Two-Phase LNG Expanders

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ABSTRACT

LNG turbines are today an important part of every new LNG liquefaction plant. They are routinely applied in single-phase duties to enhance the performance of LNG liquefiers.

This paper describes an application of the next generation of cryogenic turbines in a much more arduous duty, where expansion of methane-rich, subcooled liquid enters the two-phase region. The paper reports the successful operational experience of two turbine expanders implemented in nitrogen rejection unit revamps in order to improve their performance.

The implementation of these two-phase expanders heralds a new chapter in the use of expanders in the LNG and general cryogenic industry.

The paper describes the history of the plant, the changes that have occurred over its years of operation, the decisions taken to implement the modifications and the final configuration of the cryogenic part of the process. The paper also covers the initial start up trials, the results and the final acceptance test data following two years of expander operation. The paper discusses the operational aspects of the facility and the benefits in having the two-phase expander in the selected location.

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INTRODUCTION

A problem often encountered in the production of high BTU natural gas from underground sources is nitrogen contamination. There are many gas fields where nitrogen is present in significant concentrations and sometimes it may have been injected into the reservoirs as part of an enhanced oil recovery or enhanced gas recovery operation. Natural gases which contain a significant amount of nitrogen are often not be saleable since they do not meet minimum heating value requirements of the grid into which they are compressed. As a result the feed gas will generally undergo processing, wherein heavier components such as heavy hydrocarbons, water and carbon dioxide are removed and the remaining stream containing nitrogen and methane, and also possibly containing lower boiling or more volatile components such as helium, is separated cryogenically when passing through a nitrogen rejection unit.

The nitrogen rejection unit (NRU) comprises compact heat exchangers, pumps, cryogenic distillation columns and Joule-Thomson (J-T) valves linked together in a heavily integrated process to carry out efficient separation into the required products. J-T valves are applied to reduce the pressure of streams entering the distillation columns in order to decrease the stream temperature and assist in the provision of refrigeration to the process.

Such a plant was constructed in the 1970s in Poland to achieve this and subsequently, this plant was modified with the novel turbine application to accommodate a feed gas having a different composition to the original design range.

HISTORY OF THE NITROGEN REJECTION FACILITIES IN POLAND

The nitrogen rejection plant is located in South-Western Poland in Odolanow and comprises two trains, each processing up to 136,000 NCMH of raw feed gas.

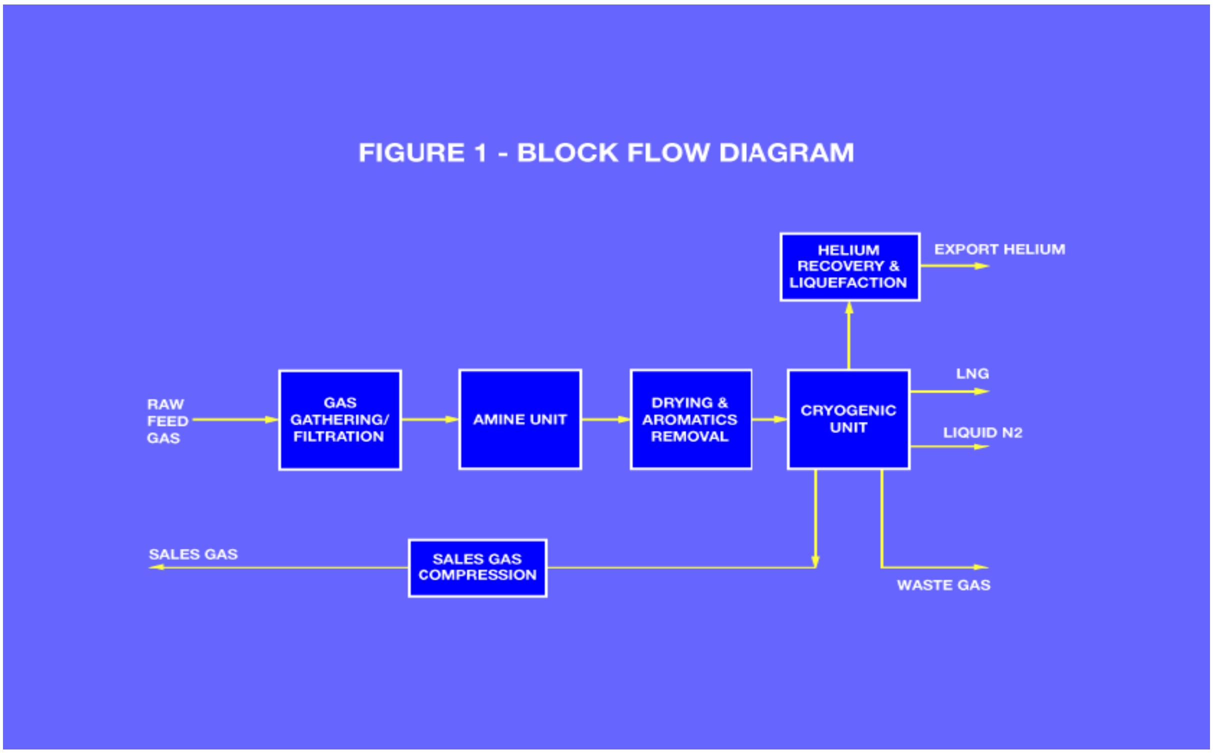


FIGURE 1 - BLOCK FLOW DIAGRAM

Figure 1 shows a block diagram of one of the processing trains and how it is linked to the supply and the sales gas compression

Raw gas is admitted from the plant supply header into each train and the first processing element is an amine unit which removes the carbon dioxide from the gas down to about 50ppm by volume. The next process block is a thermally regenerated adsorption system which consists of two adsorbers. Within the main adsorption bed there is molecular sieve to remove water to less than 0.1ppm, while the second adsorption bed is activated carbon to remove benzene and heavy hydrocarbons. A two vessel adsorption and regeneration system is utilised, one adsorbing and the other being regenerated using waste gas. The dry gas is then admitted to the cryogenic unit which separates the nitrogen from the methane using a thermally linked, double column type process. Sales gas of appropriate quality is produced for compression. In addition to nitrogen/methane separation, crude helium is also produced from the lower column which is subsequently passed to a helium purification unit and then liquefaction. Helium has always been a valuable product from this facility and the initial concentration was as high as 0.4% in the raw gas.

