Efficiency in LNG Processing through Exergy Analysis

Myles Hollingworth

Eric May
School of Mechanical and Chemical Engineering

Sophia Viglione, Mark Titley
CEED Client: Chevron Energy Technology Company

Abstract

It is desirable from both a sustainability and business perspective to improve the efficiency of LNG processing. Exergy analysis is a thermodynamic technique that evaluates a systems 2nd Law efficiency. Conventional and advanced exergy analyses provided the necessary information to make informed decisions as to where efforts should be focused to allow for maximum payoff in terms of production and/or operating costs. The objective of this project is to develop a conventional exergy analysis tool and perform both conventional and advanced exergy analyses over various sections of a generic LNG train. The resulting analysis showed that the two major contributors to exergy destruction within a LNG train are the liquefaction and inlet facilities at 39% and 28% respectively. Advanced exergy analysis conducted over a CO_2 *sequestration train showed that 42% of the exergy destruction within the* CO_2 *sequestration train is theoretically avoidable. 22% of the exergy destruction within the air coolers can be reduced via improvements to their subsequent compressors.*

1. Introduction

With increasing energy costs and a growing demand for Liquefied Natural Gas (LNG) it is desirable from both a sustainability and business perspective to improve the efficiency of LNG processing. Exergy analyses are able to provide the necessary thermodynamic information to make informed decisions as to where efforts should be focused to ensure maximum payoff in terms of production and/or operating costs.

Exergy is defined as "*the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of a reversible processes, involving interaction only with the above-mentioned components of nature*" (Szargut et al. 1987). Subsequently, a system in complete equilibrium with its environment does not have any exergy and the further a system deviates from the environment the more exergy the system carries. Contrary to energy, exergy is exempt from the law of conservation. Every irreversible phenomenon results in exergy destruction, leading to a reduction in the useful work a system can produce.

Exergy is a measure of both quality and quantity of energy hence, exergy is often referred to as a measure of 2^{nd} Law efficiency. The key advantage of exergy over other 2^{nd} Law efficiency analyses is its ability to quantify thermodynamic inefficiencies as a lost potential for work. Moreover, advanced exergy analysis is able to establish the cause of component inefficiencies, whether they be due to internal inefficiencies or the inefficiency of other components within the same system.

Exergy is split into a number of constituents, these being physical exergy, chemical exergy, kinetic exergy, potential exergy, nuclear exergy and so forth (Sciubba, Bastianoni & Tiezzi 2008). For the purposes of most systems only chemical and physical exergy need be considered. Physical exergy is the maximum amount of work obtainable when the substance under consideration is brought by a reversible physical process from its initial state (T,P) to the state of the environment (T_o,P_o), where T (K) is temperature, P (Pa) is pressure and the subscript o denotes the environmental state. The expression for the specific physical exergy of gases and liquids is given by;

$$e_{ph} = (h - h_o) - T_o(s - s_o) \tag{1}$$

Where e_{ph} (J/mol) is the molar physical exergy of a substance and h (J/mol) and s (J/K·mol) are the molar enthalpy and molar entropy of a substance respectively.

Chemical exergy is the maximum amount of work obtainable when the substance under consideration is brought from the environmental state (T_o,P_o) to the reference state via chemical reactions with the environment. Standard chemical exergies of most substances are available in literature.

1.1 Conventional Exergy Analysis

Conventional exergy analysis identifies the location, magnitude and sources of thermodynamic inefficiencies in a system, specifically the exergy destruction for each unit operation. A steady state exergy balance over a unit operation *i* yields;

$$\sum_{in} \dot{n}_{i,in} e_{i,in} - \sum_{out} \dot{n}_{i,out} e_{i,out} = \sum_{j} \int_{1}^{2} \left(1 - \frac{T_o}{T_j}\right) \delta \dot{Q}_j + \dot{W} - T_o \dot{\sigma} \tag{2}$$

Where $\dot{n}$ (mol/s) is molar flow, e (J/mol) is molar exergy, T_j (K) is the temperature at the location of heat transfer, $\dot{Q}$ (J/s) is the rate of heat transfer, $\dot{W}$ (J/s) is work and $\dot{\sigma}$ (J/K·s) accounts for any exergy irreversibilities. The left hand side refers to the exergy associated with material streams entering and exiting the unit operation. The first term on the right is the exergy transfer accompanying heat, the second term is the exergy transfer accompanying work and the third term is the exergy destruction due to irreversibility.

