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Waste Energy Recovery – Including Pressure and Thermal Energy – From LNG Regasification

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The world has been concentrating on waste heat recovery for several decades, with the vast majority of achievements making a significant contribution to the development of industry and economy. The attention has recently been paid to waste energy from cold streams. This work focuses on the recovery of waste cold energy released from Liquefied Natural Gas (LNG) regasification process, including pressure and thermal energy. A direct expansion configuration involving different steps of expansion and mass flow rate extraction at intermediate pressure levels is adopted in the mathematical models for pressure and cold energy recovery. An equation of state for methane (the main component of LNG) is employed to calculate LNG thermodynamic properties in a long-range phase transition of the regasification process. A direct configuration of the organic Rankine cycle (ORC) is employed to recover waste cold energy. The modified Peng-Robinson (PR) and Soave-Redlich-Kwong (SRK) equations of state (EOS) play important roles in calculation of thermodynamic properties of the organic working fluids used in the ORC. Several fluids are examined to select the most suitable one as the ORC working fluid. All the models are developed and solved by using MATLAB. By adopting propane as the working fluid in the ORC, the multi-stage expansion along with thermal energy extraction is shown to be the most thermodynamically efficient configuration with the recovery of up to 170 kJ pressure energy for each kg of the flowing LNG, and up to 74 kJ from thermal energy recovery.

1. Introduction

Starting from last decade, cold energy recovery from Liquefied Natural Gas (LNG) processes attracted a lot of interest. The LNG produced is commercially delivered to the market via LNG import terminals. Predictions of a highly significant number of new LNG import terminals (and expansion sites) are expected to go ahead.
At import terminals, there are two conventional processes used for regasification of LNG at receiving and expansion sites. The majority of current LNG import terminals use parallel operating vaporizers with spares. Seawater is employed to heat and vaporize LNG in Open Rack Vaporizers (ORVs). It does not make use of the cold energy stored by LNG during liquefaction processes before LNG departure around the world. Submerged Combustion Vaporizers (SCVs) use send-out gas as fuel to combust and provide heat for vaporization. Lost of cold energy is going to be dispatched uneconomically to the environment.
A considerable number of improvements in exploiting the cold energy available in LNG have been applied, such as CO_2 capture technology, air separation, etc. The organic Rankine cycles (ORC) efficiency also has been improved due to studies on working fluids, rather than making use with water or air. However, thermal stability at high pressure and condensation at cryogenic temperature without issues of freezing causes ORC application on a limited front.

1.1 LNG regasification and potential

A tremendous amount of energy is required during LNG production processes, such as separation, purification, distillation, etc. Natural Gas (NG) is chilled to cryogenic liquid state which only takes a volume of 1/600 of the gaseous phase. Liquefied state promotes storage and transportation to market with comparative ease. It is not an economical way to transport LNG through long distances once it is off-loaded at receiving terminals from tankers to storage tanks. It is then pumped for final transmission to the distribution system. Before arrivals of LNG to consumers, regasification is operated to return LNG into vaporized natural gas.

During the liquefying process, a considerable amount of mechanical energy is supplied to bring natural gas to cryogenic temperature (-161.5 ^{o}C). Regasification process consists of two operations. First, pump LNG up to the pressure of the distribution grid. Second, heat LNG up to required distribution temperature (typically in the range between 0 ^{o}C and 20 ^{o}C). In real liquefaction plants, it possibly to identify a level of 2,900 kJ/kg as the realistic amount of energy consumed during the process (Alessandro and Claudio, 2015). However, roughly 2,070 kJ/kg of energy, accounting for 9 0% of energy consumed in liquefaction, is dispatched undesirably into the environment. It is estimated 830 kJ/kg of energy, so-called “cold energy”, is preserved in LNG. Under theoretical consideration, an ideal amount of 830 kJ/kg of energy, equivalent to 0.23 kWh per kg LNG, would be recovered (Alessandro and Claudio, 2015). Considering the typical annual handling capacity at LNG import terminals, the order of magnitude of Mt/y, an enormous amount of cold energy is wasting.

