Thermodynamic Analysis of Combined Cooling and Power (CCP) System Operated by IC Engine Waste Heat

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Abstract: **This work presents a comprehensive energy analysis of a Combined Cooling and Power (CCP) system operated through waste heat of IC Engine. The integrated cycles; Organic Rankine Cycle (ORC) and Vapor Absorption Refrigeration Cycle (VARC), are utilized to produce power and cooling, respectively. Four organic working fluids, namely R142b, R113, R245fa and n-pentane were selected for ORC, while LiBr-H_20 solution in VARC. Three key performing parameters, work output, energy utilization factor (EUF) and cooling rate were related to varying temperatures of evaporator/condenser in ORC, and generation/evaporator in VARC with power only, power and with cooling and cooling only modes of operation. The results show that in the power operation mode, the maximum thermal efficiency of R113 is 12.72% and the minimum thermal efficiency of R142b is 12%. Therefore, R113 was selected as an organic working fluid for further research. The maximum EUF was found in the cooling mode of operation which increased from 12.79% to 74.5%. During the combined both cooling and power mode, optimum power output, cooling rate, and EUF were 82.08 kW, 505.10 kW, and 45.58% respectively.**

Keywords: **IC Engine, ORC, VARC, Waste Heat.**

I. INTRODUCTION

Energy is the soul of modern machine age. As energy and environmental issues become more severe, including the depletion of fossil fuels and global pollution, more attention is to be paid to environmental protection and energy conservation. [1, 2]. It is well known that energy deficiencies and environmental pollution have turned out to be global issues now a days. Since the climate variation and the deficiency of non-renewable assets, the interests in waste heat recovery has been growing remarkably, particularly in the past decade [3, 4].

Among all the available sources, the internal combustion engines well known as IC engines are the major consumer of fossil fuel around the world. The IC engine is the primary power source for transportation, power generation, construction, and agriculture sector. The efficiency of the conventional IC engine is usually less than 40%, as shown in Fig.1. Despite a lot of effort, excessive quantity of fuel energy is still lost into the atmosphere mostly through cooling water and engine exhaust. The temperature of these waste heat sources is high enough and that can be used to operate low grade energy cycle to produce power [5]. Utilizing waste heat from IC engines is one of the prospects for saving fuel consumptions. To improve thermal efficiency of IC engine by harvesting waste heat through exhaust flue gases and engine jacket cooling water, several methods and technologies have been recommended such as organic Rankine cycle (ORC), heat pumps, turbocharging, Kalina cycle System (KCS), vapor absorption refrigeration system, thermoelectric generator and many more [6, 7]. Thus, among all these strategies ORC and vapor absorption chiller has been widely recognized as efficient method for conversion of thermal energy, into mechanical and/or electrical energy due to good economic performance and environmental friendly [8]

[9] Compared ORCs and supercritical Rankine cycles for low grade heat sources and suggests that ORC shows better results due to its lower heating values and investigated that while selecting the ORC working fluid thermodynamic properties, environmental impacts, safety, physical properties, stability, cost and availability are considered as the significant parameters [10]. Reviewed that the ORC is most suitable technology for IC engine waste heat recovery for low grade to medium-grade waste heat, and no single working fluid is best for all the ORC's as the selection of the proper working fluid requires consideration of operating conditions, economic factors and environmental concerns. [11] Stated that there are two main features of ORC that are selection of turbines (expansion machine) and working fluids. He classified ORC technologies in different heat source applications with their temperature ranges and evaluate its economic parameters. [12] When compared to conventional double effect chiller with combined effect chiller, it is examined that maximum COP for single effect absorption chiller is 0.7 at 80 $°C$ to 115$°C$, similarly the COP becomes 1.2 when it is operated between 140 $°C$ and 180$°C$.

This paper introduces a combined power and cooling generation from a waste heat of IC engine including exhaust flue gases and Jacket cooling water heat. We analyze waste heat of IC Engine G3606 (technical data from Caterpillar gas compressor set). In addition, different working fluids are considered to optimize maximum efficiency of the proposed system and HTF is used to transfer heat and fraction it accordingly.