1.2 Advanced Exergy Analysis

Conventional exergy analysis cannot evaluate the mutual interdependencies among system components or the real potential for improving components. Advanced exergy analysis splits the exergy destruction of each unit operation into four basic parts (Kelly, Tsatsaronis & Morosuk 2009)

1. *Endogenous Exergy Destruction:* Exergy destruction within the k^{th} component that is due only to irreversibilities within the k^{th} component when all other system components operate in an ideal way.

2. *Exogenous Exergy Destruction:* Exergy destruction within the k^{th} component that is due only to the irreversibilities of all system components other than the k^{th} component.
3. *Avoidable Exergy Destruction:* Exergy destruction within the k^{th} component that can be reduced by improving the efficiency of the k^{th} component using the best available technology.
4. *Unavoidable Exergy Destruction:* Exergy destruction within the k^{th} component that cannot be eliminated due to the physical constraints of process conditions or the limitations of available technology.

Splitting exergy destruction identifies the location and source of irreversibilities, identifies possible improvements, and characterises the associated viability of these improvements. The most common methodology for advanced exergy analysis is the hybrid process method (Kelly 2008). The hybrid process method of advanced exergy analysis evaluates the endogenous part of exergy destruction by calculating the exergy destruction of the component when operating at its current (i.e. real) efficiency and the remaining components operating in an ideal ($e_D = 0$) or theoretical way ($e_D = min$) (Morosuk & Tsatsaronis 2013).

1.4 State of Exergy and Project Contributions

Publications related to exergy have rapidly increased since the year 2000 with key areas including fuels, thermodynamics, electrochemical, nuclear physics, ecology, mechanical engineering, chemical engineering, environmental engineering and construction (Luis 2013). However a complete conventional exergy analysis of a LNG facility has yet to be completed. Furthermore, advanced exergy analyses have yet to be applied to an Acid Gas Removal Unit (AGRU) or a CO_2 sequestration train. This project seeks to explore these areas while also creating tools to facilitate conventional and advanced exergy analysis. The creation of conventional exergy calculation tools for process simulation has been successfully attempted by a number of individuals and/or groups (Montelongo-Luna et al. 2009). However, none of these tools utilize AspenTech HYSYS and they fail to calculate the exergy destruction over components and their associated exergetic efficiency.

2. Process

The project is captured in 4 relevant stages: Literature review of exergy analysis capabilities, conventional exergy calculator tool development, LNG processing conventional exergy analysis and CO_2 sequestration advanced exergy analysis. Conventional exergy analysis of a generic LNG train was carried out in AspenTech HYSYS using the developed conventional exergy calculator, while the advanced exergy analysis of the CO_2 sequestration train was carried out using the Hybrid Process Method. Compressors in the CO_2 sequestration train were fit to performance curves that were indicative of real operating conditions while an unavoidable adiabatic efficiency of 93% was specified for all compressors. Furthermore, it was assumed that hot air from air coolers is expelled to the environment and the associated heat therefore, cannot be recovered.

2.1 Conventional Exergy Calculator

The conventional exergy calculator (CEC) was programmed in Visual C# and utilising the AspenTech HYSYS COM Type Library. The CEC executable computes the physical, chemical and total exergy of all material streams. In addition, the CEC determines the exergy destruction and exergy efficiency of all unit operations, with the option of specifying utility stream conditions for HYSYS non-physical operations (e.g. coolers and heaters). The CEC also enables the user to specify whether utility stream heat recovery is available. The CEC can be upgraded to the newest version of HYSYS simply by changing the HYSYS COM Type Library reference. To enable user data manipulation, the conventional exergy calculator can also export the results to Microsoft Excel. Figure 1 depicts the user interface of the CEC.

