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Thermal Efficiency – Design, Lifecycle, and Environmental Considerations in LNG Plant Design

Doug Yates, P.E.
LNG Operations Manager
Phillips Petroleum Company

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Abstract

Thermal efficiency is a common benchmark used to compare competing processes when a new LNG project is being developed. Often this type of comparison can be misleading when used in isolation because plant design premises are not consistent from project to project. Thermal efficiency depends on numerous issues such as gas composition, inlet pressure and temperature, and even more obscure issues such as the location of the loading dock relative to the liquefaction process. Higher thermal efficiency is also typically a trade-off between capital and lifecycle costs. Gas turbine selection, the use of waste heat recovery, ship vapor recovery, and self-generation versus purchased power all have a significant effect on the overall thermal efficiency of the process.

Process flexibility and stability of operation also need to be considered. The value of a highly efficient process is quickly lost if plant reliability and availability are sacrificed.

Design issues that extend from the inlet pipeline to the delivery of LNG onto the ship will be discussed relative to their impact on thermal efficiency. How these issues have been addressed in various designs using the Phillips Optimized Cascade LNG Process will also be reviewed to demonstrate the flexibility this LNG process can provide to balance economic merits and environmental impacts.

Introduction

Two common questions raised when a project is considering an LNG technology application are, "What is the difference in thermal efficiency between the LNG technologies available?" and "How does one technology benchmark in comparison to another?" What makes the answers to these questions so elusive or subjective is that each project introduces its own unique characteristics that determine its optimum thermal efficiency and results in the strongest economic and environmental merits for the project. Different technologies or plant designs cannot be compared on thermal efficiency without understanding and compensating for the unique differences each project brings to this evaluation process.

If a project's goal is to achieve maximum thermal efficiency and lowest lifecycle costs, then the interaction of various systems within the LNG plant design must be considered versus only attempting to optimize one section of the plant (commonly the LNG liquefaction area). Once a technology or major piece of equipment that effects thermal efficiency is selected, it also sets the course for the flexibility the plant has in the design phase and its ability in the future to adapt to changing economic and environmental issues that may impact the projects ongoing lifecycle costs. Therefore, the selection of the technology, or equipment, that provides the most flexibility for further improvements to thermal efficiency as the project evolves, is a balance that should be considered early in plant design. The stability of the operation must also be considered. The value of a highly efficient process quickly diminishes if one sacrifices plant reliability and availability.

The definition of thermal efficiency also has proven to be subjective depending on whether an entire plant, an isolated system, or item of equipment is being compared. Thermal efficiency, or train efficiency, has been expressed as the ratio of the total HHV (higher heating value) of the products to the total HHV of the feed. The use of this definition fails to recognize the other forms of thermodynamic work or energy actually consumed by the process. For example, if purchased power and electric motors are used for refrigerant and flashed gas compression, this definition would not account for the work done by these motors.

Therefore, when evaluating the benefits of achieving a high thermal efficiency with a technology or LNG plant design, a true accounting of all of the energy being consumed in the process must be considered. Achieving a high thermal efficiency is typically a choice between capital and lifecycle costs. Accurate identification of these costs and how they can change over the life of the project, are most important in this evaluation.

Economic Measures

The first step in any effort involving the evaluation of alternatives for increased thermal efficiency is to identify the key economic measures to be used. The value of the LNG, NGL components, feed gas, fuel gas and power are just some of the major merits that need to be determined. Air emissions from a plant design are becoming increasingly important in the selection of technology and equipment used in the LNG plant. It is therefore important to quantify the economic value of these emissions, whether they are greenhouse gases, NOx, SO2, or CO, when moving forward with the design process. The cost can be a tax levied by the local government, the result of an internal corporate initiative, or a cost identified by the project owners based on environmental goals selected for the specific site where the plant will be located (1).

Upstream Operation and Feed Gas Characteristics

Among the most significant economic driving forces in a plant design are the feed gas characteristics. While we typically think of these characteristics in terms of the various components that make up the feed gas stream, the temperature, pressure, and reliability of this feed gas supply will also have a significant impact on overall plant thermal efficiency.

The inlet pressure of the feed gas to an LNG plant can vary over a significant range. The optimum level for the plant design needs to not only consider its impact to the cost of the required inlet plant equipment, or the thermal efficiency options the pressure presents for the plant design, but also to consider the impact on the upstream facilities supplying this gas. One of the issues to consider includes selection of the pipeline size versus upstream or plant compression that may be required to achieve various inlet plant pressures. Generally the higher the pressure into the plant, higher the thermal efficiency, but the optimum pressure will be based on the cost of the various design options (2).