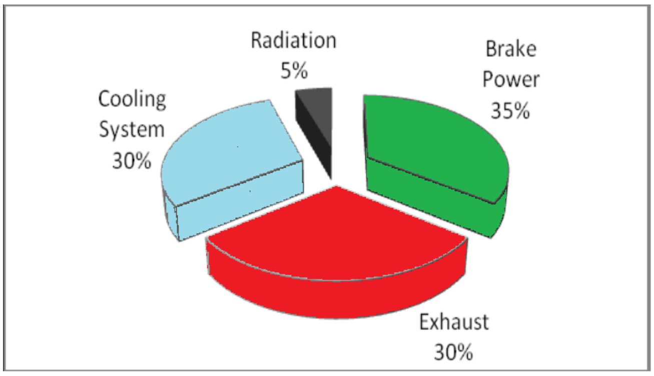


Fig. 1 Total Fuel Energy Consumption of I.C Engine

II. MATERIALS & METHODS

A. Site Selection

The IC Engine thermodynamic model and parametric study of the system is proposed for the JJVL Company. The JJVL (Jamshoro Joint Venture Limited) is located at distance of 6-7 km from Jamshoro in province Sindh. The two major products of JJVL are LPG (Liquified Petroleum Gas) and NGL (Natural Gasoline Liquid) are being recovered/extracted from natural gas. The company was constructed in 2005. JJVL has total capacity of 325 Million Standard cubic feet of inlet gas per day (MMSCFD) & it's known as the Pakistan's largest LPG producing company. However, there are 7 Single stage double acting reciprocating compressors being used in JJVL plant and their manufacturers are DRASSER RAND company. These compressors are driven by the CATERPILLAR G3606 engines which are coupled on a same shaft. Each compressor increases the gas pressure from 300 psi to 700 psi.

Table 1: Technical data of IC engine

Engine model	CAT G3606
Engine manufacturer	Caterpillar
Engine power	1300 HP
Max RPM	1000
Fuel type	Natural Gas
Fuel consumption	6903 BTU/bhp-hr
Average load	75 %
Exhaust stack temperature (75% load)	460 ^{0}C
Exhaust gas flow rate	270 m^3/min
Cooling system	Jacket cooling water

B. System Description

The heat exchangers are introduced to capture waste heat of IC engine from exhaust flue gases and jacket cooling water, as this heat energy from these two sources of IC engine was wasted to the atmosphere earlier. Fig. 2 shows the process flow diagram of the proposed cogeneration system. It can be shown that ORC and VARC systems are integrated with engine exhaust and jacket cooling water. HTF is used to circulate in a closed cycle which serves as a medium of heat transfer between heat sources to ORC and VARC. The exhaust gas of IC engine will be released into atmosphere at point 2 after heating the HTF by means of heat exchanger and similarly IC engine Jacket cooling water will enter back into engine after exchanging heat with the HTF in the heat exchanger at point 4. The portion of HTF is used in ORC to evaporate the organic fluid, causing the turbine to generate electricity. And the remaining amount of HTF is used in the generator of VARC to produce cooling effect for offices and residential buildings. Afterward, HTF leaving the ORC evaporator and VARC generator it will mix at state 31 and the cycle will continue. Hence the HTF can be distributed according to the required power and cooling load.