1.2 Cold energy recovery

A critical element of LNG regasification plants are cryogenic operating condition and high pressure. The maximum level of operating pressure about 15 MPa is a pressure ceiling technically allowed during the LNG regasification process. These features of the process provide a high opportunity of recovering the potential energy preserved in LNG, including thermal energy and pressure energy. Cryogenic power generation is a major cold energy application, the most interesting option due to its much more significant economical value, rather than the traditional electricity generation through combustion. There are several solutions to explore the energy given off by LNG regasification for electricity generation basically belonging to two widely-used mechanisms: (a) direct expansion; and (b) organic Rankine cycle.

LNG, under direct expansion cycle (Figure 1), is first compressed to a pressure level higher than the gas-supplying pressure at the distribution stations, most of the cases the VNG is requested at supercritical condition, maximum pressure allowance in conventional schemes is on the order of magnitude of 15 MPa (Alessandro and Claudio, 2015). High pressure LNG is then heated up and vaporized due to the employment of seawater or the ambient air as heat source. After that, LNG is expanded to the gas-supplying pressure requested. Multi-stage expansion of LNG is implemented by turbines in series to generate electrical power. The primary objective of this mechanism is to exploit the pressure energy and the cold energy from LNG regasification.

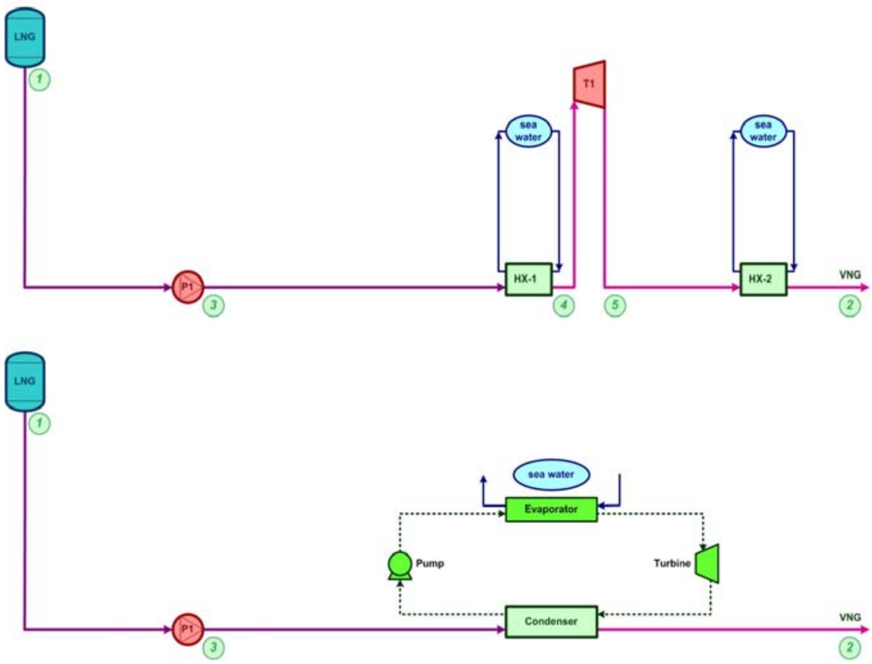

Figure 1: The LNG regasification with direct expansion scheme and organic Rankine cycle.

Organic Rankine cycle in Figure 1 is one of feasible technologies to recover waste heat and to generate electricity. ORC applied for LNG cold energy recovery is driven by the temperature difference between cryogenic conditions and, usually seawater whose sensible heat is exploited as energy input for operation of ORC. The energy extracted from seawater is carried by an auxiliary fluid, called "ORC working fluid", then delivered to ORC evaporator where the energy from heat source is transferred to vaporize LNG. Working fluid also goes through pumps to increase its working pressure and passes in turbines to drive the motor for the power generation purpose. This mechanism recovers the thermal portion of cold energy.

The aim of this study is to combine two above fundamental principles of pressure energy and thermal energy recovery under a variety of different thermodynamic schemes. Both direct expansion cycle and organic Rankine cycle are utilized to enhance the process performance, and the higher cold energy recovery efficiency can be economically achieved. By lowering condensing temperature in condensers employed within the cycle causes a greater temperature difference between heat source and heat sink, which is expected to increase the net power output, and to enhance a higher thermal efficiency of the power cycle (Matsuda, 2013).