The original incoming gas had a composition approximately as indicated in Table - 1 below.

Table – 1. Original Feed Gas Composition.

Helium	0.4 vol%
Nitrogen	42.7 vol%
Methane	56.0 vol%
Ethane	0.5 vol%
Propane+	0.1 vol% max.
CO_2	0.3 vol%
Water	Saturated at inlet conditions
Pressure	5.6Mpa
Temperature	10 – 15 ^oC
Flow	136000 NCMH

The sales gas required from the plant had to contain less than 4% nitrogen whilst the waste nitrogen was vented to atmosphere was required to have less that 1% methane. In addition, the helium recovery was required to be better than 85% having a final purity of 99.999% as liquid at -269^{o}C. The original design required that the sales gas emanated from the cryogenic unit at about 1.8MPa.

Over the years of operation, the raw feed gas has been gradually changing as old gas wells become depleted and new ones are brought on line and supplied to the Odolanow facility. Today the composition has changed markedly with about 32 – 35 % nitrogen in the feed. In addition, the helium content has decreased to a little over 0.2%. Therefore, the refrigeration potential of the feed gas has been reduced because there is now proportionally less nitrogen to expand to near atmospheric and by difference, more methane that is produced at 1.8MPa. This has gradually caused more severe operational problems for the two plants. In order to make up the "cold deficit", the plant stability was maintained by allowing a larger amount of methane to slip with the waste gas. This was clearly a temporary solution to maintain sales gas output, but resulted in a negative environmental impact and a loss of revenue from the methane emission. The plant was originally capable of producing small amounts of liquid methane or nitrogen for sale to third parties. All of this was severely impaired, or even curtailed, with the lowering of the nitrogen content in the feed gas.

In summary, there are several main factors associated with the change of initial composition of the feed gas :

- The environmental impact of increased methane content in the waste gas
- The economic loss as the consequence of methane emission
- Less stable operation of the cryogenic unit.
- Inability to produce liquid products.

With the depleting gas source the feed gas pressure may require expensive investment in a pre-compression step. It would also be desirable to improve the efficiency of the NRU operation so that even with the drop of the feed gas pressure there will be still enough cold produced in the process to be able to operate in a stable manner. The current feed gas pressure is about 5.3 MPa and is being maintained by adding new gas sources.

As a result, various studies were carried out in the late 1990s and 2000 to address the problem and find some solutions. In addition, the helium, a high value product, has decreased in concentration in the feed gas. This made it imperative that any changes to the process would not have any negative effect on the helium recovery. The study work examined many conventional and novel solutions. In order to understand these better the process is described below.

BRIEF DESCRIPTION OF THE CRYOGENIC PROCESS

In the original process, all energy needed for natural gas separation in low temperature units was provided by pressure reduction of the natural gas across Joule-Thomson valves. The process is shown in Figure 2.