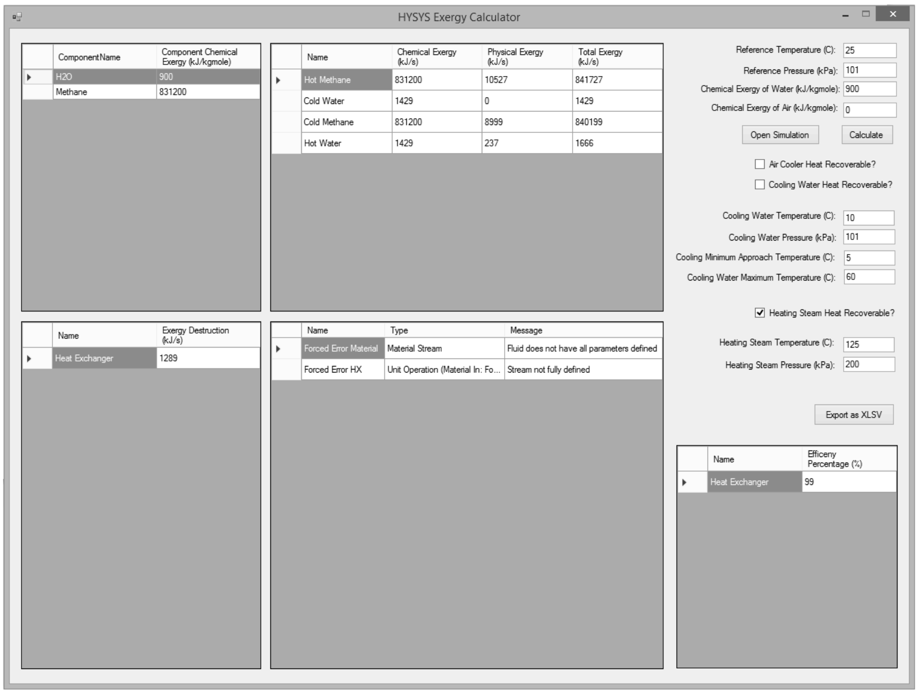

Figure 1 Conventional exergy calculator executable user interface

3. Results and Discussion

3.1 Generic LNG Train Conventional Exergy Analysis

The results of the conventional exergy analysis of a generic LNG train are shown in Figure 2.

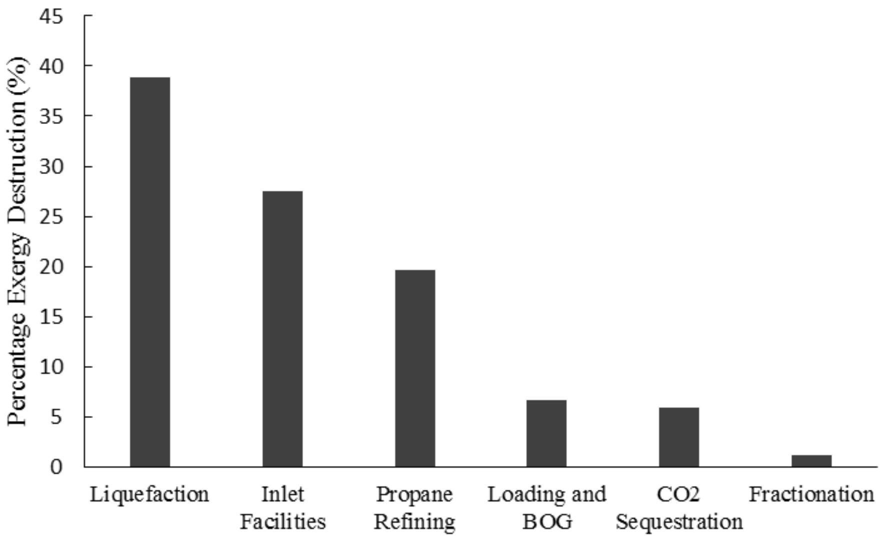

Figure 2 Percentage exergy destruction breakdown of a generic LNG train: boil off gas (BOG)

The results show that the two major contributors to exergy destruction within an LNG train are the liquefaction and inlet facilities at 39% and 28% respectively. Of particular note is the extensive exergy destruction within the AGRU unit, which accounts for approximately 65% of the exergy destruction within the inlet facilities. It is to be expected that the ARGU experiences a disproportionate amount of exergy destruction, as it is the only chemical process within the LNG train and is an energy intensive operation.

3.2 Advanced Exergy Analysis of a CO_2 Sequestration Train

The advanced exergy analysis results of the CO_2 sequestration train depicted in Figure 3 are shown in Figure 4.

