

Analysis of a Combined Power Cycle to Recover Cold Energy of Liquefied Natural Gas

Tao Lu¹, Peixue Jiang¹, Shengqiang Shen², Jiangqiang Den¹, Wei Lu¹

¹Department of Thermal Engineering, Tsinghua University, Beijing, China

²Department of Power Engineering, Dalian University of Technology, Dalian, China

Abstract: It is very important for the sustainable development of economy and society to exploit new energy and save energy. The global liquefied natural gas (LNG) trade has increased rapidly during recent years because of its steady price. A significant amount of energy is consumed to produce super-cooling LNG about $-162\text{ }^{\circ}\text{C}$ in 0.1MPa for the convenience of shipping, which has plenty of cryogenic energy. The cold energy of LNG is generally wasted when the LNG is extracted for utilization. Therefore, utilization of the cold energy of LNG is quite important at the stage of crude oil price increasing. The feasibility of using a combined power cycle to recover cold energy of LNG is analyzed in this present paper. The combined power cycle consists of three parts: fuel combustion system of compressed natural gas (CNG) drawn from natural gas after expanding through natural gas turbine, ammonia-water (AW) Rankine cycle and LNG cold energy cycle. Fuel and air rates, turbine inlet temperature and pressure, ammonia-water condensed temperature, and overall conductance of the heat exchange are considered as key parameters for given LNG flow rate and natural gas transport parameter in the combined power cycle. The present model could be applied to calculate thermal and exergy efficiencies of the combined power cycle according to different calculation parameters and to get optimum conditions of the key parameters for performance improvement of the combined cycle.

Keywords: cold energy, liquefied natural gas

1. INTRODUCTION

The use of fossil fuels as energy resources results in a serious air pollution, and the emission of CO_2 gas as a combustion exhaust is known to play a major role in global greenhouse effect. The use of energy resources with less or no influence on air pollution and environment is required, and the rational use of available energy is recommended.

Liquefied natural gas (LNG) is known as a clean energy source which is commonly used as domestic and industrial fuel for combustion. LNG is composed of 85-99% methane by mole fraction, a few percent ethane, and propane depending on its production site. Since moisture and sulfur are contained in crude natural gases, they should be removed during the liquefying preprocess. Natural gas is widely used in electricity generation and daily living for its friendly environment performance. The global liquefied natural gas (LNG) trade has increased rapidly during recent years because of its steady price and supply. It is becoming the third energy resource following coal and petroleum.

Natural gas (NG) is often found in remote regions far from consumer. For the transportation of natural gas from producing wells to utilization sites, two approaches are now applied. Pipeline suits the area where gas well and consumer are located in the same mainland or gas well sites near offshore. When oceans separate the gas source and the user, the only

viable way to transport the gas is to convert it into liquid natural gas and ship it using insulated LNG tanks. LNG is transported and stored at atmospheric pressure and at a temperature of about $-162\text{ }^{\circ}\text{C}$. Under these conditions, the volume of LNG abruptly reduces about 600 times than that of natural gas. At receiving terminals, the LNG is off-loaded into storage tanks and then pumped from storage at the required pressure and vaporized for final transmission to the consumers. In a real application, LNG should be vaporized in order to be supplied as natural gas. During the vaporization process, latent heat of vaporization and any sensible heat required to superheat the vapor should be supplied to the LNG. These are frequently termed cold energy. If LNG is used as a fuel in cogeneration systems, the waste heat of exhaust gases and the cold energy of LNG can be utilized at the same time.

Since the consumption of NG will probably increase in the future, the exploitation of the physical exergy of LNG, due to its state in liquid phase at a low temperature under that of the environment, is becoming more important. Many LNG projects are constructing or programming in east coastal regions of China.