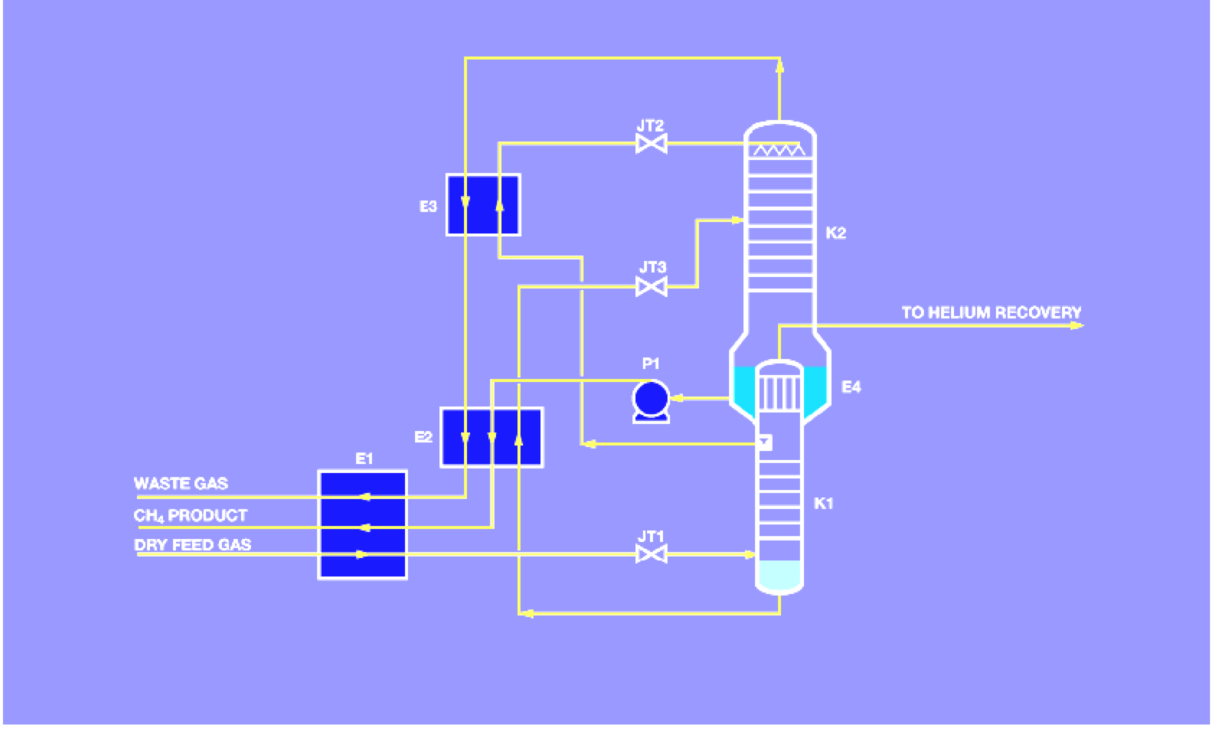


FIGURE 2 - PROCESS FLOWSCHEME FOR THE NRU CRYOGENIC SECTION

The dry feed gas is admitted into E1 of the cryogenic unit where it is cooled at 5.3MPa, condensed and subcooled before it is passed through JT1 for expansion to the lower column K1. The pressure in the lower column is about 2.1MPa and thus there is some flash into the lower column. The “rich liquid” from the base of K1 is then subcooled in E2 against returning colder methane liquid and gaseous nitrogen streams to about -150°C before passing through JT3 where the subcooled rich liquid expands to 0.2MPa, thereby creating some flash before entry into the upper column.

The upper column operates at about 0.1MPa and carries out the main distillation between nitrogen and methane. Reboil to this column is provided by condensing nitrogen at 2.2MPa in the top part of the upper column. This condensed nitrogen is very pure having less than 10ppm methane, is drawn from a downcomer seal as a sidestream from the upper column, subcooled in exchanger E3 before it is expanded across JT2 and admitted to the top of the upper column, K2. This nitrogen stream provides the necessary reflux to purify the nitrogen waste gas which returns through E3, E2 and finally, E1, before it is vented to atmosphere. Therefore, the expansion valves JT1, JT2 & JT3 provide all of the refrigeration to the process. The methane product pump, P1, raises the pressure of the methane product from 0.2MPA to about 1.8MPa before the methane is evaporated and reheated in E2 and E1 respectively. The methane product is then compressed into the sales gas pipeline to about 5.0 MPa. The block flow diagram in Figure 1 illustrates the sequence of the operations in this facility. Figure 3 shows a photograph of the plant with the two, double columns in the background.

Figure 3 - Odolanow Nitrogen Rejection Plant

Over the years of operating the plant, KRIO has seen the nitrogen reduce from 42% to 33%. It is expected that there may be a further small reduction in the nitrogen content. As the nitrogen in the feed decreases, the amount of this nitrogen reflux also decreases in proportion to the methane that enters the upper column. Consequently, the distillation process does not perform as well as before and methane content in the waste gas increases.

CONCEPT DEVELOPMENT

The study work carried out led to selecting the most effective way of providing refrigeration to the upper column. The analysis included, among others, the following options:

- separate cycle to produce cold to the upper column;
- a gas expander after partially condensing the feed;
- replacing JT1, or JT2 or JT3 with an expander.

After study the addition of an expander in parallel with Joule-Thomson valve JT3 was considered to provide the best potential for replacement with a liquid expander producing two-phase at its outlet. JT3 became a standby for the expander. Expansion turbines are inevitably more efficient since they carry out isentropic depressurisation which generates work instead of isenthalpic depressurisation across a Joule-Thomson valve, which generates no work. Turbines take energy out of the process bringing about greater cooling of the streams passing through them and thus increase overall process efficiency.

The choice of this location for an expander meant that the liquid entering the expander was well subcooled ensuring a good quality single phase at the inlet. The outlet would produce 10 – 30 mole% flash which was an unusual service. This translates to 80 – 95% by volume of liquid. This issue represented a significant challenge from two aspects. The first is the two-phase flow stability for a fluid rising to the upper column entry point for all the cases. The second, and by far the most challenging, was the design of an efficient turbine which converted not only the hydraulic energy into useful work, but also the gas expansion energy.

The first issue was successfully addressed by correct selection of the fluid regime for all the practically expected cases, use of specially design piping and entry systems to prevent surges and vortices causing problems with pressure stability at the turbine outlet and flow stability at the upper column inlet.

The second issue was to source turbines able to expand into two phases. Test programs dating as far back as the 1980s had confirmed this prospect, however, no commercial application of the technology was found. Confidence that two phase expanders would be feasible was established after an engineering study which was further supported by knowledge that:

- a similar duty was tested using a Pelton wheel open expander in air separation;
- a “gas” type expansion turbine was tested with flashing liquid nitrogen;
- there was evidence that one of the Ebara liquid expanders was producing flashing flow at its outlet since there was helium present in the gas;
- there would be no cavitation in this situation since the conditions were expanding and not collapsing gas bubbles;
- there was evidence in the field that gas oil separation facilities at the wellhead had liquid expanders that were seeing two-phases at the outlet.

The concept that was designed for the plant had a greater amount of flash than any of the above examples which represented the greatest challenge.

The expander was located taking feed upstream of JT3, routing it to the upper column to approximately the same entry point as before, except with a special arrangement for the piping. The liquid is well sub-cooled at that point since it exits exchanger, E3, at below -150^{o}C and a pressure of 2.1 – 2.4 MPa. The rich liquid contains about 1/3 nitrogen and the rest is methane. Hence, when it is expanded to 0.24MPa, it produces some vapour, through the turbine.

