ABSTRACT

Strong demand for LNG means that many operators are developing projects based on lean gas with high methane content, in locations such as North America, East Africa and Queensland Australia. The pre-treatment section of LNG plant designs varies widely to suit feed gas composition. In particular, the choice of technology for heavy ends removal and recovery of light hydrocarbons for refrigerant make up can greatly influence the operability of a liquefaction train.

The usual practice in the LNG industry is to use a scrub column, operating at the same pressure as the liquefier. Although a C2+ recovery unit with a turbo-expander is higher in CAPEX compared to a scrub column this paper will show that there are savings when the impact on the overall train are taken into account. Failing to consider savings in the MR refrigerant cycle brought by the liquefaction at high pressure, a scrub column is often selected. For a lean gas this can be a bad choice due to difficulties with ensuring stable operation in this column and in some cases the impossibility of extracting sufficient refrigerant make-up.

Through a CAPEX analysis including the surrounding units, the above-mentioned C2+ recovery processes are compared. This paper shows that a turbo-expander and booster compressor process brings technical and economic benefits, providing operational stability and flexibility.

INTRODUCTION

The gas and Liquefied Natural Gas (LNG) markets are changing with liquefaction of lean gas for export in Australia and North America. One of the causes of this evolution is the discovery of large unconventional gas reserves. The objective of this paper is to show that, considering a wide range of selection parameters, conventional liquefaction schemes might not be the most effective method for liquefaction of high methane content gas.

At end of 2011, three liquefaction projects using Coal Bed Methane (CBM) were already sanctioned by Final Investment Decision (FID) in Australia. A few more are under study in Australia with CBM. In the United States of America (USA), there are numerous terminal conversion projects starting from shale gas. All these are shown in Table 1.
Table 1: Liquefaction Projects with Unconventional Gas

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Gas source</th>
<th>Status (Dec 2011)</th>
<th>Capacity (MTPA) (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AUSTRALIA</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arrow Energy LNG</td>
<td>CBM</td>
<td>Under study</td>
<td>2 x 4</td>
</tr>
<tr>
<td>Australia Pacific LNG</td>
<td>CBM</td>
<td>Under construction</td>
<td>1 x 4.5</td>
</tr>
<tr>
<td>Fisherman’s landing</td>
<td>CBM</td>
<td>Under study</td>
<td>1 x 3</td>
</tr>
<tr>
<td>Gladstone LNG</td>
<td>CBM</td>
<td>Under construction</td>
<td>2 x 3.9</td>
</tr>
<tr>
<td>Queensland Curtis LNG</td>
<td>CBM</td>
<td>Under construction</td>
<td>2 x 4.25</td>
</tr>
<tr>
<td><strong>USA</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cove Point LNG</td>
<td>Shale</td>
<td>Under study</td>
<td>N.A.</td>
</tr>
<tr>
<td>Freeport LNG</td>
<td>Shale</td>
<td>Under study</td>
<td>2 x 4</td>
</tr>
<tr>
<td>Sabine Pass</td>
<td>Shale</td>
<td>Under construction</td>
<td>2 x 4.5</td>
</tr>
<tr>
<td>Lake Charles</td>
<td>Shale</td>
<td>Under study</td>
<td>2 x 7.5</td>
</tr>
</tbody>
</table>

Note (*): Million Ton per Annum

Even with improvement of unconventional gas extraction technologies, liquefaction cost of lean unconventional gas may remain high. Furthermore, no benefit can be derived from Natural Gas Liquids (NGL) and Condensate which are high value-added by-products and play a significant role in LNG projects’ economics.

Conversion of an import terminal to export is an opportunity to have a low cost liquefaction plant because a lot of infrastructure, storage and marine loading in particular pre-exists. However economics still remain very tight and looking for the highest liquefaction scheme efficiency and plant overall efficiency remain important targets.

These new lean gases require specific consideration when developing LNG train designs:

- Refrigerant make-up may not be easily produced,
- When very few NGLs are produced the associated storage and export facilities can be uneconomic,
- Economics are penalized by no or low non-LNG products (NGL’s, Condensate) and thus the CapEx minimization as well as the best overall efficiency need to be thoroughly optimized,
- High pressure liquefaction which is favourable in terms of overall plant efficiency can be considered.

The above requirements are different from those that lead to the conventional LNG train design using a scrub column for LPG extraction (for NGL production and refrigerant cycles make-up production).

