MID-SIZE LNG DESIGN CONSIDERATIONS FOR ROBUST AND FLEXIBLE OPERATION: YANGLING LNG PLANT AS A CASE STUDY

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Yangling LNG is a state-of-the-art 0.5 Mtpa mid-size natural gas liquefaction plant located in ShaanXi province, China. Being conceived for peak shaving and having to treat a wide envelope of gases (excursions in helium, nitrogen, and heavy hydrocarbons), the design capitalizes the cumulative experience of the authors from similar plants in China. Flexibility in the design allows substantially automatic adjustment to frequent changes in throughput and feed gas composition.

This paper will discuss general design requirements for mid-size LNG plants, and the successful special design features of the Yangling plant:

- Processes for the removal of heavy hydrocarbon and inerts from feed gases of varying composition. It will describe how the removal processes are integrated with the liquefaction process for simple operation.
- MR compressor speed control thanks to the application to a large (26.5 MW) electric motor of a high capacity, voltage source inverter (VSI). This feature enables start-up from full settle-out pressure and makes turn-down efficient and ramp-up operation straightforward.
- The main cryogenic heat exchanger and refrigerant separators that allow the liquefaction system to operate stably and efficiently over a wide range of capacities without the need to adjust refrigeration inventory. As an example, the plant was operated stably at less than 5% of capacity for over 40 hours to cooldown LNG storage, thus avoiding the import of LNG or liquid nitrogen for the initial LNG tank cooldown.

The paper will conclude with the implications for building successful mid-scale LNG projects in the future.
Introduction

The Yangling LNG plant, which is located in Shaanxi Province, consists of one single LNG train of 0.5 MTPA production with AP-SMR™ Liquefaction Process and two single containment 25,000 m3 LNG tanks for peak shaving purposes. The LNG train uses cooling water and is electrically driven from the local power grid. The feedstock is sourced from the regional pipeline grid. The plant has been successfully started up in 2015 and operated with excellent record since.

Due to its very nature of peak shaving plant fed by the local pipeline network, similar to other mid-scale plants, the Yangling design had to provide the following features:

- Flexibility to varying gas quality and quantity
- Robustness
- High efficiency at varying loads
- Operational flexibility for turn up and down
- Limited fuel gas consumption for the plant

This paper describes the experience in tackling Yangling LNG design challenges as well as the solutions to address them.

Yangling Feed Gas Quality

The Yangling LNG plant feedstock comes from the local regional pipeline grid and as is often happening with pipeline networks, the composition can vary significantly and this variation can happen quickly, as opposed to gas fields, where composition tend to change over time.
In addition, Yangling plant feedstocks was expected to be sourced from different pipelines with a very wide range of characteristics. Hereafter typical design composition from each source are presented in a table. Source A and B were provided at initial design, whilst Source C was added after design selection during the execution.

Figure 1: Design Gas Composition for different sources varies widely

<table>
<thead>
<tr>
<th>Feed component</th>
<th>Gas Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Methane</td>
<td>95.7000</td>
</tr>
<tr>
<td>Ethane</td>
<td>1.3410</td>
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<tr>
<td>Propane</td>
<td>0.2090</td>
</tr>
<tr>
<td>i-C4</td>
<td>0.0352</td>
</tr>
<tr>
<td>n-C4</td>
<td>0.0339</td>
</tr>
<tr>
<td>neo-C5</td>
<td>0.0026</td>
</tr>
<tr>
<td>i-C5</td>
<td>0.0154</td>
</tr>
<tr>
<td>n-C5</td>
<td>0.0067</td>
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<tr>
<td>Hexane</td>
<td>0.0090</td>
</tr>
<tr>
<td>Heptane</td>
<td>0.0034</td>
</tr>
<tr>
<td>Octane</td>
<td>0.0000</td>
</tr>
<tr>
<td>Nonane</td>
<td>0.0000</td>
</tr>
<tr>
<td>Methylcyclopentane</td>
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</tr>
<tr>
<td>Benzene</td>
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<tr>
<td>Cyclohexane</td>
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<tr>
<td>EthylBenzene</td>
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<tr>
<td>p-xylene</td>
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<tr>
<td>m-xylene</td>
<td>0.0000</td>
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<tr>
<td>o-xylene</td>
<td>0.0000</td>
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<tr>
<td>Hydrogen</td>
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<tr>
<td>Helium</td>
<td>0.0000</td>
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<tr>
<td>Nitrogen</td>
<td>0.0319</td>
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<tr>
<td>H2S</td>
<td>-</td>
</tr>
<tr>
<td>CO2</td>
<td>2.606</td>
</tr>
</tbody>
</table>

The above table shows Yangling feed compositions vary widely among the various sources in particular in terms of:
- Aromatics and long chain aliphatics: these components must be almost completely removed to prevent precipitation in the liquefaction unit
- Critical pressure and cricondenbar are drastically different
- Inert presence, in particular Helium

One of the challenges is that any of the sources above can contribute to the actual Plant feedstock anywhere from 0 to 100%. At design stage the actual quality of the gas is therefore difficult to identify and the plant must be able to
treat all of the sources, while not being excessively complex to operate and not excessively capital cost intensive to be profitable.