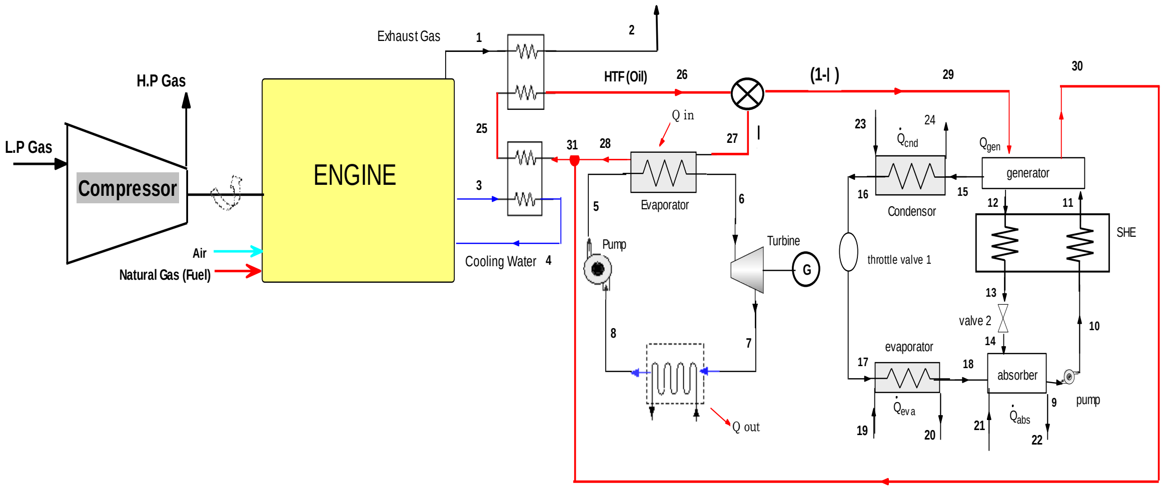


Fig. 2 : Schematic diagram of the system

C. *Working fluid selection*

The working fluid plays an important role in system operation and to determine the best working fluid an extensive range of Organic fluids are analyzed. The working fluids are selected from each group R113, R142b, R245fa and n-pentane from Chlorofluoro carbons (CFCs), Hydrochloro fluorocarbon (HCFCs), Hydrofluoro carbons (HFCs) and Hydrocarbons(HCs) respectively. Temperature range, environmental impacts (GWP and ODP), thermal stability, safety, toxity and economic availability was considered key factors while selecting the working fluid for ORC [9, 11, 13].

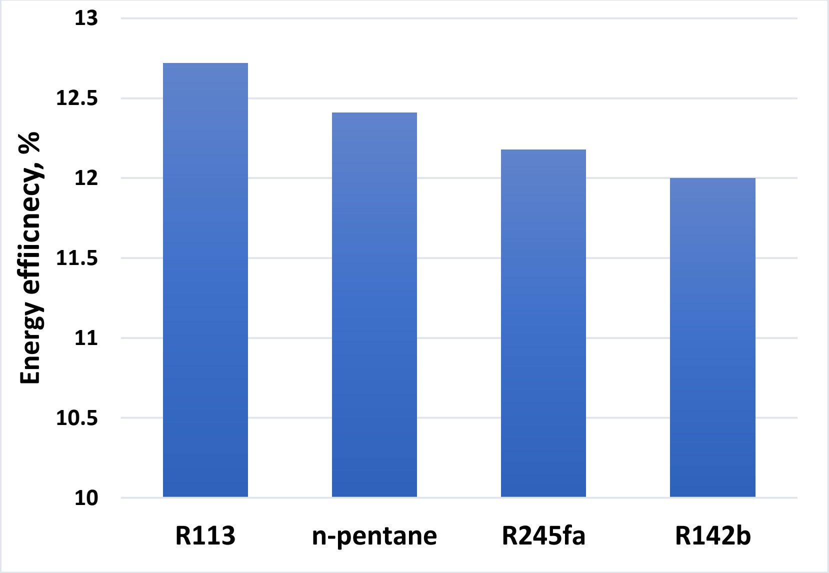


Fig. 3 Energy efficiency of ORC

The results of the four organic fluids were evaluated to find a suitable organic working fluid for ORC. As shown in Fig.3, R113 provides the maximum thermal efficiency of the ORC, whereas R142b gives minimum thermal efficiency at the rated operating conditions. Considering the greatest performance among the defined organic fluids for ORC, R113 was selected for further studies. while LiBr-H20 solution for VARC.

D. *Thermodynamic Modelling*

This section illustrates, the thermodynamic models used in Engineering Equation Solver (EES) to assess a system performance. The following constant parameters are used for the parametric study of the system, shown in table 2.

We consider the following conditions and assumptions are valid to simulate the thermodynamic modelling of IC Engine-(ORC and VARC) in EES software,

- The Exhaust gas outlet temperature is limited to 120 ° C or more to avoid acid corrosion [14].
- The outlet temperature of the IC Engine jacket cooling water is 90 $°C$ and inlet temperature is 60 $°C$, following the IC Engine manual and average environmental conditions.

- The pinch point temperature difference in all the heat exchangers is about 5 $°C$. Moreover, supercooling is not considered in the condenser.
- The pressure and heat loss in the evaporator (ORC), generator (VARC) and condensers is negligible. Dry expansion of all fluids.
- Mass flow rate of HTF is constant
- Steady-state conditions are considered for the entire system.
- Isentropic efficiency of turbine 85%
- Isentropic efficiency of pump 80%

The mass and energy balance equations are used for each component in the systems is given below.

