LIQUIFIED NATURAL GAS ENERGY CONVERSION POWER PLANT (LNGTEC)

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Abstract: - This paper has proposed a LNGTEC Power Plant model which works by regasification of Liquefied Natural Gas (LNG) and incorporating bottoming cycles to generate power by recapturing the waste heat and utilizing the cold energy available in LNG to be used as a heat sink for the system. This model has an LNG regasification unit which converts LNG to NG and is incorporated with an air treatment unit which enables in improving the efficiency of the system and also utilizes the cold energy of the NG available after vaporization. In this LNGTEC model, exhaust heat from the topping (Brayton) cycle is absorbed by a high temperature Rankine bottoming cycle which uses steam as the working medium. The waste heat rejected from this Rankine cycle is absorbed by a low temperature Rankine bottoming cycle with propane as the working medium. The heat rejected from this low temperature Rankine cycle is used to re-gasify LNG to NG thus, this unit works as the heat sink for the LNGTEC. The cold energy available in NG after vaporization of LNG is further used to cool ambient air to the inlet of the Gas Turbine (GT) thereby fully utilizing the cold energy that was contained in LNG. The NG required for combustion is provided from this regasification and the excess is stored in a reservoir which can be used as city gas. The LNGTEC power plant is modeled by considering the mass & energy balances. The model is tested under various conditions of temperatures and relative humidity. The results show that there is a substantial increase in the efficiency of the GT which translated to the efficiency of the power plant as a result of cooling the air that is fed to the GT. The LNGTEC attained a maximum efficiency of 63% at 5°C and 60% relative humidity. At ambient air intake the LNGTEC efficiency was found to be 52%. Another observation from the simulations was, as the inlet air temperature to the turbine decreases the air fuel ratio decreases. Thus, the power plant model together with LNG regasification and air cooling, utilizes most of the heat energy which is rejected from the primary Brayton cycle to convert to useful work which would else be rejected to the atmosphere along with the flue gasses which would harm our atmosphere. This LNGTEC model is a mix of various technologies and a proposal for the better utilization of energy to generate power.

Key-Words: -Gas Turbine; LNG; Waste Heat Recovery; Turbine inlet air cooling.

1 Introduction

Outlook for energy [1] predicts that electricity generation around the world will account for more than 40% of global energy consumption and the demand for natural gas will rise by more than 60% through 2040. The demand for coal will gradually start to decline because of the emerging policies to curb emissions and the world will start to look at better burning fuels of which natural gas has the capabilities to meet this need.

Natural gas is transported from the production sites to the required sites by containers, pipelines or in liquid form. Cryogenic tanks are used to transport the liquid form of natural gas. The main benefit of liquefaction of natural gas is the reduction in volume of about 1/600th of natural gas which results in more energy per volume. The burning of natural gas is much cleaner when compared to other fossil fuels.

LNG is colourless, non-toxic & non-corrosive. The heating value of LNG depends on the source of the gas and compositions.

Liquefied Natural Gas Worldwide [2] states that there are about 26 existing LNG exporting liquefaction terminals and about 60 existing LNG import or regasification terminals throughout the world. Countries are looking at more efficient ways to generate power and also looking at the best possible fuel it. Nowadays there is a lot of attention towards LNG because of its many advantages over other fuels.

The demand for LNG in power generation is increasing and the trend is expected to further increase in the years to come. The major suppliers of natural gas are concentrated in the Middle East [3]. The transport of NG to major importing destinations like JAPAN, EUROPE, USA, etc. would be in the form of LNG. It is here that this LNGTEC model would come into the picture.

In this LNGTEC model to increase the efficiency and power generation, bottoming cycles are incorporated. The topping cycle which uses natural gas as the fuel is coupled with these bottoming cycles working on the heat rejected from the topping cycle. The first bottoming cycle uses steam as the working fluid and the second bottoming cycle uses propane as the working fluid to utilize the low grade heat energy rejected from the first bottoming cycle. The heat rejected from the second bottoming cycle is utilized in re-gasifying LNG to NG. This enables the LNGTEC system to utilize the cold energy available in LNG as the heat sink. This setup results in power savings and also helps to cut the cost of maintaining a separate heat sink and air cooling unit for the system. The LNGTEC system also helps to bring down the emissions the system.