It was decided that the Ebara turbine lent itself well to exporting power, since the generator is located inside the vessel that houses the expander. The control of the unit was facilitated by Ebara's proven use of Variable Speed, Constant Frequency (VSCF) turbine speed control, using the level signal from the lower column, K1, making the expander act like a control valve. In practice, this control method works well and Variable Frequency Drives (VFD), of which the VSCF is a derivative, have been used in many areas, including pump control on the Odolanow site. This site confidence helped in the selection of this control route.

With the rich liquid cooled down further than from the control valve, JT3, more cold is routed to the upper column and the separation of methane from the nitrogen waste gas stream is considerably more effective compared to the previous J-T arrangement.

TWO-PHASE EXPANDER DESIGN CONCEPT

Two-phase expander design concepts fundamentally follow existing single-phase turbine and expander technology. The hydraulic energy of the pressurized fluid is converted by first transforming it into kinetic energy, then into mechanical shaft power and finally to electrical energy through the use of an electrical power generator.

The generator is submerged in the cryogenic liquid and mounted integrally with the expander on a common shaft. The cryogenic induction generator uses insulation systems specifically developed for cryogenic service giving submerged windings significantly superior dielectric and life properties. Lubrication for the bearings is provided by an internally designed system which takes a small portion of the liquid passing into the turbine and routing it to the bearings. This produces some inefficiency, but the design of this system is far simpler than the typical external oil lubrication system. This was another attractive feature of the “canned” turbine design since the revamp required a smaller plot area, less connections to the main process with no needs for seal gas.

Figure 4 shows the cross section of a typical Ebara International Corporation cryogenic two-phase submerged expander. The expander consists of a nozzle ring generating the rotational fluid flow, a radial inflow reaction turbine runner and a two-phase jet exducer.

Symmetrical flow is achieved in the two-phase expander by utilising a vertical rotational axis to stabilize the flow and to minimize flow induced vibrations, with the direction of flow being upward to take advantage of the buoyant forces of the vapour bubbles. (Expanders with horizontal rotational axis generate asymmetric flow conditions which can result in higher vibration levels.) The hydraulic assembly is designed for continuously decreasing pressure to avoid any cavitation along the two-phase flow passage.

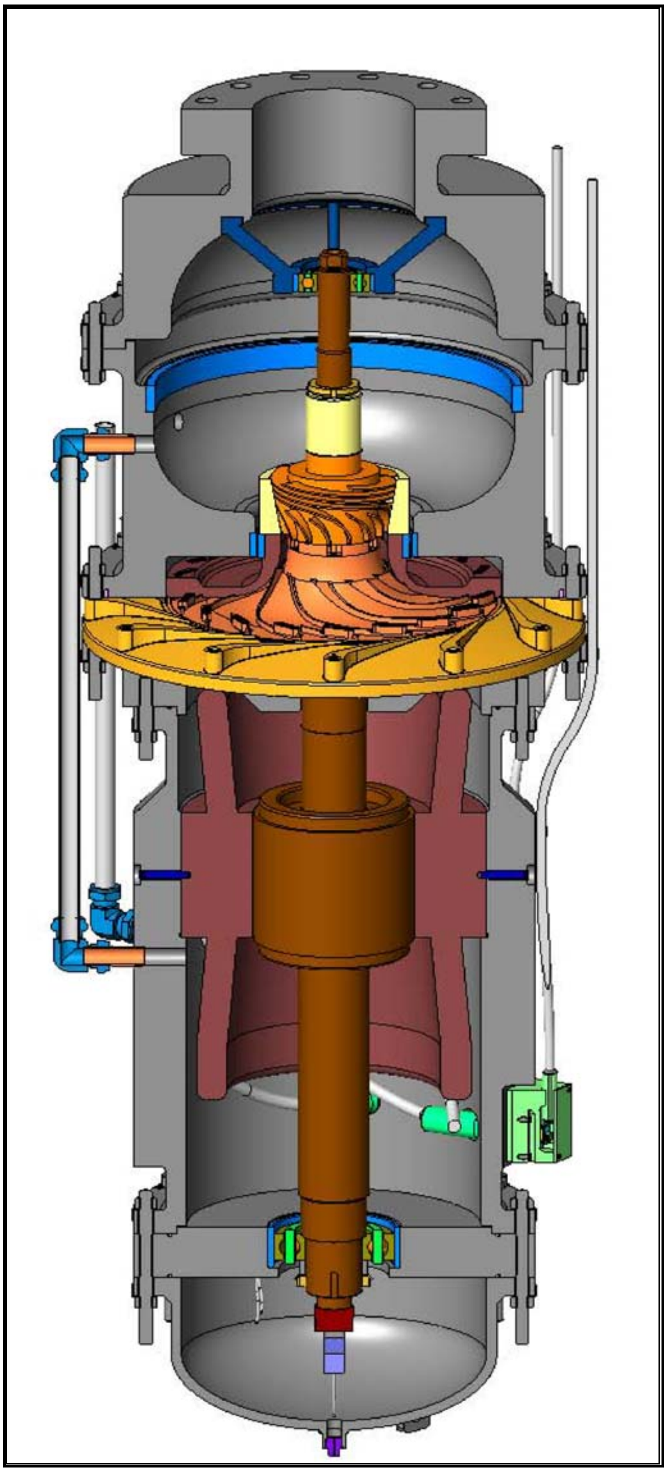


Figure 4 - Ebara Two-Phase Expander Cross Section.