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (1)$$

$$\dot{Q}_{out} + \dot{W}_{in} + \sum \dot{m}_{in} h_{in} = \dot{Q}_{out} + \dot{W}_{out} + \sum \dot{m}_{out} h_{out} \quad (2)$$

Following equations are used to determine total heat of IC engine exhaust gas and jacket cooling water.

$$\dot{Q}_{ex} = \dot{m}_{ex} Cp_{ex} (T_1 - T_2) \quad (3)$$

$$\dot{Q}_{cwt} = \dot{m}_{cwt} Cp_{cwt} (T_3 - T_4) \quad (4)$$

$$\dot{Q}_{total} = \dot{Q}_{ex} + \dot{Q}_{cwt} \quad (5)$$

Table 2. Model equations for each component of ORC and VARC with performance parameters

Model equations of ORC components	**Model equations of VARC components**
Feed pump: $\dot{W}_{FP} = \dot{m}_{ORC}(h_5 - h_8)$	SHX: $\dot{m}_{12}(h_{12} - h_{13}) = \dot{m}_{10}(h_{11} - h_{10})$
Evaporator 1: $\dot{Q}_{Evp,ORC} = \dot{m}_{ORC}(h_6 - h_5) = Q_{total}.\lambda$	Generator: $Q_{GEN} = \dot{m}_{15}.h_{15} + \dot{m}_{12}.h_{12} - \dot{m}_{11}.h_{11} = \dot{Q}_{total}.(1 - \lambda)$
Turbine: $\dot{W}_{turb} = \dot{m}_{ORC}(h_6 - h_7)$	Absorber: $Q_{ABS} = \dot{m}_{18}.h_{18} + \dot{m}_{14}.h_{14} - \dot{m}_9.h_9$
Condenser: $\dot{Q}_{CND1} = \dot{m}_{ORC}(h_7 - h_8)$	Condenser: $\dot{Q}_{CND2} = \dot{m}_{15}(h_{15} - h_{16})$
Net power output: $\dot{W}_{ORC,net} = \dot{W}_{turb} - \dot{W}_{FP} - \dot{W}_{HTF,\_P}$	Evaporator 2: $\dot{Q}_{Evp,VARC} = \dot{m}_{18}(h_{18} - h_{17})$
Thermal efficiency: $n_{th,ORC} = \frac{\dot{W}_{ORC,net}}{\dot{Q}_{Evp,ORC}}$	Coefficient of Performance : $COP = \frac{\dot{Q}_{EVP,VARC}}{\dot{Q}_{GEN}}$
Energy Utilization Factor (Overall performance): $EUF = \frac{\dot{W}_{net} + \dot{Q}_{cooling}}{\dot{Q}_{total}}$	