One option to capture this high-pressure energy involves the installation of a gas expander. The Phillips technology has been evaluated with various designs using a gas expander on the feed stream. The preferred location for this expander is a function of the feed composition. One of the more common locations considered has been the feed stream between the propane and ethylene refrigerant systems. The energy captured by the expander is then used to boost any of the three refrigerants used in the liquefaction process. This results in lower horsepower requirements from the refrigerant gas turbines, lowering fuel consumption, air emissions, and resulting in improved thermal efficiency. Where the plant design favors a lower inlet operating pressure over what is being supplied by the pipeline, lowering this pressure through the use of a Joule-Thompson valve rather than the use of an expander may be favored in certain situations.

The reliability of the feed gas supply is another important issue affecting optimal thermal efficiency. For those situations where the upstream feed supply is less reliable than the plant, the ability of the plant design to efficiently operate over a high turndown rate becomes important. If feed gas outages are brief, then the plant requires the ability to maintain a stable operation in these various turndown modes without flaring gas or experiencing a plant shutdown. Turndown ratios below 40% of the design rate can become problematic to some plant designs as a result of poor flow distribution in main plant exchangers or columns (3,4). The Phillips Optimized Cascade LNG Process has the ability to turndown to 0% LNG production and the only impact to thermal efficiency is if the turbine compressor must be on recycle. If the “two-train-in-one” turbine/compressor configuration is selected, ie two turbines/compressors on each refrigerant with a two-shaft gas turbine, then an improved thermal efficiency results versus a single turbine/compressor per refrigerant on a single shaft gas turbine. This is a result of the more efficient turndown operation in the range of 60 to 100% of design capacity provided with the two-shaft gas turbine (3).

A common approach to raise upstream feed gas availability is to operate the inlet pipeline with line pack. When there is an outage of gas being produced from the field, the line pack can continue to supply the plant. Designing the plant to use the energy released when this pressure is let down will improve the overall efficiency of the project as long as it does not compromise the purpose of holding pipeline line pack. This can be done by designing equipment in the plant that improves thermal efficiency when line pack is available, but not required to operate to achieve LNG contract volume when the line pack is not present. The gas expander, propane sub cooler, and gas-to-gas exchanger can all be used for this situation, however, in the economic justification of this equipment, one must consider the frequency it will operate and the variation in thermal efficiency achieved as the pressure changes.

Feed Gas Conditioning

Carbon dioxide and hydrogen sulfide in the feed gas will significantly impact the thermal efficiency of any LNG liquefaction process. A feed stream with a high concentration of carbon dioxide will obviously result in a lower thermal efficiency than one without. For feed streams with high carbon dioxide concentration, the use of a proprietary amine will improve thermal efficiency. Using a proprietary amine will increase the thermal efficiency, lower energy used in the amine system (both fuel gas and power), and provide capital cost savings. Costs such as licensing fees, amine makeup cost, etc. need to be part of this lifecycle evaluation to ensure this increase in thermal efficiency is economically justified (5).

The impact of hydrogen sulfide on thermal efficiency will be indirectly linked to the carbon dioxide composition. If the hydrogen sulfide concentration is low and carbon dioxide high, then carbon dioxide will drive the size of the amine system and the additional energy required to remove the hydrogen sulfide will be minimal. Disposal of the hydrogen sulfide for this feed condition will likely reduce the thermal efficiency. If the hydrogen sulfide concentration in the amine system vent is too high for direct venting to the air, then thermal oxidation, or other hydrogen sulfide management options must be used. If an acid gas incinerator is selected for a high carbon dioxide and low hydrogen sulfide situation, the thermal efficiency is impacted by the need to heat up the carbon dioxide to the temperature where hydrogen sulfide is converted to sulfur dioxide.

There are numerous other components in the feed gas that will impact the final selection of the amine system to be used and therefore the optimum thermal efficiency to be achieved when considering the various capital costs involved for these options. When selecting the amine for use in any plant design, it's important to also look at the hydrocarbons that are released from the process with the carbon dioxide and hydrogen sulfide waste streams. The hydrocarbons will not only lower the thermal efficiency of the overall plant design, but they also become an environmental air emission issue to be managed and a cost to be considered.

A common design option to further improve thermal efficiency in a process where gas treating is required is the installation of waste-heat recovery on the gas turbines, where the recovered heat is used in the amine system. The use of waste-heat recovery can also result in another review of system optimization since the size of the waste-heat recovery system can be driven by the efficiency of the amine solution being used. While it can be premised the waste heat is "free" and therefore a lower efficiency amine can be used, the trade off may be an increase in the size of the waste-heat unit required. This needs to be reflected in the lifecycle analysis.

