NUR FARHANA AJUA BT. MUSTAFA B. ENG. (HONS) CHEMICAL ENGINEERING SEPTEMBER 2015

ANALYSIS OF OPERATIONAL ENERGY INTENSITY IN LNG VAPORIZER DESIGN VIA DECOMPOSITION METHOD

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Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Chemical Engineering)

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CERTIFICATION OF APPROVAL

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(CHEMICAL ENGINEERING)

Approved by,

____

(Assoc Prof Dr Shuhaimi Mahadzir)

UNIVERSITI TEKNOLOGI PETRONAS
BANDAR SERI ISKANDAR, PERAK
September 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

NUR FARHANA AJUA BINTI MUSTAFA

ABSTRACT

In LNG process chain, a huge amount of operational energy was consumed especially by LNG regasification process. Therefore, the reduction of energy consumption by vaporizer systems is necessary to significantly reduce the costs, without reducing the energy performance. In this project, energy intensity are employed as the indicator of changes in energy efficiency of vaporizer system. .However, it is very crucial to analyze the energy intensity of a complex vaporizer system. Thus, this project used a decomposition method which is found to be an effective way to simplify the complex vaporizer system. This project proposed to reduce the amount of energy intensity of LNG vaporizer designs. Thus, a few analysis has been carried out on the system performance in order to evaluate the best LNG vaporizer technology to be optimized subsequently. Aspen Hysys software is used to simulate and analyze an optimized vaporizer design. The result show that Open Rack Vaporizer consume the lowest amount operational energy intensity compared to the other type of vaporizer. For an optimum condition of ORV, this project proposed the LNG injection pressure in ORV to be at 4 barg with E-100 discharge temperature is more than saturation temperature, -60.28 C.As a result, energy intensity of LNG vaporizer can be reduced up to 3.45 Wh/kg with maximum amount of 1st and 2nd Law Efficiency which is 99.10% and 94.99% respectively

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CHAPTER 1
INTRODUCTION

1.1 Background of study

The rising demand of natural gas around the globe drives the force for the exportation activity of LNG across the ocean. Generally, LNG is the natural gas which was liquefied for the ease of transportation and storage. According to Chevron website (2015), in the liquefaction process, the natural gas was cooled to -162°C and was compressed to $1/600^{th}$ of its original volume. In turn of this process, more volume natural gas can be safely shipped and efficiently aboard in the specially designed cryogenic cargo's vessel.

After all, the LNG will be offloaded to the export terminals and being vaporized based on the demand. This process is known as regasification where the LNG is being vaporized to turn it back as a gaseous state at ambient temperature, 15°C. The regasification process takes place by heat exchanging system in the vaporizer.

The vaporizers have its own operational energy intensity which contributes to the LNG energy consumptions. Since Kumar et al (2013) expounded that the regasification utilities consumed substantial operational energy intensity, hence this paper is focused to analyze the operational energy intensity for the three commonly used in LNG regasification industries which are Open Rack Vaporizer (ORV), Intermediate Fluid Vaporizer (IFV) and Submerged Combustion Vaporizer (SCV).

In this case of study, the operational energy was analyzed by using decomposition method where the complex system of LNG vaporizer is being segregated into a simpler heat exchanger system in logical sequence. With that, the parameters or components which contribute significant operational energy intensity could be determined and analyzed certainly for the performance optimization.

1.2 Problem statement

In the case of LNG price depletion, the LNG industrial company had a pressure for operational cost reduction. Based on Littlefield (2015) in his article, energy intensity contributes more than 50% of the cost of production. So the small reduction of energy intensity might result in a substantial reduction of LNG regasification cost. Kumar et al (2013) expounded that the main operating cost in LNG regasification terminal is the LNG vaporization process since it’s consumed approximately around 800 kJ/kg of operational energy.

Therefore, the reduction of energy consumption was necessary to significantly reduce the costs with subsequently a better energy performance. To trace the energy performance, it is very crucial to analyze the energy intensity of a complex vaporizer system. Thus, this project needs a systematic procedure to simplify the complex vaporizer system and come out for an extensive performance analysis for the system optimization.

1.2 Objectives

The main objectives of this project are to:

i. Decompose complex LNG vaporizer system into simpler heat exchanger sequences
ii. Evaluate the operational energy intensity and energy performance of Open Rack, Intermediate Fluid and Submerged Combustion Vaporizer
iii. Suggest the optimum LNG vaporizer structure and operational condition for system optimization.

1.4 Scope of study

This project is mainly focused on the three types of vaporizers which are:

i. Open Rack Vaporizer
ii. Intermediate Fluid Vaporizer
iii. Submerged Combustion Vaporizer

For the analysis stage, the energy intensity and system's energy performance was analyzed by decomposition method using the Aspen Hysys Software. For an optimization stage, this project was focusing on the best LNG vaporizer technology which was selected based on the operational energy intensity and performance analysis since it might not feasible to be carry out for all types of vaporizers within the timeframe.

1.5 Relevancy of the project

As the LNG vaporizer consumed a substantial amount of operational energy, it is vital to carried out some optimization into the system. This project was began by analyzing the operational energy intensity and system performance before getting into the optimization stage. This project is relevant to the course of chemical engineering as it is applies the concept of thermodynamics into the project.

1.6 Feasibility of the project

This project is feasible to be carried out within the scope and timeframe. The period given to complete this project was enough for the simulation, analysis and optimization to be carried out. Moreover, there are no sophisticated chemicals and equipment was required for the project since its only being carried out using the software which is Aspen Hysys.

CHAPTER 2
LITERATURE REVIEW

2.1 Operational Energy Intensity concept and definition

According to U.S Department of Energy (2012), energy intensity is the number of Megawatt or powers needed to produce the substantial products. While, energy intensity also defined as the aggregated sectoral level which is the total manufacturing energy use of value added (Schipper et al., 1992).It is measured by the amount of energy required per unit output. The total of energy consumed in a system is a product of energy required per unit of output.

Energy intensity is an important indicator of aggregated energy efficiency in any policy discussion (Samuelson, 2013). This is supported by Malika (1996) which expounded in her report that the energy intensity is the most commonly used basis for assessing trends in energy efficiency as absolute figure of energy efficiency can only be obtained through measurements of energy intensity at the level of a particular process.

Energy intensity is depend on the operation of the equipment as well as the technical energy efficiency (Schipper et al ,1992).From the study, energy intensity is understood to be inversely related to efficiency in which the less energy required to produce a unit of output or service, the greater the efficiency (Malika,1996).

However, any change in energy intensity does not result from the change of efficiency but somehow its result from the structural changes of a system such as the demographic changes, fuel-use shift and the overall level of activity in the economy (Energy Department,2010). For economic system, high energy efficiency was required with a lower operational energy intensity rate. Hence, to improve the operational energy intensity, a details analysis need to be done so that a few alternatives can be introduced in the vaporizer system for a better performance efficiency with a lowest amount of energy consumption.

2.2 Energy consumptions of LNG

According to Franco et al (2012) to transport the natural gas across the ocean, it is necessary to liquefied it as a LNG and convey it using insulated LNG cryogenic tanker. The LNG process chain consists of three steps which are liquefaction, transportation and storage as well as the regasification (Roszak & Chorowski, 2013).

Fajiang etal (2012) explained in their papers about the LNG process chain, where the gaseous form of natural gas is cooled up to -162 °C through a complex cryogenic process. Then, the LNG was stored in cryogenic holding tank or pumped into the ships for transportation. At the LNG receiving terminals, Raunek (2013) clarified that the tanker is moored at the unloading quay and the LNG is offloaded by infusing into the three arms which situated at the quay, known as LNG unloading line. The LNG is then then put away in the specialized cryogenic liquids tank. Along the regasification process, the recycling system involving compressor and condenser are required in order to prevent the outflow of LNG from the system.

Depending on the demand, the LNG is pumped from the storage container to the vaporizer and regasified. As had been referred to Kidnay et al (2011) in their handbook of Natural Gas Processing, the regasification take place by the heat transfer from the sea water, air, or by fuel burning vaporizer

Based on the papers of Fajiang et al. (2012), the vaporization of LNG is an important stage of ultimate usage of natural gas. Most of the LNG terminal regasify the liquid using the thermal energy if seawater which need about 800 kJ//kg of heat energy for LNG vaporization take place (Franco, 2012)

However, Roszak et al. (2013) found in their study that the gasification process is the only step which having high optimization potential since the perfection in liquefaction technology have achieved its limit approaching the thermodynamic minimum requirement which about 0.35Kw h/kg of LNG or even less.

2.3 Type of LNG vaporizer and its Operating Parameter

2.3.1 Open Rack Vaporizer (ORV)

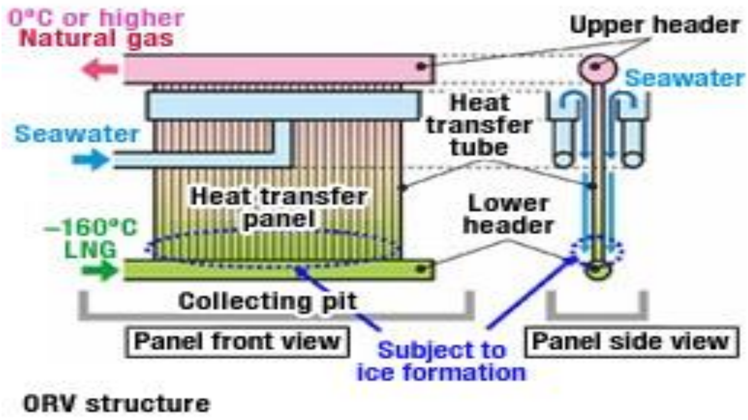

FIGURE 2.1 Schematic of Open Rack Vaporizer (ORV)

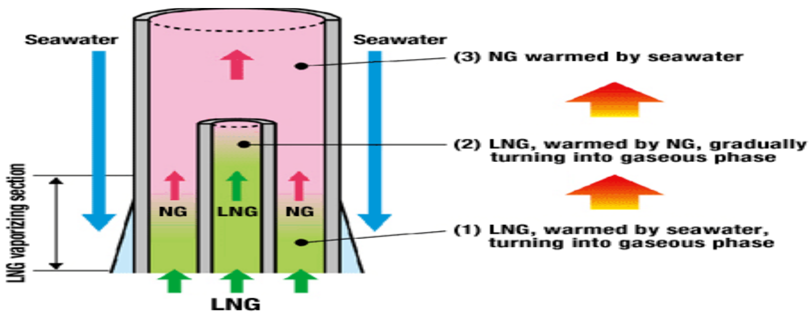

FIGURE 2.2 Schematic of heat transfer tube in ORV system

As per cited by Hsu (2007), Open Rack Vaporizer (ORV) was commonly used for the regasification of LNG and it required the seawater as the heating source to vaporize the LNG. Reasonably, Patel et al.(2013) additionally upheld that the seawater had been used as the heating medium where the preferred seawater temperature for ORV operation was above of 5°C.

The main part of the ORV is hundreds of heat transfer tube. Egashira (2013) edified that each panel of the ORV consists of vast amount of aluminum alloy coated heat-transfer tube which having high thermal conductivity. The thermal conductivity of the spirally twisted heat transfer tube is about 300 W/Mk (Singli et al., 2010). As the LNG flow inside of the heat transfer tube, the heat exchange would occur with the sea water which flows outside of the heat-transfer tube counter currently (Egashira,2013) .The heat exchange causes the LNG being heated and vaporized to the natural gas.

Sea water is the most economic heating medium since it did not required any cost. Then again, its turn out to be less preferred because of the ecological concern. This is because, the evaporator will reject the cooled seawater to the waterway surrounding. (Faka,2011) Thus, there are usually had a regulated limits for both the volume of sea water used and the amount of cooling permitted for sea during heat exchange with LNG. With respect of the issue, Hsu (2007) expressed in his article, where temperature drop of the sea water returned to the sea following the heat exchange with LNG may not more than 20°F (6.6°C).

Osaka Gas Co.,Ltd and Kobe Steel organizations have together invent the technology of open rack LNG vaporizer known as SuperORV. SuperORV have a duplex heat transfer tube structure and perform better thermal efficiencies compared to the conventional ORV. The ORV was invented to be SuperORV sort subsequent to 1988 in Osaka, Japan. (Endo,n.d). In this way, in this paper the new innovation of ORV are being connected as it was been utilized these days. According to Jin et (2014) , SuperORV contains the twofold tube structures which is the vaporization section (lower part) and heating section (upper part) . Jin et al. (2014) likewise clarified that the vaporization section of the tubes heat and vaporize the sub cooled LNG to the natural gas state while the heating section heats the natural gas to the superheated state. The double structured of the heat transfer tube allow the slim gas layer to flow between the external side of the tube and LNG. This could prevent the ice formation at the outer surface of the heat transfer tube.

The heat transfer calculation can be computed by dividing along the heat transfer tube based on constant enthalpy difference using the heat transfer and energy conservation equations. As per Yamazaki et al (1998), the vaporization rate of the ORV is 350 kg/h per heat transfer tube with sea water/LNG flow rate ratio of 30.The figure of the mass flow rate and fluid ratio can be obtained by referring to Figure 2.3 .

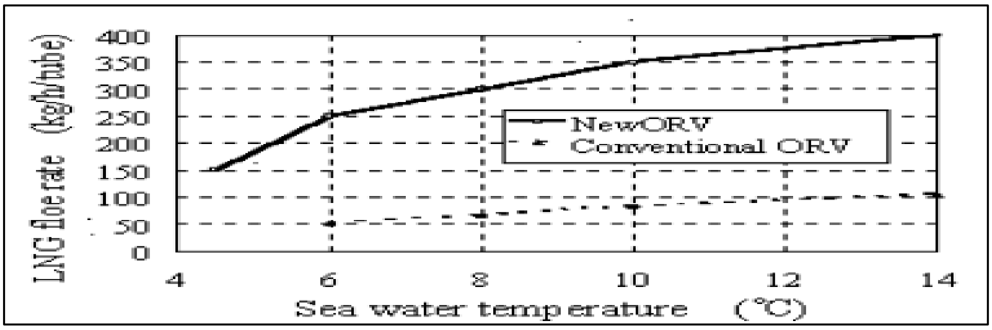

FIGURE 2.3 Sea water temperature and LNG flow rate

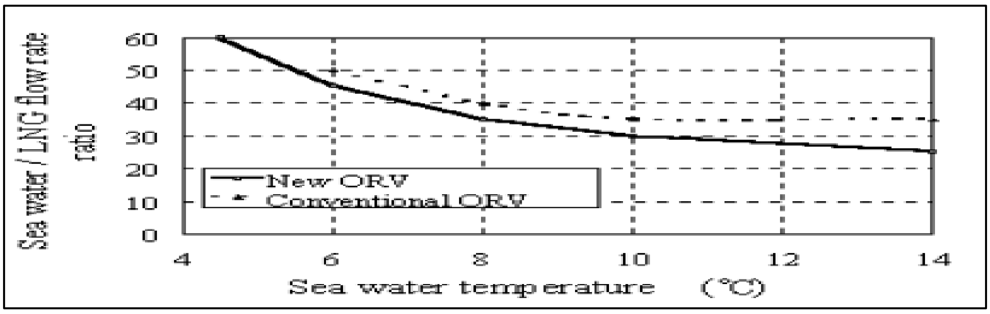

FIGURE 2.4 Sea water temperature and sea water/LNG flow rate ratio

Yamazaki et al. (1998) additionally found that the ideal length of the heat exchange tube is 8 m. An appropriated parameter model was assembled by Jinn et al (2014) in order to simulate the LNG evaporating process in the SuperORV heat transfer tube. In this case, some specialized parameters had been presents as in Table 2.1.

TABLE 2.1 Technical parameters and boundary condition for simulation

Parameters	Values	Parameters	Values
OD of finned tube (mm)	40	Flow rate of LNG (kg/s)	0.06
ID of finned tube (mm)	24	Inlet temp. of LNG (K)	133
OD of inner tube (mm)	18	Outlet temp. of sea water (K)	280
ID of inner tube (mm)	14	Required outlet temp. of NG (K)	275
Flow rate of sea water (kg/s)	2.5	Design pressure (MPa)	4

Source: Simulation and performance analysis of ORV

According to the simulation condition, The LNG will enter the ORV at 133 K (-140 ℃) and leaving in the vaporous stage at around 187K (-86 ° C) which is at the saturation temperature of 4 Mpa. Hypothetically, the saturation temperature is the temperature for a corresponding saturation pressure at which a liquid bubbles into its vapor stage.

2.3.2 Intermediate Fluid Vaporizer (IFV)

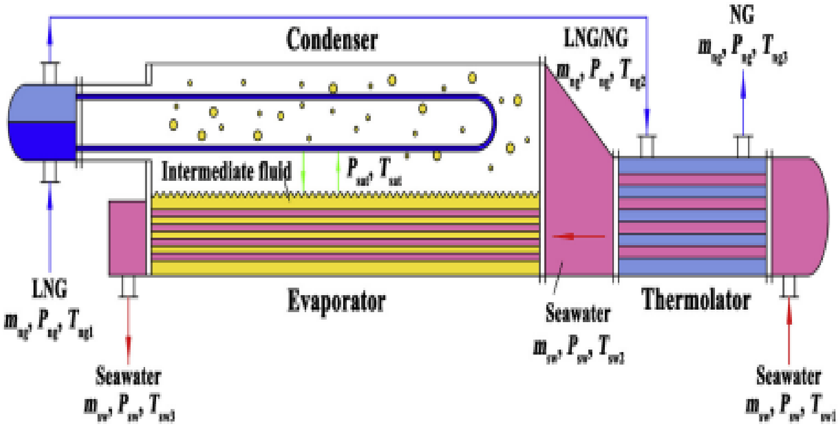

FIGURE 2.5 Intermediate Fluid Vaporizer (IFV) Schematic Diagram

IFV is a vaporizer which does not vaporize the LNG directly. Instead of using direct heating system, IFV used the heating medium such as propane, the refrigerant and water-glycol blend to vaporize the LNG .The intermediate fluid candidate may vary but the selection of intermediate fluid should be made cautiously since it can influence heat transfer coefficient (HTC) of the vaporizer (Xu et al.,2015).