Defu Che [4] evaluated the performance of a combined cycle using low temperature waste heat recovery of LNG. A good performance with net electrical & exergy efficiency for a typical operating condition were achieved.

Y. Hisazumi [5] proposed a high efficiency power generation system with an LNG vaporizing system. The results of this study show that the net efficiency of over 53% HHV can be achieved and in the case of an LNG terminal receiving 5 million tons of LNG per year the system can generate 240MW and reduce the power of the sea water pump by more than 2MW.

The NG is further used to cool down the ambient air fed to the Gas Turbine (GT). The cooling of air to the GT improves the efficiency of Brayton cycle. This results in utilizing almost all the energy which is fed to and rejected from the Brayton cycle.

J O Jaber [6] evaluated the cooling of the air intake on GT & found that it boosted the power output & as well enhancing the efficiency of the GT.

Thamir K. Ibrahim [7] investigated the performance of a GT and found that the performance mainly depends on the inlet air temperature. This study found that for a rise of 1°C temperature of inlet air there was a decrease in power output by 1%. They concluded that with inlet air cooling systems there is an increase in the performance of GT power plants.

L Garooci Farshi [8] evaluated the improvement of simple and regenerative GT's using refrigeration. This research showed a performance result of about 6-10% increase in the net work and 1-5% increase in efficiency for every 10°C decrease on inlet temperature.