Yangling Plant Description

Yangling LNG Plant line up is typical of LNG liquefaction facilities:

- the feed gas is metered and compressed
- CO2 and H2S are removed in the Acid Gas Removal section
- Water is removed in the Dehydration Unit
- Many C5+ components are removed in the Heavy Hydrocarbon Removal Unit
- Mercury is removed in the guard bed
- The clean, sweet, dry natural gas is liquefied in the Main Cryogenic Heat Exchanger (MCHE), which is composed of three distinct bundles for this specific application
- LNG is partially flashed in the flash drum and then sent to the LNG tanks.
- Boil Off gas and flash gas are recirculated to the feed gas compression recovered from the LNG tanks (from both flash and vaporization due to heat in leaks).
- The small fuel gas demand can be taken from the feed gas to supply the process heat demand.

Liquefaction pressure

Yangling feed gas pressure can vary between 25 bara to 40 bara during the year. Considering the very low liquefaction efficiency expected at 25 bara, it was advantageous to install a compressor at the inlet of the plant and raise the working operating pressure of both the pretreatment train and liquefaction.

After a thorough study, the pretreatment train inlet was optimized to be at approximately 68 bara considering the following factors:

- Higher feed gas pressure yields better overall efficiency of the Mixed Refrigerant (MR) process (and hence the smaller the capital cost for liquefaction and the associated operating costs)
- Higher feed gas pressure requires \higher Feed Gas Booster compressor pressure
- A higher pretreatment working pressure leads to smaller equipment and piping and therefore improved capital costs, avoiding when overstepping the limit of the piping class
- Optimizing MR compressor size may also lead to reducing the circulating refrigerant flows together with reducing the associated equipment size and refrigerant imports

By choosing the adequate trade-off between MR compressor duty and Feed Gas compressor duty, not only the overall plant efficiency and liquefaction unit can be optimized, but also the overall capital and operating costs will benefit greatly.
The above chart shows how the reduction in MR power leads to an overall decrease in total power: high feed gas pressure increases the feed compressor power, but lowers the MR power, thus leading to overall capital cost gain. In addition, it can be noted that going from 40 bara to 68 bar reduces the circulating refrigerant flowrate by 15% in terms, with proportional benefit to the equipment and piping size. This figure also shows that up to 77 bara, the total power steadily decreases. The calculation includes only the thermodynamic benefit from the higher operating pressure and not the gain in pressure drop and smaller piping, so it is somewhat conservative.

Heavy Hydrocarbon Removal and Integration with Liquefaction

Heavy Hydrocarbons (HHCs) need to be removed for one or more of the following reasons:
- Meeting LNG Heating Value specifications
- Recover Natural Gas Liquids (NGLs) and/ or condensates, which can be sold as valuable byproducts
- Recover HHCs to supply the required refrigerant make ups
- Prevent freezeout in the liquefaction equipment

For Yangling LNG, the first three objectives do not apply; the HHCs are considered as impurities. The type of HHCs removal processes for the above purposes can be broadly distinguished into the following groups:

- **Vapour/ Liquid (V/L) separation:**
  These processes work on the basis that the HHCs concentrate in the liquid phase. The liquid can then be removed, leaving a lean natural gas. For moderate amounts of HHC, a single stage can be integrated with the liquefaction unit, called Partial Condensation. Higher removal levels require many vapor/liquid equilibrium stages, typically contained within a distillation column. The column can be integrated with liquefaction (called a “scrub column”) or stand-alone (such as NGL recovery unit). Regardless of the V/L separation type, natural gas pressure will have to be below cricondenbar pressure for the separation to take place effectively, so that both vapor and liquid phases are present. This means that if the V/L process...
is integrated with the liquefaction unit (i.e., using Partial condensation or Scrub Column), then the liquefaction pressure will be below the same limit. If the column is in a stand-alone NGL recovery unit, an additional compressor can allow the liquefaction to operate at an independent pressure.