In the meantime, the intermediate fluids in the reported applications are mostly constrained to propane. (Bai et al,2013 ;Xu et al., 2015).Also, propane have a decent thermodynamic properties which is low flash point and high latent heat. (Karsten, 2010; Xu et al., 2015).

The IFV have some advantage over the alternate sorts of LNG vaporizers. Generally, it is having better versatility than the ORV. There are no icing issues and plus, require low seawater quality. The IFV likewise have better vitality proficiency in contrasted with SCV, in which no burning are involved in the system. (Dendy and Nanda,2008;Lin et al. 2013;Patel et al.,2013;Pu et.al,2014; Xu et al.,2015)

IFV system consists of three type of shell and tube heat exchanger which are evaporator, condenser and thermolator. Firstly, the intermediate fluid is vaporized by a heating medium which is the sea water and then will be condensed to the base of the shell (Fenxia,2013).Meanwhile, the cold LNG with temperature -161°C is being hosted into the titanium heat transfer tube at evaporator and result in the heat transferred between the LNG and the heat generated by the condensation. The LNG is then vaporized and the resultant natural gas produced is heated by the heat exchanger of thermolator to a temperature rise equaling to 15°C. Xu et al. (2015) turn out with the configuration detail of the average IFV in his examination paper which is referred to Table 2.1.

TABLE 2.1 Design specification for the LNG regasification task

LNG/NG				Seawater				Intermediate fluid	
m_{ng} (kg s^{-1})	P_{ng} (kPa)	T_{ng1} (K)	T_{ng3} (K)	P_{sw} (kPa)	T_{sw1} (K)	T_{sw2} (K)	T_{sw3} (K)	Type	T_{sat} (K)
90	12,000	111.15	275.15	400	283.15	280.15	278.15	Propylene/propane/isobutane/butane/dimethylether	263.15–268.15

Source: Journal of Natural Gas and Engineering

Based on this table, the Natural gas was rejected from the thermolator at 12 kPa with the mass flow rate of 90 kg/s. The gulf seawater temperature is about at 10 °C. Notwithstanding, Iwasaki et al (2002) argued, in which he expressed that the temperature of the seawater would vary between 4°C to 6°C.

The LNG is gasified into natural gas with the temperature of 2-3°C. (Fengxia,2013).According to Fenxia (2013), the operating pressure of intermediate fluid is at 0.45 Mpa with its resultant saturation temperature of -1.65 °C. Therefore, the temperature of the propane should not higher than -1.6 °C to ensure it was remain as in liquid state.

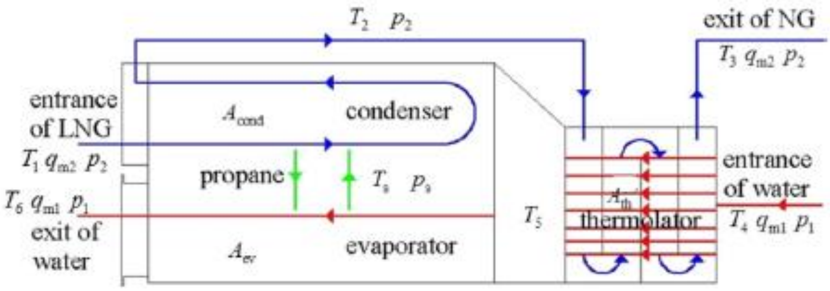

FIGURE 2.6 Sketch schematic of the IFV heat transfer process

Based on the Figure 2.6, Pu et al. (2014) likewise gives the geometric parameters and the heat transfer areas of the evaporator, condenser, and thermolator as in Table 2.2. While, the default values for the known parameters are indicated in Table 2.3.

TABLE 2.2 Fundamental geometrical parameters of the IFV

Item	Evaporator		Condenser		Thermolator	
	Symbol	Value	Symbol	Value	Symbol	Value
Area of heat transfer (m^2)	A_{ev}	1507.2	A_{cond}	602.88	A_{th}	400.4
Length of tube (m)	L_{ev}	16.0	L_{cond}	16.0	L_{th}	3.6
External diameter of tube (m)	$D_{ev\text{-}O}$	0.02	$D_{cond\text{-}O}$	0.02	$D_{th\text{-}O}$	0.02
Internal diameter of tube (m)	$D_{ev\text{-}I}$	0.016	$D_{cond\text{-}I}$	0.016	$D_{th\text{-}I}$	0.016

Source: Journal of Applied Thermal Engineering

TABLE 2.3 Default value of known parameter

T_4 (K)	T_1 (K)	q_{m2} (kg s^{-1})	q_{m1} (kg s^{-1})	p_1 (MPa)	p_2 (MPa)
283.0	108.0	95.0	2500.0	0.4	12.2

Source: Journal of Applied Thermal Engineering

Based on Table 2.3, the temperature of the inlet of sea water was the same as stated by Xu et al (2015) which is at 10°C at 0.4 Mpa while the entrance of LNG is at -165°C with 122 Mpa. The mass flow rate of LNG are almost similar with Xu et al. (2015) studies which are ate 95 kg/s. In her study, the mass flow rate of sea water was assumed at 2500.0 kg/s.

2.3.3 Submerged Combustion Vaporizer

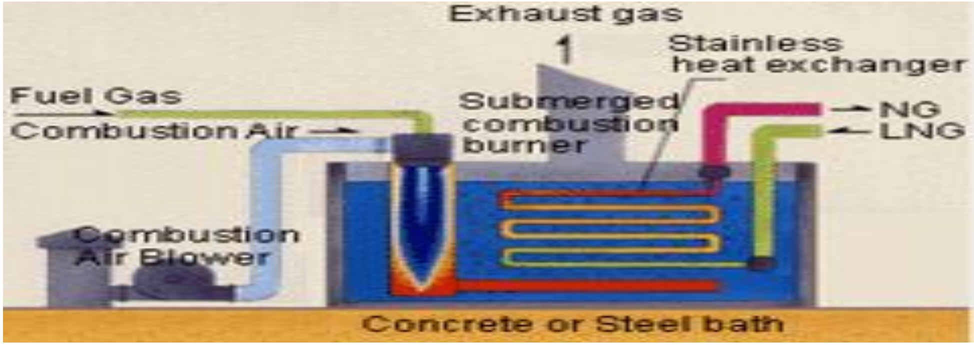

FIGURE 2.7 Submerged Combustion Vaporizer Schematic Diagram

As indicated by Faka (2011), the SCV embody a tube immersed in water which with a combustion gas infused into the burner. The regular SCV system was demonstrated in figure 8 where the burning items are released into the water bath (Engdahl,2007).

LNG flows through a stainless steel tube coil in the water bath which directly in contact with the hot pipe gas from a submerged gas burner (Patel, 2013). Ertl et al. (2005) likewise clarified about the SCV system where the water bath act as an intermediate fluid for exchanging the heat from combustion to the LNG. The flue gas is sparging into the water using a distributor which located under the heat transfer tubes.

According to Patel (2013), among of other vaporizer, SCV would give a higher thermal efficiency reaching up to 98% yet obliges a higher operation cost. This is because, the burner system involves a high horsepower blower to provide the combustion air. As the SCV depths goes deeper, a larger horsepower combustion air blower was required (Engdahl, 2007).

Generally, the fuel burnt by the SCV's system makes their running cost is more expensive than others. It is because the SCV system require approximately 1.5% of the aggregate vaporized LNG as a fuel gas (Ertl et al, 2005).According to Dinh (n.d) due to its high operating cost, SCVs is then usually used as a back-up facilities in LNG regasification system. However, the construction cost of SCV can be lessened since it does not require any facilities for water intake and discharge compared to ORV and IFV (Egashira, 2013).

As known theoretically, the heat capacity of water is at 4.18 kJ/kg.C. Egashira (2013) enlightened one of the special features of SCV which in case of the combustion burner stop, this high heat capacity enable heating to proceed from the supply of vaporizer gas within a restricted time.

However, the SCV have its own limitation for operation. According to Petel (2013) the water bath is acidic as the combustion gas product condensed into the water. The acidity carries a few drawbacks which would erode the heat transfer tubes as well and additionally can imperil the marine life once the water bath is being released to open water. Therefore, the caustic chemicals such as sodium carbonate or sodium bicarbonate are necessary to added to water bath so that the pH level can be controlled effectively

.

2.1.1 Decomposition method

2.2.1 Decomposition method overview

According to Nanduri (1998) in her paper, as from the most recent decade, indicators that reflect changes in energy intensity have been utilized to screen productivity advance and distinguish business patterns and proficiency for performance enhancement opportunities. Decomposition methods, which endeavor to disentangle changes in structural effects from changes in “pure” energy intensity are useful for contemplating and comprehension the evolution of industrial energy consumption patterns and for forecasting energy demand (Ang and Lee, 1994; Nanduri, 1996).Generally, there are several numerical methods to calculate the energy intensities via this decomposition analysis such as :

i. Laspeyres method
ii. Paasche index
iii. Simple average divisia method
iv. Fischer Ideal

v. Parametric Division Method I (PMD I) and II (PMD II)

vi. Log Mean Division I (LMD I) and II (LMD II)

According to Heinen (2013) , Laspeyres and LMD I are the favored techniques since it is simpler to be caught on. Heinen (2013) also explained in his training pack of Internal Energy Agencies about the energy use with decomposition method where it's generally used to quantify the relative contributions of pre-defined factors to the change of energy consumption. Besides, this method can track down the origin in the energy consumption variations.

Several decomposition method was used to capture the adjustments in the drivers of energy demand and thus to isolate the changes in energy efficiency (Ang and Choi 1997; Baksi and Green 2007). Thus, with this method, the effectiveness of the technology can be measured in an ideal way.

2.1.1 Existed operational energy intensity analysis by decomposition method

This study was being done by the previous researcher who is Liu et al. (2015) which saying that through this study, the energy flows was analyzed through the five sequential loops which extract energy from the conditioned spaces and rejects it to the environment. Liu et al. (2015) further explained that this decomposition method is to analyze the impact of specific consumption and delivered fluid ratio on global energy intensity.

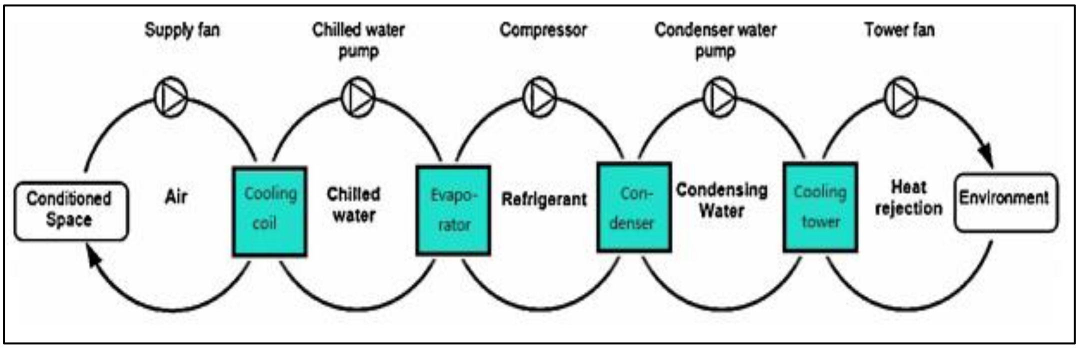

FIGURE 2.8 Entire thermal loops for a typical air HVAC system with water-cooled chiller

The operational of HVAC system shown in Figure 2.8 can be deduced as a heat transfer series that extract the energy from conditioned spaces and reject it to the environment via five consecutive loops which are air loop(AL),chilled water loop (CHL),refrigerant loop (RL), condensing loop (CL) and heat rejection loop (HRL).

Each loop embraces energy consumption devices and are interconnected by heat exchanger devices (Liu et al.,2015). According to Liu et al (2005) in their paper, Global energy consumption of the HVAC system can be obtained by the summation of the energy use of all its energy consuming devices in its sequential five loops.

$$C_{HVAC} = \sum_{i=1}^{5} C_i = C_{AF} + C_{CHP} + C_{COM} + C_{CDP} + C_{TF} \tag{1}$$

The energy intensity of the HVAC system can be express as the following equation, where EI is the energy intensity after its meet the thermal comfort condition, kW/kW and Q is the cooling load,kW after its meet the thermal comfort. L_i is the volume of delivered fluid ratio of *i*th loop, m³/h.

$$\begin{aligned} EI = \frac{C_{HVAC}}{Q} &= \frac{C_{AF} + C_{CHP} + C_{COM} + C_{CDP} + C_{TF}}{Q} \\ &= \frac{C_{AF}}{L_{AF}} \times \frac{L_{AF}}{Q} + \frac{C_{CHP}}{L_{CHP}} \times \frac{L_{CHP}}{Q} + \frac{C_{COM}}{L_{COM}} \times \frac{L_{COM}}{Q} + \frac{C_{CDP}}{L_{CDP}} \times \frac{L_{CDP}}{Q} \\ &\quad + \frac{C_{TF}}{L_{TF}} \times \frac{L_{TF}}{Q} \end{aligned} \tag{2}$$

The effect of the change of specific consumption and delivered fluid ratio on the energy intensity (EI) can be calculated as by the equation.

$$\begin{aligned} \Delta EI &= \sum_i \left(e_i^{''} p_i^{''} - e_i^{'} p_i^{'}\right) = \sum_i \left(e_i^{''} p_i^{''} - e_i^{'} p_i^{''} + e_i^{'} p_i^{''} - e_i^{'} p_i^{'}\right) \\ &= \sum_i p_i^{''} \left(e_i^{''} - e_i^{'}\right) + \sum_i e_i^{'} \left(p_i^{''} - p_i^{'}\right) \end{aligned} \tag{3}$$

Where the right hand side equation referring to the effect of the changes of specific consumption on energy intensity while the left hand side referring to the effect of the changes of delivered fluid ratio on energy intensity.

CHAPTER 3
METHODOLOGY / PROJECT WORK

3.1 Project Flow Chart

The methodology of this study is divided into three parts which had been summarized as follows;

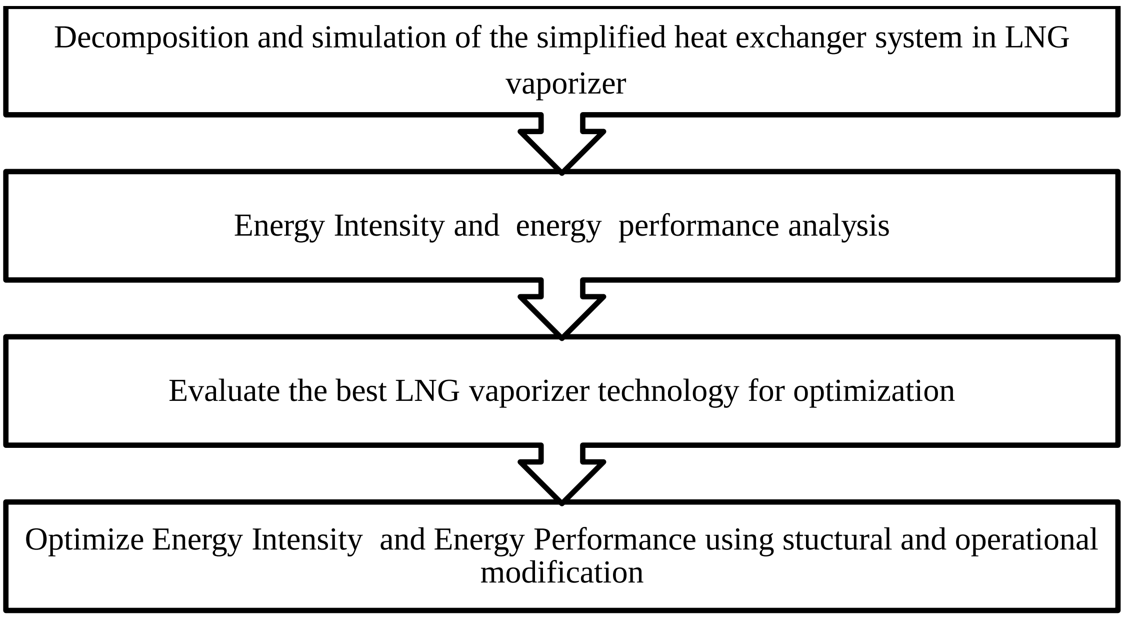

FIGURE 3.1 Project flow chart

3.2 Process Simulation

The software used in this study was Aspen Hysys version 8.0.The chosen Fluid Package is Peng Robinson since it is the most compatible package for the oil and gas based component in the simulation. Then, the equipment was arranged according to the process scheme and the streams were defined by specifying all the parameters required for the simulation By specifying the involving parameters, choosing the right thermodynamics packages, and following the right decomposition of vaporizer system, the Energy Intensity of the LNG vaporizers can be determined precisely.