Various processes have been considered to utilize the physical exergy of LNG. Lee et al.^[1] studied thermodynamic analysis of the extraction processes from a constant pressure LNG vessel in which a binary mixture of 90% methane and 10% ethane by mole fraction was existed. The changes of

the thermodynamic properties and the amount of utilizable cold energy were predicted during the extraction processes. Kim and Ro^[2] analyzed the feasibility of using inlet air cooling by virtue of the cold energy of LNG to increase power output of gas/steam combined cycle power plants during warm seasons. Air cooling capacity and power augmentation for a combined cycle system based on a high performance gas turbine were demonstrated as a function of the ambient temperature and humidity. Their results shown the relative increase in power of the combined cycle plant amounts to 8% for drying air condition (relative humidity lower than 30%) and 6% for 60% relative humidity. Sun et al.^[3] theoretically and numerically investigated the performance of a LNG cold energy conversion thermoelectric generator. Deng et al.^[4] proposed a new cogeneration power with two energy sources of fuel chemical energy and LNG cryogenic energy, and two outputs of electrical power and cooling power. Their results shown that the system had excellent energy saving due to the advanced integration of system and cascade utilization of LNG cryogenic energy: chemical energy of fuel and LNG cryogenic energy were saved by 7.5-12.2 and 13.2-14.3%, respectively. Wang et al.^[5] investigated a power cycle with natural gas directly expanding based on the cold energy of LNG and a low-grade heat source. Their results indicated that the temperature of low-grade heat source, the condensing temperature of second medium, and the inlet pressure of the turbine were the key factors affecting the thermal and exergy efficiencies of the power cycle. The thermal and exergy efficiencies would be improved with the increase of the temperature of the low-grade heat source, the decreasing of the condensing temperature and the increasing of the inlet pressure of the turbine. Miyazaki et al.^[6] developed a combined power cycle, which consisted of an ammonia-water Rankine cycle with refuse incinerator using refuse incineration and LNG cold energy, and conducted parametric analysis to investigate the effects of key parameters including ammonia condensing temperature, turbine inlet and outlet pressures and overall conductance of the condenser on the thermal and exergy efficiencies. Kaneko et al.^[7] presented that using the mirror gas turbine to recover the cryogenic exergy of LNG, which was a new kind of combined cycle of a conventional gas-turbine worked as a topping cycle and thermal generator (inverted Brayton cycle) as a bottoming cycle. Their results showed that the presented cycle was superior to the current-use gasification systems in employing seawater heat in terms of thermal efficiency and specific output. Bisio and Tagliafico^[8] developed that a combined systems using LNG vaporization as low-temperature thermal sink and analyzed a system utilizing waste energy as heat source and with a single working fluid. They pointed out that the use of a single fluid was not the best solution from a thermodynamic point of view. Thus, a series of cascading cycle was outlined. Hisazumi et al.^[9] proposed a high-efficiency power-generation with LNG vaporizing system, which consisted of a Rankine cycle using a Freon mixture, natural-gas Rankine cycle and a combined cycle with gas and steam turbines. The heat sources for this

system were the latent heat from the steam-turbine's condenser and the sensible heat of exhaust gas from the waste-heat recovery boiler.

The objectives of this paper are to develop a combined power generation cycle using compressed natural gas combustion and LNG cold energy, and to computer the thermal and exergy efficiencies for evaluating the performance of the combined cycle. Fuel and air rates, turbine inlet temperature and pressure, ammonia-water condensed temperature, and overall conductance of the heat exchange are considered as key parameters for given LNG flow rate and natural gas transport parameter in the combined power cycle.

2. CYCLE DESCRIPTION

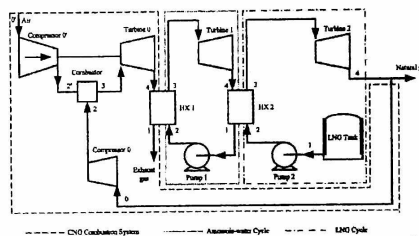


Figure 1: The flow diagram of combined power cycle

Fig. 1 shows the combined power cycle, which consists of a compressed natural gas (CNG) combustion system, an ammonia-water (AW) Rankine cycle, and a LNG Cycle. The left hand side in Fig. 1 is CNG combustion system, which includes two compressors, one combustor, and a combustion turbine. The air in the ambient temperature is compressed to 15 times ambient pressure by air compressor 0'. The fuel drawn from natural gas is compressed to 1.5 times combustion pressure in combustor.