2. Evolutions of LNG regasification cold energy recovery

The main goal of an LNG regasification site is to transform the LNG from the LNG storage tanks under typical storage condition, at the cryogenic temperature of –161.5 ^oC and at the atmosphere pressure of 0.101325 MPa. Then turns LNG into its normally utilizable gaseous phase and delivers LNG to distribution stations, from where the LNG departs for consumers/clients through regional distribution networks or National Grid. In general, the send-out LNG from the storage requires a certain level of the output pressure from LNG vaporizing. This pressure varies within a low range of pressure around 2.5 – 3 MPa in case of local distribution. For long distribution, the typical requested pressure level up to 6 – 8 MPa.

As discussed above, there are two fundamental mechanisms applicable for the goal of energy recovery, including pressure energy and thermal energy. Therefore, the option of combination of both direct expansion cycle and organic Rankine cycle promotes a promising thermodynamic configuration.

2.1 Pressure energy recovery via direct expansion cycles

The direct expansion mechanism is basically the simplest thermodynamic scheme for power generation. LNG is compressed up to a pressure higher than those of distribution terminal requirement, most of cases the maximum pressure allowed approaches the level of 15 MPa; then passes through the evaporator system (heat exchangers) where it is warmed up, regasified and superheated by means of seawater; thereafter the vaporized LNG drives the turbine-generator and eventually reheated to the VNG condition requested. Basically, direct expansion generates electrical power. Nevertheless, somehow it appears inconvenient from the perspective of energy recovery. Thermodynamically, it is possible to consider recycle a part of the main flowrate back to create a small thermodynamic cycle with another step of expansion to generate power. A feasible version of multi-stage expansion is given in Figure 2a (Alessandro and Claudio, 2015), which shows a meaningful thermodynamic scheme from the point of view of energy recovery. Similar to direct expansion scheme, nonetheless, instead of pumping directly cryogenic liquid LNG at storage condition to the very high pressure, three compressing stages are utilized to first increase LNG pressure up to an intermediate level. Furthermore, vaporized LNG before leaving for distribution terminals, a portion of the main flowrate is recycled and mixed with the main stream in the mixer locating after the intermediate pumps. A process-to-process heat exchanger is suggested install to internally recover heat based on temperature difference among process streams. This modified version is optimized to obtain the maximum of net power based on power produced from turbines and work consumed by pumps. For the optimization of this scheme, there are several key manipulating variables defined as flow rates of recycle streams and the intermediate pressure levels. For each value of intermediate pressure, varying the recycling stream flowrate shows range of net power obtainable.

For the sake of simplicity, LNG is assumed to be composed totally of pure substance methane CH_4 so that CH_4 represents a significant advance in fields of physical properties and chemical behaviours. The process works under some constrained conditions: the outlet of mixer has to be fully guaranteed of single liquid phase; the mixer operates at a particular pressure, requiring all inlet and outlet streams equally pressured. A mathematic model is written for this thermodynamic scheme based on mass balances and energy balances of each point along the flow streams as well as each of device employed along the process.

Given data at LNG storage (-161.5 ^oC and 0.101325 MPa), and at LNG distribution terminals (15 ^oC and 6 MPa). Assume that LNG storage condition is the low bound of temperature and pressure, while VNG condition is the upper bound. Furthermore, the maximum pressure allowance of the process is 15 MPa. All heat exchangers using seawater give the outlet stream temperature of 15 ^oC. All pumps and turbines have isentropic efficiency of 0.9.

Thermodynamic properties of methane primarily based on the new equations of state in the form of a fundamental equation explicit in the Helmholtz free energy developed by the National Institute of Standards and Technology (NIST, see Setzmann and Wagner, 1991). All calculations and computing programming codes are written and solved using the programming language and computing environment MATLAB. Mathematic models including those relevant material and energy balances and those operating constraints for describing this scheme are skipped here due to space limitation.