3.2.1. Basis of simulation

To obtain the reliable result, the basis of the simulation was made based on the normal operating condition of LNG vaporizer. For this case of study, the basis was applied to all type of vaporizer for comparative study purposes.

TABLE 3.1 Basis of simulation

Properties	**Values**
Mass flow rate of LNG	300 kg/h
Mass flow rate of Sea water	9600 kg/h
Mass Flow rate Propane	100 kg/h
Temperature LNG inlet	-162 °C
Temperature Sea water inlet	25 °C
Temperature of Propane	-1.66 °C
Composition (wt%)	CH_4 : 89.63
	C_2H_6 : 6.32
	C_3H_8 : 2.16
	C_4H_{10} : 1.20
	N_2 : 0.69

Source: *Liquefied Gas Carrier (2013)*

3.3 Decomposition of LNG vaporizer system

Operational energy intensity of a LNG vaporizer system is analyzed by decomposing the complex system into a sequence of heat exchanger system. The method allows the operational energy intensity and the whole energy performance of the system to be measured precisely. The decomposition for this type of LNG vaporizer system is discussed in the following sections.

3.3.1 Open Rack Vaporizer

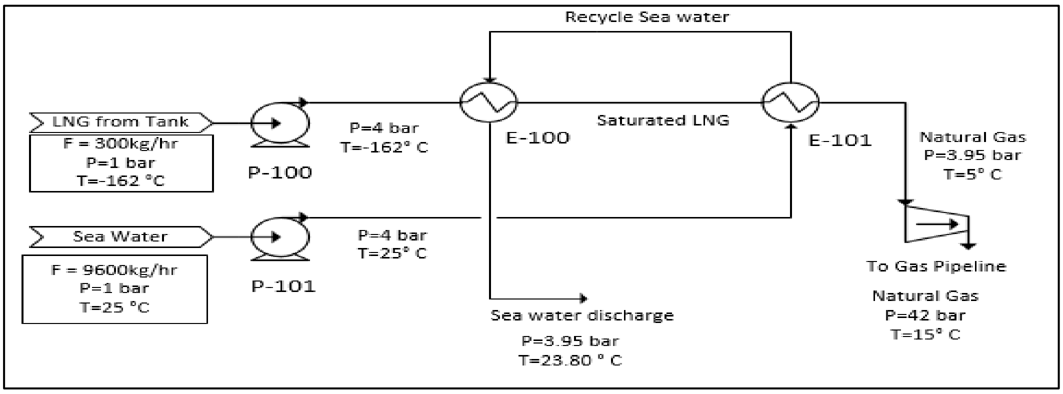

FIGURE 3.2 Simplified heat exchanger system of Open Rack Vaporizer

Based on Figure 3.2, the Open Rack Vaporizer, ORV system is decomposed into two sections which are used for heating and vaporization of LNG.E-101 is used for heating up the resultant saturated natural gas from vaporization section E-100 to 5°C .

The seawater coming out from E-101 Is used to be as the hot utility for LNG vaporization through E-100 at 4 barg. In E-100, LNG is vaporized to saturation and then flowing through E-101 to be heated .Before being distributed into the gas pipeline, the natural gas produced throughout this system are compressed into gas pipeline pressure, 42 barg.

3.3.2 Intermediate Fluid Vaporizer

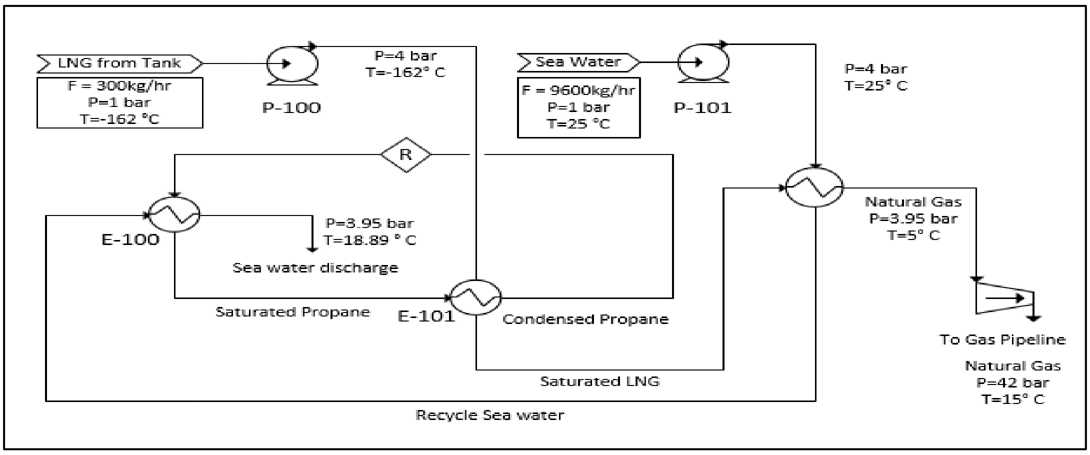

FIGURE 3.3 Simplified heat exchanger network of Intermediate Fluid Vaporizer

Based on the above figure, the whole Intermediate Fluid Vaporizer system, IFV is decomposed into three sections which are used as the Intermediate Fluid vaporizer, LNG vaporizer and Natural Gas heater.

In an IFV system, the seawater is the heating medium for LNG regasification. The seawater is injected into the vaporizer through E-102 at 4 bars and flowing into the tube of E-100 to bring the propane into saturation. The vaporized propane will heat up the LNG and allows the saturation of LNG in the stream. The resultant saturated LNG is then flowing into the tube side of E-102 to be heated up to 5°C and compressed to 42 barg before being injected into the gas pipeline.

3.3.3 Submerged Combustion Vaporizer

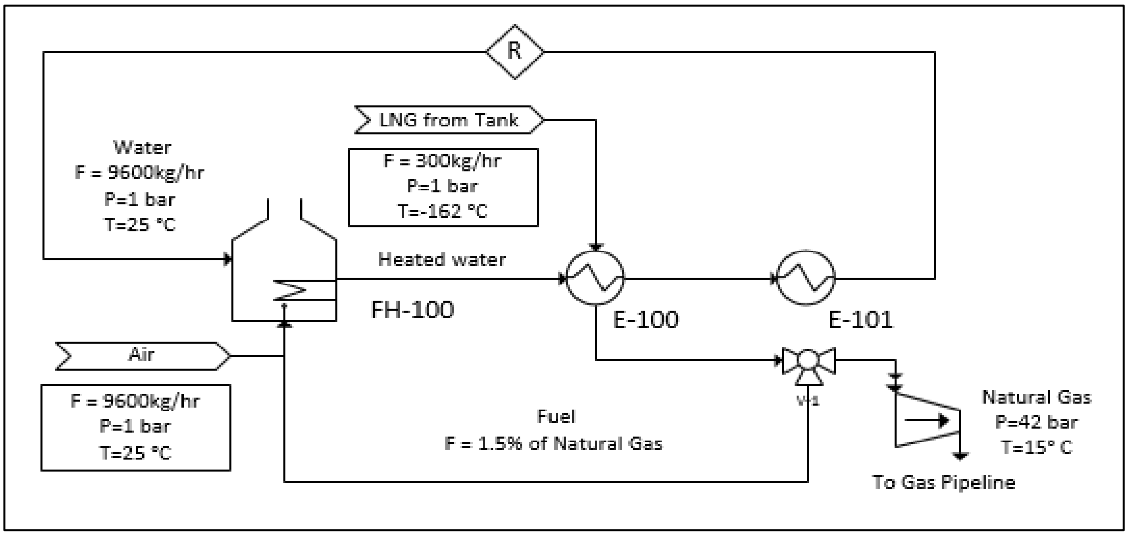

FIGURE 3.4 Simplified Submerged Combustion Vaporizer system

Referring to Figure 3.4, Submerged Combustion vaporizer can be decomposed into two sections which are combustion and vaporization section. In this system, the combustion is take place in the fired heater for heating up the water.

The heat energy in the heated water from fired heater is then conveyed to the LNG stream through E-100. The LNG in turn is to 5 °C and compressed at 42 bars before distributed into the gas pipeline. In SCV system, 1.5% of the natural gas produced is then being used again as the fuel for combustion to take place.

3.4 Performance Analysis

Each component in the vaporizers must be analyzed to determine the best vaporizer which gives the highest efficiencies. This must be done in terms of Energy Intensity as well as the Thermal and Exegetic efficiencies.

3.4.1 Operational Energy Intensity

Energy Intensity was defined the amount of energy used in producing a given level of output or activity (US Department of Energy, 2015). Energy Intensity have very wide application in many sectors, such as in transportation, industrial, residential, electricity and etc. Basically, in many cases, the energy intensity was calculated as unit of energy per unit of Gross Domestic Product (US Department of Energy, 2015).

However, concerning the concept of operational energy intensity in the vaporizer systems, it was defined as the amount of energy consumed to vaporize every kilogram of LNG to 5°C of Natural Gas. In this research, Energy Intensity was used as an indicator for the energy consumption of the systems. The energy intensity for each of vaporizer system can be calculated as the follows;

$$EI = (\Sigma\ Q)/m_{i,LNG} \tag{4}$$

Where; EI = Energy Intensity, kWh/kg

Q = Heat Duty, kJ/hr

$M_{i,LNG}$ = Mass Flow rate inlet of LNG

After calculating the energy intensity, the vaporizers was then evaluated to determine which technologies give the lowest energy intensity for LNG vaporization.

3.4.2 Heat Transfer equation and First Law Efficiency

Referring to Equation 5, the 1st law efficiency or also known as thermal efficiency follows the 1st law of thermodynamics which subjected the principle of conservation of energy where the energy cannot be created nor destroyed (Lucas, 2015). However, it can be converted to another form of energy. Hence, the ratio of energy in and out of the system should not be less than 1.

According to Chalmers (2011), the energy efficiencies describe how much energy had been recovered by the equipment with respect to the total energy supplied to the system .The heat recovered by the equipment was related to the 1st law efficiency where higher energy efficiency will result a better energy performance.

The heat duty can be calculated as follows;

Heat Exchanger (Phase Change);

$$Q = m \times \lambda \tag{5}$$

Where Q = Heat duty or the total heat transferred, kW

m = Fluid mass flow rate, kg/s

λ = Latent heat of vaporization/condensation, kJ/kg

Heat Exchanger (No Phase Change);

$$Q = m * C_P * \Delta T \tag{6}$$

Where Q = Heat duty or the total heat transferred. kW

m = Fluid Mass flow rate, kg/s

C_p = Heat capacity , J/kg.°K

ΔT = Temperature change in fluid, °C

Fired Heater;

$$Q_u = Q_{heated\ fluid} - Q_{fluid\ in} \tag{3.1}$$

Where Q_u = Heat Duty , kJ/h

$Q_{heated\ water}$ = Heat Flow in heated water , kJ/h

$Q_{water\ feed}$ = Heat Flow in water feed , kJ/h

The energy balances for any system are as the following equation;

Heat Exchanger;

$$m_H \times Cp_H \times (Ti_H - To_H) = m_C \times Cp_C \times (To_C - Ti_C) \quad (7)$$

Where m = Mass flowrate of the stream

Cp = Heat Capacity of the stream

T = Temperature of the stream

Fired Heater ;

$$Q_{rls} + Q_{air} + Q_{fuel} + Q_{fluid} = Q_R + Q_{shld} + Q_{losses} + Q_{flue\ gas} \quad (8)$$

Where ; $Q_{in} = Q_{air} + Q_{fuel} + Q_{fluid}$

$Q_{out} = Q_R + Q_{shld} + Q_{losses} + Q_{flue\ gas}$

Thermal efficiency can be obtained from the following formula;

Heat Exchanger;

$$\eta_{1st\ law} = (W_{net\ out})/(Q_{in}) = (Q_{in})/(Q_{out}-Q_{in}) = 1 - (Q_{out})/(Q_{in}) \times 100 \quad (9)$$

Where η_{th} = 1_{st} law efficiency

$W_{net\ out}$ = Net work output,

Q_{in} = Heat absorbed into the system

Q_{out} = Heat rejected from the system

Fired Heater;

$$\eta th = (Q_n)/(Q_{in}) \times 100 \quad (10)$$

Where η_{th} = 1_{st} law efficiency/Thermal Efficiency

Q_n = Heat Duty ,Kj/h

Q_{in} = $Q_{air} + Q_{fuel} + Q_{fluid}$

3.4.3 Exergy Equation and Second Law Efficiency

Gundersen (2011) explained that the exergy of a system was defined as the maximum amount of work that can be obtained when the system moves from the system to the ideal condition where equilibrium with the surrounding. In other words, exergy is the amount of energy which available to be used. Once the system reach equilibrium, the amount of exergy would be zero (Aaron, n.d). In contrast with the principle of conservation of energy, exergy accounts for the irreversibility of a process due to the decrease of the entrophy. Thus, the exergy was always destroyed due to the temperature changes. (Honerkamp ,2002).The exergy can be obtained by the following formula ;

$$e = (h-h_o)-T_o\,(S-S_o) \qquad (11)$$

Where e = Exergy flow , kJ/kg

h_o = Enthalpy at reference temperature

h = Enthalpy at respective temperature

S_o = Entropy at reference temperature

T_o = Reference Temperature

Second law efficiency or also known as exegetics efficiencies is a measure of the energy quality which it comparing the system thermal efficiency to the maximum possible efficiency. To analyze the second law efficiencies, the exergy source,E_{source} and exergy sink, E_{sink} for all equipment must be calculated using Equation 12.

Heat Exchanger;

The exergy which comes from the hot stream was sink to the cold stream of the heat exchanger. The exergy source and sink, Ei for heat exchanger can be calculated by Equation 3.10.

$$E_i = m_i\,(e_{i,outlet} – e_{i,inlet}) \quad (12)$$

Where Ei = Exergy source and exergy sink

mi = Mass Flowrate

$e_{i,outlet}$ = Exergy of outlet stream

$e_{i,inlet}$ = Exergy of inlet stream

Fired Heater;

The exergy source was come from the fuel, air mixture and the flue gas while the exergy was sink to water stream which flowing through the fired heater.

Exergy source, E_j for fired heater is

$$E_j = m_j(e_{j,fuel\ gas} + e_{j,air} + e_{j,flue\ gas}) \quad (13)$$

Where E_j = Exergy sink for fired heater

m_j = Mass Flowrate of fired heater

$e_{j,fuel}$ = exergy of fuel gas stream

$e_{j,air}$ = exergy of air stream

$e_{j,flue\ gas}$ = exergy of flue gas stream

Exergy sink,E_k of fired heater is ;

$$E_k = m_k\,(e_{k,water\ in} - e_{k,heated\ water}) \quad (14)$$

Where E_k = Exergy sink for fired heater

m_k = mass flow rate of fired heater

$e_{k,water\ in}$ = exergy of water in stream to the fired heater

$e_{k,heated\ water}$ = exergy of heated water stream

From the exergy data obtained, the second law efficiencies can be calculated through this equation;

$$\eta_{2nd\ law} = (\Sigma\ E_{sink})/(\Sigma\ E_{source}) \times 100 \quad (15)$$

Where $\eta_{2nd\ law}$ = Second law efficiency

$\Sigma\ E_{source}$ = Summation of Exergy source

$\Sigma\ E_{sink}$ = Summation of Exergy sink

3.5 Energy Performance Analysis

The best LNG vaporizer technology for optimization was then being selected by evaluating the three parameters which would give the lowest operational energy intensity, with the maximum performance efficiency.