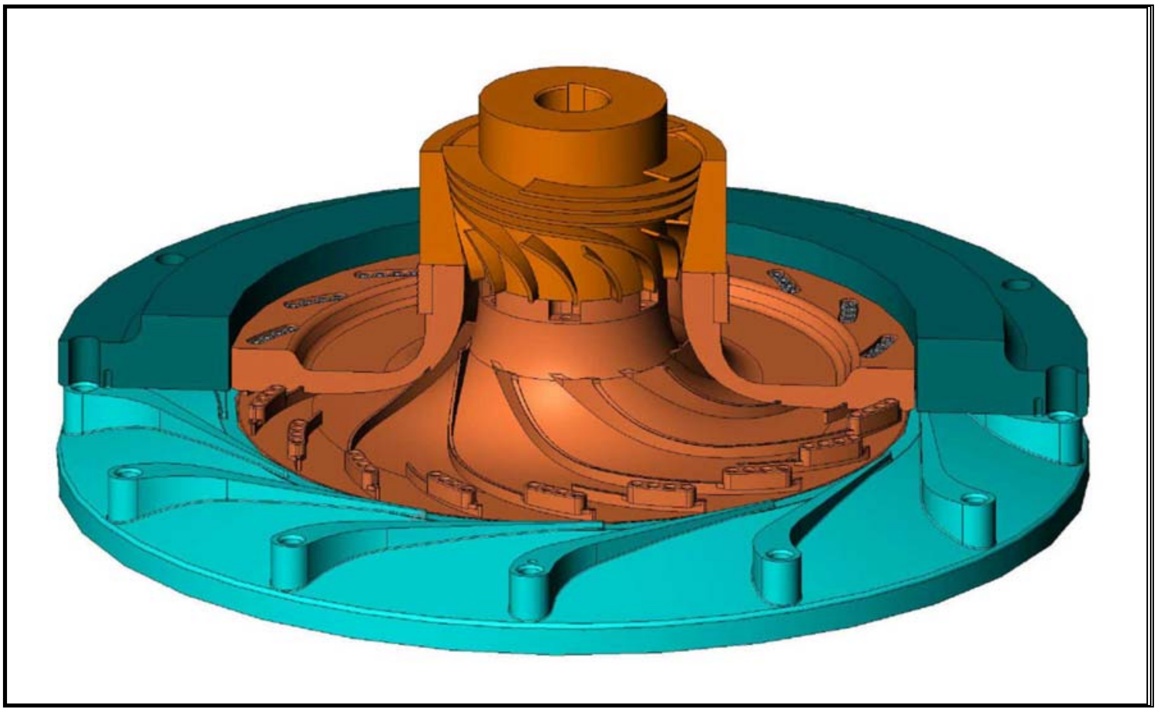


Figure 5 - Ebara Two-Phase Hydraulic Assembly.

Figure 5 illustrates an enlarged cross section of the two-phase hydraulic runner assembly with inlet nozzle ring.

FIELD EXPERIENCE USING TWO-PHASE EXPANDERS

To upgrade low-methane natural gas by extracting undesired nitrogen, two Ebara two-phase expanders (each located in parallel to JT3, see Figure 2) were installed in January 2003. The Polish Nitrogen Rejection Unit is shown pictorially in Figure 3. During an optimisation period modifications were made to the turbine runner and exducer in order to enhance power output and hence cold production. The operations staff had an excellent feel for the cryogenic unit behaviour and were able to contribute considerable support in process and turbine improvements.

Figures 6 & 7 Expander assembly and installation on site

Briefly, based upon the operational experience the following statements can be made :

- The expanders required limited modification of the existing equipment and consequently their installation is normally very easy and retrofitting can be done very quickly. Figures 6 and 7 show the size of the expander assembly and lifting of the expander assembly into its vessel.
- The two-phase expanders have been in stable operation, each for more than 10,000 hours. Throughout that period regular inspections have shown no incipient failures in bearings or materials, vibration levels have been less than 20% of API 610 allowable limits.
- The expanders operate surprisingly quietly; they are not heard while working with neighbouring equipment of average noise level below 80dB.
- The employed expanders have made the process really flexible in terms of its adjustment to changing mass flows, varying even by 100% . Even with such considerable changes they assure easy and precise regulation of level in the lower columns of both trains, which is of fundamental value for stable running of the process.
- Due to the greater temperature difference achieved by the expander, the heat exchangers (particularly E3) operate in a more efficient and flexible way assisting in producing colder waste gas temperatures leaving the upper column than was previously possible. This, in turn has the effect of reducing the methane content of the waste gas which is both environmentally and economically beneficial.
- The use of this two-phase expander in place of JT3 allows the sales gas product from the NRU to be at considerably higher outlet pressure, increasing by approximately 0.2MPa. The benefits of this have appeared as lower compression requirements downstream of the NRU, thus with lower fuel gas consumption per compressed unit. This means that the methane pumps can operate at a higher discharge pressure than before.
- The NRU has the facility to produce either liquid nitrogen or LNG for sale to third parties. With the expanders operating there is a significant increase of up to 250% in LNG output from the NRU compared to when Joule-Thomson valves JT3 were in operation in Train 1 and Train 2. Alternatively, the plant was able to produce similar quantities of liquid nitrogen for export. Both LNG and liquid nitrogen can be withdrawn from the double column arrangement into vacuum insulated storage tanks awaiting export by road tankers.

The two-phase expanders operate at variable speeds in order to adjust to the changing mass flows and pressure conditions of the plant. Figure 8 presents the hydraulic performance of the two-phase expanders as a scatter graph with trend lines. Hydraulic efficiency is defined as the ratio of electrical power generated divided by the hydraulic power input. Hydraulic power input is the product of mass flow and differential pressure. The solid vertical red line depicts rated mass flow and the solid horizontal red line indicates rated differential pressure. The "Holy Grail" in such duties is to extract more than just the hydraulic power from the expansion. For the duty in question, the hydraulic power that could be extracted by the turbine was estimated to be about 65kW. The actual power extracted from the turbine generator into the grid as export was between 80 and 85kW clearly demonstrating that gas expansion energy was being utilised effectively. When calculating the overall expansion, thermodynamic efficiency, the value was found to be relatively low (below 60%) compared with the large single phase gas expanders of today which regularly achieve over 80%. However, this is a small machine where friction losses are high in proportion to the flow and these losses reduce in significance as such machines increase in scale.

