants, it has been proposed to use nitrogen as a refrigerant for the precooling and liquefaction of natural gas. In this scheme, the nitrogen refrigerant is compressed and expanded through several stages of gas expanders to provide necessary refrigeration. Although the process efficiency is generally lower than using hydrocarbon refrigerants, this process is considered as a safer option for the FPSO as it does not require a large storage of flammable hydrocarbon refrigerants.

LIQUID EXPANDER

Cryogenic turbines are also known as liquid expanders, turbine expanders or cryogenic turbine generators. Cryogenic liquid expansion turbines of the first generation, operating at a constant speed connected with an external generator; and the new generation of submerged cryogenic turbine generators, using variable speed operation, have been applied to recent baseload LNG plants. Both operational characteristics and equipment designs are very different. In conventional liquefaction processes, high pressure LNG or liquid refrigerant stream is reduced in pressure by expansion across a Joule-Thomson valve. Recent technology advancement in cryogenic liquid expansion turbines has enabled the replacement of the Joule-Thomson expansion valve with a cryogenic power recovery turbine. Cost savings can be achieved by reducing specific liquefaction power or increasing LNG production. The installation of liquid expansion turbines has demonstrated a significant cost reduction and a pay back time of less than one year.

Variable Speed Liquid Expansion Turbines

Cryogenic turbines of the first generation were operating at a constant speed and required an additional control valve to adjust the turbine expansion to different process conditions. The new generation of cryogenic turbines, installed at the most recent LNG plant in Oman, uses variable speed operation, and both turbine and generator are completely immersed in the LNG fluid stream. Compared with constant speed turbines, these turbines are about one quarter in weights and one third in sizes, and their design also eliminates the complex wicket gate and its cryogenic seal scheme. Variable speed turbines have essentially two functions: power recovery and process control over pressure and mass flow. The use of speed controlled cryogenic turbines optimizes the process by extracting maximum enthalpy from the fluid stream, increasing the LNG output as well as reducing the power input.

Advanced Process Control

Cryogenic turbines expand liquefied gases from high pressure to low pressure converting the hydraulic energy into electrical energy to reduce the enthalpy of the liquefied gas and to recover energy. In conventional baseload LNG plants, liquid expanders are applied to the mixed refrigerant circuit and the LNG product circuit as shown in Figure 1. Liquid expanders are operated as close as possible to the best efficiency point (BEP), which is defined for certain flow rates and expansion ratios. Figure 2 shows a typical process arrangement to operate the liquid expander in the LNG product circuit at the BEP. The process improvement discussed below is only applicable to LNG expanders installed between the main heat exchanger and the atmospheric pressure LNG storage tank or the phase separator, and is not applicable to cryogenic liquid expanders installed in mixed refrigerant cooling cycles.

Because of variations and uncertainties of the pressure drop in the system, it is necessary to install a control valve preferably between the expander and downstream system to meet the best efficiency point of the expander. If the turbine is expanding the differential pressure (P_1 - P_2), then the control valve expands exactly the remaining differential pressure (P_2 - P_3) to meet the target pressure P_T of the terminal vessel. The control valve reduces the liquid pressure in a Joule-Thomson expansion without any enthalpy reduction and with zero isentropic efficiency. This inefficient Joule-Thomson expansion has to be as small as possible to increase the overall process efficiency. Variable speed liquid expanders operate at variable differential pressures and variable flow rates and are therefore essentially both a turbine and a control valve. Figure 3 demonstrates the process arrangement for a variable speed liquid expander operating simultaneously as a control valve. The expander is able to expand the total differential pressure (P_1 - P_3) to the exact value necessary to meet the target value P_T.

The differential pressure (P_2 - P_3) is now expanded through the turbine reducing the enthalpy of the liquefied gas and increasing the power recovery. The target pressure P_T in the terminal vessel determines the correct speed of the turbine expander, the control speed N_C. This advanced method of controlling the overall process through the expansion ratio of the turbine expander offers a maximum power recovery and enthalpy reduction of the liquefied gas.