The propane pre-cooled / mixed refrigerant (C₃/MR) liquefaction process and the use of Air Products (AP) coil wound main cryogenic heat exchangers (MCHE) allow liquefaction at high pressure. A higher liquefaction pressure modifies the shape of the enthalpy curves of liquefaction and allows a better fit of warm and cold enthalpy curves with an almost constant and low temperature approach throughout the heat exchanger.

Bearing in mind that several LNG plants with liquefaction pressures around 65-70 barg are in operation around the world and that recent projects use even higher liquefaction pressures, a comparison between two liquefaction solutions is described: one using a scrub column scheme while the other comprising a turbo-expander based NGL recovery unit upstream.
Case Study Description and Basis of Design
The case studied considers lean gas liquefaction using widely referenced industrial equipment and liquefaction processes.

Two liquefaction plant configurations have been compared:
- NGL extraction through a scrub column integrated with the main cryogenic heat exchanger in the liquefaction unit.
- NGL extraction using a stand-alone turbo-expander process and a booster compressor, upstream and independent from liquefaction unit.

The purpose of the study is to perform a Capital Expenditure (CapEx) comparison of the two configurations and discuss their respective advantages and drawbacks with regards to equipment count, efficiency, operability.

The lean gas composition indicated in Table 2 is representative of recent gas field discoveries.

It corresponds to the gas composition exiting the pre-treatment section of an LNG train (after removal of wellhead condensate, acid gases, water and mercury).

<table>
<thead>
<tr>
<th>Component</th>
<th>Mol. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>50 ppm</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.30</td>
</tr>
<tr>
<td>Methane</td>
<td>97.27</td>
</tr>
<tr>
<td>Ethane</td>
<td>1.60</td>
</tr>
<tr>
<td>Propane</td>
<td>0.35</td>
</tr>
<tr>
<td>i-Butane</td>
<td>0.20</td>
</tr>
<tr>
<td>n-Butane</td>
<td>0.20</td>
</tr>
<tr>
<td>i-Pentane</td>
<td>0.02</td>
</tr>
<tr>
<td>n-Pentane</td>
<td>0.02</td>
</tr>
<tr>
<td>C6+ incl. Benzene</td>
<td>0.04</td>
</tr>
</tbody>
</table>

To allow a fair comparison, the well-known C3/MR Air Products process is the liquefaction technology considered for both schemes.

The LNG production rate is fixed at 4.8 Mtpa for the both schemes to be representative of a common LNG plant size and to be achievable with referenced liquefiers and compressor drivers.

Refrigerant compressors drivers are combinations of heavy duty gas turbines and electric motors, adapted in each configuration to match the targeted LNG production.

In view of the very low amount of Liquefied Petroleum Gases (LPGs) in the feed gas, no LPG production is considered i.e. any excess LPG is injected into the LNG.

However as the importation of refrigerant (ethane and propane) is undesirable in remote LNG plant locations, ethane and propane production rates from the NGL extraction unit are set to allow the replenishment of the refrigerant cycles after shutdown and compensate continuous refrigerant loop losses. Ethane and propane quality is compatible with refrigerant cycle requirements.
Each NGL extraction scheme proposed shall therefore be designed to:

- Extract the required refrigerant production (ethane and propane),
- Remove heavy hydrocarbons that would freeze in the liquefaction process (benzene and C$_{6+}$),
- Supply treated gas to the liquefaction at optimum conditions.

Air cooling was assumed for this study, however, similar conclusions would be expected with water cooling.

Each scheme has been optimised for maximum efficiency with minimum equipment.

**Description of the Scrub Column Scheme (Extraction Section)**

With regards to the NGL extraction scheme selection, the usual practice is to use a scrub column process, which is integrated to the liquefaction unit.

The process of NGL extraction in a scrub column scheme (Figure 1) comprises the following steps:

- The feed gas available at high pressure from upstream units is pre-cooled in propane chillers down to a temperature achievable using low pressure propane,
- If required for the column operation, the feed gas is let-down to a lower operating pressure. The extraction of refrigerants from lean gas cannot be performed without a reflux.
- The gas leaving the top of the scrub column is partially condensed in the warm bundle of the Main Cryogenic Heat Exchanger (MCHE) then separated in the scrub column reflux drum. The liquid recovered in the reflux drum is used as reflux for the scrub column.
- The treated gas at the outlet of the reflux drum is free of heavy hydrocarbons such as C$_{5+}$ and benzene and sent back to the middle bundle of the MCHE to be liquefied.
- The extracted NGLs from the feed gas with dissolved methane are collected at the bottom of the scrub column and sent to the Demethaniser column to separate the methane from the ethane and heavier (C$_{2+}$) cut. The NGLs are then routed to the fractionation unit to produce individual refrigerant products.
- First, the Deethaniser produces on-specification ethane make-up as overhead product and at the bottom a propane and heavier (C$_{3+}$) cut to feed the next column, the Depropaniser.
- Similarly, the Depropaniser produces a propane make-up at the required specification and a C$_{4+}$ cut to the Debutaniser.
- The Debutaniser separates butane from the heavy hydrocarbons (C$_{5+}$) that can be mixed with hydrocarbon condensate produced in an upstream stabilisation unit.
- When not used for make-up, the NGLs (Ethane, Propane and Butane) produced in the fractionation unit are either recycled to the scrub column to improve the NGL recovery or injected in the LNG using dedicated drum and pumps.
Description of the Possible Turbo-Expander NGL Extraction Schemes and Selection of the Most Appropriate One

