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Energy and Exergy analysis of diesel engine powered trigeneration systems

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Abstract

This article presents the thermodynamic analysis of diesel engine powered trigeneration system considering the actual engine data of 200 kVA engine systems. Trigeneration systems considered for analysis comprises of a diesel engine integrated with absorption chillers. For better thermodynamic performance of a trigeneration system for cooling applications, absorption chillers integrated with engine systems should accept the heat energy at almost the same temperature at which it is available. With this consideration two trigeneration systems are examined. System one uses low grade heat energy recovered from engine jacket water with single effect chiller and high grade heat energy of exhaust gases in double effect chiller. System two combines recovered energy for use in a single chiller. Analysis of such trigeneration configurations cannot be based on first law analysis alone. This paper through an energy and exergy analysis of a trigeneration system under cooling mode, recommends the use of a trigeneration system with two chillers over a trigeneration system with single chiller. Operating the trigeneration system near the rated capacity of engines improves its energetic as well as exergetic performance. Though the initial cost of a trigeneration system with two chillers is more than the one with single chiller, life cycle costing analysis reveals the former is attractive even on economic basis.

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1. Introduction

Trigeneration with reciprocating engines as prime movers involve recovery of energy rejected from engines and using this energy to satisfy cooling and heating demand of a given load. Energy recovered from exhaust gases is

Nomenclature

C_p	specific heat of water [kJ/kg K]
C_{pg}	specific heat of engine exhaust gases [kJ/kg K]
CRF	capital recovery factor
COP	coefficient of performance
DEC	double effect chiller
DG	diesel generator
d	discount rate
e	specific exergy [kJ/kg]
EJ	diesel engine jacket
EHRU	Exhaust heat recovery unit
E_F	Exergy of fuel
E_P	Exergy of product
E_q	Exergy associated with heat transfer
E_D	Exergy destroyed
HE_1	Heat exchanger for heat transfer from engine jacket water to water input of desorber
m_g	mass flow rate of exhaust gases of the engine [kg/s]
m_a	mass flow rate of air consumed by the engine [kg/s]
m_f	fuel consumption rate of engine [kg/s]
m_h	mass flow rate of hot water entering the desorber of single effect chiller [kg/s]
m_w	mass flow rate of engine jacket water [kg/s]
m_c	mass flow rate of chilled water from single effect chiller [kg/s]
m_c	mass flow rate of chilled water from double effect chiller [kg/s]
P	Pump
P_c	Cooling load in TR
P_e	electrical power output
SEC	single effect chiller
S	specific entropy in kJ/kg K
T	temperature of the fluid in K
T_0	dead state temperature in K
TR	tons of refrigeration
y^*	exergy destruction in component with respect to exergy input
y	exergy destruction in component with respect to total exergy destruction in system
η_e	exergetic efficiency

commonly harnessed using suitably designed heat exchangers [2,3]. Absorption chillers come in different configurations and types which affects its performance [4]. Systems approach in analyzing trigeneration systems has been used in many studies indicating the desirability of trigeneration [5]. Trigeneration systems are required to satisfy the variable power demand or variable thermal demand depending on the load curve and the mode of operation of diesel generator [6]. Diesel generators operating in electricity demand following mode would operate at part loads at times. Part load behavior of engines would result in corresponding reduction in output of absorption chillers.

Integrating absorption chillers with diesel engine generators requires a thorough understanding of both quantity as well as quality of energy recoverable from the engine. The energy balance of diesel generators is investigated thoroughly by many researchers. It is known that the exhaust gas quantity as well as its temperature varies

appreciably with engine loading. These results in reduction of energy recovered from exhaust gases at part loads and in degradation of the quality of recovered energy. The temperature of water exiting the jacket of diesel generator is much lower and performance of absorption chiller with such a low temperature hot water as input is poor. At part engine loads, the performance would be poorer. Understanding the performance of the system integrated with exhaust fired absorption chiller at rated as well as part engine loads is therefore attempted in this paper. Exergetic analysis is used by researchers to study and analyse engine based Trigeneration systems [7,8]. An investigation from energy, exergy and economic basis is presented for a trigeneration system with two chillers at full load as well as part load conditions. The performance is compared with another trigeneration system using a single chiller.