- **Adsorption separation:**
  Natural gas containing HHCs enter the adsorber vessel where HHCs are retained by the adsorbent that undergoes cyclic regeneration with hot gas. After the adsorbent is saturated with HHCs, the vessel is regenerated with a hot gas stream. After the adsorbed HHCs are removed from the bed, the adsorbent is cooled with cool vapour, and then placed back onstream. While one vessel is online adsorbing, the other is offline being regenerated. Because the process cycles between a hot and ambient temperature, it is called Temperature Swing Adsorption (TSA). This type of process does not have any limitation of pressure and can work at critical pressure and above.

For Yangling LNG, the following phase envelope curves were calculated for feed gas Source A and B:

![Figure 3: Gas Envelopes for different feedstocks](image)

Source A is supercritical at the desired liquefaction pressure (55 to 60 bara) whereas Source B is below critical point.

Removing Source A impurities by V/L separation would require a significant pressure reduction with subsequent loss of liquefaction efficiency.

To optimize HHC removal for a supercritical lean gas A with few HHC and a rich gas with more HHCs that is amenable to V/L separation, different configurations were studied. The TSA plus a single of partial condensation stage was selected; the partial condensation liquid has a stripping column on the liquid to reduce the C1 losses. This combined the advantages of both adsorption and V/L separation, while optimizing the liquefaction equipment as well as the capital cost of the HHC removal unit.
Figure 4: HHC Removal Integration with Liquefaction

Figure 4 shows the HHC integration implemented in Yangling: the TSA beds are located upstream the liquefaction to remove the BTEX and longer aliphatic chains, whereas hexanes and heptanes are removed in the partial condensation stripping column.

When gas comes from very lean pipelines such as source A, only the TSA beds are used, and the stripper column is not operated, either being bypassed or left in line. Lean gases can then be liquefied at maximum pressure, thus optimizing the efficiency. In turn, when the gas comes from richer pipelines Sources B or C, then the TSA is designed to be saturated with BTEX, whilst other aliphatic heavies are recovered downstream at the stripper. In fact, thanks to this configuration the TSA bed design does not have to be oversized to capture the whole heavy fraction with evident capital cost benefits.

The stripping column separation relies on the precooling in the warm bundle to generate liquid; the stripping gas is adjusted to avoid excess fuel gas at the condensate stabilizer. The stripping gas replaces a reboiler and simplifies the liquefaction equipment design.

During design, additional Source C with high concentrations of BTEX and C6+ was added to the plant operating envelope. TPFMC and APCI worked together to assess the impact and possible optimizations using the predictive model developed and successfully tested by APCI in previous projects [1]. The new feed required increasing TSA beds volume and the regeneration gas quantity. Staggered regeneration was proposed to limit the vessel size and the regeneration flowrate. In staggered mode, the regeneration gas coming from cooling step can be reused for heating, thus halving the amount of overall gas taken for the regeneration. Here is a simple sketch for each system.
The advantages of staggered regeneration are the following:
- Regeneration gas is halved with respect to parallel regeneration
- The peak concentration of hexanes and alkanes concentration in feed gas to the liquefaction unit, caused by the roll-up effect (note 1) is reduced by approximately 50%, because such concentration increase is diluted by the product gas from another bed
- Any residual thermal wave (hump in temperature profile) in the bed due to incomplete regeneration is also decreased by up to 50%. This reduces the likelihood of liquefaction trip and the cyclic thermal stress on the warm bundle

(1) Roll-up effect: Rollup occurs when two or more components are adsorbed by a single adsorbent, where both are adsorbed, but one is displaced by a more strongly adsorbed component. In an HHC removal unit, the higher boiling hydrocarbons will displace the lower boiling hydrocarbons. The lower boiling hydrocarbons’ exit concentration will be higher than their feed concentration for a period of time. This can be particularly problematic if the solubility limit is above the feed composition, but below the rollup concentration. In that case, a cursory examination of the feed composition would make it appear that precipitation will not occur, but in actual operation, due to rollup, the component will freeze out and potentially create blockages in the equipment. A key feature of the Yangling LNG design is that the partial condensation in the stripper can significantly reduce the peaks from roll up, preventing precipitation.

**Flexibility in midscale plants and application in Yangling LNG**

When the LNG plant feed is supplied from the regional pipeline network, not only the quality but the quantity can vary, and this is especially true for Yangling LNG plant that is designed as a peakshaving facility, exposed to seasonal variations.

The following considerations explain why ensuring that efficiency and stability is maintained throughout all capacity loads is crucial for the profitability of mid-scale plants:

- Mid-scale LNG plants do not usually have long-term commercial agreements and must quickly match their production to punctual market demand and price. This may require operating the plant at reduced capacity, when the pipeline pressure is rather low, and so potentially for longer spells of time as opposed to traditional base load plants turndown operations.

