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# A case study: Application of energy and exergy analysis for enhancing the process efficiency of a three stage propane pre-cooling cycle of the cascade LNG process

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ABSTRACT

The propane pre-cooling cycle has been widely used in most LNG plants as the first cooling cycle in the natural gas liquefaction process. As LNG plants consume high amounts of energy, enhancements in the process design and plant operation will minimize the overall energy consumption of the plant. The aim of this study is to enhance the process efficiency of a three stage propane pre-cooling cycle of the Cascade LNG process for the large-scale LNG train by determining the optimal operating conditions of the propane evaporator that will minimize the overall energy consumption. Energy and exergy analysis methods are adopted to evaluate the process efficiency of the propane pre-cooling cycle. Six case studies were presented to determine the optimal operating conditions of the propane evaporator that gives maximum energy reduction. The propane pre-cooling cycle is modelled and simulated using Aspen HYSYS with detailed thermodynamic information obtained to calculate the exergy loss. The results of the energy and exergy analysis indicate that Case 6 gives the highest coefficient of performance (COP) and the maximum exergy efficiency compared to the baseline case, which are 15.51% and 18.76% respectively. The results indicate that by reducing the cooling duty at the intermediate stages of propane evaporator about 13.5% energy saving can be achieved compared to the baseline case.



## 1. Introduction

As the demand on LNG is drastically increasing and the discovery of new large gas fields is continuously taking place worldwide, the pace of change and development in LNG liquefaction technology is becoming more rapid than ever before. LNG production is estimated to hit 320 million tonnes per annum (MTPA) by 2015 and to 450 MTPA by 2020 as reported by Wood (Wood, 2012). In order to meet this escalating demand, most of the existing and new LNG plants are looking for opportunities to make a further increase in their LNG capacity and building larger LNG trains which will provide economic benefits and be process efficient. Since the 1970s, when the kick started for the LNG plant and until the present day, three main LNG processes have been applied in the LNG plants viz. Single mixed refrigerant (SMR), Propane precooled mixed refrigerant (C3MR) and cascade liquefaction process (Lim et al., 2013). In the last 10–15 years, the innovations of LNG technologies have drastically progressed whereby new LNG processes have been introduced such as Mixed fluid cascade (MFC), Air Products (AP-X™), Dual mixed refrigerant (DMR) and Parallel mixed refrigerant (PMR) (Castillo et al., 2010). Most of the existing LNG plants have three main cooling cycles, namely the pre-cooling, liquefying and sub-cooling cycle. Earlier LNG plants that employed the SMR process did not have the pre-cooling cycle, instead the natural gas was cooled directly to −160 °C using a single mixed refrigerant. The pre-cooling cycle is the first cycle in an LNG process which removes the heat from natural gas to a temperature range between −30 °C to −55 °C depending on the pre-cooling

*Abbreviations:* AC, air cooler; COP, coefficient of performance; EOS, equation of state; HP, high pressure; HX, heat exchanger; LNG, liquefied natural gas; LP, low pressure; MP, medium pressure; MTPA, million tonnes per annum; PR, Peng Robinson; UA, product of overall heat transfer coefficient and heat exchanger area; SP, specific power.

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**Nomenclature**

| | |
|---|---|
| $E_x$ | exergy [MW] |
| $Ex_{HX, loss}$ | exergy loss of heat exchanger [MW] |
| $Ex_{COMP, loss}$ | exergy loss of compressor [MW] |
| $Ex_{v, loss}$ | exergy loss of valve [MW] |
| $Ex_{MIX, loss}$ | exergy loss of mixer [MW] |
| $Ex_{AC, loss}$ | exergy loss of air cooler [MW] |
| e | specific exergy (MJ/kg) |
| H | enthalpy (MJ/kg) |
| n | mass flow rate [kg/s] |
| P | pressure [bar] |
| Q | refrigeration duty [MW] |
| S | entropy [MJ/kg K] |
| $T_0$ | ambient temperature [K] |
| W | compressor power [MW] |

*Subscripts*

| | |
|---|---|
| f | fluid |
| i | inlet |
| o | outlet |

*Greek symbol*

| | |
|---|---|
| $n_{ex}$ | exergy efficiency |

*List of symbols*

| | |
|---|---|
| $C_2H_6$ | ethane |
| $C_3H_8$ | propane |
| $CH_4$ | methane |
| $N_2$ | nitrogen |

technology applied. As a result of technological advancement, the pre-cooling cycle can now be designed using either pure refrigerant or mixed refrigerant. Castillo et al. (Castillo et al., 2013) reported that 95% of the current LNG plants employ the pre-cooling cycle; 85% of which are dominated by propane refrigerant compared to mixed refrigerant.