2 Methodology

For the LNGTEC model the selected GT is GE

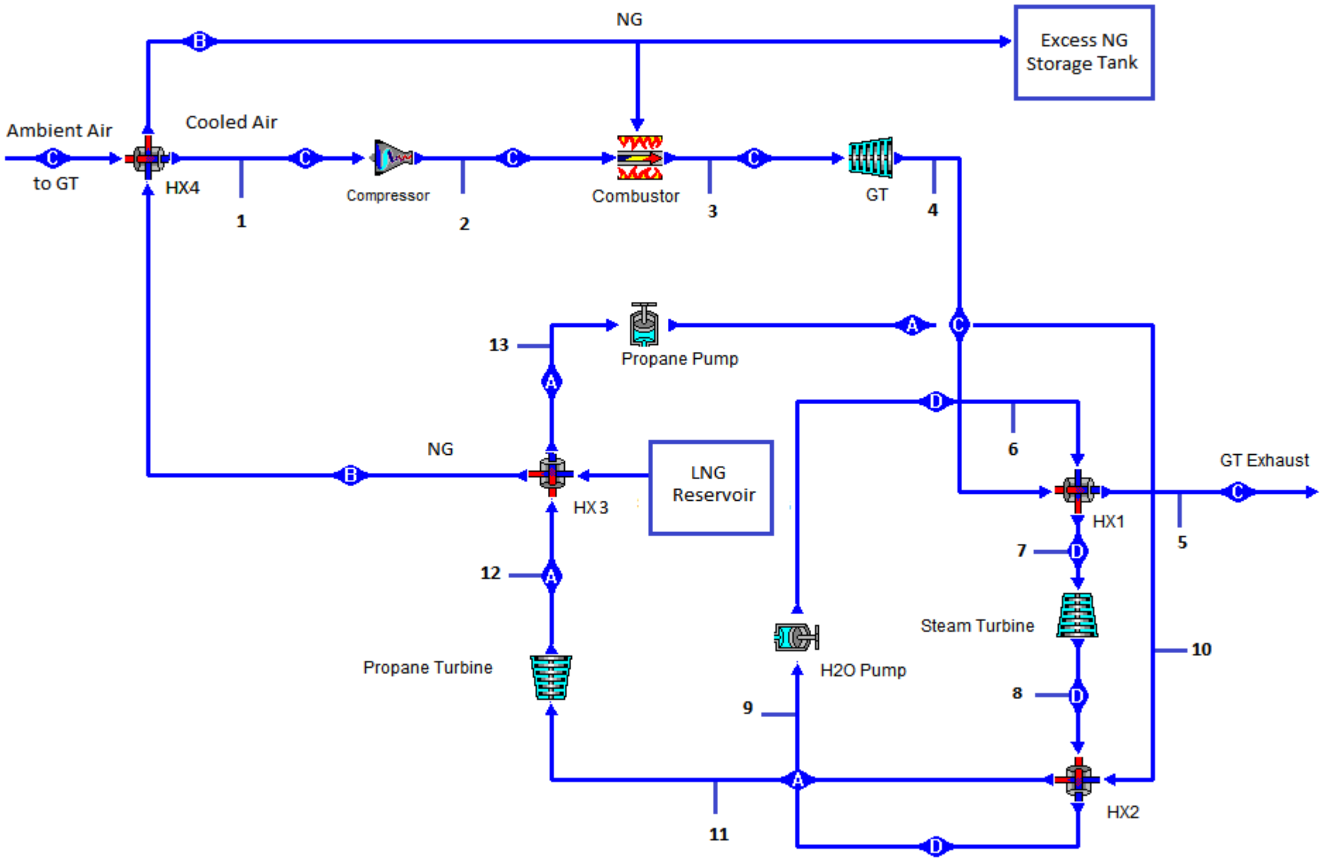

Figure 1: Schematic of proposed LNGTEC model with LNG regasification and air cooling.

PG9351FA. The specifications of the GT and the bottoming cycles are given in Table 1. GTs use air and fuel for combustion to produce power. With the ever increasing cost of fuel it is necessary that we come up with solutions to maximize the efficiency of each drop of fuel consumed by the system. In hot & humid conditions especially around the equatorial regions of the world, the efficiency of a GTs can easily drop far below the expected & tested values [7].

In the LNGTEC model designed here, there are 3 cycles - a Brayton cycle, a steam bottoming cycle and a propane bottoming cycle. A LNG vaporizing unit & inlet air treatment unit is coupled to the LNGTEC model. The LNG vaporizing unit is a vital component of the system as it would enable us to make use of the cold energy available in LNG to be used as a heat sink for the system.

Natural gas is burnt in the GT along with the appropriate quantity of air for combustion. The air used in the GT is treated to reduce the temperature and control moisture content from intake before entering compressor. The treatment unit provides the compressor with more dry air thus lowering the air fuel ratio to the GT [9] [10]. The exhaust gas from the GT is passed through a heat exchanger (HX1) where energy is transferred to the steam bottoming cycle.

The heated steam is then expanded in the turbine of the steam bottoming cycle to produce power. The spent steam from this turbine is then fed to a heat exchanger (HX2) where energy is transferred from the spent steam to the propane bottoming cycle, thereby condensing the steam to water and heating up propane.

The heated propane is then expanded in the turbine of the propane bottoming cycle to produce energy. The spent propane from the turbine is then fed to a heat exchanger (HX3) where energy is transferred from the spent propane to the LNG. This results in the vaporization of the LNG to NG.

The vaporized NG at sub-zero temperatures is then passed through a heat exchanger (HX4) where the cold energy is transferred to the moist ambient air, conditioning it to a lower temperature and controlling the moisture content. The conditioned air is then fed to the GT for combustion making it more efficient than directly using the ambient air [11].

The LNGTEC model recovers almost all the energy carried away by the GT exhaust with the incorporation of the bottoming cycles. The LNG vaporization unit recovers the cold energy spent in liquefying NG to LNG by enabling us to cool the air fed to the GT for combustion at the same time working as the sink for LNGTEC.