3.6 Energy Performance Optimization

In order to improve for a better system performance, the influential parameters of LNG vaporizer should works at the optimum condition and a few modification for the system should be suggested subsequently so that a lower operational energy intensity of LNG vaporizer can be obtained with a higher energy performance

3.7 Gantt chart and key milestones

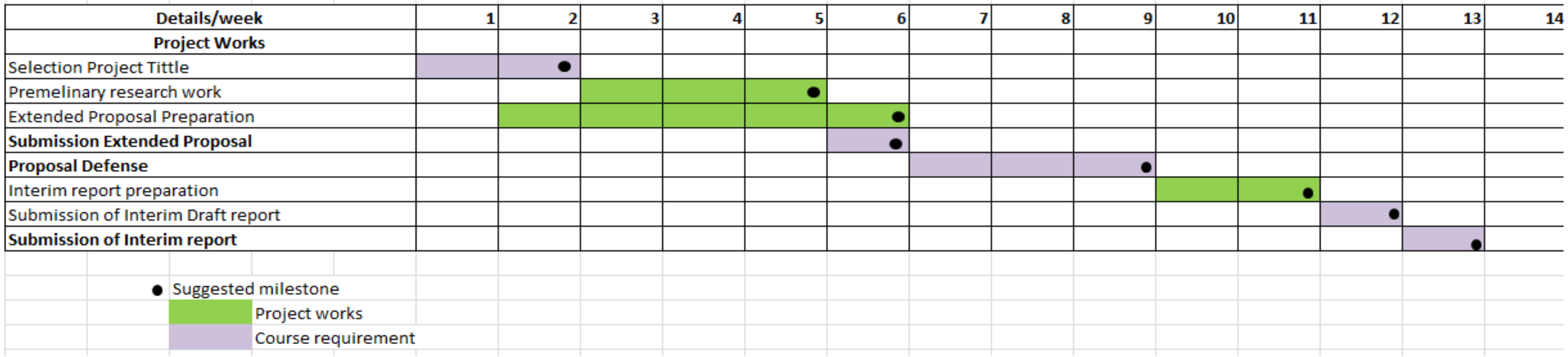

FIGURE 3.5 Gantt Chart for FYP I

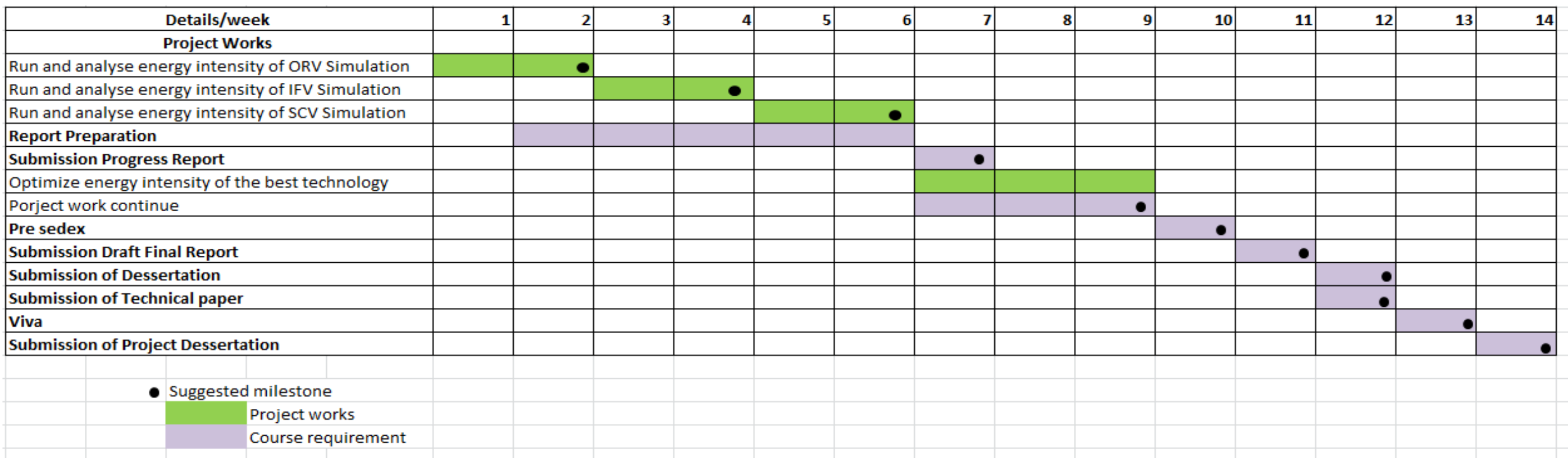

FIGURE 3.6 Gantt Chart for FYP II

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Operational Energy Intensity and System Performance Analysis

After the decomposition of LNG vaporizer system was carried out, an analysis of operational energy intensity and energy performance are required in order to select the best technology for a system optimization. The analysis has been discussed briefly in the following sections.

4.1.1 Operational Energy Intensity Analysis

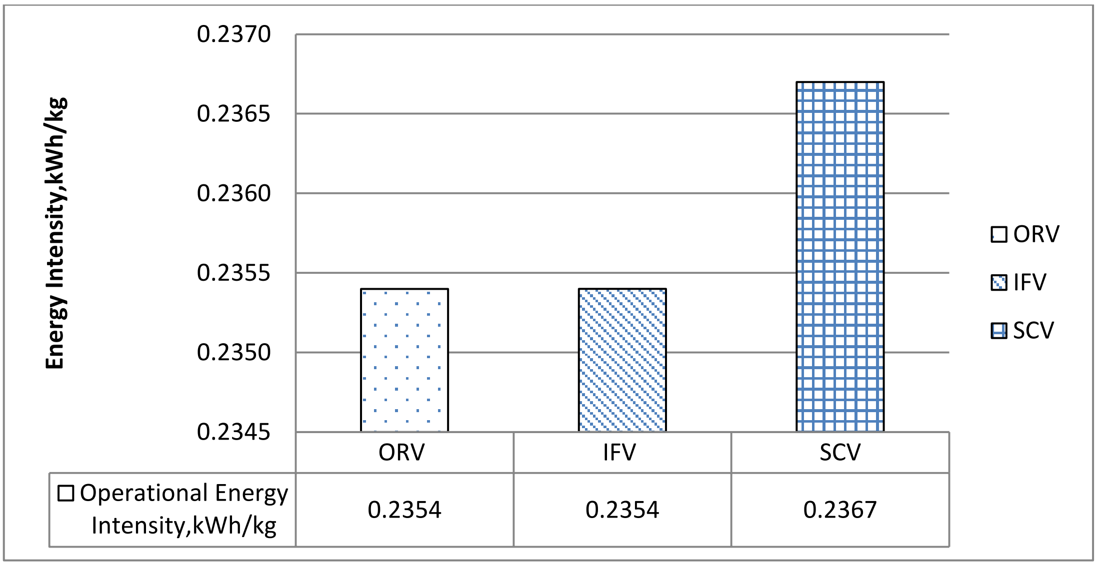

FIGURE 4.1 Operational Energy Intensity of LNG vaporizers

Above figure shows the amount of energy intensity of ORV, IFV and SCV vaporizers to regasify 300 kg/hour LNG into 5°C of Natural Gas. As accordance to analysis, SCV consume the highest amount of operational energy intensity which is 0.2367 kWh/kg compared to the other type of vaporizer.

By studying the system of SCV in Figure 3.4, the energy intensity is basically from the duty of FH-100 and E-101. The duty from E-100 is not contributed into the energy intensity since it is just receiving the energy conveyed from FH-100 for LNG vaporization. Thus, FH-100 gives a huge duty into the system and superficially contributes a major amount of energy intensity which is at 0.2069 kWh/kg.

Another finding which clearly shown from Figure 4.1 is ORV and IFV having the same amount of operational energy intensity which is at 0.2354 kJh/kg.It is because, E-100 and E-101 in ORV gives the same duty as E-100 and E-102 in IFV system. As from an analysis in IFV system, E-101 duty does not contributed to the amount of operational energy intensity as it consumed the energy conveyed from E-100 for LNG saturation process.

Since, ORV and IFV gives the same amount of operational energy intensity, therefore an extensive analysis with regards of its energy performance are required in order to select the best LNG vaporizer technology for modification and optimization..

4.1.2 Energy Performance Analysis

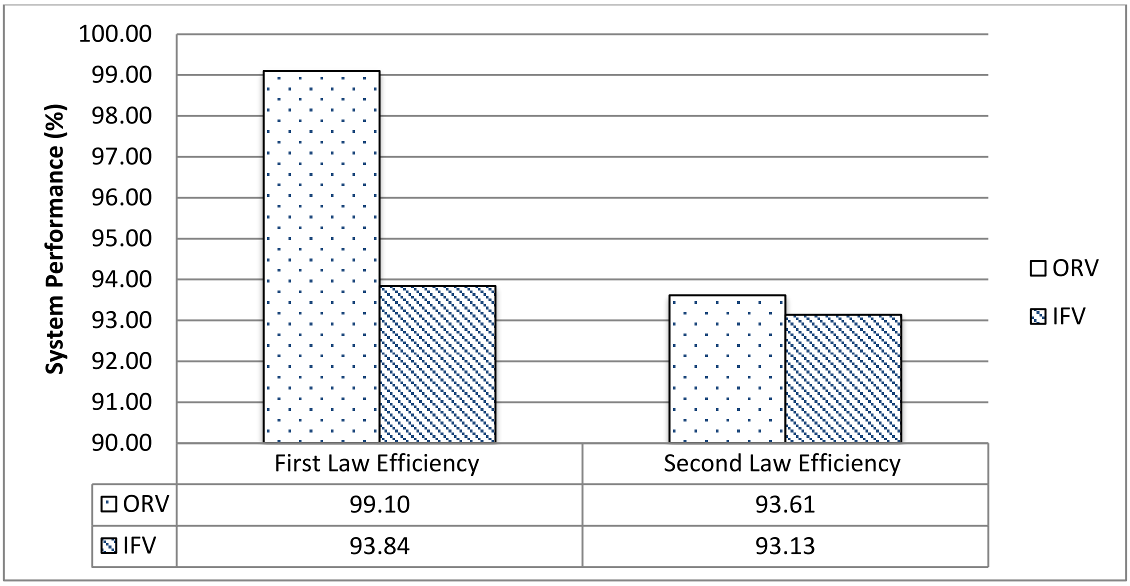

FIGURE 4.2 Energy Performance Analysis of ORV and IFV

In an energy performance analysis, First Law and Second Law Efficiency have been evaluated. Theoretically, First Law Efficiency is derived from the First Law of Thermodynamics which stated that the energy cannot be created nor destroyed. The First Law Efficiency or also known as Thermal efficiency provide a quantification of the amount of energy transferred to a given desired and relative to an input (Ford,et al.,1975). In other means, a lower amount of First Law Efficiency indicate that there are more heat loss from the system as there are not much energy has been transferred to the desired system. Besides, Second Law Efficiency is defined as a measure of how much is the system's thermal efficiency has been achieved as compared to maximum possible efficiency. The effectiveness of the system can be evaluated as the difference to the theoretical ideal process can be measure in term of its exergy. Its present a lower values as higher exergy is destroyed in a process (Andre, 2010).

Based on Figure 4.2, the first law efficiency of ORV and IFV are 99.10% and 93.61% respectively. As from an analysis, the first law efficiency of ORV is 5.5% higher than IFV. Which mean, more heat are losses in IFV system compared to ORV.

Besides, ORV also has a higher mean of second law efficiency compared to IFV which is 93.61% and 93.13% respectively. It is clearly shown that ORV vaporizer system has the most effective efficiency as compared to IFV since it has a lesser amount of exergy destroyed from the system. Therefore, ORV system can be described as the best LNG vaporizer which will be modified for system optimization stage in this project.

4.2 System Optimization

In system optimization stage, there are two modifications have been categories into this project which are:

a) Structural modification
b) Operational modification

4.2.1 Structural modification

4.2.1.1 Alternatives structure

Structural modification is the first step for a system optimization on ORV system. Basically, is to determine the best structure for ORV to obtain a better energy performance. In this project, there are three alternatives which are found to be applicable on ORV system. These alternatives had been designed based on the present ORV structures.

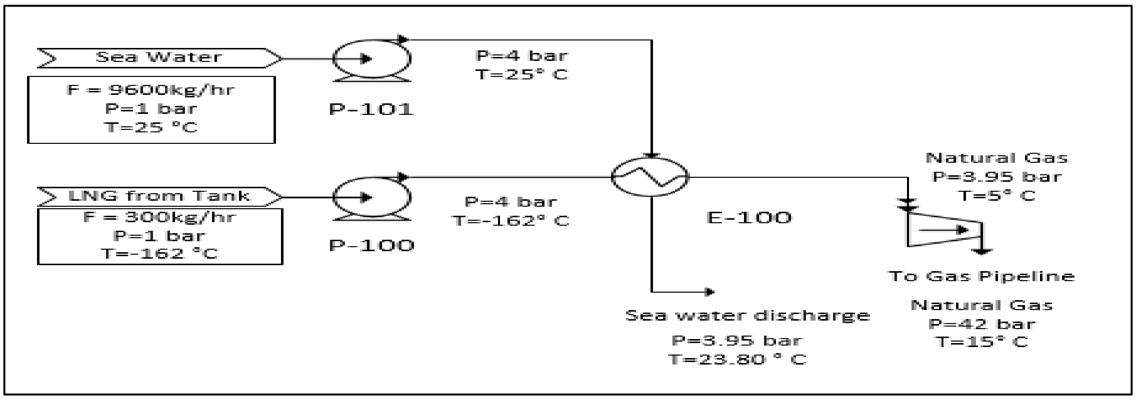

FIGURE 4.3 Alternative I Structure

The above figure shows the heat exchanger system in Alternative I structures which has been modified for ORV System. In this structure, LNG is vaporized directly by sea water to 5 °C throughout E-100. The heating section from the present ORV structure has been removed from this modified ORV structure.

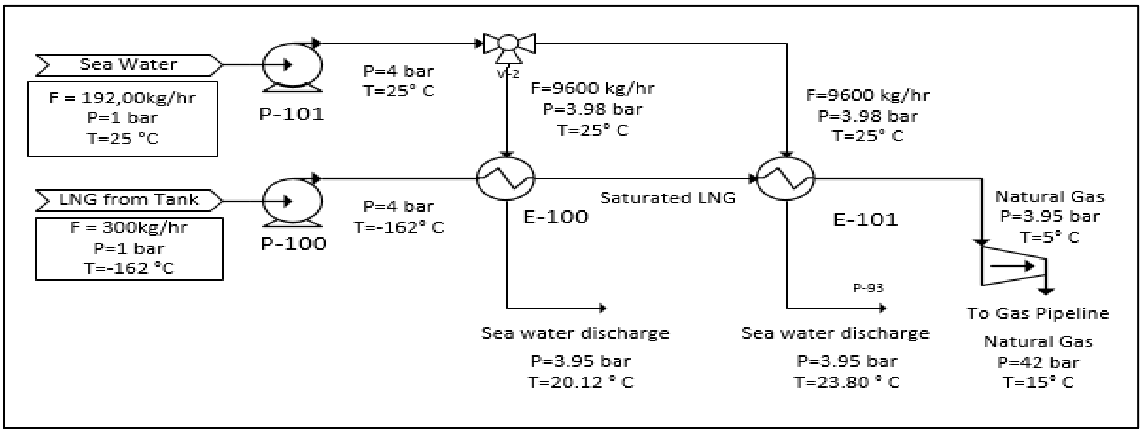

FIGURE 4.4 Alternative II Structure

Alternative II structure is illustrated as in the above figure. In this modified system, the fresh sea water has been introduced into both heat exchangers of heating and vaporization section. It is because, in the present ORV structure, the heating medium of E-100 is introduced from the heating section, E-101.The restricted amount of heat energy contained in the sea water from E-101 may affect the performance of the overall system.

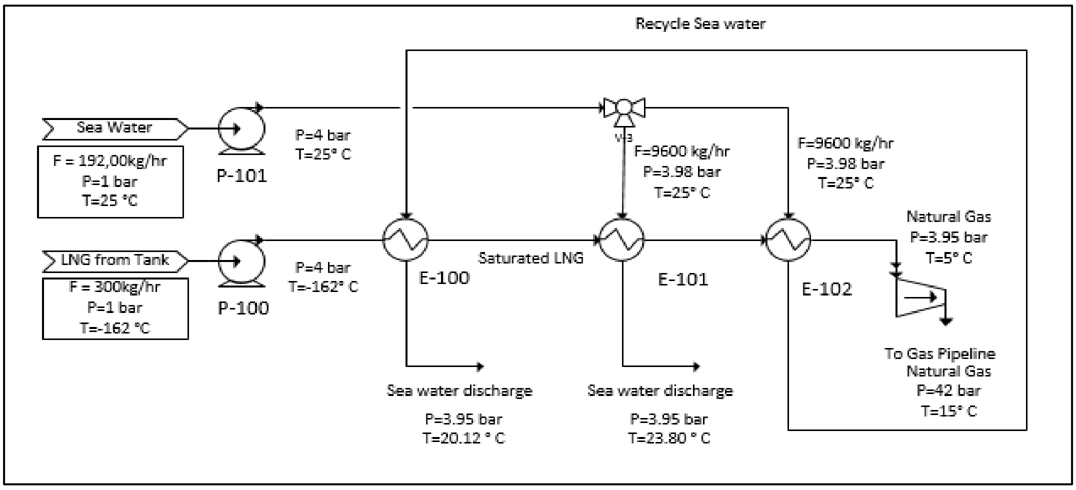

FIGURE 4.5 Alternative III Structure

The schematic diagram in Figure 4.5 shows the third alternative applicable for ORV system. In this modified system, E-100 has been installed and used for reheating the LNG from heating section and brings it to two phase of LNG before flowing into the tubes of E-101 in vaporization section. This alternative is implied to reduce the duty of E-101 for bringing LNG to saturation.

4.2.1.2 Energy performance analysis after structural modification

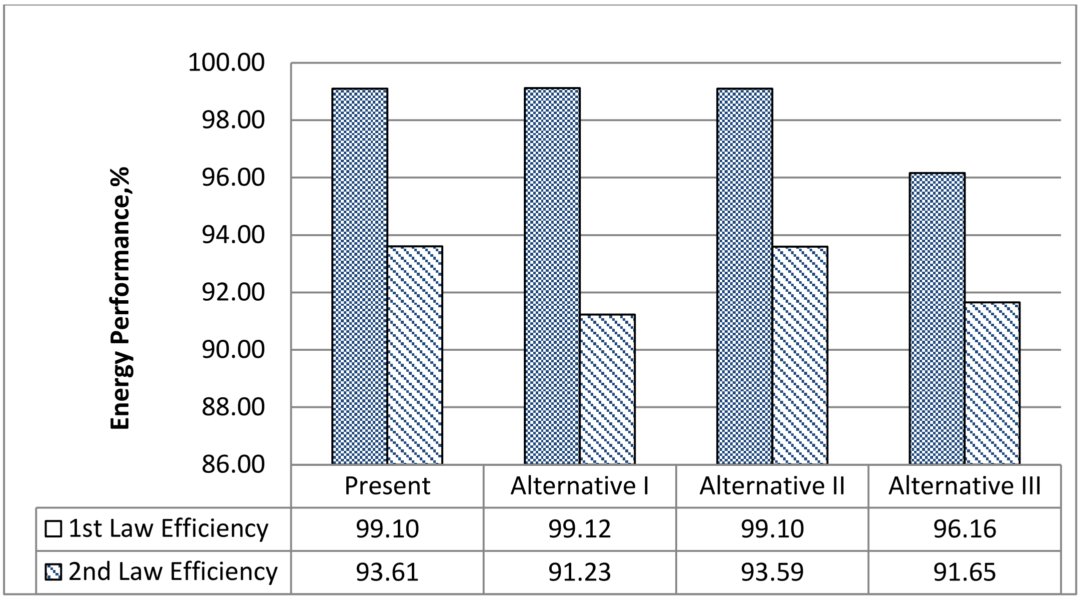

FIGURE 4.6 Energy performance analysis of ORV after structural modification

As from an analysis, all of the modified system gives the same amount of energy intensity with the present ORV structure which is 0.2354 kWh/kg, Therefore, the performance of these alternative are evaluated with respect to the first and second law efficiency.