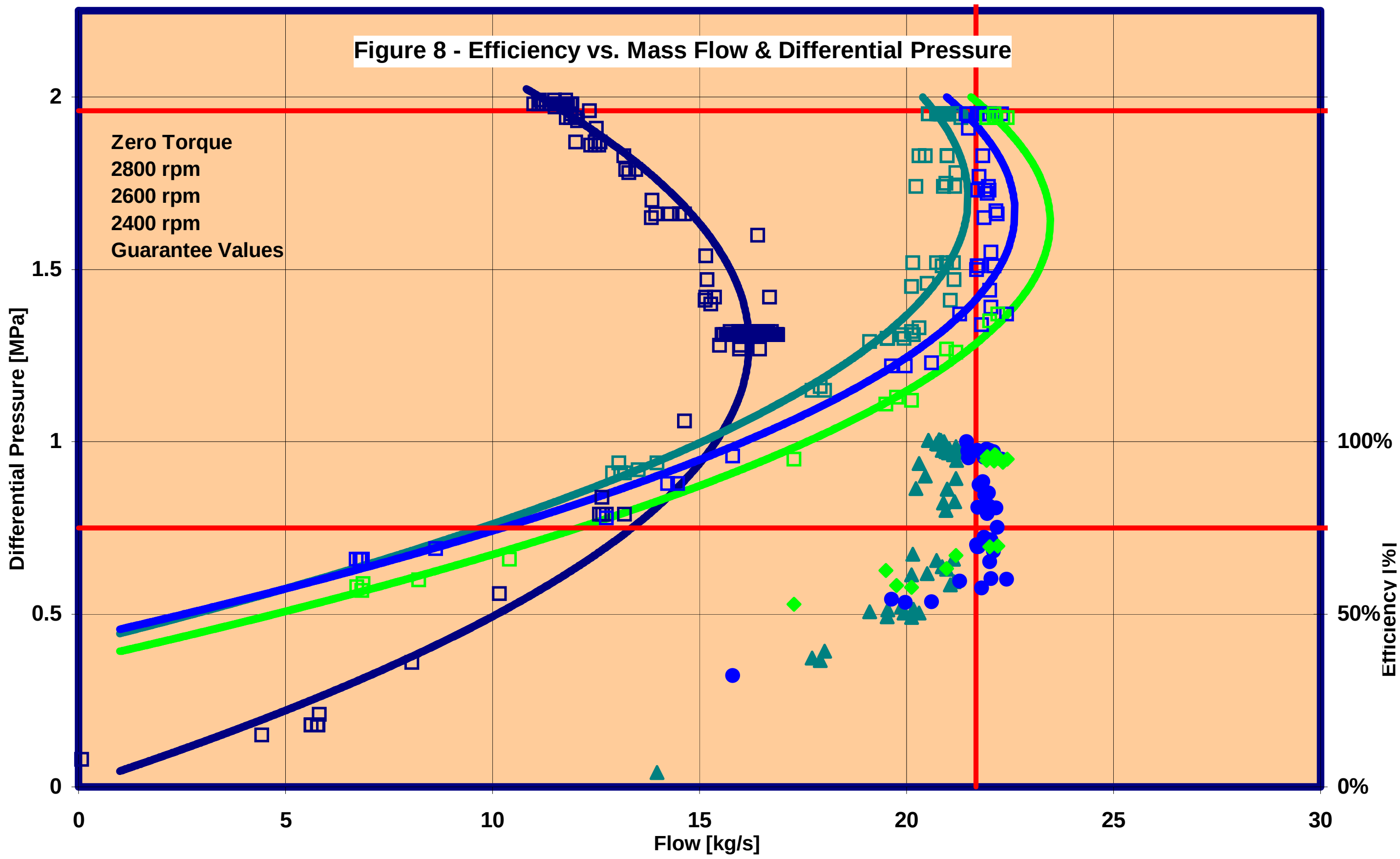


Figure 8 - Efficiency vs. Mass Flow & Differential Pressure
Zero Torque
2800 rpm
2600 rpm
2400 rpm
Guarantee Values
Differential Pressure [MPa]
Efficiency [%]
Flow [kg/s]
0
0.5
1
1.5
2
0%
50%
100%
0
5
10
15
20
25
30