2. Trigeneration configurations

For better thermodynamic performance of a trigeneration system for cooling applications, absorption chillers integrated with engine systems should accept the heat energy at almost the same temperature at which it is available. With this consideration two trigeneration systems with a diesel engine generator integrated with waste energy recovery system is examined at full loads and part loads. Trigeneration system with two chillers integrates a low grade heat energy recovered from engine jacket water with single effect chiller and high grade heat energy from exhaust gases with double effect chiller. This system with two chillers is shown in Fig.1. This trigeneration system comprises of diesel generator, exhaust heat recovery unit, single and double effect absorption chiller. The performance data of engine at rated and part load conditions is given in Table 1.

The absorption chillers are of lithium bromide water type available from manufacturers like Thermax and Voltas in India. The exhaust fired absorption chiller is double effect type while the hot water driven absorption chiller is a single effect configuration. The energy recovered from exhaust gases is input to the desorber of double effect chiller. The quality and quantity of this energy varies with engine loading. At rated conditions, the quantity and quality of energy is maximum as reflected from the temperature and mass flow rate of exhaust gases. The energy recovered from the engine jacket water is input to the desorber of single effect chiller. The engine jacket water is maintained at a temperature of 90°C at its inlet. The jacket water temperature at exit will vary depending on the engine load. It is possible to design a trigeneration system by combining the energy recovered from exhaust gases and engine body for use in a single chiller. Such a system is shown in Fig 2. This trigeneration configuration comprises of two heat exchangers and a single effect hot water driven absorption chiller.

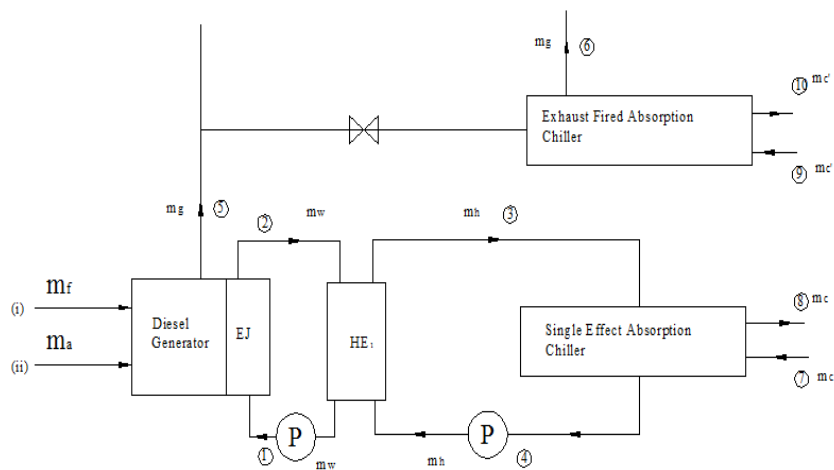


Fig. 1. Trigeneration with two chillers.