Thermodynamic analysis has been widely used in the LNG plants to determine the sources and locations of the main process irreversibilities that occur within the process or are due to an individual unit operation. Energy analysis or the first law of thermodynamic method only indicates the energy conservation of the overall process which is measured using two parameters i.e. COP and specific power (SP). However, to locate the irreversibility that occurs within the unit operation of the process, the exergy analysis method is applied. These methods are widely applied by other scholars to evaluate the energy conversion process efficiency. Vatani et al. (Vatani et al., 2014), Kanoglu (Kanoglu, 2002), Cipolato, et al. (Cipolato et al., 2012), Al-Otaibi et al. (Al-Otaibi et al., 2004) and Mehrpooya et al. (Mehrpooya et al., 2006) applied the energy and exergy analysis methods for analysing the process efficiency of various LNG processes. In a nutshell, these methods are also widely used in some power plants as mentioned in the following references (Cihan et al., 2006; Aljundi, 2009; Kaushik et al., 2011).

Converting natural gas to liquid utilizes an extensive amount of energy. According to Alfadala et al. (Hasan et al., 2009), a typical base load LNG plant consumes about 5.5–6 kWh of energy per kgmole of LNG produced. An energy-efficient refrigeration system will enhance the plant operation and provide economic benefits (Lee et al., 2002). Several authors have discussed the area of enhancing the efficiency of the pre-cooling cycle. Paradowski et al. (Paradowski et al., 2004) discussed two operating parameters of the pre-cooling cycle in the C3MR process that can enhance the process efficiency plus debottleneck the existing LNG plant capacity to 5.5 MTPA. The pre-cooling temperature of the low pressure (LP) stage and the propane compressor speed were the operating parameters that were adjusted to meet the new capacity requirement.

Castillo et al. (Castillo and Dorao, 2013) studied suitable choices of refrigerants that are applicable for pre-cooling cycle by analysing the effects of various refrigerants (i.e. $N_2$, $CH_4$, $C_2H_6$, $C_3H_8$) on the compressor power using the Linde-Hampson process. It was found that compared to other refrigerants, propane has a higher specific refrigerant effect which makes it the preferred refrigerant to be used in the pre-cooling cycle. Ransbarger (Ransbarger, 2007) studied the comparison between three stage and four stage propane cycles for the cascade LNG process which resulted in a power reduction of 1%; nonetheless the economic evaluations did not justify the increased cost associated with the additional stage. Evolution in the design of the propane pre-cooling cycle has emerged in recent decades. In this context, various studies have been presented that were related to the enhancement of the efficiency of the propane cycle with respect to significant changes made in the process configuration. Mortazavi et al. (Mortazavi et al., 2012) suggested the replacement of the conventional expansion valves in the C3MR process with expanders to improve the liquefaction efficiency. In another study, Mortazavi, et al. (Mortazavi et al., 2010) investigated the usage of waste heat from gas turbines by installing absorption chillers in the propane cycle of the C3MR process. Kalinowski et al. (Kalinowski et al., 2009) proposed the replacement of the propane evaporator with an absorption refrigeration system utilizing waste heat from the electrical power generating gas turbines.

Although many studies have been conducted focussing on the efficiency enhancement of the LNG plants through modification of the process configuration (Kanoglu, 2002; Mortazavi et al., 2012, 2010; Kalinowski et al., 2009; Remeljej and Hoadley, 2006), there is only very scant information available which focuses on the operation perspective. In this study, we to analyse the impact of changing the operating conditions of the propane evaporator towards the energy consumption of the process. Six case studies are proposed with different operating conditions applied to the propane evaporator. The development of these case studies is discussed in Section 2.2 of the manuscript. The sensitivity of COP, specific power (SP), exergy loss and exergy efficiency are analysed for all case studies presented.

### 1.1. Description of propane pre-cooling cycle process

Treated feed gas enters the three stage propane cycles at 29 °C and 75 bar and is cooled to −40 °C. The propane evaporator (i.e. kettle type) also cools methane and condenses ethylene. Cooling of the process stream is achieved by the evaporation of propane in the pool on the shell side with the process streams flowing inside the immersed tubes. The propane compressor (i.e. centrifugal type) with side streams recovers the evaporated propane and compresses the vapour to 18 bar. Propane is finally condensed at 49 °C using the air cooler. The condensed propane is then recycled back to the propane evaporator. Fig. 1 shows the simplified process scheme of propane pre-cooling cycle.