Nitrogen is another feed gas component that can have a significant impact on thermal efficiency. Generally the presence of nitrogen results in higher energy consumption and lower thermal efficiency as this gas is cooled to LNG temperature. Removal of nitrogen becomes a balance of the cost to do so versus the energy savings achieved. There are several methods available to remove nitrogen. The use of membrane technology to process feed gas has progressed significantly in the last several years to the point where a serious review of options to remove nitrogen before it evens enters the LNG plant is warranted. There are also numerous options within any given LNG technology to remove nitrogen in the liquefaction process itself. The optimum solution again becomes a balance of the capital cost and thermal efficiency impacts on the lifecycle cost of these options.

Rejection of the nitrogen into the fuel gas stream is a common method to handle nitrogen. Issues to be considered when evaluating this type of process are the Wobbe Index and/or btu content for the resulting fuel mixture. While a gas turbine can operate over a wide range of btu content, it's important to evaluate the range that will occur under different operating conditions. This is required to ensure that the turbines can operate satisfactorily with the fuel nozzle design required for the selected turbine. All gas turbines have different fuel operating ranges as a result of the configuration of the fuel system. This becomes even more important if the gas turbine selected is premised to use dry, low NOx, steam, or water injection for additional air emissions control. As nitrogen composition increases, there is a point where the costs associated with dual fuel nozzles, system operability and reliability, dictate other options for nitrogen rejection to meet LNG product specifications. For high-nitrogen rejection requirements, the addition of a nitrogen-rejection unit in the LNG process, resulting in a separate high purity nitrogen stream, becomes another option for consideration. This stream can have commercial value depending on the level of purity achieved and introduces options for additional processing if other components such as helium are present.

When evaluating the nitrogen rejection options for an LNG technology, sensitivity cases need to be performed for various levels of nitrogen removal and the overall LNG process impact. The typical maximum concentration of nitrogen in LNG is 1%. Where nitrogen is rejected in a process and therefore how it impacts the performance of downstream equipment should be considered in the sensitivity cases. Issues to be considered are the impact on the size of the equipment (i.e. gas compression) and the piping system (i.e relief valves, vessels and pipe).

LNG Liquefaction Technology

The previous discussion on nitrogen removal introduced some of the design issues that need to be considered when selecting and evaluating LNG liquefaction technology. Other issues to be considered in liquefaction technology selection include the thermodynamic efficiency of the process, the lifecycle operational characteristics of the plant, refrigerants and the turndown capabilities of the technology.

The liquefaction cooling curve performance is another benchmark that is reviewed in LNG technology comparisons and is often misunderstood or incorrectly applied when considering energy performance relative to lifecycle cost. Caution should be used with this type of performance comparison. A detailed knowledge of the design of each liquefaction process, the options they can achieve at different performance levels along this curve, and the cost impact for these options is required to make a valid comparison.

The cascade liquefaction process offers considerable flexibility to maximize performance along this cooling curve depending on the number of cooling stages used and where these stages are located in the process. The use of pinch technology analysis and case studies will result in the optimum efficiency and capital cost balance for a range of operating conditions. The plate fin heat exchangers used in this process are also recognized for their ability to achieve an exceptionally close outlet temperature approach. The use of pure refrigerants also allows accurate prediction of refrigerant performance continually during plant operation without the need for on-line refrigerant monitoring. Therefore, for a given feed gas composition range, the cascade liquefaction technology provides the plant designer with flexibility in cooling stage locations, heat exchanger area, and operating pressure ranges in each stage resulting in a process that can achieve high thermal efficiency throughout a wide range of feed conditions.

The type of refrigerant used in a process is frequently used as a comparative measure. The relative merits of refrigerants in terms of lifecycle value and thermal efficiency need to be thoroughly evaluated. It would seem obvious that refrigerant make-up from the LNG plant products needs to be taken into account in any overall thermal efficiency calculation and in the final lifecycle cost evaluation. The same is true if the refrigerants are imported. However, the consideration of refrigerant loss is typically not considered when comparisons are being made between LNG technology thermal efficiencies. Refrigerant losses need to be considered for two major areas. One is the refrigerant loss that occurs during normal plant operations, and the other is during abnormal operations. During normal operations the loss of refrigerant can occur from several sources. The main losses are from the compressors' seal systems and leaks through flanges, valve stems, and process equipment. Dry gas seal systems have significantly reduced refrigerant losses and are areas that should always be reviewed in equipment and process selection. Valve and process equipment leaks are areas that also need to be considered in design selection. While there are valve designs that have low losses from stem packing, these come at a cost and therefore need to be compared to the cost of the refrigerant and environmental regulations or goals. Inerts in a refrigerant will impact the performance of the refrigerant compressor. Removal of these inerts results in some loss of refrigerants, that, again require a makeup process. The refrigerant system tendency to build up inerts and the mode of rejection from the process have an impact on thermal efficiency and lifecycle costs.