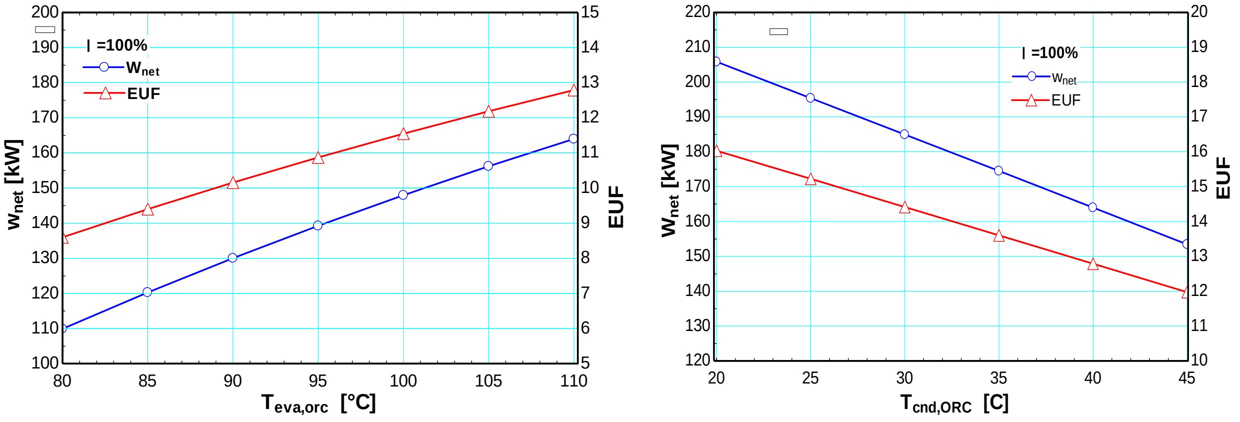
III. RESULTS AND DISCUSSION

In this study, comprehensive energy analysis of ORC and VARC operated by waste heat of IC Engine has been performed in these three modes of operation maintained by the HTF's mass flow fraction (λ). The working modes are well-defined as power only (λ = 1.00), combined power and with cooling (λ = 0.50) and cooling only (λ = 0). Three key performing parameters, cooling rate, work output, and the energy utilization factor (EUF) are related to changing temperatures of evaporator/condenser in ORC, and generation/evaporator in these modes of operation respectively. Using EES software, the thermodynamic analysis and parametric studies were conducted to check effects of energy performance of the system on temperature changes.

A. Power mode (λ = 1)

When λ is set to 1.0, the system operates in power mode, which means that the entire HTF points to the ORC. The effect of evaporator temperature in ORC on the net power output is shown in Fig. 4(a). It can be observed that as the ORC evaporator temperature rises from 80ºC to 110ºC, the ORC net output power and EUF of R113 increase from 110 kW to 164 kW and 8.5% to 12.72%, respectively. The supplied thermal heat energy increases the mass flow of the ORC working fluid and enthalpy difference along the turbine, thereby increasing the net power output of Organic Rankine cycle and EUF.

The effect of condenser temperature of ORC at T_2=110 ºC is shown in Fig. 4(b). The behavior of graph clearly indicated that as condenser temperature increases from 20ºC to 45ºC, the net power output of ORC and EUF of the system starts decreasing from 206 kW to 154 kW and 16% to 12% respectively due to the decrease in sink temperature and enthalpy difference along the condenser. Therefore, lower the condenser temperature, higher will be the net power output.

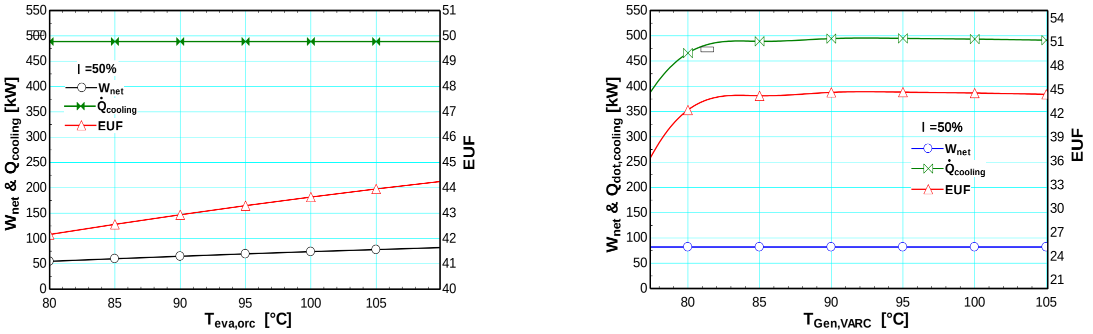


(a) (b)

Fig. 4 Impact of evaporator temperature (a) and Condenser temperature (b) on net power output and EUF

B. *Combines power and cooling mode ($\lambda = 0.5$)*

The impact of evaporator temperature of ORC on cooling rate of VARC, net power output (ORC) and EUF at $\lambda = 0.5$ is illustrated in Fig. 5(a), which indicates that 50% of HTF is circulated towards ORC and remaining 50% of HTF flows towards VARC. The response of graph shows that as the evaporator temperature (ORC) rises from 80ºC to 110ºC, the net power output and EUF increases from 58 kW to 82 kW and 42.1% to 44.2% respectively. This is due to the supplied heat energy in evaporator increases the mass flow rate of ORC working fluid and the enthalpy difference along the turbine. While the cooling rate is constant at 495 kW because evaporator temperature of ORC will only affect the results of ORC. The effect of generator temperature in VARC on cooling rate and EUF is shown in Fig. 5(b). It is observed that cooling rate and EUF of VARC for LiBr-H_20 increases from 460 kW to 495 kW and 42% to 44.8% respectively with increase in generator temperature from 80 ºC to 105 ºC. It can also be realized that when the system is operated in power and cooling mode (i.e., $\lambda = 0.5$) at same operating conditions, the EUF is increased as compared to power mode of operation due to the use of more thermal energy is utilized with fraction of HTF circulated in VARC and ORC closed loops.