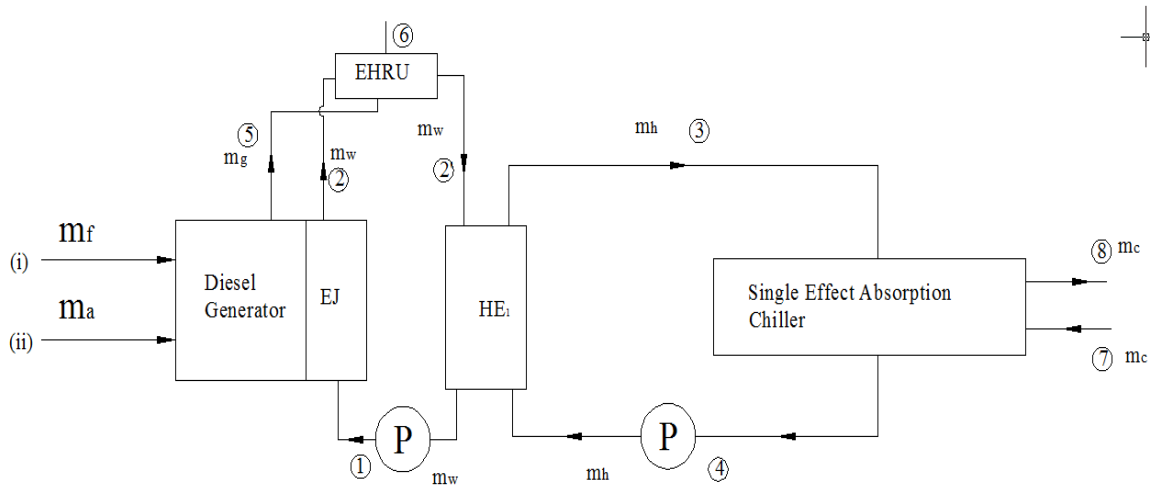


Fig. 2. Trigeneration with single chiller.

Table 1.Engine data obtained from actual trials

Percentage loading	Engine power	Mass flow rate of exhaust gases (kg/s)	Exhaust gas temperature °C	Temperature of jacket water at the engine outlet °C	Mass flow rate of jacket water (kg/s)	Specific fuel consumption kg/kWh
100	180	0.25	5400C	95	2.08	210
75	135	0.19	4460C	93.5	2.08	220
50	90	0.13	3840C	92.3	2.08	227

Table 2.System parameters and economic data (2014 prices in Indian Rupees)

Load	Peak power demand is 180 kW and may vary to 135 kW and 90 kW .Cooling demand is to be met by absorption chillers.
Engine	V type turbocharged water cooled diesel engine with 180 kW capacity at 1500 rpm and compression ratio of 16.7.Capital cost is Rs 6000/kW. Life of engine 10 years. Fuel cost is Rs 60/kg.LHV of diesel 40,600kJ/kg.
Absorption chiller	Thermax make, exhaust gas driven double effect lithium bromide water system of capacity 40 TR and COP=1.4.Single effect chiller of system two is hot water driven and of capacity 30 TR and COP =0.7.Capital cost of single effect chiller is Rs 75000/TR while for the double effect machine it is Rs 50000/TR. Discount rate is 10%.Life of chillers is 10 years.

3. Thermodynamic properties

Table 3 shows the pressure, temperature, mass flow rate, enthalpy and entropy of thermodynamic states of Fig.1. Some thermodynamic states were defined as input data and some were obtained from the property tables. This table represents the data for the engine and the chiller operating at full load. Properties at part load conditions were also obtained though they are not included in the paper.

Table 3. Thermodynamic properties of state points in Fig. 1 at full load

State no.	Fluid	Pressure (bar)	Temperature ($^{\circ}\text{C}$)	Mass flow rate (kg/s)	Enthalpy (kJ/s)	Entropy (kJ/kg $^{\circ}\text{C}$)	Specific Exergy (kJ/kg)	Exergy rate (kW)
i	Fuel	1.00	27	0.011			44730	447.3
ii	Air	1.00	30	0.24	303.5	5.712	0.0	
1	Water	3.1	90.0	2.08	376.9	1.193	25.95	53.97
2	Water	3.0	95.0	2.08	398	1.250	30.06	62.52
3	Water	3.0	90.0	1.91	376.9	1.193	25.95	49.56
4	Water	2.9	85.0	1.91	355.9	1.134	22.54	43.05
5	Exhaust	1.1	540.0	0.25	817.07	1.001	522	130.5
6	Exhaust	1.1	200.0	0.25	475.36	0.4575	343.7	85.92
7	Water	1.0	12.0	5.72	50.4	0.181	1.02	5.83
8	Water	0.9	7.0	5.72	29.4	0.106	2.37	13.55
9	Water	1.0	12.0	1.61	50.4	0.181	1.02	1.64
10	Water	0.9	7.0	1.61	29.4	0.106	2.37	3.81