The other area where refrigerant losses can be excessive is during abnormal process operation, typically during shutdown or startup periods. The startup of a compressor connected to a single shaft turbine can result in high refrigerant losses if these refrigerants need to be vented in order to lower system pressure to minimize the startup torque requirements. There have been several design options to minimize these refrigerant losses, some of which consist of compressing refrigerant into piping systems that can hold refrigerant and re-introducing it into the system after or during plant start up. These designs add cost and therefore need to be considered in the lifecycle costs. If the process will be down for a period of time, the process' ability to hold the refrigerant without the need to flare, or require the refrigerant to be transferred back to the storage area, will impact the overall lifecycle cost of the process. While a shutdown of a mixed refrigerant can cause a loss of lighter components from the refrigerants, the Phillips Optimized Cascade LNG Process has demonstrated the ability to hold refrigerants in the process during shut down periods for several days. This also results in a rapid startup after prolonged shutdown, since the process is still cold and liquid levels are readily established. After these extended shutdowns, the Phillips process can come back up to full production in less then four hours, resulting in less flaring and refrigerant loss. This capability translates directly into improved lifecycle costs and efficiency for the project. For shutdowns where mixed refrigerant has been lost, or after system maintenance, this process will require a longer period to achieve design efficiencies since the optimum mixed refrigerant composition has to be reestablished (4).

Turndown capabilities of an LNG process also need to be considered when thermal efficiency and lifecycle comparisons are being made. Thermal efficiency comparisons are typically made based on the process operating at its design conditions. In an actual plant environment, this design point is elusive and an operator is always chasing the "sweet point" where the plant will operate at its peak performance under existing conditions. As the temperature changes during the day, whether it's impacting the performance of the air fins, the turbines, or the process fluid and equipment, the operator needs to continually adjust plant parameters to achieve maximum performance. Designing a plant to allow an operator to continually achieve this optimum performance point will impact the overall thermal efficiency of the plant and lifecycle costs. There are numerous tools to add to the process design to improve plant response to changing operating conditions. Advance Process Control is one of these tools. Only by continually analyzing the plant response to changing conditions, and tuning the plant accordingly, can an operator achieve maximum efficiency. A comparison of LNG technologies at one design condition does not address the reality of what a technology must actually achieve in an operating environment. A two-shaft gas turbine, with its ability to control compressor performance without the need for recycle, can deliver significant improvements in thermal efficiency versus a single-shaft machine which has a very limited speed range and, requires compressor recycle earlier in a turndown application. For a plant design that may see significant production swings during the day as a result of ambient temperature effect, the performance of the gas turbine and compressor package needs to be considered in any comparison of plant thermal efficiency.

While no plant operator wants to have a plant that is subject to wide swings in plant throughput as a normal course of business, some projects may require a process technology that can maintain peak efficiency over a large turndown range. If a plant is servicing several different LNG markets with ships of various sizes, managing storage tank inventory and plant turndown can become a daily optimization exercise. This is where the Phillips "two-trains-in-one" design can provide significant flexibility to a plant operator. If weather delays result in a ship being late, storage tank levels can result in the need to cut back LNG production. Depending on the length of the delay, the Phillips process can provide the operator several options to reduce LNG production while minimizing the impact on overall plant thermal efficiency. For production reductions that occur for 12 hours or less, the operator can reduce feed and lower the speed of the two-shaft machine, if so outfitted, or recycle the refrigerant compressors. Long-term production reduction can be achieved by shutting down one train of refrigerant compressors. This results in a reduction of throughput by about 45% and the remaining train of gas turbines can be operated at 100% speed and maximum efficiency. The lower throughput through the plate fins exchangers used in the Phillips' Optimized Cascade LNG Process result in an improvement in efficiency since more surface area is available. Higher thermal efficiencies are actually achieved at this half-rate operation versus full rate. Half-rate production operation also allows some routine maintenance to be scheduled without impacting plant availability. Maintenance personnel can do a water wash on the turbines that are offline and allow the plant to go back to full-rate production with improved gas turbine efficiency.