The NGL recovery process using a turbo-expander comprises the following steps:

- The high pressure feed gas from upstream units is cooled in the main feed gas exchanger against the treated gas from the recovery tower.

- The feed gas is then expanded through the turbo-expander, cooled and sent to the recovery tower for cryogenic distillation. The gas stream from the expander still contains some heavy hydrocarbons and significant amounts of NGLs. The required NGL extraction cannot be achieved without an additional reflux.

- The reflux can be selected among one or a combination of the following options:
  - By-pass of the turbo-expander,
  - Treated gas recycle,
  - NGL recycle,

  and this selection is discussed in the following section.

Any of these reflux streams can achieve the objectives in terms of treated gas specifications at the inlet of the liquefaction unit (benzene, C_{5+} content in treated gas) and in terms of production of the ethane and propane make up rates.

- At the bottom of the recovery tower, the methane is stripped from the C_{2+} product using a reboiler.

- The liquid C_{2+} product is sent to fractionation, where, similarly to the scrub column configuration, ethane and propane make-up are produced in the Deethaniser, Depropaniser columns respectively. As by-products, Butane and hydrocarbon condensate are produced in the debutaniser column.

- When not used for make-up, the NGLs (Ethane, Propane and Butane) produced in the fractionation unit can be either recycled to the recovery tower to improve the NGL recovery or injected in the LNG.

- The treated gas from the overhead of the recovery tower, after passing through the main feed gas exchanger is compressed successively in the re-compressor driven by the turbo-expander and a dedicated booster compressor to be sent at high pressure to liquefaction.
The selection of the most appropriate reflux for the NGL recovery unit is performed by comparing the equipment count, heat exchanger surface and booster compressor power. The C5+ and benzene content must be within the treated gas specification during normal and transient operation.

In this case study for the given composition, several combinations of recovery tower reflux have been studied and the most efficient are the following:

- Single treated gas reflux (Figure 2)
- Combination of treated gas and by-pass of the turbo-expander reflux (Figure 3).

In these two schemes, the equipment count is identical and the heat exchanger surfaces are similar.

Indeed, the key driver for the case studied is the power demand of the booster compressor and the operability of the unit in the feed gas composition range.

The single treated gas reflux is one of the simplest schemes that can achieve the heavy hydrocarbons removal and refrigerant make-up recovery from the treated gas with a limited number of equipment and a high quality reflux.

In a second alternate dual reflux scheme, a combination of treated gas recycle and by-pass of the turbo-expander as reflux to the recovery column brings additional flexibility. The addition of the second reflux improves NGL recovery while the treated gas reflux ensures robustness in case of liquid carryover. The consequence is reduced booster compressor power demand.

Furthermore, when the liquefaction plant sees a wide range of feed gas compositions, NGL extraction can be easily adjusted thanks to the flexibility of the dual reflux. Moreover, should a leaner gas be processed, the dual reflux scheme booster compressor power will be lower than the single reflux scheme.
As a conclusion the dual reflux, turbo-expander based NGL recovery scheme was selected for this study.

**Integration of NGL Extraction and Liquefaction**

For the comparison, two LNG train designs were developed and optimised using the two NGL extraction configurations selected in the above sections (scrub column and turbo-expander) and the Air Products C3/MR liquefaction process.

The C3/MR liquefaction technology is composed of two refrigerant cycles.

- A propane cycle is used to precool the treated gas and partially condense the mixed refrigerant.
- A mixed refrigerant cycle liquefies the natural gas in the Air Products Main Cryogenic Heat Exchanger.

The main differences when integrating the above described NGL extraction schemes are explained below.

- With a scrub column scheme, the Main Cryogenic Heat Exchanger Warm bundle is used as the condenser of the scrub column. The treated gas leaving the scrub column reflux drum is successively sent to the middle bundle where it is condensed and sub-cooled in the cold bundle.