4. Energy, Exergy and Economic Model

All the components of trigeneration system which includes diesel engine generator, heat exchangers, and absorption chillers can be approximated as steady flow energy devices and analyzed using control volume approach. Applying the first law and second law to control volume at steady state with negligible kinetic and potential energy changes yields us expressions (1) and (2). Work is high grade energy and hence represents exergy. The exergy transfer associated with heat transfer is obtained from equation (3). The specific flow exergy can be calculated using equation (4) where the subscripts o stands for restricted dead state and T_o is the dead state temperature. Exergy destruction in the expression (2) quantifies the irreversibility occurring in each component. To calculate exergy destruction as the difference between exergy input and exergy output terms like exergy fuel and exergy products are defined in literature and included in equations (5) to (7) Where \dot{E}_i and \dot{E}_e stands for exergy input and exergy output respectively. These rates of exergy destruction in each component are best captured by comparing them to overall exergy input to the trigeneration system and are expressed as equation (8). Alternatively the component exergy destruction rate can be compared to the total exergy destruction rate within the system. The annualized capital cost is arrived at using expressions (11) and (12) with the assumptions in Table 1 and 2. The equivalent electrical energy from absorption system is calculated assuming a COP of compression chiller as 3.5. The fuel consumption and the fuel cost is estimated from the specific fuel consumption data assumed in the Table 1. Annualized life cycle cost is calculated using the units of electrical energy generated from generator and equivalent electrical output from absorption chiller.

$$\dot{Q} + \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \quad (1)$$

$$\dot{E}_q + \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i + \dot{E}_{dest} \quad (2)$$

$$\dot{E}_q = \sum \left(1 - \frac{T_o}{T} \right) \dot{Q} \quad (3)$$

$$e = (h - h_o) - T_o (s - s_o) \quad (4)$$

$$E_f = \sum \dot{E}_i \quad (5)$$

$$E_p = \sum \dot{E}_e \quad (6)$$

$$E_D = E_f - E_p \quad (7)$$

$$y_{dest,k}^* = \frac{E_{dest,k}}{E_{fuel}} \quad (8)$$

$$y = \frac{E_{dest,k}}{E_{dest,total}} \quad (9)$$

$$\eta_e = \frac{P_e + E_q}{e_{fuel}} \quad (10)$$

$$A = C \times CRF \quad (11)$$

$$CRF = \frac{d(i+d)^n}{(i+d)^n - 1} \quad (12)$$

5. Thermodynamic performance of Trigeneration system with two chillers

The energetic performance of the trigeneration system is captured by the parameters like power output (W), refrigerating effect and by writing a component wise energy balance. The exergetic performance is obtained by calculating the exergy of fuel (E_f) and products(E_D), exergy output to the exergy input, exergy destruction per component, to the total exergy destruction and exergetic efficiency. Exergy destroyed per ton of refrigeration is another parameter for performance evaluation. All these values were computed for full load, 75% of full load and 50% of full load and are tabulated in Tables 4 to 6.

Table 4. Energetic and exergetic evaluations of the components of diesel engine trigeneration system at full load for system with two chillers

Components	Q (kW)	W(kW)	\dot{E}_f (kW)	\dot{E}_p (kW)	\dot{E}_D (kW)	y (%)	y (%)	η_e (%)	\dot{E}_D/TR (KW)
Engine	441	180	469.66	353.97	115.69	72.48	24.63	75.36	2.46
Double effect chiller	100	0.0	44.58	7.72	36.86	23.09	7.84	17.31	0.92
Heat exchanger water tank (HE1)		0.0	105.57	103.53	2.04	1.27	0.43	98.06	-
Single effect chiller	40	0.0	6.51	1.502	5.01	3.13	0.92	23.07	0.715
Overall system			626.32	466.72	159.60	100	33.82	66.01	3.39

Table 5. Energetic and exergetic evaluations of the components of diesel engine trigeneration system at 75% of full load for system with two chillers

Components	Q (kW)	W(kW)	\dot{E}_f (kW)	\dot{E}_p (kW)	\dot{E}_D (kW)	y (%)	y (%)	η_e (%)
Engine	346.5	180	369.02	254.46	114.56	82.22	31.04	68.95

Double effect chiller	51	0.0	24.6	4.24	20.36	14.61	5.51	17.23
Heat exchanger water tank (HE1)		0.0	91.96	91.07	0.89	0.63	0.24	99
Single effect chiller	30	0.0	4.87	1.356	3.514	2.52	0.95	27.84
Overall system			490.45	351.126	139.32	100	37.74	62.24

Table 4 reveals that the exergy destruction is maximum in engine followed by exhaust gas fired double effect chiller. The larger value of exergy destruction in exhaust fired absorption chiller is due to poor temperature matching between exhaust gases and refrigerant boiling in the desorber of chiller. Exergy destruction in engine is due to the irreversibility of combustion phenomenon..Part loading of engine increases the contribution of engine in total exergy destruction as seen from y^* values though the absolute values of exergy destroyed would reduce at lower loads. Exergy destruction in other components is negligible. Exergy destruction calculated per ton of refrigeration calculated for full load is a parameter useful in comparing the system with two chillers with the one with single chiller. A better clarity on the performance parameters is obtained from the figures 3 to 6.