Table 1 Base Data for Simulation

Parameter(unit)	**Value**
Ambient temperature (K)	311.15
Atmospheric Pressure (kPa)	101.325
Relative Humidity (%)	90
Fuel: Natural Gas, LHV (kJ/kg)	50,050
GEPG9351FA Gas Turbine [12]	
Gross Power (MW)	255.6
Compression Ratio	15.4
High Temperature Rankine Cycle	
Steam Turbine (MPa / K)	4 / 813.15
Low Temperature Rankine Cycle	
Propane Turbine (MPa / K)	4 / 373.15

3 Assumptions

1. The ambient air is at 38°C and 90% RH
2. The efficiency of the GT increases 5% for every 10°C drop in temperature [8]
3. At ISO rated conditions the GT thermal efficiency is 36.9% [13]
4. The effectiveness of heat recovery is 97%
5. The pump efficiency is 85%
6. The steam turbine efficiency is 91.8%
7. The propane turbine efficiency is 90%
8. LHV of LNG is 50,050 kJ/kg [14]
9. Flue gas exit temperature 50°C

4 Results & Discussions

To investigate the effect of turbine inlet air cooling on the thermal efficiency of the GT, analysis has been conducted under various conditions of temperature.

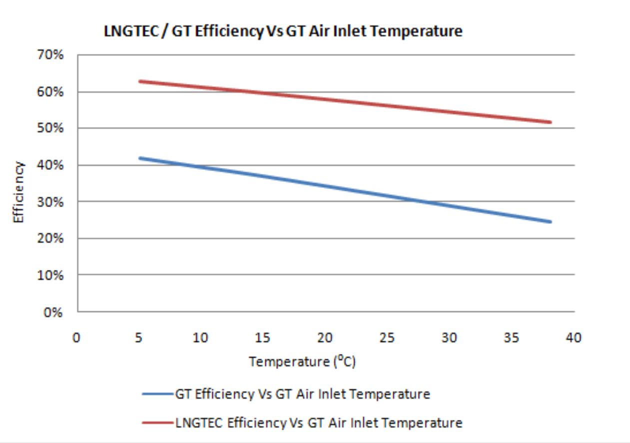

Figure 2: The effect of GT air inlet temperature on thermal efficiencies

$$\eta GT_{cycle\ th} = \frac{W_{GT} - W_C}{\mathrm{Q}_{\mathrm{GT}_{\mathrm{cycle\ in}}}} \qquad (1)$$

$$\eta_{\mathrm{LNGTEC}} = \frac{\left(\mathrm{W}_{\mathrm{GT}_{\mathrm{cycle}}} + \mathrm{W}_{\mathrm{ST}_{\mathrm{cycle}}} + \mathrm{W}_{\mathrm{PT}_{\mathrm{cycle}}}\right)}{\mathrm{Q}_{\mathrm{GT}_{\mathrm{cycle\ in}}}} \qquad (2)$$

To find the thermal efficiency of GT and the LNGTEC model the above equations [15] were used. The results of the analysis can be observed in Figure 2, it can be noticed that as temperature decreases the efficiency of both the LNGTEC and simple cycle increases. This is due to dry air entering the GT for combustion and as a result the compressor has to do less work.

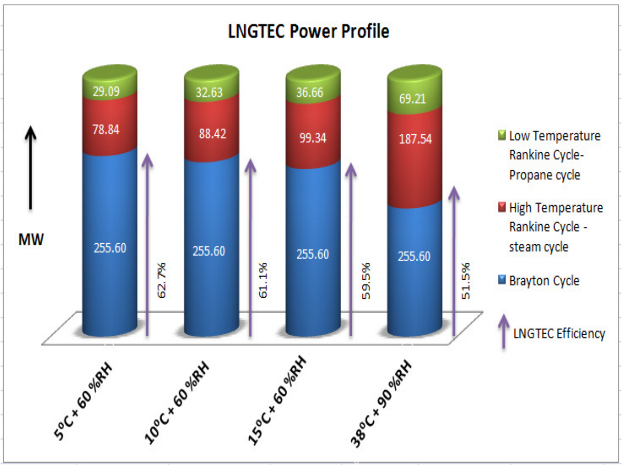

Figure 3: Effect of GT air inlet temperature on Power profile of LNGTEC and simple cycle.