Liquid Expander Dynamics

Dynamic behavior of variable speed turbines is governed by the conservation laws of mass, energy and momentum. The mass flow across the inlet and outlet of the turbine are generally the same, so conservation of mass is automatically satisfied. The equation for conservation of energy implies that the sum of static and kinetic energy is constant:

$$H = \alpha Q^2 + \beta N^2$$

H, the differential head, represents the static energy across the turbine. The translatory and rotatory kinetic energies are represented with the squared values of volumetric flow Q and rotational speed N. The conservation law of angular momentum defines the shaft torque T, which determines the shaft power S.

$$S = TN = [\tau Q\,(Q - \lambda N)]\,N$$

The constants α, β, λ and τ are design and fluid specific parameters. Figure 3 shows the typical performance curves of a variable speed turbine with flow Q and head H as coordinates. Q_R, H_R and N_R define the rated point R, which is in most cases also the best efficiency point. For $T = 0$ the turbine performs with a freely spinning rotor along the zero-torque characteristic, which intersects the rated speed curve N_R for the minimum flow rate Q_{0R}. For the fluid density ρ the pressure values of Figures 2 and 3 are related to the differential heads in Figure 4 in the following way:

$$H_R = (P_2 - P_1) / \rho \qquad H_C = (P_3 - P_2) / \rho \qquad H_C + H_R = (P_3 - P_1) / \rho$$

The efficiency η_R of the turbine expander at the rated point is the ratio between rated shaft power $S_R = [\tau Q_R (Q_R - \lambda N_R)] N_R$ and hydraulic power $(\rho Q_R H_R)$. The control valve in Figure 2 has no power output and has an efficiency $\eta_C = 0$. The total overall efficiency η_T of the control valve and the turbine expander is calculated by $\eta_T = S_R / [\rho Q_R (H_R + H_C)]$ with the result that η_T is always smaller than η_R.

In the case of a variable speed turbine expander simultaneously operating as a control valve as shown in Figure 3, the turbine operation moves from the rated point R to point C and the speed increases from the rated speed N_R to control speed N_C. The turbine efficiency η_C at point C is defined by the following ratio:

$$\eta_C = [\tau Q_R (Q_R - \lambda N_C)] N_C / [\rho Q_R (H_R + H_C)]$$

The ratio ε compares the efficiencies η_C and η_T:

$$\varepsilon = \eta_C / \eta_T = [N_C (Q_R - \lambda N_C)] / [N_R (Q_R - \lambda N_R)]$$

The simultaneous operation of turbine and control valve is economically beneficial if

$$[N_C (Q_R - \lambda N_C)] > [N_R (Q_R - \lambda N_R)]$$

This expression simplifies to the condition: $Q_R > \lambda (N_C + N_R)$

The constant λ is the speed specific flow for the zero-torque operation of the turbine with the following relation: $\lambda = Q_{0R} / N_R = Q_{0C} / N_C$, which allows eliminating λ in the above equation: $Q_R > Q_{0R} + Q_{0C}$. Q_{0R} and Q_{0C} are the flow rates for zero-torque turbine operation at the speed N_R and N_C, also known as “zero-torque-flow” for “zero-torque-speed.”

Process Optimization

The effect of the simultaneous turbine-control valve operation is shown in Figure 4. The condition for a beneficial operation as defined in the previous paragraph is described as “the rated flow has to be larger than the sum of the zero-torque-flows for the rated speed and the control speed”. This condition is true for the shaded area in Figure 4. This area is defined by three curves. The left boundary is the zero-torque curve shifted to the point $Q = Q_{0R}$ along the Q-axis. To the right side of this curve the condition $Q_R > Q_{0R} + Q_{0C}$ is satisfied and the value of the efficiency ratio ε is always greater than 1. The maximum differential head determines the upper boundary as a horizontal line $H = H_C + H_R$. The rated speed curve of a constant N_R defines the lower to the right boundary.

The shaded area specifies the range for which the simultaneous turbine-control valve operation (Figure 3) offers higher overall process efficiency than the operation of turbine and conventional control valve with Joule-Thomson expansion (Figure 2). The variable speed turbine expander is able to operate at any flow and differential head within the shaded area. This feature allows the turbine expander to determine at any time and for changing process

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conditions, the optimal mass output of the process. The adjustment of the turbine speed can be set to slow in the range of minutes or set to fast within milliseconds. The term “control turbine” is introduced to identify the particular use and characteristics of variable speed turbine expanders operating simultaneously as control valves in process plants. Due to their unique features, control turbines are excellent devices for continuous process optimization.

Control Turbine Performance

It is important to understand the performance of control turbines and their range of beneficial operation, identified as the shaded area in Figure 4. The rated point R for the corresponding flow rate Q_R is being replaced by the operation point C at the same flow rate Q_R, and the control turbine expand the total differential head to $H_C + H_R$ under enthalpy reduction. The conventional solution is that the differential head H_C is reduced in a control valve at constant enthalpy and only the differential head H_R is expanded in a turbine under enthalpy reduction. The difference between these two cases can be represented by ratio ε.