Without any rotating equipment between the scrub column and the MCHE, the natural gas stream liquefaction pressure is dictated by the scrub column operating pressure. The installation of a compressor to boost the liquefaction pressure is not practical for the following reasons:

  - Re-heating of the already cooled down treated gas.
  - Operating pressure of the scrub column reflux drum,
  - Temperature difference between tube path at the MCHE middle bundle,

- With a turbo-expander scheme, NGL recovery is independent from the liquefaction unit. In this case, the Main Cryogenic Heat Exchanger is made of two bundles: one to condense the treated gas, the second to sub-cool the liquefied natural gas.
The treated gas from the NGL extraction booster compressor feeds successively the propane chillers and the Main Cryogenic heat exchanger to be condensed and sub-cooled and liquefaction can be at high pressure, up to the limit of the mechanical design of the MCHE.

**Results**

From the above descriptions, advantages and disadvantages can be identified for the NGL extraction schemes in terms of capital cost, production efficiency and operability of the units.

This study demonstrates that considering NGL extraction and liquefaction units together is of prime importance in the technology selection for a liquefaction plant.

**Equipment comparison**

Both configurations have been developed with referenced equipment used within the LNG industry.

The scrub column configuration presents the advantage of having mainly static equipment.

The turbo-expander scheme requires a large turbo-expander driven compressor and a booster compressor. And no additional heat exchanger is requested other than the MCHE (additional bundle).

The scrub column configuration requires an additional Demethaniser column compared to a turbo-expander NGL extraction scheme. However the number of equipment of the NGL extraction unit using a scrub column scheme is lower.

The installation of two items of rotating equipment and additional exchangers to perform the cold recovery, the NGL with turbo-expander scheme (without consideration of the liquefaction pieces of equipment) is inherently more costly than a scrub column scheme.

**Production/efficiency comparison**

A liquefaction plant consumes a large amount of energy. Generally, a part of the natural gas fed to the plant is used to provide the power required to liquefy the gas. When selecting a liquefaction scheme, it often turns into optimising the efficiency of liquefaction - meaning the power required to liquefy a certain quantity of natural gas.

Whereas, some liquefaction plants generate revenues not only by the LNG, but also by selling by-products such as hydrocarbon condensates or LPGs, when it comes to liquefying lean gas, LNG is the sole valuable product of the plant.

Therefore, the efficiency of the lean gas liquefaction unit becomes of prime importance. Improving the efficiency of the process by limiting the natural gas conversion into power, will bring additional LNG to be sold and consequently additional revenues.

The study has also compared the performance of the combined liquefaction and NGL extraction process.

**Table 3: Main Power Consumption and Efficiency**

<table>
<thead>
<tr>
<th>Criteria / Scheme</th>
<th>Scrub Column</th>
<th>Turbo-expander</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNG Production (Mtpa)</td>
<td>(Mtpa) 4.8</td>
<td>(Mtpa) 4.8</td>
</tr>
<tr>
<td>Liquefaction Power (C₃+MR compressors)</td>
<td>(MW) Reference</td>
<td>-16%</td>
</tr>
<tr>
<td>Liquefaction pressure</td>
<td>(bara) Reference</td>
<td>+30 bar</td>
</tr>
<tr>
<td>Liquefaction power (C₃+MR+Booster Compressors)</td>
<td>(MW) Reference</td>
<td>-4%</td>
</tr>
<tr>
<td>Efficiency (C₃+MR)</td>
<td>(kWh/t) Reference</td>
<td>-16%</td>
</tr>
<tr>
<td>Efficiency (C₃+MR+Booster)</td>
<td>(kWh/t) Reference</td>
<td>-4%</td>
</tr>
<tr>
<td>Fuel Gas consumption</td>
<td>MW Reference</td>
<td>-4%</td>
</tr>
</tbody>
</table>
The liquefaction efficiency considering the power required for the C3 and MR cycles drivers is lowered by 16% for the NGL extraction by turbo-expander with booster compressor configuration. This improvement is a direct consequence of the increase of the liquefaction pressure by approximately 30 bar using the booster compressor, which reduces the MR cycle required power.

When the power of the booster compressor, is included in the comparison, the power required by the liquefaction plant is still lower by approximately 4%. This has a direct impact on the fuel gas consumption, which is also reduced by 4%.

From the above comparison, the liquefaction efficiency at constant LNG production is improved by the increase of the liquefaction pressure provided by the booster compressor in a NGL recovery unit with turbo-expander.