$$\mathrm{W}_{\mathrm{GT}_{\mathrm{cycle}}} = \mathrm{W}_{\mathrm{GT}} - \mathrm{W}_{\mathrm{C}} \qquad (3)$$

$$\mathrm{W}_{\mathrm{ST}_{\mathrm{cycle}}} = \mathrm{W}_{\mathrm{ST}} - \mathrm{W}_{\mathrm{SP}} \qquad (4)$$

$$\mathrm{W}_{\mathrm{PT}_{\mathrm{cycle}}} = \mathrm{W}_{\mathrm{PT}} - \mathrm{W}_{\mathrm{PP}} \qquad (5)$$

$$\mathrm{W}_{\mathrm{LNGTEC}} = \mathrm{W}_{\mathrm{GT}_{\mathrm{cycle}}} + \mathrm{W}_{\mathrm{ST}_{\mathrm{cycle}}} + \mathrm{W}_{\mathrm{PT}_{\mathrm{cycle}}} \qquad (6)$$

The powers generated by LNGTEC and simple cycle were found using the above set of equations [15]. The results of the analysis of GT air inlet temperature on power profile of the LNGTEC and simple cycle can be observed in Figure 3. As the temperature decreases the net power developed by the LNGTEC model also decreases. This is due to the higher efficiency of the topping cycle at lower temperatures and results in topping cycle rejecting less heat thus limiting the power generated. As the temperature increases the topping cycle has lower efficiencies and rejects more heat which is captured by the bottoming cycles. Thus, the power generated at higher temperatures would be higher for LNGTEC.

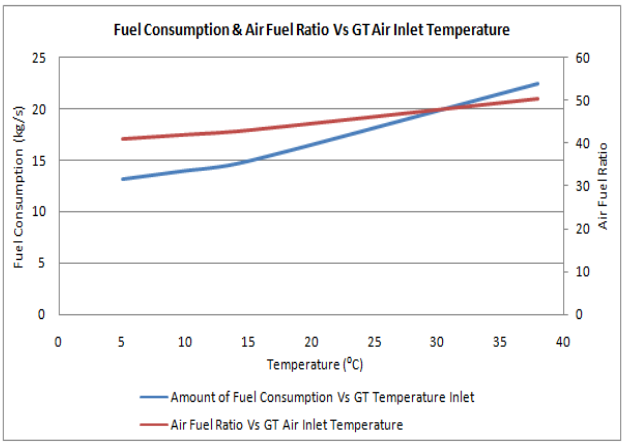

Figure 4: The Effect of GT Air Inlet Temperature on Fuel Consumption & Air Fuel Ratio

$$\dot{m}f \times LHV = \dot{m}a \times Cp_a \times \Delta T \qquad (7)$$

The air fuel ratio of LNGTEC is found using the above equation [16]. From Figure 4 we can see the air fuel ratio & fuel consumption at various temperatures. As the GT air inlet temperature decreases the LNGTEC attains higher efficiency and consumes less fuel for combustion. As the GT air inlet temperature increases the LNGTEC efficiency decreases and the air fuel ratio increases and thereby increasing the fuel consumption.

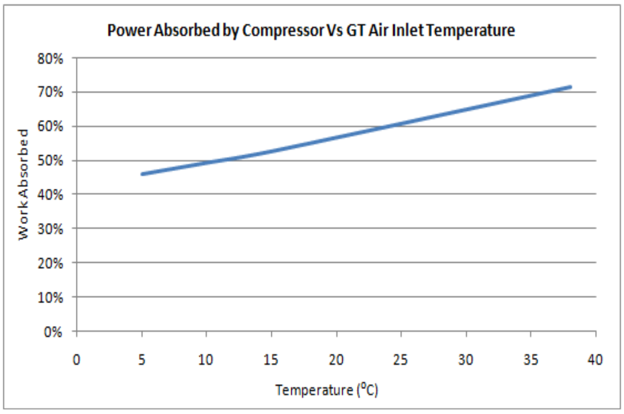

Figure 5: The effect of GT air inlet temperatures on power absorbed by the compressor