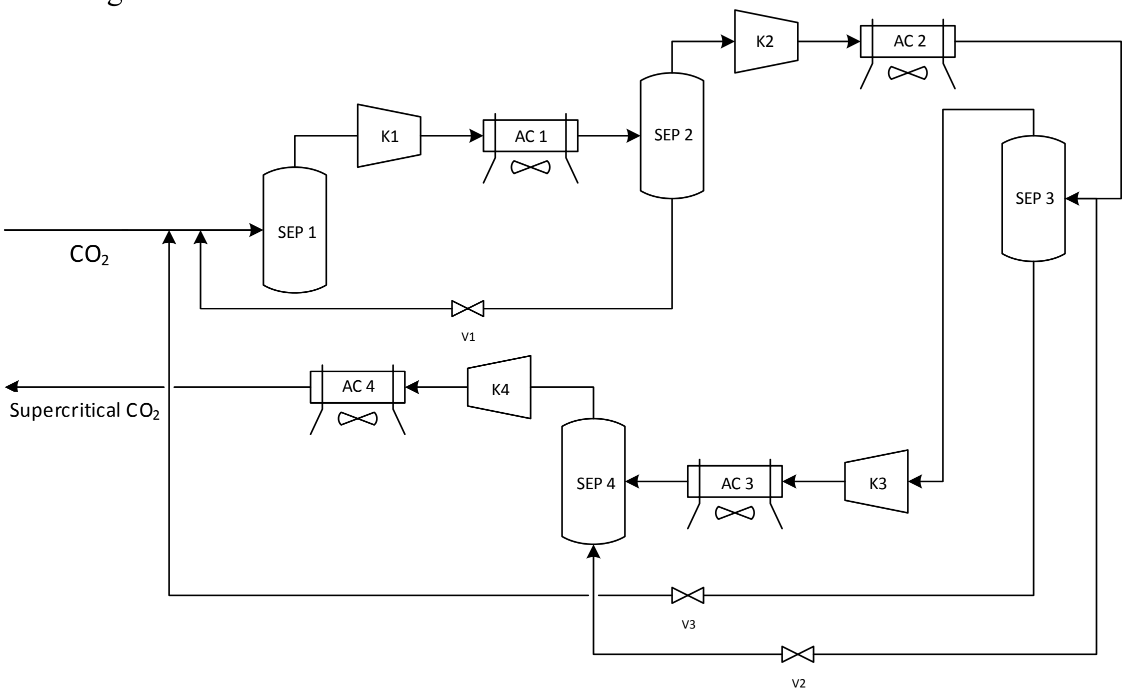

Figure 3 CO_2 sequestration train process flow diagram

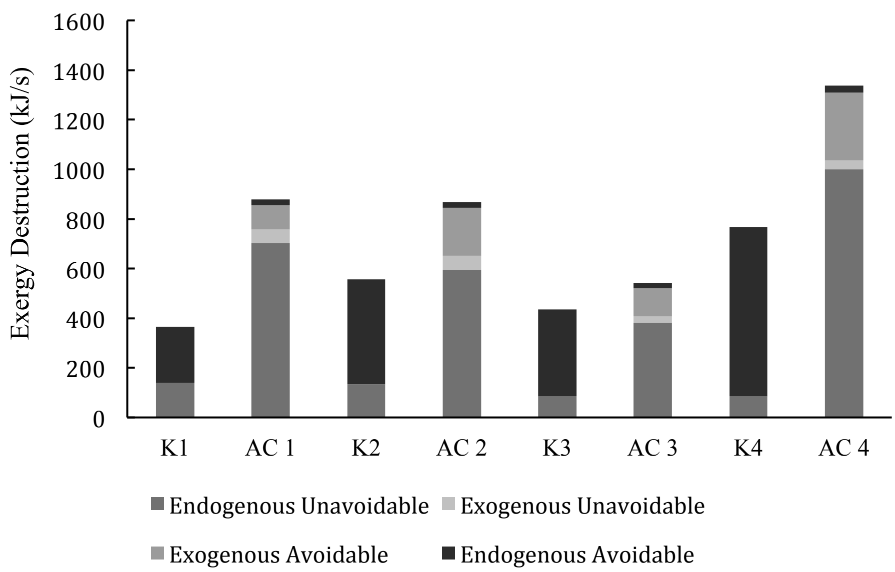

Figure 4 CO_2 sequestration train advanced exergy analysis: air cooler (AC), compressor (K)

The real potential for improvement of a component is not revealed by its total exergy destruction, but rather by its avoidable part. Results show that 42% of the exergy destruction within the CO_2 sequestration train is theoretically avoidable through better air cooler approach temperatures and/or improved compressor adiabatic efficiency. Moreover, 22% of the exergy destruction within the air coolers can be reduced via improvements to the adiabatic efficiency of their upstream compressors.

4. Conclusions and Future Work

The work completed to date has depicted the benefits of exergy analysis. Applying the developed conventional exergy calculator tool to a generic LNG train revealed that the largest contributors to exergy destruction were the liquefaction and inlet facilities. Specifically, the ARGU was the largest contributor to exergy destruction within the train excluding the refrigeration loops. An advanced exergy analysis was conducted for the CO_2 sequestration train and the interdependencies between compressor performance and air cooler exergy destruction were demonstrated. The next stage of work will include conducting an advanced exergy analysis upon an AGRU and the development of an advanced exergy analysis assistant tool.

6. References

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