Fuel is compressed by compressor 0 and then injected into the combustor. The high pressure mixture of air and fuel combusts in combustor, then high temperature and pressure combustion gas is produced. The high temperature and pressure combustion gas drives the turbine 0 to generate electricity and the compressor 0' to compress the air. The combustion exhausts from out of turbine 0 with relative high temperature as heat fluid of heat exchanger I (HX I) heats the ammonia-water to superheated vapor state with high temperature and pressure. The ammonia-water vapor enters the turbine 1 where the power is generated. Ammonia-water steam exhaust from outlet of turbine 1 is cooled down to saturated liquid by LNG with lower temperature in heat exchanger II (HX II), and then the liquid of ammonia-water is pumped into the HX I by pump 1 to finish the Rankine cycle. LNG with -162 °C and ambient pressure is pumped into HX II by pump 2 from LNG tank and heated to superheat vapor state. Then superheated vapor of natural gas enters the turbine 2 in which power is generate. The natural gas discharged from turbine outlet with pressure higher than ambient is sent to consumer. The cold energy of

LNG is covered through the combined power cycle mentioned above, which costs less natural gas as fuel and generates large amounts of power.

Table 1: The calculation Parameters

Cycle	Items	units	value
CNG	Air ambient temperature	°C	15
Combustion system	Air ambient pressure	MPa	0.1
	Air pressure ratio		15
	Turbine efficiency	100%	0.8
	Turbine inlet temperature	°C	1300
	Compressor efficiency	100%	0.85
	Exhaust gas pressure	MPa	0.1
	Pressure loss ratio in HX I	100%	0.03
	Lower heating value of NG (methane)	KJ/kg	50056
Ammonia-water	NG combustion efficiency	100%	0.98
	Turbine inlet temperature	°C	300
	Turbine inlet pressure	MPa	3
Rankine cycle	Turbine efficiency	100%	0.8
	Pressure loss ratio in HX II	100%	0.03
	Pump efficiency	100%	0.7
	Overall heat conductance	kW/K	200
LNG cycle	Ammonia-water ratio in mass		0.7
	LNG temperature	°C	-162
	LNG pressure	MPa	0.1
	Pump efficiency	100%	0.7
	Pressure loss ratio in HX II	100%	0.03
	Overall heat conductance	kW/K	400
	Turbine inlet temperature	°C	120
	Turbine inlet pressure	MPa	5
Others	Turbine efficiency	100%	0.8
	Natural gas pressure	MPa	0.5
	Pinch point temperature difference	°C	10
	Reference ambient temperature	°C	20
	Reference ambient pressure	MPa	0.1013

3. MODEL

The combined power cycle is modeled in terms of energy and exergy balances for each component. Thermal conditions for calculations are listed in table 1. Pressure loss of fluid is not taken into consideration but in heat exchangers. Properties of air, ammonia-water, combustion gas, and LNG/NG are calculated by commercial package [10]. It is assumed that LNG/NG is a mixture of methane, ethane, and propane in mole ratio 0.8534, 0.079, and 0.0676, respectively. The combustion gas is considered as ideal gas and its properties are calculated according to air when absence of combustion gas data.

3.1 Energy balance equations

Air compressor 0' and NG fuel compressor 0

$$\begin{aligned}
 W_{Ci} &= m_j (h_{CNG-k} - h_{CNG-i}) \\
 &= m_i (h_{CNG-k} - h_{CNG-i}) / \eta_{Ci} \quad (1) \\
 (i, j, k) &= (0', A, 2') \text{ or } (0, NG, 2)
 \end{aligned}$$

Where h' is enthalpy calculated from an isentropic process.

Combustor

$$\begin{aligned}
 \eta_{CMB} m_{NG} LHV_{NG} + m_{NG} h_{CNG-2} \\
 + m_A h_{CNG-2} &= m_G h_{CNG-3} \quad (2)
 \end{aligned}$$

Where

$$m_G = m_{NG} + m_A \quad (3)$$

Turbine 0, turbine 1, and turbine 2

$$\begin{aligned}
 W_{Ti} &= m_j (h_{k-3} - h_{k-4}) \\
 &= \eta_{Ti} m_j (h_{k-3} - h_{k-4}') \quad (4) \\
 (i, j, k) &= (0, G, CNG)
 \end{aligned}$$

or (1, AW, AW) or (2, LNG, LNG)

Where h' is enthalpy calculated from an isentropic process.