Within the shaded area control turbines improve performance for varying flow rates Q_R and for varying differential heads $H_C + H_R$. The ratio ε has a maximum value ε_{max} within the shaded area. The derivative $\partial\varepsilon / \partial N_C = 0$ determines the maximum value of ε for the control speed $N_C = Q_R / 2\lambda$, with $\lambda = Q_{0R} / N_R$ transformed to $N_C = N_R Q_R / 2Q_{0R}$:

$$\varepsilon_{max} = ¼\, \omega^2 / (\omega - 1) \quad \text{with } \omega = Q_R / Q_{0R}$$

The parameter ω is the ratio between rated and zero-torque speed. Typical values of ω are between $2.5 < \omega < 3.0$ for variable speed turbine expanders, and this ω-range results in ε_{max} values between $1.04 < \varepsilon_{max} < 1.12$.

Process Economics

The unique ability to fine tune the overall process through variable speed control turbines replacing conventional process control valves provides the means to extract maximum enthalpy from the liquefied gas. It optimizes the thermodynamic expansion of the overall system and increases LNG output for the same input power. The installation and operation of control turbines in natural gas liquefaction plants could potentially further increase the LNG output above 4%, subject to thermodynamic, mechanical and process constraints, compared to conventional liquefaction plants operating with liquid expander and separate control valve.

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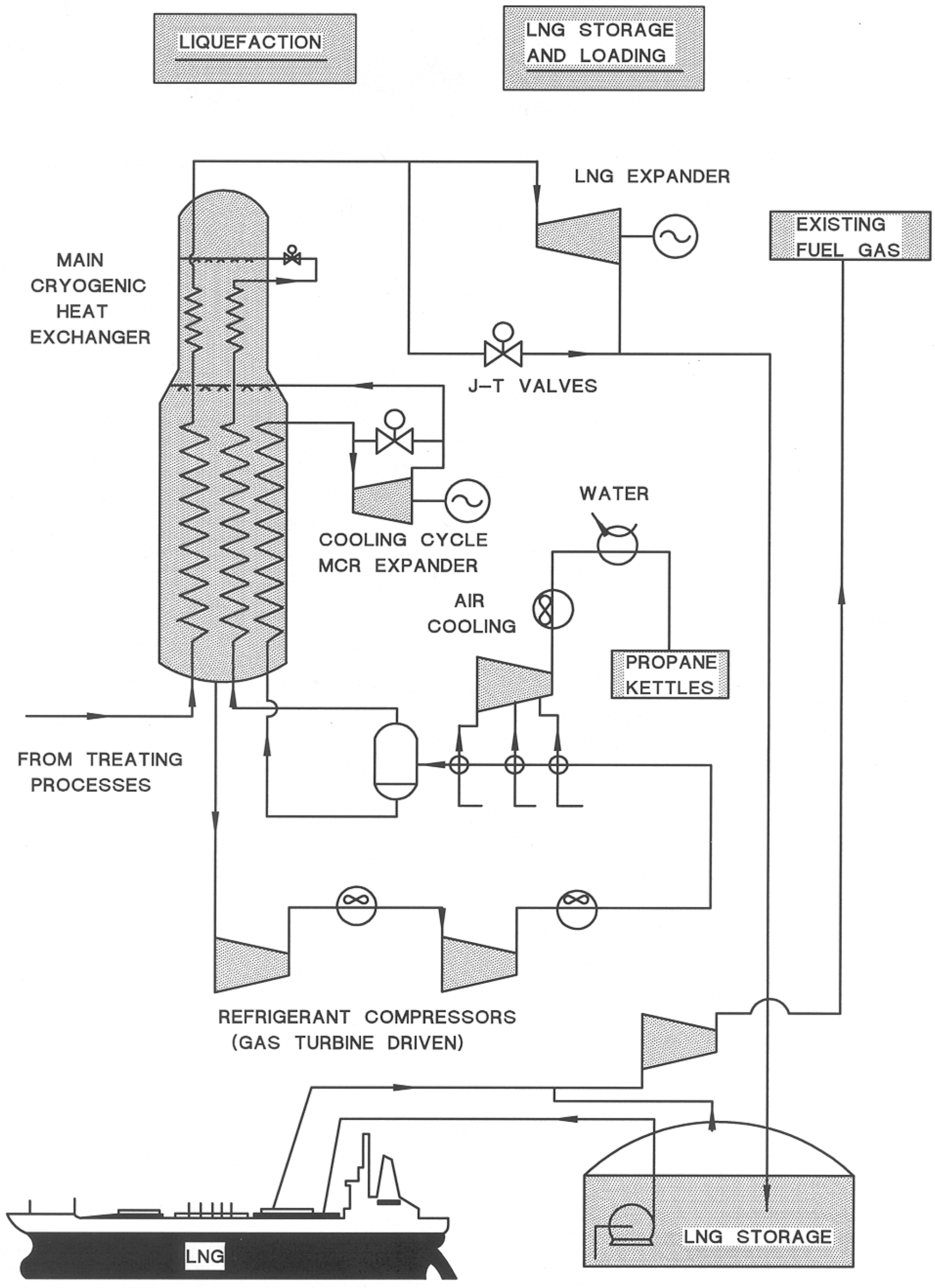