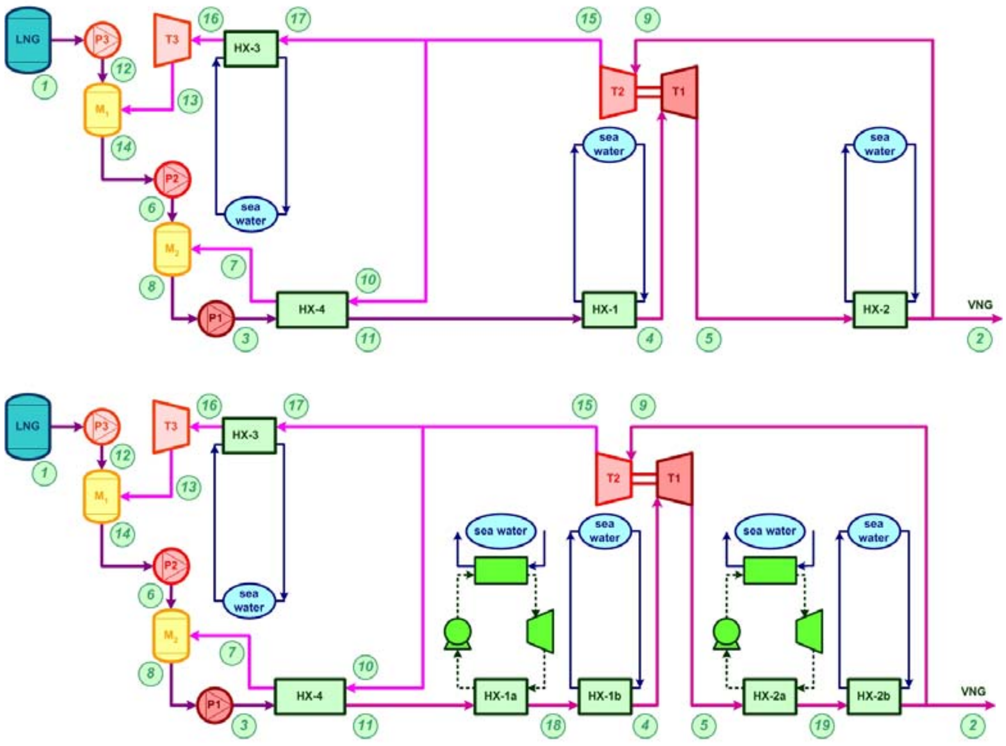

Figure 2: The LNG regasification with two internal cycles and internal heat exchangers (Alessandro and Claudio, 2015), and implementation of two ORCs for further energy recovery.

2.2 Thermal energy recovery via organic Rankine cycles

ORC is a promising alternative for recovery of LNG cold energy. As shown in Figure 2, after exploiting a part of cold energy preserved in LNG by applying thermodynamic cycles, one realizes a noticeable amount of cold energy wastefully releases to the environment through heat transfer system using seawater. After being pumped up to the maximum pressure allowed and transferring with all possible internal hot streams within the process, it is transformed into gaseous phase by the means of seawater. Instead of totally employing seawater and paying all remained cold energy to seawater, employing ORC for utilizing part of LNG cold energy releasing purposelessly during the vaporization is declared to be more effective and economical due to the power generation of ORC. Working fluid, an “energy-man” collecting and delivering energy, is pumped to high pressure then vaporized by extracting energy from heat source, seawater, to become saturated vapour. The saturated vapour of working fluid goes drive a turbine to generate power, simultaneously is relaxed the pressure becoming low pressure vapour. The vapour carrying energy from heat source delivers to LNG at a condenser by condensing itself into saturated liquid and vaporizing LNG. After leaving condenser, saturated liquid working fluid now is ready to be pumped again, complete the cycle.

Pump and turbine within ORC are assumed to be isentropic with efficiency 0.8. The modified PR EOS and SRK are applied for calculations of thermodynamic properties of working fluid. Coefficients for vapour pressure, heat capacity and latent heat are referenced from Perry’s Handbook (Don and Robert, 2008). Some working fluids, especially hydrocarbons are potential candidates. In this study, propane, n-butane, n-pentane and n-hexane were recruited, due to their popularity, availability, and safety.