Based on the graph in Figure 4.6, Alternative I give the highest value of First Law efficiency which is 99.12%.However, it does not show a significant difference with Alternative II and the present ORV structure. Besides, Alternative III has the lowest amount of energy performance which is at 96.16%. From this finding, its indicate that the system in this alternatives allows more heat losses from the system as compared to the other alternatives.

Another finding has found in this analysis in which the present ORV structure has the best energy performance in term of its second law efficiency which is at 93.61%. While, the lowest second law efficiency is shown as in Alternative I, 91.23%..Based on the study on this analysis, the present ORV structures give the best effectiveness of the energy performance compared to the other alternatives. Although the actual amount of First Law Efficiency in Alternative I is the highest, but somehow its energy performance effectiveness is the lowest as compared to the other alternatives. It's means, there are a huge gap for maximizing the thermal efficiency to the maximum possible efficiencies of the system.

Therefore, the present ORV structure is seems to be the most ideal structure as compared to the other alternatives. So, an extensive analysis on the heat exchanger system in the present ORV structure was carried out in the following section.

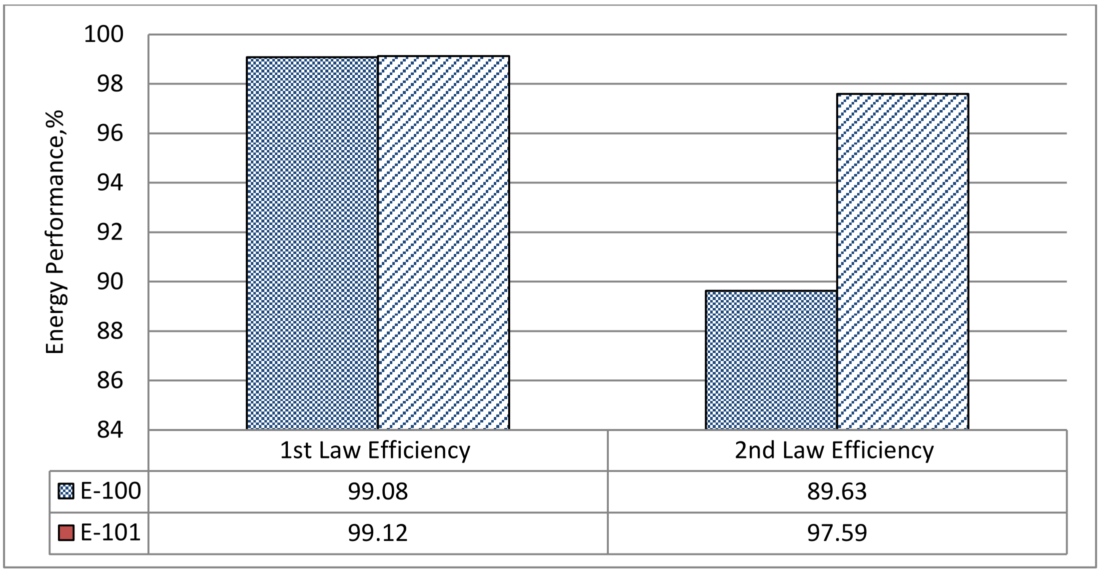

FIGURE 4.7 Energy performance analysis for present ORV structure

In order to improve the energy performance of the present ORV structure, an extensive has been carried out as in Figure 4.7. Based on the analysis, a high energy performance is mainly contributed by E-101 which is in the heating section. While, E-100 in the vaporizing section gives the lowest amount of energy performance.

Based on Figure 4.7, the first and second law efficiency of E-100 is 99.08% and 89.63 % respectively. The low amount of second law efficiency of E-100 indicated that the E-100 is less effective compared to the E-101 heat exchanger. Therefore, an operational modification has to be carried out in E-100 so that an optimum operational parameter can be suggested subsequently for a better energy performance.

4.2.2 Operational modification

In operational modification steps, there are two parameters have been varying which are:

a. LNG Injection Pressure
b. Outlet temperature from E-100

4.2.2.1 LNG Injection Pressure variation

Operating pressure is one of the key variables for system performance. In this analysis, the LNG injection pressure has been vary to study its effect to the energy performance. The figures show the trending of first law and second law efficiency onto the heat exchanger system with respect to the LNG injection pressure variation.

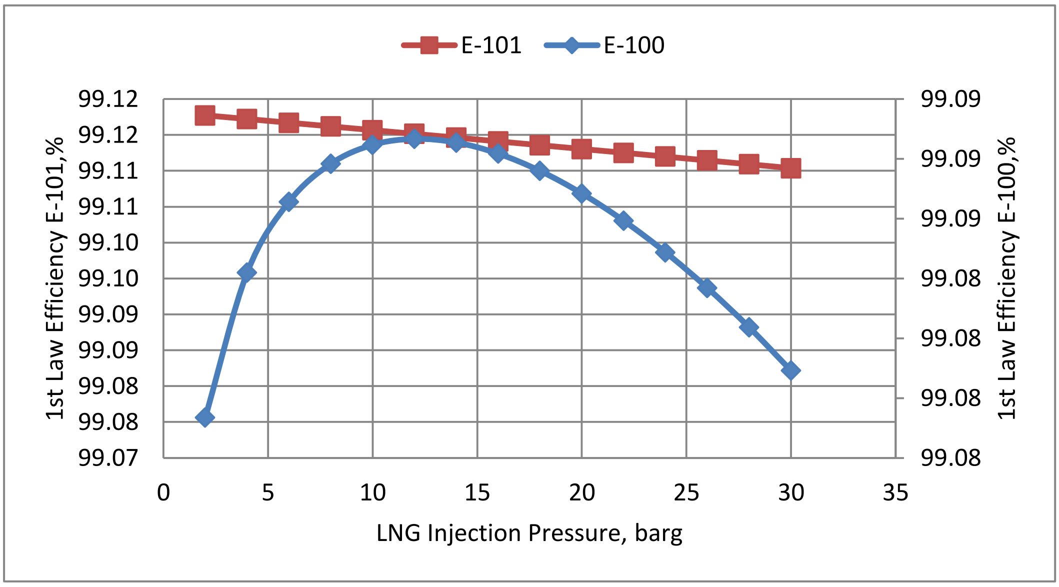

Figure 4.8 Effect of LNG pressure Injection Pressure to First Law Efficiency in ORV

Based on Figure 4.8, the first law efficiency in E-100 is increasing as the LNG injection pressure increase up to 14 barg. It is because, as the LNG pressure increases the inlet temperature of E-100 would also increases and result in a higher thermal efficiency.

However, the first law efficiency is dropping as the pressure goes more than 14 barg. Theoretically, the tube side heat transfer coefficient is directly proportional to the mass velocity. When the pressure of LNG is higher and higher, the LNG velocity will be reduced. Therefore, the higher pressure of the heat exchanger tube side will result in a lower mass velocity which may reduce the heat transfer coefficient and gives lower thermal efficiency (Kevin, 2006). This case can be also seen in E-101 where its first law efficiency start to drop as the LNG injection pressure goes higher.

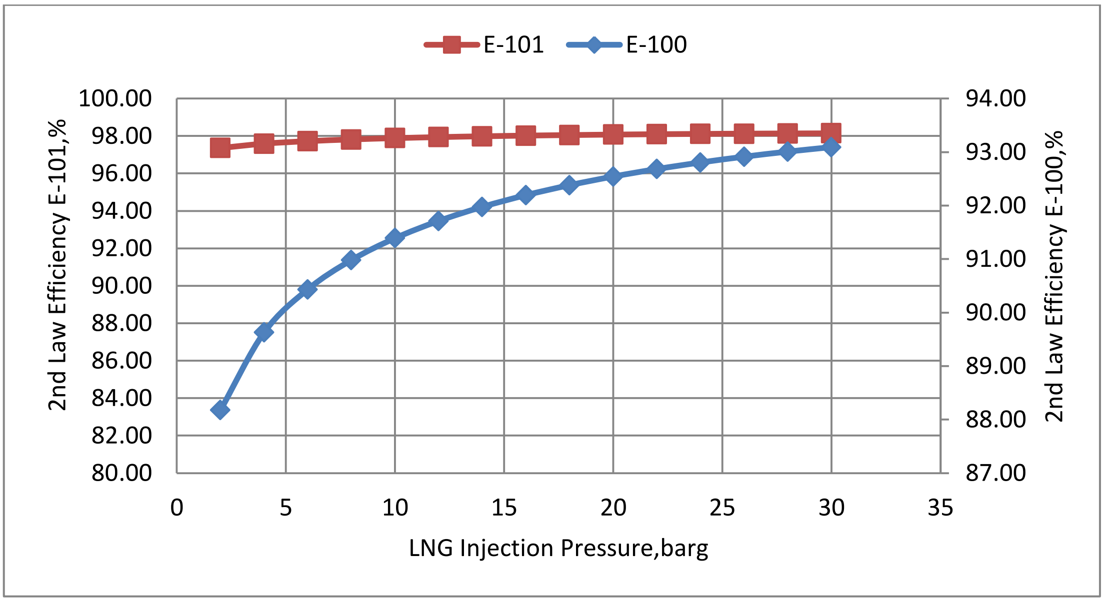

Figure 4.9 Effect of LNG pressure variation to Second Law Efficiency in ORV

The result in Figure 4.9 shows the second law efficiency in E-100 and E-101 is increasing exponentially with respect to LNG injection pressure. Enrico et.al (2012) have explained in their 25th International Conference paper, as the operating pressure increases ,the exergy loss of a system is reduced and total system output exergy can be improved and result in a higher second law efficiency. However, the growth rates of efficiency become less and less with the increase injection pressure.

Throughout this analysis, an operating pressure constraint is found to be applied in the ORV system so that any dropping of energy performance in E-100 and E-101 can be avoid effectively. In this system, the LNG injection pressure should be in between 6 to 14 barg. However, in addition of higher injection pressure, will results in the increase of the cost of investment (Enrico et.al,2012).Therefore, it is necessary to choose the most optimum pressure for ORV operation. The optimum pressure for the ORV system is discussed in the following figures

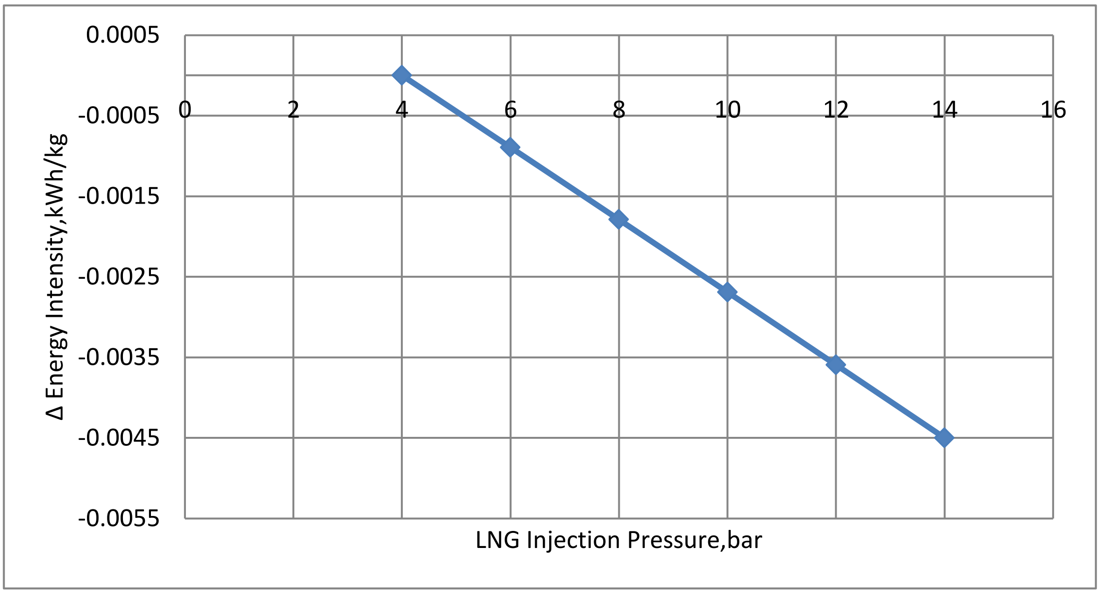

Figure 4.10 Effect of LNG Injection Pressure to the change of the Energy Intensity in ORV

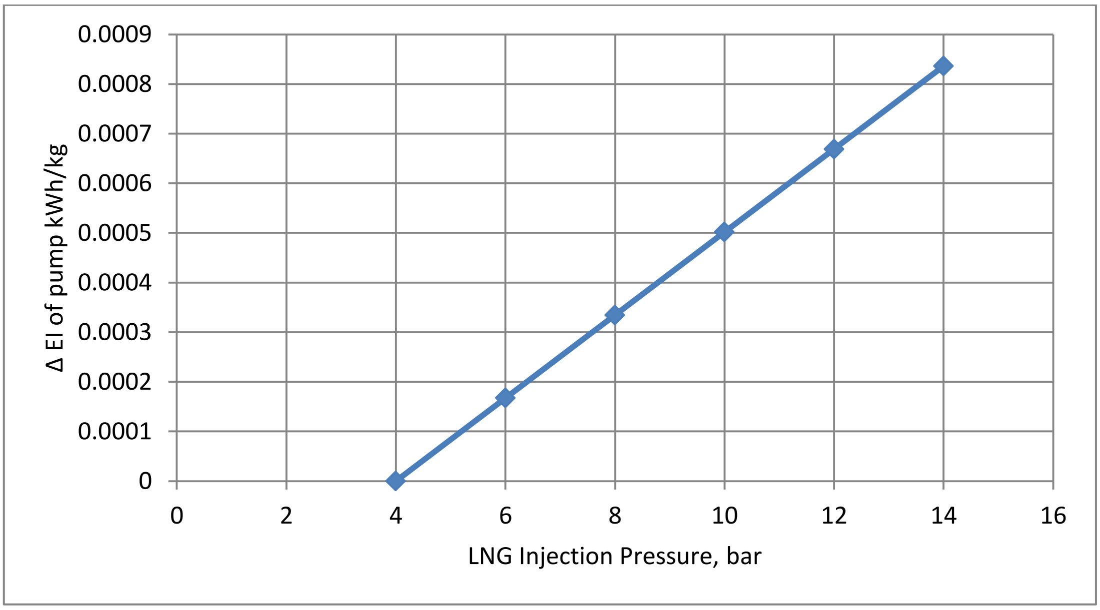

Figure 4.11 Effect of LNG Injection Pressure to the change of the Energy Intensity in pump

Based on figure 4.10, the amount of Energy Intensity is decreasing linearly with respect to the LNG injection pressure. It is because, a higher value of operating pressure would give a lower heat of vaporization. Therefore, less energy is required to turn LNG into gaseous phase.

As from this analysis, 14 barg give the biggest changes in the amount of Energy Intensity which is at 0.0045 kWh/kg . However, as the injection pressure is higher, the duty of pump must take into consideration.

Figure 4.11 shows the change of energy intensity in pump with respect to the increase of LNG injection pressure. The amount of energy required to pump LNG up to 14 barg LNG is the highest which is about 0.0008 kWh/kg. Thus, an extensive analysis is carried out as in figure 26 in order to avoid any increase of the cost of investment.

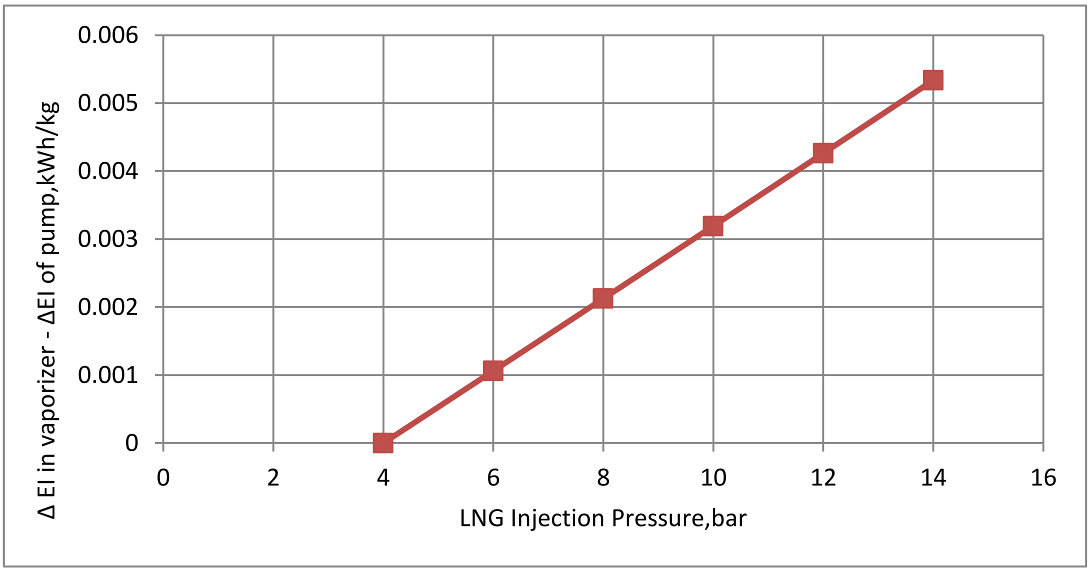

Figure 4.12 Difference of Energy Intensity reduced in vaporizer with the Energy Intensity required by pump

According to the above analysis, 14 barg is the most optimum pressure for LNG injection since it gives the biggest difference between the energy intensity reduced in vaporizer with the energy required in pump. Its means, with sufficient amount of energy required by pump, the ORV system with 14 barg LNG injection pressure are able to reduce the highest amount of energy intensity as compared to the other injection pressure.