Indeed, the booster compressor fed with gas at ambient temperature and fully independent from the liquefaction unit provides additional flexibility in the LNG train operation. Other advantages of the booster compressor are that:

- It allows recycling during start-up operations to minimise flaring,
- It ensures operational flexibility of the recovery tower to cope with a large range of feed gas compositions while achieving the heavy hydrocarbon removal and extraction of refrigerant make-up from the feed gas.

**CapEx comparison**
The outcome of the cost comparison between Scrub Column and turbo-expander configurations shows that there is no overall difference between both schemes.

<table>
<thead>
<tr>
<th>Equipment count / Scheme</th>
<th>Scrub column</th>
<th>Turbo-expander</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGL Extraction Unit</td>
<td>Reference</td>
<td>More</td>
<td></td>
</tr>
<tr>
<td>Overall Equipment count</td>
<td>Reference</td>
<td>Similar</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 4: Equipment Count Comparison**

<table>
<thead>
<tr>
<th>Cost Comparison / Scheme</th>
<th>Scrub column</th>
<th>Turbo-expander</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGL Extraction Unit</td>
<td>Reference</td>
<td>+300%</td>
<td></td>
</tr>
<tr>
<td>Liquefaction Unit (including refrigeration)</td>
<td>Reference</td>
<td>-10%</td>
<td></td>
</tr>
<tr>
<td>Fractionation Unit</td>
<td>Reference</td>
<td>Similar</td>
<td></td>
</tr>
<tr>
<td>Overall Installed Cost</td>
<td>Reference</td>
<td>Similar</td>
<td></td>
</tr>
</tbody>
</table>

**Table 5: Simplified CapEx Comparison**

- The main differences in cost come from NGL extraction and liquefaction units. The contribution of fractionation is minor,
- The turbo-expander configuration has more costly equipment in NGL extraction (Compressors, Cold Box, Expander & Air Coolers),
- Overall equipment costs are higher in the Scrub Column configuration due to the size and weight of the refrigeration section,
• Bulk Materials and construction cost are similar in both configurations. The estimated quantities are about the same for both schemes,
• Engineering works and associated man-hours cost are slightly higher in a turbo-expander configuration due to the relative complexity.

Even if the NGL extraction with turbo-expander configuration is by essence more costly due to the additional equipment, this additional cost is compensated by the savings in the mixed refrigerant cycle (for the same LNG production).

**Comparison operability / flexibility**
Comparison of the operability and flexibility of the NGL extraction configurations considers: sensitivity to composition variations, reliability of refrigerant make-up production, availability and impact on annual production.

With regards to composition variation, a turbo-expander configuration is more flexible. Indeed, if the feed gas is leaner than expected, the operating pressure of the scrub column would need to be reduced and consequently, the LNG target production will be missed. Thanks to the presence of dual reflux streams and the operating range of the booster compressor, the turbo-expander NGL extraction scheme will achieve the unit objectives with minor adjustment of operating parameters.

Being independent from the mixed refrigerant cycles, the NGL recovery unit with turbo-expander can produce make-up during the start-up sequence prior to the start-up of the liquefaction unit provided the methane can be disposed. Propane and ethane refrigerant can be produced from the feed gas.

It is recognised that there is one additional driver (Booster compressor) in the turbo-expander NGL extraction scheme that could impact the liquefaction unit availability. However, it is important to emphasise that LNG production can be maintained at lower rate (around 60%) when the booster compressor is not available.

This study considered fixed LNG production. Depending on plant owner strategy and field development possibilities, a similar study could be performed to improve the plant revenues.

By using the maximum installed power from the gas turbines and helper motors on the refrigerant cycles with the turbo-expander and booster compressor NGL extraction scheme, one could increase the LNG production and improve the revenues of the plant instead of reducing the CapEx.

**CONCLUSION**
This paper has demonstrated that the selection of the NGL extraction solution for a new-built LNG plant shall be performed in deep conjunction with the liquefaction unit development.

Failing to consider the savings in the liquefaction unit brought by the presence of the booster compressor could lead to a non-optimum selection. This means that global integration and optimization of the NGL recovery unit and liquefaction has to be considered together rather than developing the units separately.

Also considering the selection of an NGL recovery unit allows an increase of the LNG train production for a given refrigerant compressor selection taking advantage of the high pressure liquefaction process and bringing more attractive economics.

Not surprisingly, this NGL extraction configuration is now commonly selected offshore for FLNG design where safety, robustness, layout constraints, operability and efficiency are the key drivers.

This paper showed that when designing lean gas liquefaction plants, the selection of a turbo-expander scheme for NGL extraction upstream of a liquefaction unit improves the efficiency, the operability and the flexibility of the plant at no cost.