Any approach value can be feasible but not economical. Lower the value of approach the higher the number of shells in series and higher the economics. Two following constraints carry a guarantee of design and operation of a heat exchanger that minimum approaching temperature difference:

$$t_C^{out} - \left[T_{LNG}^{out} - \frac{f_m c_{pm}\left(t_T^{out} - t_C^{out}\right)}{FC_{LNG}} \right] \geq \Delta T_{\min} \quad (1)$$

$$\left[T_{sea}^{out} + \frac{f_m c_{pm}\left(t_E^{out} - t_P^{out}\right)}{FC_{sea}} \right] - t_E^{out} \geq \Delta T_{\min} \quad (2)$$

Assuming seawater is sufficient so that Tseain ≈ Tseaout if seawater flowrate fsea is large enough, the fraction inside the bracket of Eq(2) approaches zero, and seawater outlet and inlet temperature are almost the same. Figure 3 illustrates the concept of ΔTmin of heat exchangers (i.e., evaporator and condenser) where working fluid isothermally changes phase. LNG receives transferred heat from working fluid in condenser, since under the maximum pressure level, the transition between cryogenic LNG and vaporized LNG becomes a second-order transition.

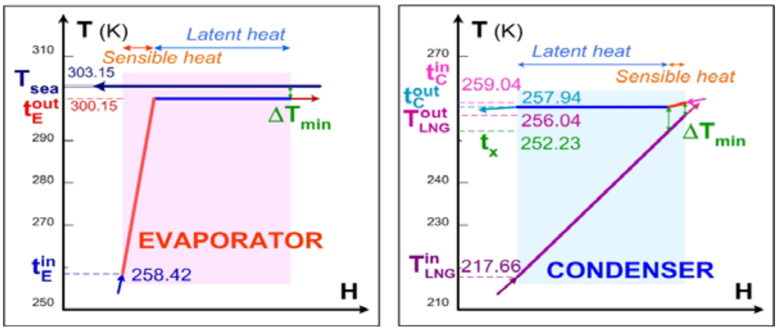

Figure 3: Minimum approaching temperature difference ΔT_{min} for evaporator and condenser.

Table 1: Optimization result of LNG regasification with two internal cycles and internal HEs.

		T (°C)	P (MPa)	ρ (kg/m³)	h (kJ/kg)	f (kg/s)	W (kW)
	1	-161.5	0.10133	422.38	-911.01	1	
P3							1.42
	12	-161.32	0.64124	422.62	-909.58	1	
	13	-83.42	0.64124	6.856	-245.9	0.1813	
	14	-133.15	0.64124	376.86	-807.73	1.1813	
P2							11.427
	6	-131.35	3.93535	379.37	-798.06	1.1813	
	7	-67.45	3.93535	50.92	-292.17	0.8554	
	8	-88.71	3.93535	258.51	-585.58	2.0367	
P1							62.962
	3	-70.32	15	290.02	-554.67	2.0367	
HX4							134.521
	11	-55.49	15	255.82	-488.63	2.0367	
HX1							624.268
	4	15	15	127.19	-182.11	2.0367	
T1							165.234
	5	-43.53	6	70.12	-263.24	2.0367	
HX2							358.322
	2	15	6	45.24	-87.31	1	
	9	15	6	45.24	-87.31	1.0367	
T2							49.344
	15	-12.92	3.93535	32.81	-134.91	1.0367	
	10	-12.92	3.93535	32.81	-134.91	0.8554	
	17	-12.92	3.93535	32.81	-134.91	0.1813	
HX3							12.803
	16	15	3.93535	28.49	-64.28	0.1813	
	T3						32.924
W_{net}							171.7

3. Results and discussion

Running results show a maximum power recovered 171.7 kW with the optimized low pressure of 0.64124 MPa and the optimized medium level at 3.93535 MPa, the optimized flowrate of recycling stream to mixer M1 0.18128 kg/s and to mixer M2 0.85541 kg/s for each kg/s of cryogenic LNG. The optimized configurations are summarized in Table 1. Optimized results with two ORCs for additional energy recovery, 74.8 kW for 1 kg/s of LNG, are shown in Table 2, where working fluid chosen is propane (C_3H_8) for the two-ORC scenario.