4.3.2.2 Temperature variation

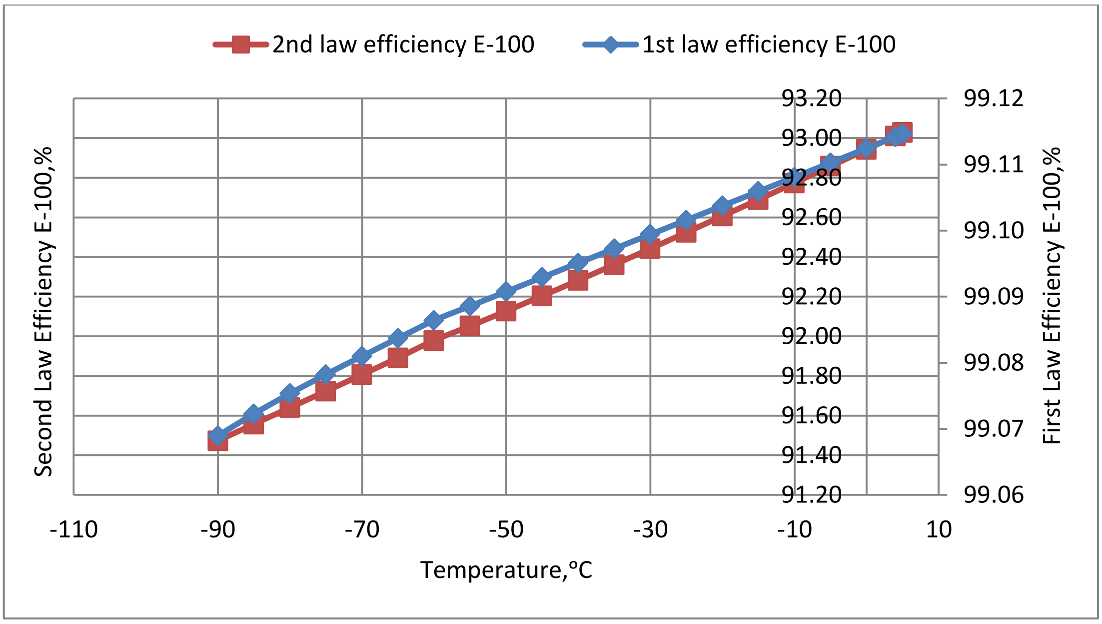

Figure 4.13 Effect of Outlet Temperature E-100 variation to Energy Performance at 14 barg LNG Injection Pressure

As referring to the above figure, energy performance is increasing linearly as the discharge temperature from E-100 tube goes higher. A high temperature in the outlet streams of E-100 would cause a larger temperature difference in the cold streams and result in higher energy performance. To avoid any drops of energy performance, the outlet temperature from E-100 should be ensured to be higher than the saturation temperature, -60.18 °C.

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

Based on the decomposition method, Open Rack vaporizer is the best technologies since it consume the lowest amount of operational energy intensity and has the highest energy performance among of other type of vaporizer. In this project, LNG Intensity can be reduced up to 3.45 Wh/kg with maximum amount of 1st and 2nd Law Efficiency which is 99.10% and 94.99% respectively

5.2 Recommendations

The optimum condition for ORV to have the lowest amount of Energy Intensity is when operating at 14 barg of LNG Injection Pressure. Also, the discharge temperature of the E-100 should be higher than the saturation temperature, -60.28 C so that any drop of energy performance can be avoided effectively.

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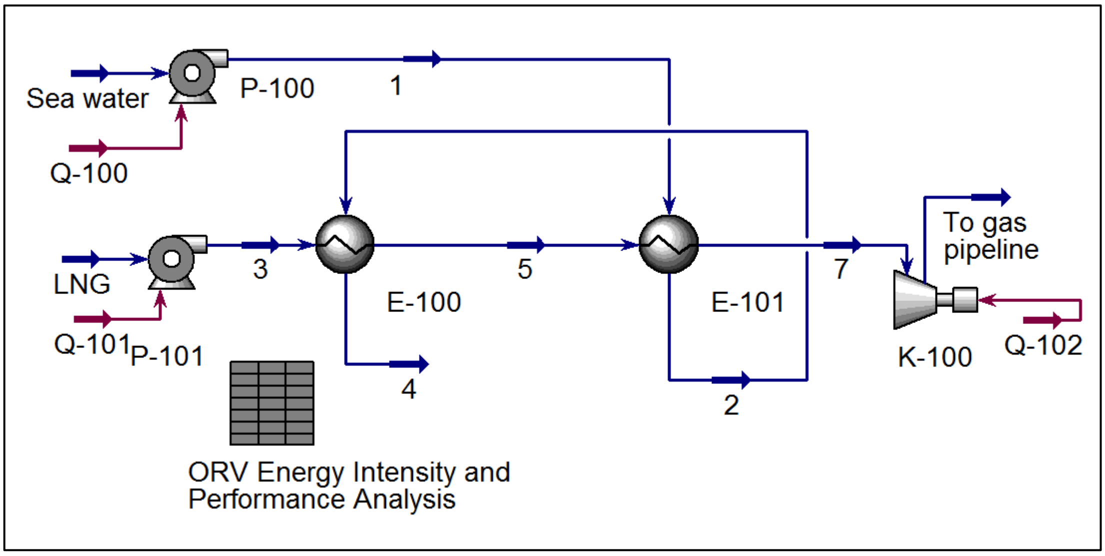
APPENDICES

Appendix A

Appendix A: Open Rack Vaporizer Simulation and Material Stream



Material Streams | Compositions | Energy Streams | Unit Ops

Name	Sea water	1	2	3	LNG	5	7	4
Vapour Fraction	0.0000	0.0000	0.0000	0.0000	0.0000	1.000	1.000	0.0000
Temperature [C]	25.00	25.03	23.80	-161.8	-162.0	-75.80	5.000	18.89
Pressure [kPa]	100.0	400.0	399.8	400.0	110.0	399.8	399.5	399.5
Molar Flow [kgmole/h]	532.9	532.9	532.9	17.67	17.67	17.67	17.67	532.9
Mass Flow [kg/h]	9600	9600	9600	300.0	300.0	300.0	300.0	9600
Liquid Volume Flow [m3/h]	9.619	9.619	9.619	0.9729	0.9729	0.9729	0.9729	9.619
Heat Flow [kJ/h]	-1.525e+008	-1.525e+008	-1.526e+008	-1.601e+006	-1.601e+006	-1.397e+006	-1.346e+006	-1.528e+008

Name	To gas pipeline
Vapour Fraction	1.000
Temperature [C]	232.6
Pressure [kPa]	4200
Molar Flow [kgmole/h]	17.67
Mass Flow [kg/h]	300.0
Liquid Volume Flow [m3/h]	0.9729
Heat Flow [kJ/h]	-1.181e+006

Appendix B

Appendix B: Open Rack Vaporizer Spreadsheet

Spreadsheet: ORV Energy Intensity and Performance Analysis

Connections | Parameters | Formulas | Spreadsheet | Calculation Order | User Variables | Notes

Current Cell: G10 Variable: Exportable Angles in: Edit Rows/Columns

	A	B	C	D	E
2	Heat Duty Data	LNG Mass Flowrate	Exchanger Duty	Energy Intensity , kWh/kg	
3	E-100	300.0 kg/h	2.032e+005 kJ/h	0.2354	
4	E-101	300.0 kg/h	5.099e+004 kJ/h		
5					
6					
7	Heat Flow Data	Heat Flow in	Heat Flow out	Heat Loss	1st law efficiency
8	E-100	-1.526e+008 kJ/h	-1.397e+006 kJ/h	1.512e+008 kJ/h	99.08
9	E-101	-1.525e+008 kJ/h	-1.346e+006 kJ/h	1.512e+008 kJ/h	99.12
10				Average	99.10
11					
12	Entropy data		Entropy in	Entropy out	Entropy difference
13	E-100	Cold Stream	4.501 kJ/kg-C	9.373 kJ/kg-C	4.872 kJ/kg-C
14		Hot stream	2.963 kJ/kg-C	2.891 kJ/kg-C	7.188e-002 kJ/kg-C
15					
16	E-101	Cold stream	9.373 kJ/kg-C	10.09 kJ/kg-C	0.7211 kJ/kg-C
17		Hot stream	2.981 kJ/kg-C	2.963 kJ/kg-C	1.785e-002 kJ/kg-C
18					
19	Enthalpy data		Enthalpy in	Enthalpy out	Enthalpy difference
20	E-100	Cold Stream	-5335 kJ/kg	-4658 kJ/kg	677.4 kJ/kg
21		Hot stream	-1.589e+004 kJ/kg	-1.591e+004 kJ/kg	21.17 kJ/kg
22					
23	E-101	Cold stream	-4658 kJ/kg	-4488 kJ/kg	170.0 kJ/kg
24		Hot stream	-1.589e+004 kJ/kg	-1.589e+004 kJ/kg	5.311 kJ/kg
25					
26	Exergy data		Mass Flow	Reference Temperature	Exergy Flow
27	E-100	Cold Stream	300.0 kg/h	25.00 C	555.6 kJ/kg
28		Hot stream	9600 kg/h	25.00 C	19.37 kJ/kg
29					
30	E-101	Cold stream	300.0 kg/h	25.00 C	151.9 kJ/kg
31		Hot stream	9600 kg/h	25.00 C	4.865 kJ/kg
32					
33	Unit	Exergy Source	Exergy Sink	Exergy Lost	2nd law efficiency
34	E-100	1.860e+005 kJ/h	1.667e+005 kJ/h	1.929e+004 kJ/h	89.63
35	E-101	4.670e+004 kJ/h	4.558e+004 kJ/h	1125 kJ/h	97.59
36				Average	93.61
37					

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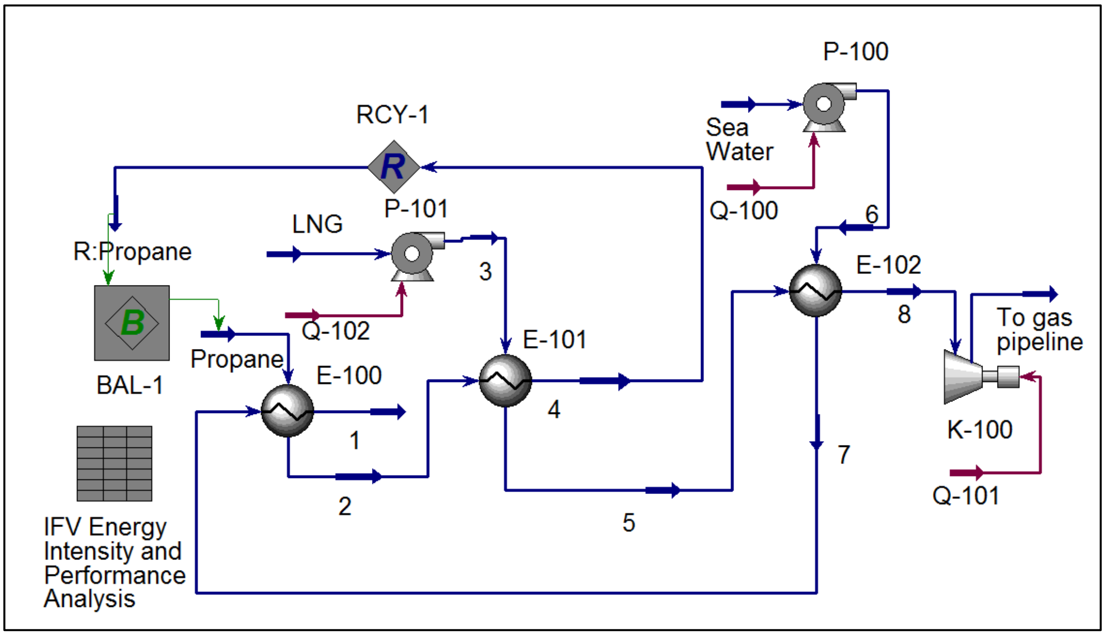
Appendix C: Intermediate Fluid Vaporizer Simulation and Material Stream



Material Streams | Compositions | Energy Streams | Unit Ops

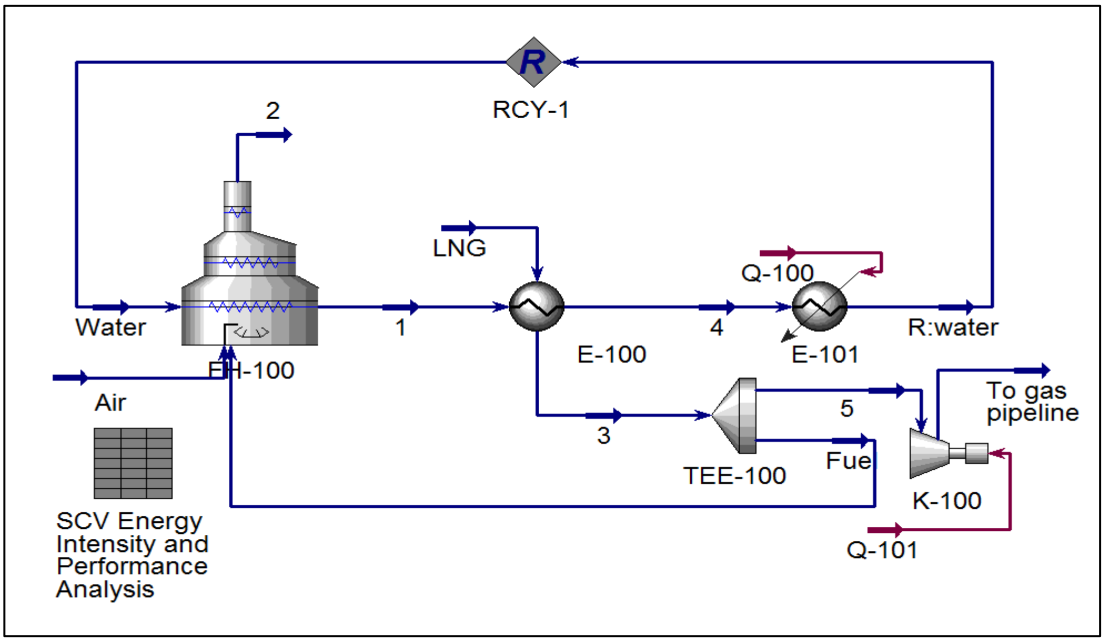
Name	Sea Water	6	Propane	2	1	5	LNG
Vapour Fraction	0.0000	0.0000	0.0000	1.000	0.0000	0.1297	0.0000
Temperature [C]	25.00	25.03	-1.660	-1.671	18.89	-141.3	-162.0
Pressure [kPa]	101.3	400.0	450.0	449.8	399.5	399.8	110.0
Molar Flow [kgmole/h]	532.9	532.9	2.268	2.268	532.9	17.67	17.67
Mass Flow [kg/h]	9600	9600	100.0	100.0	9600	300.0	300.0
Liquid Volume Flow [m3/h]	9.619	9.619	0.1974	0.1974	9.619	0.9729	0.9729
Heat Flow [kJ/h]	-1.525e+008	-1.525e+008	-2.793e+005	-2.414e+005	-1.528e+008	-1.563e+006	-1.601e+006
Name	3	8	7	4	R:Propane	To gas pipeline	
Vapour Fraction	0.0000	1.000	0.0000	0.0000	0.0000	1.000	
Temperature [C]	-161.8	5.000	19.80	-1.692	-1.692	232.7	
Pressure [kPa]	400.0	399.3	399.8	449.5	449.5	4200	
Molar Flow [kgmole/h]	17.67	17.67	532.9	2.268	2.268	17.67	
Mass Flow [kg/h]	300.0	300.0	9600	100.0	100.0	300.0	
Liquid Volume Flow [m3/h]	0.9729	0.9729	9.619	0.1974	0.1974	0.9729	
Heat Flow [kJ/h]	-1.601e+006	-1.346e+006	-1.527e+008	-2.793e+005	-2.793e+005	-1.181e+006	