- Similar to many midscale plants, Yangling design imports refrigerants due to:
  - Generally, fairly lean gas in conjunction with unreliable and varying content of C2/C3/C4 in the pipeline feedstock (more often considered as spiking impurity than as a valuable product to be recovered)
  - Capital cost associated with additional extraction and fractionations units

Refrigerant import may represent significant operating costs and is therefore to be optimized. This corresponds not only to ensuring an optimum efficiency and MR circulating rate at varying plant operating loads, but also to reducing or eliminating all refrigerant venting and draining that may occur when switching between operating capacities.

**Turndown and efficiency versus refrigerant consumption**

In terms of process power demand at different loads, Yangling LNG plant technology is extremely efficient and robust with regards to turndown.

The robustness and flexibility of equipment are also important to consider when designing an LNG facility with frequent turndown operation. During transition between full capacity and reduced capacity, matching the refrigerant flow with the required heat load is necessary to prevent rapid and large thermal stress in the liquefaction equipment. The robustness of the Coil Wound Heat Exchanger (CWHE) during transient temperature changes (start-up, upset and turndown) has been proven in over 85 operating base-load LNG plants in the past 40 years.
When properly engineered, utilizing high performance internals, CWHEs can operate stably over a very wide range of LNG production, covering greater flow regimes than other heat exchanger types. [4]

Figure 7 reflects a reduction in capacity study done specifically for Yangling LNG and shows how the use of variable speed MRC and adjusting MR composition allows to maintain an efficiency very close to the design point: in fact, efficiency is fairly constant at 80% production and it barely increases by 11% at 40% turndown. It is also worthy of notice that even at 40% turndown the compressors valves remain closed. Furthermore, it has been proven on site that AP-SMR™ stability is high enough to allow stable operation at a production rate as low as 5%. The plant operated stably for more than 40 hrs to allow cooldown of the LNG tanks. This avoided importing LNG for the initial cooldown and flaring by producing just enough LNG to match the maximum cooldown rate imposed by the LNG tank.

Another aspect to be tackled in the design of midscale plants is to ensure that day to day short term variations are dealt with efficiently and with minimum or no venting of refrigerants. This is different from baseload plants, where the variations are not as frequent and large, and refrigerants are readily available at a low cost. An outstanding feature of the AP-SMR™ technology is that the circulating MR inventory adjusts itself with the plant capacity, without having to dispose or make-up refrigerant during capacity swings. This is because at turndown, the MR inventory and recirculation rates are reduced in the CWHE and piping. The refrigerant is then stored in the MR separators, which prevents having to vent MR. In addition, special features are added to ensure that after shutdown all of the MR could be recovered and re-used.

**Variable Speed Drive**

When considering flexibility and prolonged turndown, a variable speed drive coupled to the MR compressor is a logical choice considering the immediate benefits:
• Increased ability to adjust to production demand changes without the need to purge costly refrigerants
• Increased operating window without the compressor recycling
• Ease of operation for startup and shutdown
• Restart from settle out pressure, thus avoiding venting of refrigerant

It should also be noted that most mid-scale LNG plants take advantage of a reliable local power grid and use electric drives for the rotating machinery. However, variable speed drives are often required to decrease the current inrush when starting a large electrical motor and to stay within the grid capacity.

Speed variation can be achieved using one of several available technologies: several types of electronic frequency variation (VFD) or a variable ratio hydraulically coupled gear associated with a fixed speed motor. In Yangling a variable voltage source inverter was installed with successful performance.

Selection was made carefully, considering parameters such has electrical power grid strength, available footprint, shaft dynamics, compressor/driver interface, ease of maintenance and operator preferences, utilities consumption at full capacity and at turndown with respect to the expected operating windows.

Conclusion

A small to midscale LNG plant does not equate to small to midscale design challenges: on the contrary, a small to mid-scale LNG plant requires additional effort to minimize capital and operating costs in a wider and somewhat more unpredictable operating window.

It is therefore critical to offer a design that is robust and flexible for all the expected and unexpected operating cases, while at the same time to avoid unnecessary plant complexities.

Yangling plant was a success in several ways: the plant line-up and integration of the units was optimized and verified for all known gas compositions and this thorough work of verification allowed not just to optimize the efficiency, but also to reduce the capital cost.

Furthermore, thanks to this design work and accurate selection of design done in the early phase of design, the addition of new sources to the plant operating envelope could be implemented without drastic changes to the process configuration and while still maintaining the nameplate capacity.

References