Table 2: Optimization result for LNG regasification process with additional ORCs

		Propane C_3H_8	Butane C_4H_{10}	Pentane C_5H_{12}	Hexane C_6H_{14}	ORC 1 (C_3H_8) 1st stage	ORC 1 (C_3H_8) 2nd stage	ORC 2 (C_3H_8) 1st stage	ORC 2 (C_3H_8) 2nd stage
T^C_{out}	K	257.94	256.69	256.79	256.74	257.94	278.06	263.72	281.38
T^P_{out}	K	258.42	256.79	256.82	256.75	258.42	278.44	264.23	281.73
T^E_{out}	K	300.15	300.15	300.15	300.15	300.15	300.15	300.15	300.15
T^T_{out}	K	259.04	266.27	268.43	269.00	259.04	278.86	264.86	282.07
P^E	kPa	1002.69	259.193	73.627	22.019	1002.69	1002.69	1002.69	1002.69
P^C	kPa	289.605	52.963	10.964	2.315	289.61	550.31	352.54	606.03
T^{LNG}_{in}	K	217.66	217.66	217.66	217.66	217.66	256.04	229.62	261.86
T^{LNG}_{out}	K	256.037	255.037	255.046	254.87	256.04	275.76	261.86	278.76
f_m	kg/s	0.92186	0.86686	0.87425	0.88279	0.92186	0.44271	0.53661	0.26369
Q_C	kW	366.685	357.743	357.823	356.25	366.685	164.457	209.726	96.635
						531.142		438.923	
w^T_{ORC}	kW	41.5152	42.0628	42.3161	42.8454	41.5152	9.7685	20.4482	4.8888
w^P_{ORC}	kW	1.4054	0.3429	0.1009	0.0315	1.4054	0.4539	0.7576	0.2396
w^{net}_{ORC}	kW	40.1099	41.7199	42.2152	42.8139	40.1099	9.3147	19.6906	4.6491
						50.4246		24.3397	

Within hydrocarbon family, it seems the heavier alkane is, the better to be ORC working fluid due to the higher net power recovered. Furthermore, because of longer-chain structure, saturated vapour pressure, operating pressure of ORC, of heavier alkanes tends to be lower and lower. For n-Butane, n-Pentane and n-Hexane, vapor pressures are too low (vacuum ORC operating pressure) for technical operation. It is reasonable to choose Propane as working fluid. According to results obtained, each column represents the optimized operating condition to recover maximum net power. With respect to given temperatures of heat source (seawater) and heat sink (LNG), operating pressures in evaporator and condenser are revealed to be the largest possibly difference satisfying ORC working fundamental. Maximizing ORC net power, subtraction of pump work from turbine power, is considered as minimizing pump work and maximizing turbine power simultaneously. Either pump work or turbine power is defined as enthalpy difference between inlet and outlet streams. For pump, the work is outlet enthalpy subtracts inlet enthalpy, and minimizing the pump work means maximizing the pump inlet enthalpy. Inversely, turbine power is defined as inlet enthalpy subtracts outlet enthalpy, maximizing turbine power means maximizing turbine inlet enthalpy. Since operating fundamental of ORC designs states of pump and turbine inlets are designed to be saturated liquid and vapor. Thermodynamically, degree of freedom of saturation curve equation is one. Only given temperature, one can derive saturated pressure and enthalpy. For hydrocarbons mentioned, enthalpy and saturated pressure are proportional to temperature within temperature range investigated. It is reasonable that the lowest possible condenser pressure and the highest evaporator pressure propose the maximum net power. After obtaining results for one ORC, it is easy to recognize that temperature of LNG still far away to the design value (15 ^oC) will be a potential to install a next ORC. 2-ORCs-in-series results are shown in the right-hand-side of Table 2. One could say this is results for solving optimization problem separately on 2 ORCs. A better result is expected if the above optimization problem is considered to be solved simultaneously.

4. Conclusion

This study suggests an additional method to exploit the potential energy resource hiding inside LNG. By employing pressure energy recovery from direct expansion of LNG and using ORC for LNG cold energy recovery, 246.5 kW (171.7 kW plus 74.8 kW) net power can be recovered from 1 kg/s of LNG. Approach and explore LNG cooling capacity by adapting a new appearance of working fluid or enhance performance of thermodynamic cycles promises a new target of cold energy recovery that is reasonable and soon achievable.

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