The work absorbed by the compressor varies with temperature. This can be observed from Figure 5. As the GT air inlet temperature decreases the compressor has to do less work since there is a reduction in the moisture content of the air entering the system. At higher temperatures the air entering the compressor will have more moisture content so the compressor has to do more work to provide the turbine with necessary air to enable combustion.

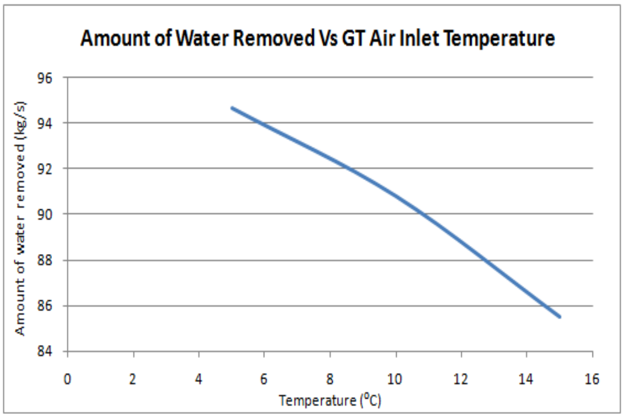

Figure 6: Amount of water removed at various temperatures

$$\dot{m}_a = \frac{(A.V)1}{\left(R/_{Ma}\right)\times\left(T/_{pa1}\right)} \qquad (8)$$

$$\omega = 0.622 \times \left(\frac{pv}{p-pv}\right) \qquad (9)$$

$$\frac{\dot{m}_w}{\dot{m}_a} = \Delta\omega \qquad (10)$$

The amount of water removed from the ambient air is calculated using the above equations [15]. As the GT inlet air is cooled to lower temperatures the amount of water removed increases. From Figure 6 we can observe the amount of water that is being captured in the process of cooling the ambient air. Thus, the cooling unit removes the moisture content of the inlet air and increases the density of the air entering the GT.

5 Conclusion & Future Works

From the analysis it can be observed that, as a result of incorporation of the ambient air treatment unit in the LNGTEC model efficiency can be increased. The efficiency of the GT is less at higher temperatures and this loss in efficiency can be made up / captured by employing bottoming cycles. The bottoming cycles together with the LNG vaporization and ambient air conditioning units put forward an efficient method of recovering the energy in LNG power production.

The LNGTEC model has showed a maximum efficiency of 63% at the lowest evaluated temperature of 5°C at a power output of 360MW. If only simple cycles were included in the analysis the output would be 255.6 MW, the rated power for the selected GT.

This proves that the rejected heat coming from the GT cycle has enough energy to run two bottoming cycles, an LNG vaporizing unit and an air cooling unit to cool the GT air inlet temperature. This also helps in reducing the heat rejected to the environment. Thus, the LNGTEC model analyzed here has many advantages over the conventional setups.

The LNGTEC model is a simple design of coupling bottoming cycles with topping cycle. More work will be done to enhance the design to commercialization.

6 Nomenclature

HX	Heat Exchanger
η	Efficiency
W	Work
$\dot{m}$	Mass Flow Rate
Cp	Heat Capacity
Q	Heat Transfer
h	Enthalpy
s	Entropy
T	Temperature
1,2,3…13	States
Pa	Partial Pressure of dry air
Pv	Partial Pressure of Vapor
ω	Relative Humidity

Subscripts

GT	Gas Turbine
C	Compressor
SP	Water Pump
PT	Propane Turbine
PP	Propane Pump
PT_{cycle}	Propane Cycle
PP	Propane Pump
ST_{cycle}	Steam Cycle
a	Air
w	Water
in	inlet
out	outlet

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