Appendix D: Intermediate Fluid Vaporizer Spreadsheet

Spreadsheet: IFV Energy Intensity and Performance Analysis

	A	B	C	D	E
1					
2	Heat Duty Data	LNG Mass Flowrate	Exchanger Duty	Energy Intensity,kWh/kg	
3	E-100	300.0 kg/h	3.794e+004 kJ/h	0.2354	
4	E-102	300.0 kg/h	2.163e+005 kJ/h		
5					
6	Heat Flow Data	Heat Flow in	Heat Flow out	Heat Lost	1st law efficiency
7	E-100	-1.527e+008 kJ/h	-2.414e+005 kJ/h	1.525e+008 kJ/h	99.84
8	E-101	-1.601e+006 kJ/h	-2.793e+005 kJ/h	1.321e+006 kJ/h	82.55
9	E-102	-1.525e+008 kJ/h	-1.346e+006 kJ/h	1.512e+008 kJ/h	99.12
10				Average	93.84
11					
12	Entropy data		Entropy in	Entropy out	Entropy difference
13	E-100	Cold stream	1.806 kJ/kg-C	3.204 kJ/kg-C	1.398 kJ/kg-C
14		Hot stream	2.905 kJ/kg-C	2.891 kJ/kg-C	1.351e-002 kJ/kg-C
15					
16	E-101	Cold stream	4.501 kJ/kg-C	5.507 kJ/kg-C	1.006 kJ/kg-C
17		Hot stream	3.204 kJ/kg-C	1.806 kJ/kg-C	1.398 kJ/kg-C
18					
19	E-102	Cold stream	5.507 kJ/kg-C	10.09 kJ/kg-C	4.588 kJ/kg-C
20		Hot stream	2.981 kJ/kg-C	2.905 kJ/kg-C	7.622e-002 kJ/kg-C
21					
22	Enthalpy data		Enthalpy in	Enthalpy out	Enthalpy difference
23	E-100	Cold stream	-2793 kJ/kg	-2414 kJ/kg	379.4 kJ/kg
24		Hot stream	-1.591e+004 kJ/kg	-1.591e+004 kJ/kg	3.953 kJ/kg
25					
26	E-101	Cold stream	-5335 kJ/kg	-5209 kJ/kg	126.5 kJ/kg
27		Hot stream	-2414 kJ/kg	-2793 kJ/kg	379.5 kJ/kg
28					
29	E-102	Cold stream	-5209 kJ/kg	-4488 kJ/kg	720.8 kJ/kg
30		Hot stream	-1.589e+004 kJ/kg	-1.591e+004 kJ/kg	22.53 kJ/kg
31					
32	Exergy data		Mass Flow	Reference Temperature	Exergy Flow
33	E-100	Cold stream	100.0 kg/h	25.00 C	344.5 kJ/kg
34		Hot stream	9600 kg/h	25.00 C	3.615 kJ/kg
35					
36	E-101	Cold stream	300.0 kg/h	25.00 C	101.4 kJ/kg
37		Hot stream	100.0 kg/h	25.00 C	344.6 kJ/kg
38					
39	E-102	Cold stream	300.0 kg/h	25.00 C	606.1 kJ/kg
40		Hot stream	9600 kg/h	25.00 C	20.62 kJ/kg
41					
42	Unit	Exergy Source	Exergy Sink	Exergy Lost	2nd law efficiency
43	E-100	3.470e+004 kJ/h	3.445e+004 kJ/h	251.3 kJ/h	99.28
44	E-101	3.446e+004 kJ/h	3.041e+004 kJ/h	4046 kJ/h	88.26
45	E-102	1.980e+005 kJ/h	1.818e+005 kJ/h	1.612e+004 kJ/h	91.86
46				Average	93.13

Appendix E: Submerged Combustion Vaporizer Simulation and Material Stream



Material Streams | Compositions | Energy Streams | Unit Ops

Name	2	1	Air	LNG	3	4	Fuel	5
Vapour Fraction	1.000	0.0000	1.000	0.0000	1.000	0.0000	1.000	1.000
Temperature [C]	24.98	30.37	25.00	-162.0	5.000	24.20	5.000	5.000
Pressure [kPa]	100.0	99.75	100.0	110.0	109.8	99.50	109.8	109.8
Molar Flow [kgmole/h]	334.0	532.9	333.7	17.67	17.67	532.9	0.2651	17.41
Mass Flow [kg/h]	9605	9600	9600	300.0	300.0	9600	4.500	295.5
Liquid Volume Flow [m3/h]	11.19	9.619	11.18	0.9729	0.9729	9.619	1.459e-002	0.9584
Heat Flow [kJ/h]	-2.452e+005	-1.523e+008	-2682	-1.601e+006	-1.345e+006	-1.526e+008	-2.018e+004	-1.325e+006

Name	Water	R:water	To gas pipeline
Vapour Fraction	0.0000	0.0000	1.000
Temperature [C]	25.00	25.00	370.2
Pressure [kPa]	99.75	99.75	4200
Molar Flow [kgmole/h]	532.9	532.9	17.41
Mass Flow [kg/h]	9600	9600	295.5
Liquid Volume Flow [m3/h]	9.619	9.619	0.9584
Heat Flow [kJ/h]	-1.525e+008	-1.525e+008	-1.034e+006

Appendix F: Submerged Combustion Vaporizer Spreadsheet

Spreadsheet: SCV Energy Intensity and Performance Analysis

Connections | Parameters | Formulas | Spreadsheet | Calculation Order | User Variables | Notes

Current Cell

Exportable

F17 Variable: Angles in:

Edit Rows/Columns

	A	B	C	D	E
1					
2	Heat Duty Data	LNG Mass Flowrate	Heat Duty	Energy Intensity,kWh/kg	
3	FH-100	300.0 kg/h	2.223e+005 kJ/h	0.2367	
4	E-101		3.331e+004 kJ/h		
5					
6	Heat Flow Data	Heat Flow in	Heat Flow out	Heat Loss	1st Law Efficiency
7	FH-100	1.525e+008 kJ/h	1.525e+008 kJ/h	0.5911 kJ/h	82.94
8	E-100	-1.523e+008 kJ/h	-1.345e+006 kJ/h	1.510e+008 kJ/h	99.12
9	E-101	-1.526e+008 kJ/h	-1.525e+008 kJ/h	3.331e+004 kJ/h	2.183e-002
10					60.69
11					
12	Entropy data		Entropy in	Entropy out	Entropy difference
13	FH-100		18.99 kJ/kg-C	8.338 kJ/kg-C	10.65 kJ/kg-C
14	E-100	Cold stream	4.499 kJ/kg-C	10.74 kJ/kg-C	6.238 kJ/kg-C
15		Hot stream	3.058 kJ/kg-C	2.969 kJ/kg-C	8.862e-002 kJ/kg-C
16	E-101		2.969 kJ/kg-C	2.981 kJ/kg-C	1.165e-002 kJ/kg-C
17					
18	Enthalpy data		Enthalpy in	Enthalpy out	Enthalpy difference
19	FH-100		2.037e+004 kJ/kg	1.589e+004 kJ/kg	4482 kJ/kg
20	E-100	Cold stream	-5336 kJ/kg	-4484 kJ/kg	852.0 kJ/kg
21		Hot stream	-1.586e+004 kJ/kg	-1.589e+004 kJ/kg	26.62 kJ/kg
22	E-101		-1.589e+004 kJ/kg	-1.589e+004 kJ/kg	3.469 kJ/kg
23					
24	Exergy data		Mass Flow	Reference Temperature	Exergy flow
25	FH-100		9600 kg/h	25.00 C	4216 kJ/kg
26	E-100	Cold stream	300.0 kg/h	25.00 C	696.0 kJ/kg
27		Hot stream	9600 kg/h	25.00 C	24.41 kJ/kg
28	E-101		9600 kg/h	25.00 C	3.178 kJ/kg
29					
30	Unit	Exergy Source	Exergy Sink	Exergy Lost	2nd Law Efficiency
31	FH-100	1.990e+004 kJ/kg	1.542e+004 kJ/kg	4482 kJ/kg	77.47
32	E-100	2.343e+005 kJ/kg	2.088e+005 kJ/kg	2.552e+004 kJ/kg	89.11
33	E-101	1.597e+004 kJ/kg	1.596e+004 kJ/kg	3.178 kJ/kg	99.98
34				Average	88.86
35					
36	Fh-100 Streams Data	Mass Flowrate	Heat Flow	Enthalpy	Entropy
37	Water in	9600 kg/h	-1.525e+008 kJ/h	-1.589e+004 kJ/kg	2.981 kJ/kg-C
38	Air	9600 kg/h	-2682 kJ/h	-0.2794 kJ/kg	5.271 kJ/kg-C
39	Fuel	4.500 kg/h	-2.018e+004 kJ/h	-4484 kJ/kg	10.74 kJ/kg-C
40	Heated water	9600 kg/h	-1.523e+008 kJ/h	-1.586e+004 kJ/kg	3.058 kJ/kg-C
41	Waste Gas	9605 kg/h	-2.452e+005 kJ/h	-25.52 kJ/kg	5.280 kJ/kg-C
42					

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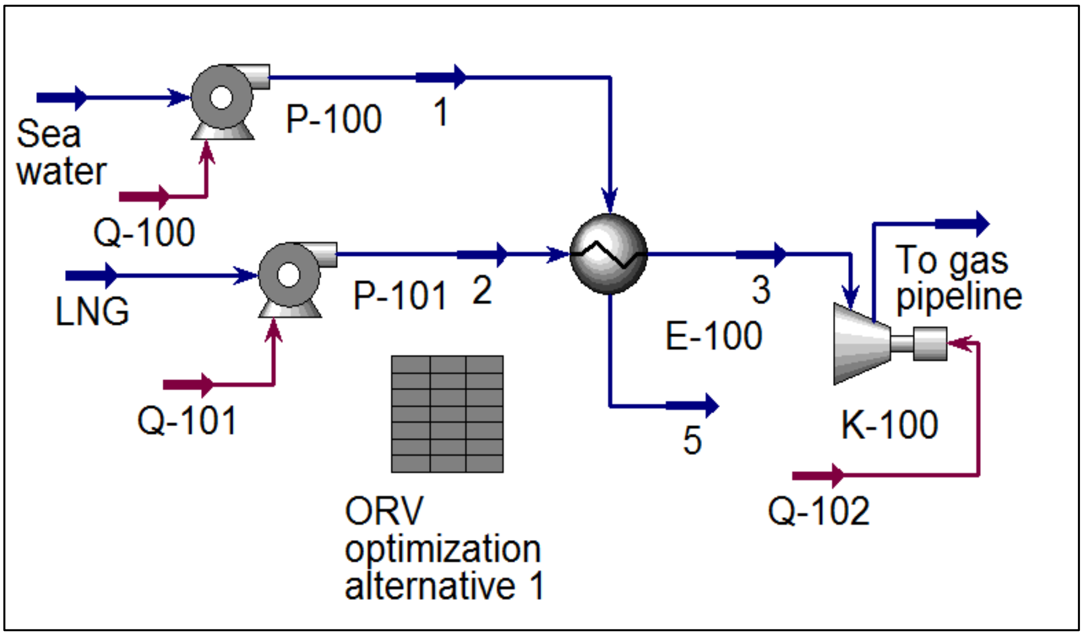
Appendix G: Alternative I Structure Optimization Simulation and Material Stream

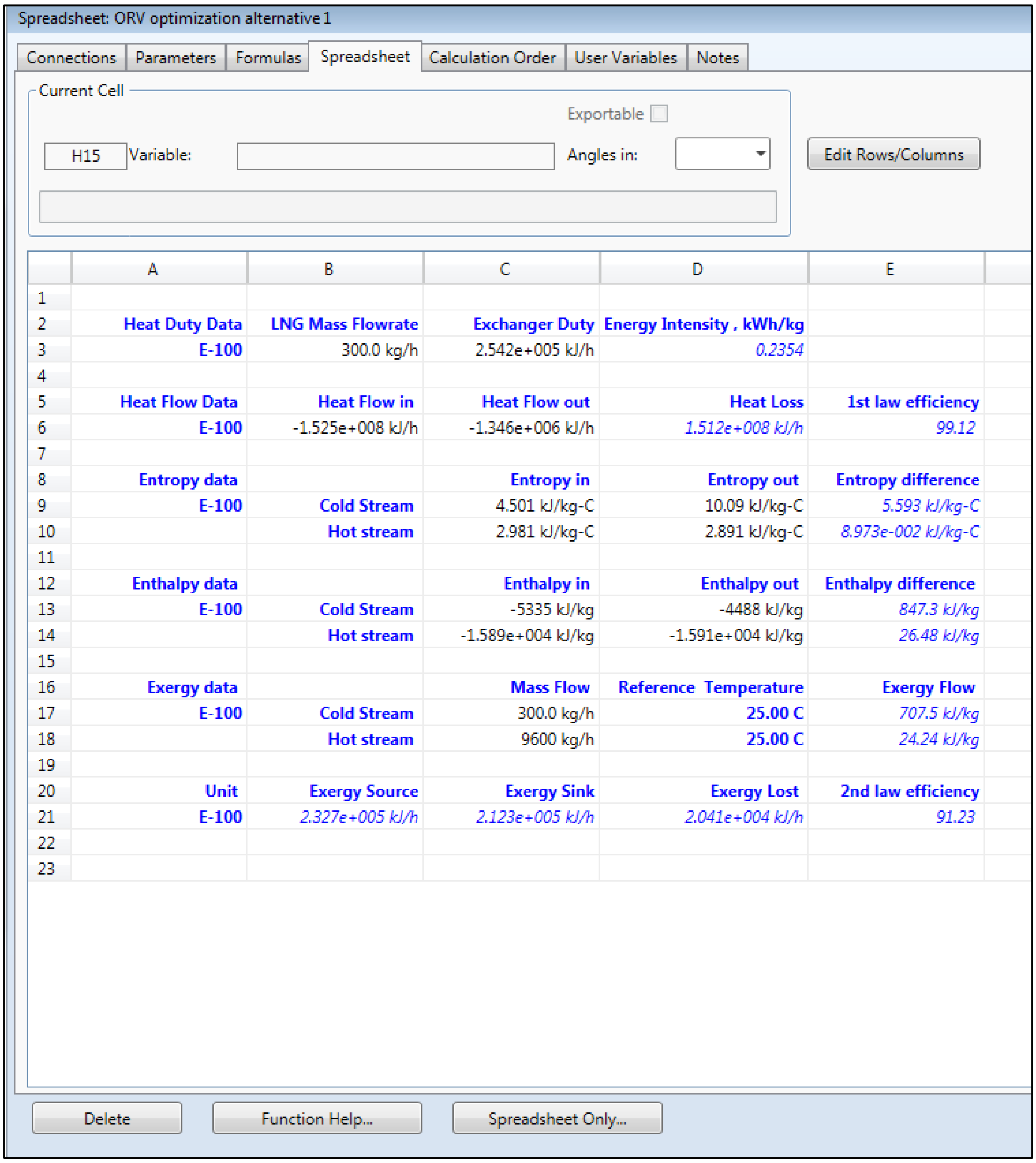


Material Streams | Compositions | Energy Streams | Unit Ops

Name	Sea water	1	2	LNG	3	5
Vapour Fraction	0.0000	0.0000	0.0000	0.0000	1.000	0.0000
Temperature [C]	25.00	25.03	-161.8	-162.0	5.000	18.89
Pressure [kPa]	100.0	400.0	400.0	110.0	399.8	399.8
Molar Flow [kgmole/h]	532.9	532.9	17.67	17.67	17.67	532.9
Mass Flow [kg/h]	9600	9600	300.0	300.0	300.0	9600
Liquid Volume Flow [m3/h]	9.619	9.619	0.9729	0.9729	0.9729	9.619
Heat Flow [kJ/h]	-1.525e+008	-1.525e+008	-1.601e+006	-1.601e+006	-1.346e+006	-1.528e+008

Name	To gas pipeline
Vapour Fraction	1.000
Temperature [C]	232.5
Pressure [kPa]	4200
Molar Flow [kgmole/h]	17.67
Mass Flow [kg/h]	300.0
Liquid Volume Flow [m3/h]	0.9729
Heat Flow [kJ/h]	-1.181e+006

Appendix H: Alternative I Structure Optimization Spreadsheet



	A	B	C	D	E
1					
2	Heat Duty Data	LNG Mass Flowrate	Exchanger Duty	Energy Intensity , kWh/kg	
3	E-100	300.0 kg/h	2.542e+005 kJ/h	0.2354	
4					
5	Heat Flow Data	Heat Flow in	Heat Flow out	Heat Loss	1st law efficiency
6	E-100	-1.525e+008 kJ/h	-1.346e+006 kJ/h	1.512e+008 kJ/h	99.12
7					
8	Entropy data		Entropy in	Entropy out	Entropy difference
9	E-100	Cold Stream	4.501 kJ/kg-C	10.09 kJ/kg-C	5.593 kJ/kg-C
10		Hot stream	2.981 kJ/kg-C	2.891 kJ/kg-C	8.973e-002 kJ/kg-C
11					
12	Enthalpy data		Enthalpy in	Enthalpy out	Enthalpy difference
13	E-100	Cold Stream	-5335 kJ/kg	-4488 kJ/kg	847.3 kJ/kg
14		Hot stream	-1.589e+004 kJ/kg	-1.591e+004 kJ/kg	26.48 kJ/kg
15					
16	Exergy data		Mass Flow	Reference Temperature	Exergy Flow
17	E-100	Cold Stream	300.0 kg/h	25.00 C	707.5 kJ/kg
18		Hot stream	9600 kg/h	25.00 C	24.24 kJ/kg
19					
20	Unit	Exergy Source	Exergy Sink	Exergy Lost	2nd law efficiency
21	E-100	2.327e+005 kJ/h	2.123e+005 kJ/h	2.041e+004 kJ/h	91.23
22					
23					