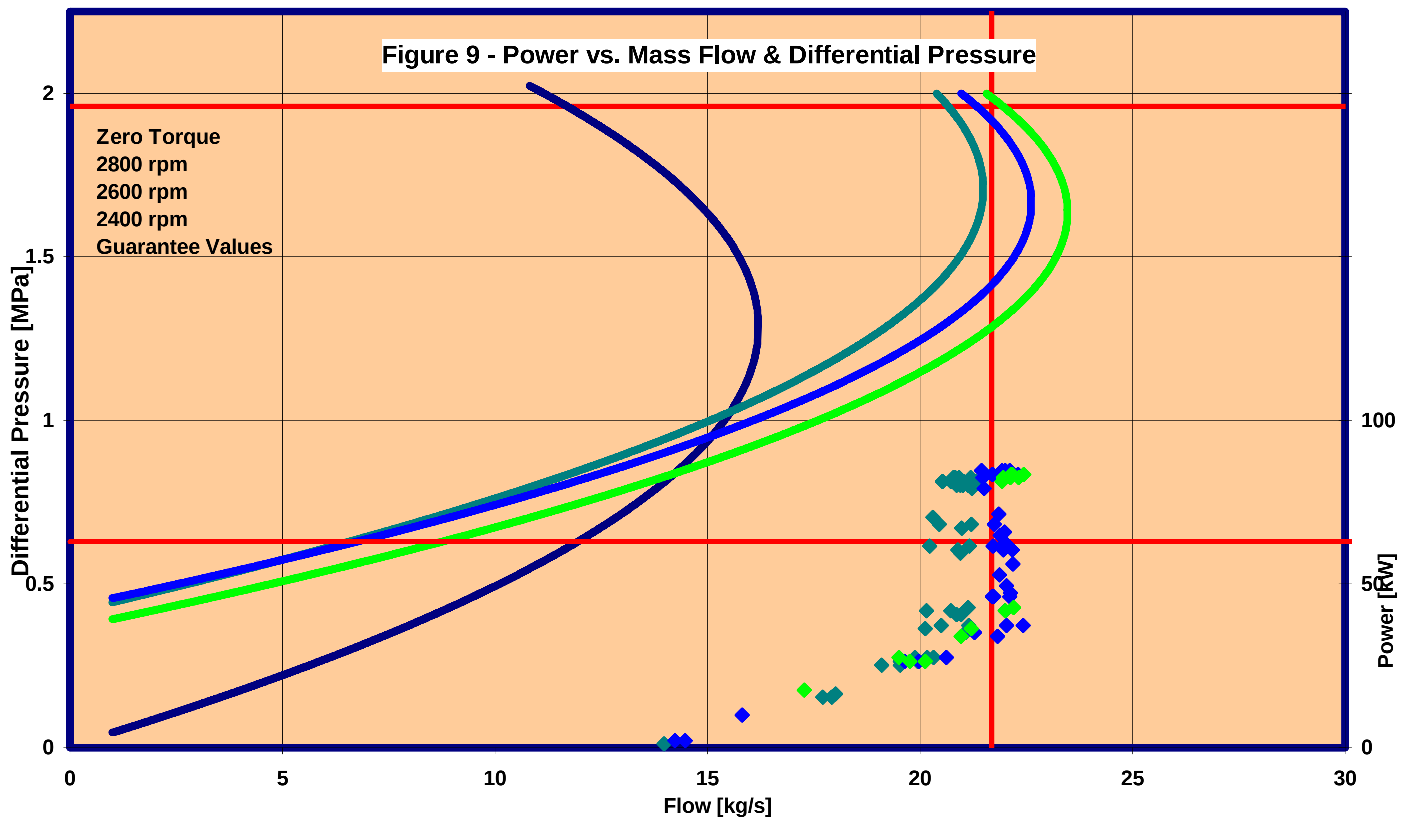
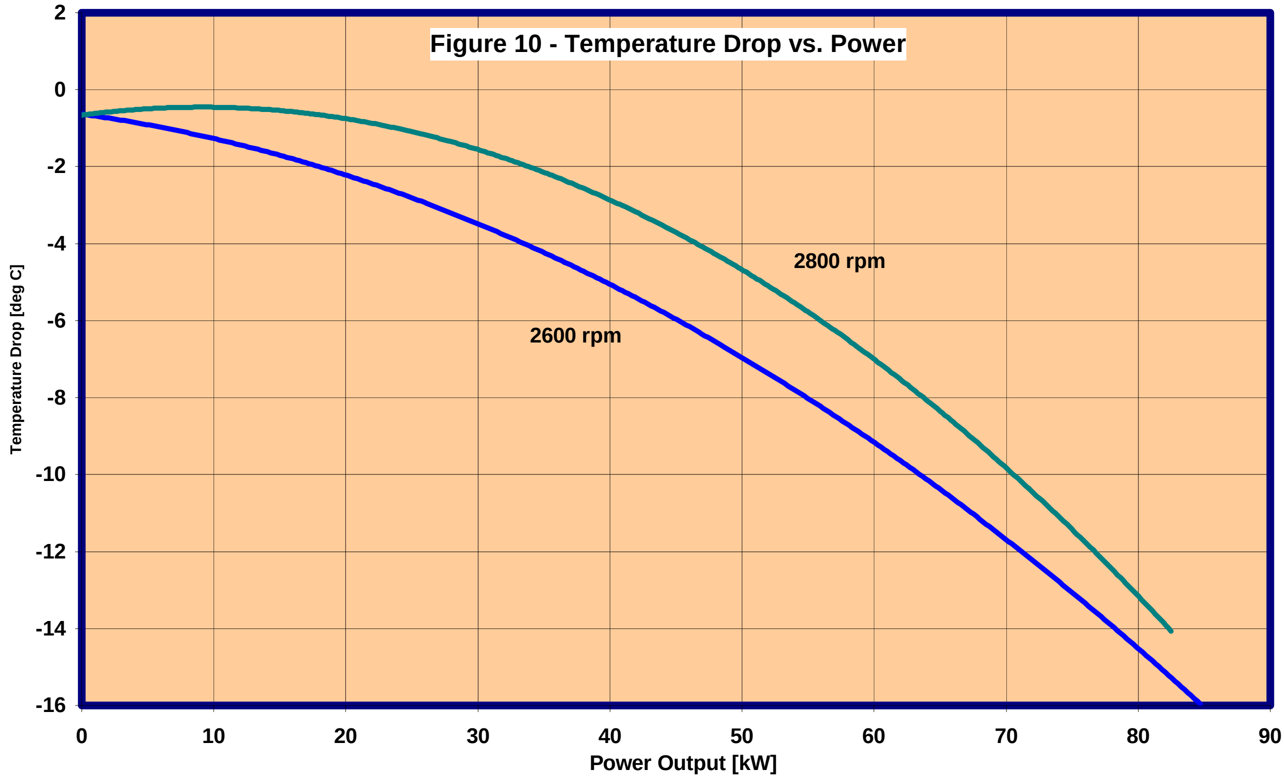


Figure 9 - Power vs. Mass Flow & Differential Pressure
Zero Torque
2800 rpm
2600 rpm
2400 rpm
Guarantee Values
Differential Pressure [MPa]
Power [kW]
Flow [kg/s]
0
0.5
1
1.5
2
0
50
100
0
5
10
15
20
25
30

Figure 9 presents the same data as Figure 8, but plotted as a line chart for differential pressure and power versus mass flow. The solid red lines in Figure 9 indicate the rated differential pressure and the rated mass flow. The volumetric flow increases with increasing differential pressure due to the expansion of the two-phase fluid and is seen here as reducing mass flow.