Heat exchanger HX I and heat exchanger HX II

$$\begin{aligned}
 m_i (h_{j-4} - h_{j-1}) &= m_k (h_{k-3} - h_{k-2}) \\
 &= UA LMTD_s \quad (5) \\
 (i, j, k, s) &= (G, CNG, AW, I)
 \end{aligned}$$

or (AW, AW, LNG, II)

Where

$$LMTD_s = \frac{(T_{j-4} - T_{k-3}) - (T_{j-1} - T_{k-2})}{\ln \left(\frac{T_{j-4} - T_{k-3}}{T_{j-1} - T_{k-2}} \right)} \quad (6)$$

Pump 1 and pump 2

$$\begin{aligned}
 W_{Pi} &= m_j (h_{j-2} - h_{j-1}) \\
 &= m_j (h_{j-2} - h_{j-1}') / \eta_{Pi} \quad (7) \\
 (i, j) &= (1, AW) \text{ or } (2, LNG)
 \end{aligned}$$

Where h' is enthalpy calculated from an isentropic process.

Overall energy balance

$$\begin{aligned}
 \eta_{CMB} m_{NG} LHV_{NG} \\
 &= W_{T0} - W_{C0'} - W_{C0} \\
 &+ W_{T1} - W_{P1} + W_{T2} - W_{P2} \\
 &+ m_G h_{CNG-1} - m_A h_0 - m_{NG} h_0 \\
 &+ m_{LNG} (h_{LNG-1} - h_{LNG-4}) \quad (8)
 \end{aligned}$$

The thermal efficiency is defined as

$$\eta_{th} = \frac{(W_{T0} - W_{C0} - W_{C0} + W_{T1} - W_{P1} + W_{T2} - W_{P2})}{m_{NG} LHV_{NG}} \quad (9)$$

3.2 Exergy balance equations

The exergy is defined as follows

$$e = (h - h_0) - T_0 (s - s_0) \quad (10)$$

The exergy balance formula is

$$E_{in} = E_{out} + E_{loss} \quad (11)$$

Where

$$E_{in} = m_{NG} LHV_{NG} + m_{LNG} e_{LNG-1} + m_{NG} e_{CNG-0} + m_A e_{CNG-0} \quad (12)$$

$$E_{out} = E_{out_CNG} + E_{out_AW} + E_{out_LNG} \quad (13)$$

$$E_{out_CNG} = m_g (e_{CNG-3} - e_{CNG-4}) - m_A (e_{CNG-2} - e_{CNG-0}) - m_{NG} (e_{CNG-2} - e_{CNG-0}) \quad (14)$$

$$E_{out_AW} = m_{AW} (e_{AW-3} - e_{AW-4}) - m_{AW} (e_{AW-2} - e_{AW-1}) \quad (15)$$

$$E_{out_LNG} = m_{LNG} (e_{LNG-3} - e_{LNG-4}) - m_{LNG} (e_{LNG-2} - e_{LNG-1}) \quad (16)$$

The exergy efficiency is defined as

$$\eta_{ex} = \frac{E_{out}}{E_{in}} \quad (17)$$

4. RESULTS AND DISCUSSION

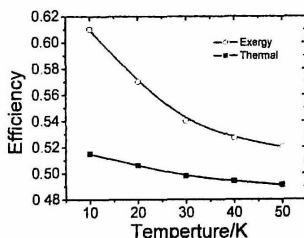


Figure 2: The thermal and exergy efficiency changes with different condensation temperature of HX2

Theory analysis is carried out to calculate the thermal and exergy efficiency of the present combined cycle to recover cold energy of LNG. According to the calculation parameters shown in table 1, Fig. 2 shows that the thermal efficiency and exergy efficiencies change with different condensation temperature at point 1 of HX 2. The thermal efficiency of the

combined cycle decreases as the condensation temperature increases because the outlet pressure of turbine 1 increases with increasing condensation temperature, and the higher outlet pressure of turbine 1 results in a lower turbine output leading to a lower thermal efficiency. Also, the exergy efficiency of this cycle has the same trend as the thermal efficiency. This is because the outlet pressure of the turbine 1 increases with increasing the condensation temperature of HX2, and the higher outlet pressure results in a lower exergy output leading to a lower exergy efficiency.

Other results such as the influences of Fuel and air rates, turbine inlet temperature and pressure, and overall conductance of the heat exchange on the thermal and exergy efficiencies can be obtained, but not present here due to limitation of paper length. This model can be used to get optimum conditions of the key parameters for performance improvement of the combined cycle.

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