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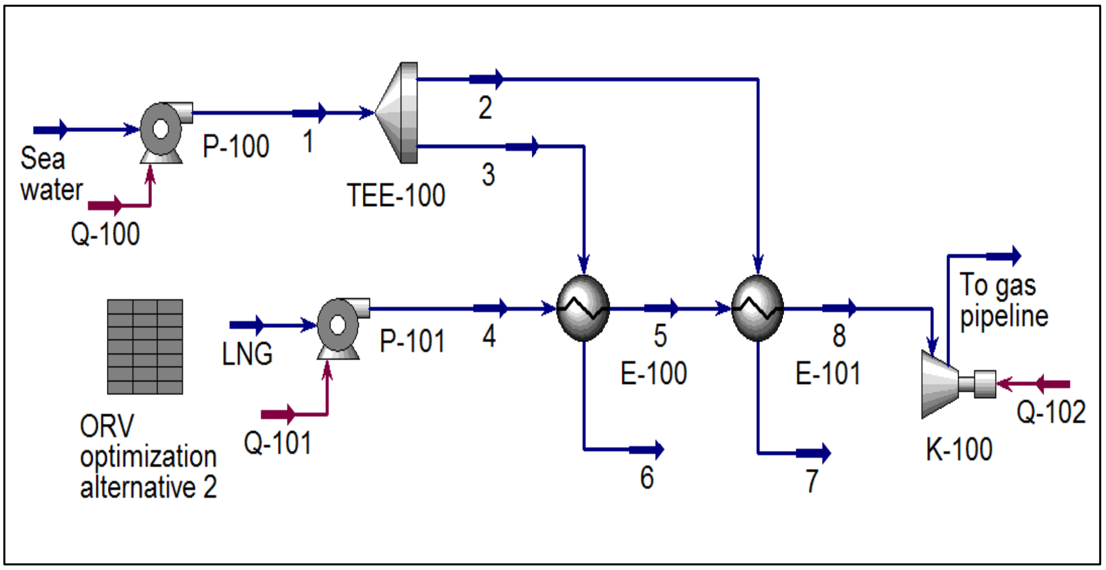
Appendix I: Alternative II Structure Optimization Simulation and Material Stream



Material Streams | Compositions | Energy Streams | Unit Ops

Name	Sea water	1	7	4	LNG	5
Vapour Fraction	0.0000	0.0000	0.0000	0.0000	0.0000	1.000
Temperature [C]	25.00	25.03	23.80	-161.8	-162.0	-75.80
Pressure [kPa]	100.0	400.0	399.8	400.0	110.0	399.8
Molar Flow [kgmole/h]	1066	1066	532.9	17.67	17.67	17.67
Mass Flow [kg/h]	1.920e+004	1.920e+004	9600	300.0	300.0	300.0
Liquid Volume Flow [m3/h]	19.24	19.24	9.619	0.9729	0.9729	0.9729
Heat Flow [kJ/h]	-3.050e+008	-3.050e+008	-1.526e+008	-1.601e+006	-1.601e+006	-1.397e+006

Name	8	6	2	3	To gas pipeline
Vapour Fraction	1.000	0.0000	0.0000	0.0000	1.000
Temperature [C]	5.000	20.12	25.03	25.03	232.6
Pressure [kPa]	399.5	399.8	400.0	400.0	4200
Molar Flow [kgmole/h]	17.67	532.9	532.9	532.9	17.67
Mass Flow [kg/h]	300.0	9600	9600	9600	300.0
Liquid Volume Flow [m3/h]	0.9729	9.619	9.619	9.619	0.9729
Heat Flow [kJ/h]	-1.346e+006	-1.527e+008	-1.525e+008	-1.525e+008	-1.181e+006

Appendix J: Alternative II Structure Optimization Spreadsheet

Spreadsheet: ORV optimization alternative 2

Connections | Parameters | Formulas | Spreadsheet | Calculation Order | User Variables | Notes

Current Cell

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G29 Variable: Angles in: Edit Rows/Columns

	A	B	C	D	E
2	Heat Duty Data	LNG Mass Flowrate	Exchanger Duty	Energy Intensity , kWh/kg	
3	E-100	300.0 kg/h	2.032e+005 kJ/h	0.2354	
4	E-101	300.0 kg/h	5.099e+004 kJ/h		
5					
6					
7	Heat Flow Data	Heat Flow in	Heat Flow out	Heat Loss	1st law efficiency
8	E-100	-1.525e+008 kJ/h	-1.397e+006 kJ/h	1.511e+008 kJ/h	99.08
9	E-101	-1.525e+008 kJ/h	-1.346e+006 kJ/h	1.512e+008 kJ/h	99.12
10				Average	99.10
11					
12	Entropy data		Entropy in	Entropy out	Entropy difference
13	E-100	Cold Stream	4.501 kJ/kg-C	9.373 kJ/kg-C	4.872 kJ/kg-C
14		Hot stream	2.981 kJ/kg-C	2.910 kJ/kg-C	7.158e-002 kJ/kg-C
15					
16	E-101	Cold stream	9.373 kJ/kg-C	10.09 kJ/kg-C	0.7211 kJ/kg-C
17		Hot stream	2.981 kJ/kg-C	2.963 kJ/kg-C	1.785e-002 kJ/kg-C
18					
19	Enthalpy data		Enthalpy in	Enthalpy out	Enthalpy difference
20	E-100	Cold Stream	-5335 kJ/kg	-4658 kJ/kg	677.4 kJ/kg
21		Hot stream	-1.589e+004 kJ/kg	-1.591e+004 kJ/kg	21.17 kJ/kg
22					
23	E-101	Cold stream	-4658 kJ/kg	-4488 kJ/kg	170.0 kJ/kg
24		Hot stream	-1.589e+004 kJ/kg	-1.589e+004 kJ/kg	5.311 kJ/kg
25					
26	Exergy data		Mass Flow	Reference Temperature	Exergy Flow
27	E-100	Cold Stream	300.0 kg/h	25.00 C	555.6 kJ/kg
28		Hot stream	9600 kg/h	25.00 C	19.38 kJ/kg
29					
30	E-101	Cold stream	300.0 kg/h	25.00 C	151.9 kJ/kg
31		Hot stream	9600 kg/h	25.00 C	4.865 kJ/kg
32					
33	Unit	Exergy Source	Exergy Sink	Exergy Lost	2nd law efficiency
34	E-100	1.860e+005 kJ/h	1.667e+005 kJ/h	1.936e+004 kJ/h	89.59
35	E-101	4.670e+004 kJ/h	4.558e+004 kJ/h	1125 kJ/h	97.59
36				Average	93.59

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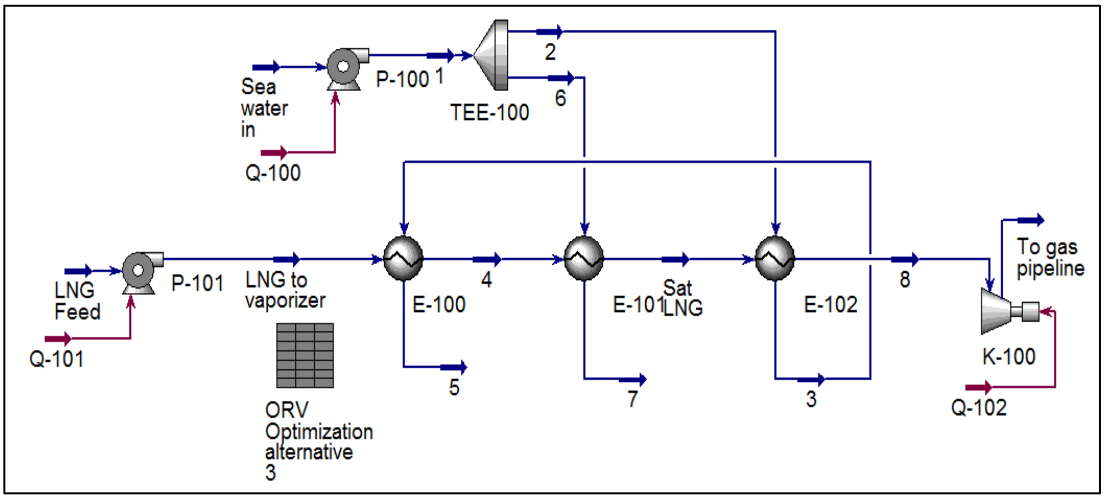
Appendix K: Alternative III Structure Optimization Simulation and Material Stream



Material Streams | Compositions | Energy Streams | Unit Ops

Name	Sea water in	2	3	LNG to vaporizer	LNG Feed	4	8
Vapour Fraction	0.0000	0.0000	0.0000	0.0000	0.0000	9.278e-002	1.000
Temperature [C]	25.00	25.03	23.80	-161.8	-162.0	-141.4	5.000
Pressure [kPa]	100.0	400.0	399.8	400.0	110.0	399.8	399.3
Molar Flow [kgmole/h]	1066	532.9	532.9	17.67	17.67	17.67	17.67
Mass Flow [kg/h]	1.920e+004	9600	9600	300.0	300.0	300.0	300.0
Liquid Volume Flow [m3/h]	19.24	9.619	9.619	0.9729	0.9729	0.9729	0.9729
Heat Flow [kJ/h]	-3.050e+008	-1.525e+008	-1.526e+008	-1.601e+006	-1.601e+006	-1.568e+006	-1.346e+006
Name	5	7	Sat LNG	1	6	To gas pipeline	
Vapour Fraction	0.0000	0.0000	1.000	0.0000	0.0000	1.000	
Temperature [C]	23.00	20.91	-75.81	25.03	25.03	232.7	
Pressure [kPa]	399.5	399.8	399.5	400.0	400.0	4200	
Molar Flow [kgmole/h]	532.9	532.9	17.67	1066	532.9	17.67	
Mass Flow [kg/h]	9600	9600	300.0	1.920e+004	9600	300.0	
Liquid Volume Flow [m3/h]	9.619	9.619	0.9729	19.24	9.619	0.9729	
Heat Flow [kJ/h]	-1.526e+008	-1.527e+008	-1.397e+006	-3.050e+008	-1.525e+008	-1.181e+006	

Appendix L: Alternative III Structure Optimization Spreadsheet

Spreadsheet: ORV Optimization alternative 3

Connections | Parameters | Formulas | Spreadsheet | Calculation Order | User Variables | Notes

Current Cell

Exportable

A1 Variable: Angles in: Rad

Edit Rows/Columns

	A	B	C	D	E
1					
2	Heat Duty Data	LNG Mass Flowrate	Exchanger Duty	Energy Intensity , kWh/kg	
3	E-100	300.0 kg/h	3.293e+004 kJ/h	0.2354	
4	E-101	300.0 kg/h	1.703e+005 kJ/h		
5	E-102	300.0 kg/h	5.099e+004 kJ/h		
6					
7	Heat Flow Data	Heat Flow in	Heat Flow out	Heat Loss	1st law efficiency
8	E-100	-1.526e+008 kJ/h	-1.568e+006 kJ/h	1.510e+008 kJ/h	98.97
9	E-101	-1.525e+008 kJ/h	-1.397e+006 kJ/h	1.511e+008 kJ/h	99.08
10	E-102	-1.525e+008 kJ/h	-1.346e+006 kJ/h	1.512e+008 kJ/h	99.12
11				Average	99.06
12					
13	Entropy data		Entropy in	Entropy out	Entropy difference
14	E-100	Cold Stream	4.501 kJ/kg-C	5.380 kJ/kg-C	0.8785 kJ/kg-C
15		Hot stream	2.963 kJ/kg-C	2.952 kJ/kg-C	1.157e-002 kJ/kg-C
16					
17	E-101	Cold Stream	5.380 kJ/kg-C	9.374 kJ/kg-C	3.994 kJ/kg-C
18		Hot stream	2.981 kJ/kg-C	2.921 kJ/kg-C	5.990e-002 kJ/kg-C
19					
20	E-102	Cold stream	9.374 kJ/kg-C	10.09 kJ/kg-C	0.7212 kJ/kg-C
21		Hot stream	2.981 kJ/kg-C	2.963 kJ/kg-C	1.785e-002 kJ/kg-C
22					
23	Enthalpy data		Enthalpy in	Enthalpy out	Enthalpy difference
24	E-100	Cold Stream	-5335 kJ/kg	-5226 kJ/kg	109.8 kJ/kg
25		Hot stream	-1.589e+004 kJ/kg	-1.590e+004 kJ/kg	3.430 kJ/kg
26					
27	E-101	Cold Stream	-5226 kJ/kg	-4658 kJ/kg	567.6 kJ/kg
28		Hot stream	-1.589e+004 kJ/kg	-1.591e+004 kJ/kg	17.74 kJ/kg
29					
30	E-102	Cold stream	-4658 kJ/kg	-4488 kJ/kg	170.0 kJ/kg
31		Hot stream	-1.589e+004 kJ/kg	-1.589e+004 kJ/kg	5.312 kJ/kg
32					
33	Exergy data		Mass Flow	Reference Temperature	Exergy Flow
34	E-100	Cold Stream	300.0 kg/h	25.00 C	87.81 kJ/kg
35		Hot stream	9600 kg/h	25.00 C	3.141 kJ/kg
36					
37	E-101	Cold Stream	300.0 kg/h	25.00	467.8 kJ/kg
38		Hot stream	9600 kg/h	25.00	16.24 kJ/kg
39					
40	E-102	Cold stream	300.0 kg/h	25.00 C	151.9 kJ/kg
41		Hot stream	9600 kg/h	25.00 C	4.865 kJ/kg
42					
43	Unit	Exergy Source	Exergy Sink	Exergy Lost	2nd law efficiency
44	E-100	3.016e+004 kJ/h	2.634e+004 kJ/h	3813 kJ/h	87.36
45	E-101	1.559e+005 kg/h	1.403e+005 kg/h	1.558e+004 kg/h	90.01
46	E-101	4.671e+004 kJ/h	4.558e+004 kJ/h	1125 kJ/h	97.59
47				Average	91.65
48					

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Appendix M: Effect of Pressure variation to Energy Performance

Pressure LNG,bar	**First Law Efficiency**		**Second Law Efficiency**	
	E-100	E-101	E-100	E-101
2	99.08	99.12	88.18	97.36
4	99.08	99.12	89.63	97.59
6	99.09	99.12	90.43	97.72
8	99.09	99.12	90.98	97.82
10	99.09	99.12	91.39	97.89
12	99.09	99.12	91.71	97.94
14	99.09	99.11	91.97	97.98
16	99.09	99.11	92.19	98.02
18	99.09	99.11	92.38	98.05
20	99.09	99.11	92.54	98.07
22	99.08	99.11	92.68	98.10
24	99.08	99.11	92.81	98.11
26	99.08	99.11	92.91	98.13
28	99.08	99.11	93.01	98.14
30	99.08	99.11	93.09	98.14

Appendix N: Effect of Pressure variation to Operational Energy Intensity of ORV vaporizer

Pressure LNG,bar	First Law Efficiency		Second Law Efficiency		Energy Intensity,kWh/kg
	E-100	E-101	E-100	E-101	
2	99.08	99.12	88.18	97.36	0.236265102
4	99.08	99.12	89.63	97.59	0.235374252
6	99.09	99.12	90.43	97.72	0.234480415
8	99.09	99.12	90.98	97.82	0.233583609
10	99.09	99.12	91.39	97.89	0.232683855
12	99.09	99.12	91.71	97.94	0.231781179
14	99.09	99.11	91.97	97.98	0.230875611

Appendix O: Effect of E-100 discharge temperature to the Energy Performance

Temperature (tube out)	**1st law efficiency** E-100	**1st law efficiency** E-101	**2nd law efficiency** E-100	**2nd law efficiency** E-101	**Energy Intensity**
-90.000000	99.068950	99.114628	91.472927	96.982312	0.230876
-85.000000	99.072269	99.114628	91.556924	97.177093	0.230876
-80.000000	99.075334	99.114628	91.640033	97.356286	0.230876
-75.000000	99.078224	99.114628	91.723066	97.524082	0.230876
-70.000000	99.080995	99.114628	91.806605	97.683562	0.230876
-65.000000	99.083707	99.114628	91.891762	97.838545	0.230876
-60.000000	99.086394	99.114628	91.978940	97.991777	0.230876
-55.000000	99.088576	99.114628	92.052025	98.114471	0.230876
-50.000000	99.090751	99.114628	92.127058	98.233175	0.230876
-45.000000	99.092921	99.114628	92.203800	98.348134	0.230876
-40.000000	99.095087	99.114628	92.282038	98.459568	0.230876
-35.000000	99.097252	99.114628	92.361583	98.567661	0.230876
-30.000000	99.099416	99.114628	92.442268	98.672570	0.230876
-25.000000	99.101580	99.114628	92.523942	98.774410	0.230876
-20.000000	99.103745	99.114628	92.606470	98.873237	0.230876
-15.000000	99.105913	99.114628	92.689733	98.968995	0.230876
-10.000000	99.108085	99.114628	92.773621	99.061350	0.230876
-5.000000	99.110260	99.114628	92.858037	99.149024	0.230876
0.000000	99.112441	99.114628	92.942892	99.225138	0.230876
4.000000	99.114189	99.114628	93.011039	99.183977	0.230876
5.000000	99.114627	99.114628	93.028107	33.185928	0.230876