Cooling the methane-rich liquid feed to the upper column is significantly more efficient using two-phase expanders rather than single-phase expanders or other devices. Figure 10 presents the LNG temperature drop versus the power output for the previously described two-phase expander and the cooling effect on the LNG stream is seen to be directly related to the power output



BENEFITS TO THE PROCESS MODIFICATION

Following a series of modifications to the expander runner and exducer the expander was utilising more gas expansion energy and an acceptance test run was carried out on both the trains during the 4th quarter of 2004.

Table 2a – Examples of plant data taken during the test runs.

Train	Case	LNG T/D	Liq. N2 T/D	Measured kW
1	1	21.6	0	82.2
1	2	0	45	80.9
1	3	32.9	0	78.7
2	1	15.7	0	81.2
2	2	0	52	84.7
2	3	22.6	0	80.5

Case 1	Minimum liquid production
Case 2	Maximum liquid nitrogen production
Case 3	Maximum LNG production

Table 2b – Plant data before expanders and during the test runs with expanders.

	Feed Mol%		Crude Helium Mol%		Waste N2 Mol%		Sales Gas Mol%		LNG Mol%	
	Before	After	Before	After	Before	After	Before	After	Before	After
Helium	0,235	0,19	88,87	79,3	0,06	0,04	-	-	-	-
Nitrogen	33,0	35,1	11,13	20,7	96,04	99,66	3,2	3,14	3,2	3,14
Methane	65,62	63,54	-	-	3,9	0,3	95,12	95,60	95,12	95,60
Ethane	1,145	0,84	-	-	-	-	11,68	1,26	1,68	1,26
Flow NCMH	100000	101600	226	240	32000	32700	66500	66400	700	1860
Pressure Mpa	5,2	5,2	2,1	2,1	Atmos	atmos	1,8	2,0	0,2	0,2
Temperature C deg	25	25	-180	-190	20	20	20	20	-161	-160
Flow T/day	-	-	-	-	-	-	-	-	12	32

The NRU mass balance data post installation of the turbine expander are shown in Tables 2a and a comparison before and after in 2b. Note that the original design was for 42% nitrogen in the feed. With the composition as tested, prior to installation of the expanders, the waste gas methane content rose to above 3% with very poor plant stability and frequent operator intervention. In addition, the liquid production had been severely impaired and in some cases had not been possible when using just the J-T valve as cold producers. Some key benefits found after installation of the expanders are listed below:

- Because of the higher efficiency of the described process employing Ebara liquid two-phase expansion turbines the upper column feed is colder which helps to further cool the upper column top section leading to a lower methane content in the waste gas, when processing the lower nitrogen content feed gas.
- By the use of the presented method one can run the process of nitrogen and methane separation even with short-term carbon-dioxide increases without having to prepare expensive and extensive additional carbon dioxide removal steps. The employed liquid two-phase expansion turbine can accept short term higher carbon dioxide concentration with no danger of plugging or consequent shut-down of the whole NRU. This added tolerance is only temporary, since the plant would have to be thawed out later on in any case. Whilst one would not design a new plant in this way, it gives operations staff more flexibility and a greater on-stream time.
- The described process, being very efficient, allows for running it at a lower feed gas pressure, though this is not a big issue at the moment. In case of reducing pressure of the feed gas from depleting sources one could postpone the decision to install an expensive pre-compression step.
- Due to the high efficiency of the process presented above there is a possibility of taking out of the process considerable amounts of low-pressure LNG or a liquid nitrogen stream, running the nitrogen methane separation in a stable manner at the same time. The possibility of producing LNG may be useful for the plants where the Peak Shaving concept is going to be applied. If taking out liquid nitrogen is considered, one should be aware of the increased methane content in waste gas and the associated cost of that.
- Employing liquid two-phase expansion turbines in the separation of nitrogen and methane generates electrical energy that can exported or used as drive power for another duty.
- One of the most significant benefits of the turbine operation has been the enormous flexibility that the plants now have. The process is easy to operate and controllable with no danger of shut-down even with considerable changes of feed gas parameters.

- The operators can easily switch from one mode of operation to another within a matter of a few hours and are therefore, whilst maintaining less than 1% methane in the waste gas, is able to rapidly respond to market needs for:
    - Maximum sales gas output.
    - Maximum helium recovery.
    - Up to 40t/day liquid nitrogen.
    - Up to 30 t/day LNG per train.

CONCLUSIONS

The installation of the Ebara expanders fulfilled and in some instances, exceeded the initial design expectations and offers an excellent solution to ensure efficient operation when the plant is given feed gas with much lower nitrogen content than it was initially designed for. Apart from reducing emissions of methane from the plant the turbine expanders have:

- Improved operational stability even with low nitrogen.
- Allowed greater LNG or liquid nitrogen production.
- Increased an overall plant on-line time.

The two-phase turbine expanders have now been in operation for over 10,000 hours each, which demonstrate that this solution is an excellent way of adding refrigeration to cryogenic processes.

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