FIG.1: TYPICAL LNG LIQUEFACTION PROCESS SCHEME

Figure 1

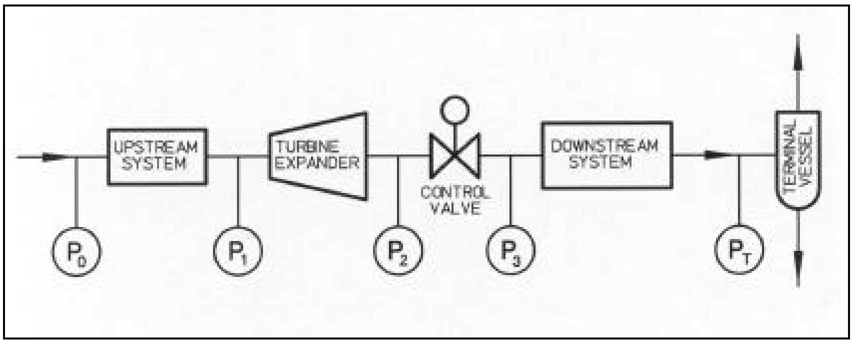

Figure 2

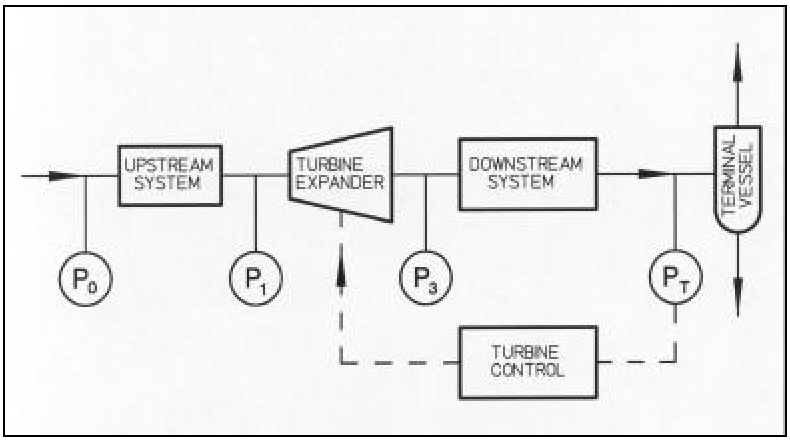

Figure 3

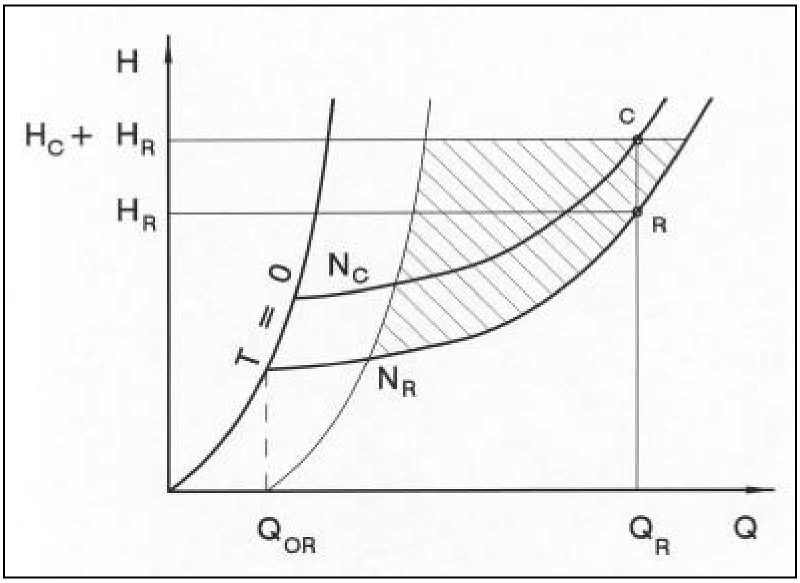

Figure 4