The use of liquid expanders is another option that can further improve thermal efficiency. The expansion of a liquid phase though a hydraulic turbine, versus the traditional pressure let down through a control valve, allows the recovery of energy otherwise left in the system as heat. This improves process efficiency and the energy recovered by the hydraulic turbine can then be utilized to generate power or compress the refrigerant or feed stream. The application of this technology can be compared to the refrigerant power saved, the electrical power generated, or the incremental LNG sales that can be achieved (6).

Gas turbine selection is another common benchmark comparison made between two technologies and projects. Gas turbine selection is always made on the economic merits the turbine will deliver for the overall lifecycle cost of the project. Where high fuel costs are expected, the selection of a high thermal efficiency driver becomes a stronger criterion in the lifecycle cost evaluation. However, by the nature of a LNG project, i.e. a development to monetize stranded gas reserves, the low value of fuel has favored industrial gas turbines. There are numerous studies underway by various LNG projects where the use of an aero derivative gas turbine is being considered. Aero derivative gas turbines can achieve thermal efficiencies over 25% higher then industrial gas turbines. This can result in a 3% or higher increase in overall plant thermal efficiencies. This efficiency improvement comes at a cost and the cost needs to be considered in the lifecycle selection process for the most appropriate turbine to use. Maintenance costs for an aeroderivative gas turbine are normally higher and they also have a lower reliability. Positive aspects are the improved plant availability as a result of the ability to completely change out a gas turbine generator in less then three days versus fourteen -plus days that could be required for a major overhaul on an industrial gas turbine.

Power Requirements

Electrical power consumption in a LNG design will depend on many factors, some of which can be controlled by the process design and others that are related to the project site. A project in an area with minimal existing infrastructure will need to generate more power for a camp, canteen, water system pumps, etc. The power requirements of the process will be determined based on alternatives to electrical power, for example compressor helper motors versus additional gas turbine horsepower. The total capital cost for the installed capacity should be considered in the thermal efficiency comparison. If there is a high starting motor power requirement for a process which drops off to a lower demand during operation, a large amount of capital has been spent that sits idle for the majority of its life.

The feed gas conditioning unit of the plant can also be a high electrical power consumer in an LNG process. Here is an example where high carbon dioxide in the feed gas results in not only higher fuel cost for the solvent reboiler requirement, but also higher power consumption by the solvent pumps. Therefore, how power is used in a process and its source, self generated or purchased, needs to be considered in any thermal efficiency comparisons and lifecycle cost evaluation.

Storage and Loading

The distance the storage tanks are located from the process will impact the thermal efficiency of the LNG plant design and lifecycle costs. When the storage tanks are located a significant distance from the process, the rundown line to the LNG tanks becomes a source of heat gain into the LNG resulting in higher flashed LNG vapors in the storage tanks. These vapors need to be compressed back to fuel gas pressure, or for recovery in the LNG process, requiring either higher fuel costs or electric power usage.

Another design option that needs to be considered is the vapor recovery of the flashed vapors during LNG loading. If maximum thermal efficiency for the project is the goal, or if environmental goals/regulations prevent flaring of the ship-loading vapors, ship loading will require the installation of additional vapor recovery equipment. The disposition of the vapors from ship loading will typically be the same as the vapor from the storage tank for any given project. Because the volumes are short in duration but high in volume, the design must consider the impact this cyclic load will have on the process re-entry point. If the flash gas is compressed back into the feed gas stream, the horsepower available for LNG production will be reduced during this time period. If the gas is sent to a fuel system, then the normal fuel source will need to be reduced. This could result in corresponding cyclic swings in the LNG process depending on where fuel is being pulled out of the process.

Some improvement to the performance of the storage and loading system can be gained by the use of vacuum jacketed rundown and LNG loading lines. The reduction in heat gain to the LNG will reduce flashed vapors and, therefore, the size of the equipment required for recompression. This thermal efficiency gain needs to be balanced with the lifecycle cost of the use of this piping system.

Conclusion

In summary, when evaluating the economic merits and environmental impacts of an LNG project, each project will introduce its own unique characteristics that will determine the optimum thermal efficiency resulting in the strongest economic and environmental merits for the project. Different technologies or plant designs cannot be compared or benchmarked on thermal efficiency unless the unique differences each project brings to this evaluation process are understood and compensated for. The project team must consider not just the design operating characteristics of a technology, but the performance that can be achieved for the changing lifecycle conditions that the project will experience.

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