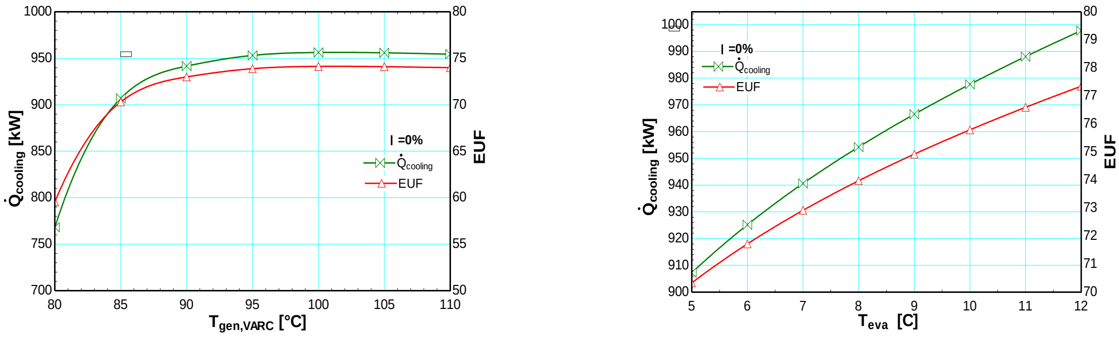


(a) (b)

Fig. 5 Impact of evaporator temperature (a) and Generator temperature (b) on cooling rate, net power output and EUF

C. *Cooling mode ($\lambda = 0$)*

In cooling mode of operation, the entire HTF is directed towards VARC. The impact of generator temperature in VARC on the net cooling rate is shown in Fig. 6(a). It is observed that cooling rate and EUF of VARC for LiBr-H_20 increases from 770 kW to 958 kW and 59% to 74.5% respectively with increase in generator temperature from 80 ºC to 110ºC. The cooling rate is increased because the temperature and enthalpy of working fluid is increased in VARC. Fig. 6(b) shows that the increase in evaporator temperature of VARC system will increase the cooling rate and EUF from 908 kW to 997 kW and 70.2% to 77.3% respectively with increase in evaporator temperature from 5 ºC to 12ºC. The cooling rate is increased because the temperature of cooling requirement load on evaporator is increased so the it will be result in increase in cooling rate.



(a) (b)

Fig. 6 Effect of variation of generator temperature (a) and VARC generator temperature (b) on cooling rate and EUF

Therefore, HTF can be fractionalized accordingly to meet JJVL's total demand for power and cooling load. By utilizing the waste heat of a total seven IC engines, company can meet power and cooling demand without compensation, and they can save a huge amount to meet energy needs and contribute to environmental protection.

IV. CONCLUSION

The thermodynamic analysis of the IC engine waste heat resources include exhaust gas and jacket cooling water are employed to produce combined power and cooling system. The appropriate working fluids have been selected for the ORC system to optimize maximum system efficiency and decrease environmental impacts. The system was operated in three operating modes i.e. the power only, combined power and cooling and the cooling only to find the ORC net power output, cooling rate of VARC and EUF of the system. Engineering Equation Solver (EES) software was used for performing thermodynamic and parametric study. The main conclusion from the presented study are summarized as given below:

- The results show that with increase in evaporator temperature (ORC) and generator temperature (VARC), the net power output and cooling rate increases respectively, whereas by the increasing condenser temperature the net power output and cooling amount decreases.
- Working fluid R113 shows the maximum system efficiency of ORC and net power output was 164 kW at evaporator temperature 110 $°C$ with thermal efficiency of the ORC system 12.72% in only power mode of operation.
- In combined power and cooling mode, 82 kW power output and 505 kW (143 tons of refrigeration) cooling rate was produced with EUF of 45%.
- Maximum EUF was found in only cooling mode that is 74.5% and COP of VARC system is 0.76.
- Total capital cost of the cogeneration system is 1.208 Million USD and the payback period of this proposed cogeneration system is about 3.2 years, when fuel cost is 6.6 USD/MMBTU.

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