Table 6.Energetic and exergetic evaluations of the components of diesel engine trigeneration system at 50% of full load for system with two chillers

Components	Q (kW)	W(kW)	\dot{E}_F (kW)	\dot{E}_P (kW)	\dot{E}_D (kW)	$y^*(\%)$	y (%)	$\eta_e(\%)$
Engine	238.35	180	253.84	167.25	86.59	86.99	34.11	65.88
Double effect chiller	27.99	0.0	12.58	2.173	10.40	10.44	4.097	17.24
Heat exchanger (HE1)		0.0	78.81	78.62	0.19	0.19	0.074	99.75
Single effect chiller	20	0.0	3.24	0.891	2.349	2.35	0.92	27.5
Overall system			348.47	248.93	99.54	100	39.20	60.78

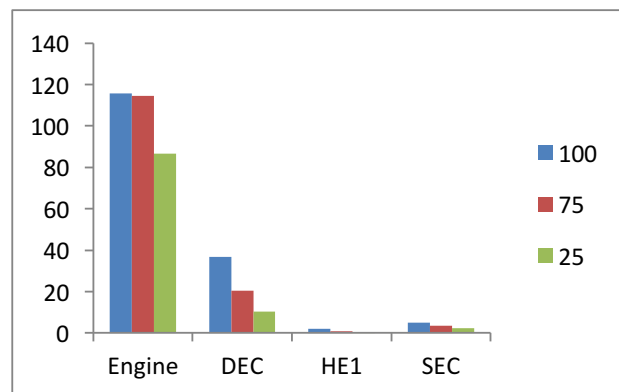
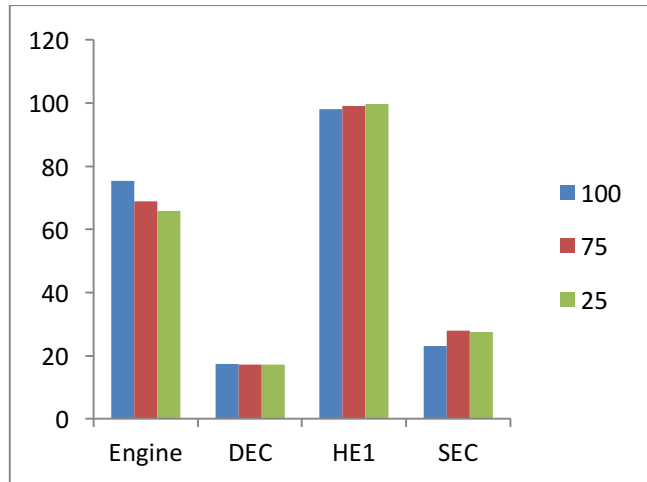
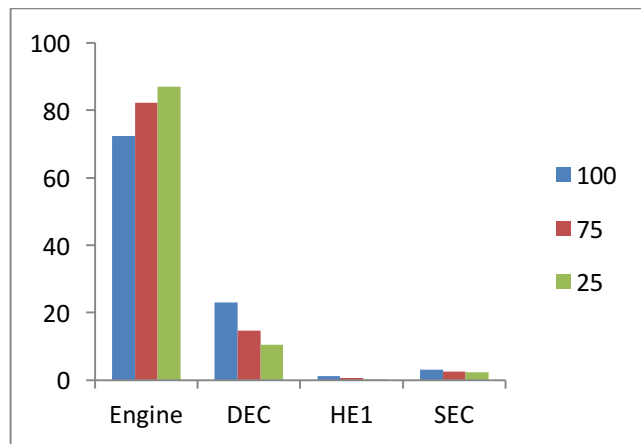
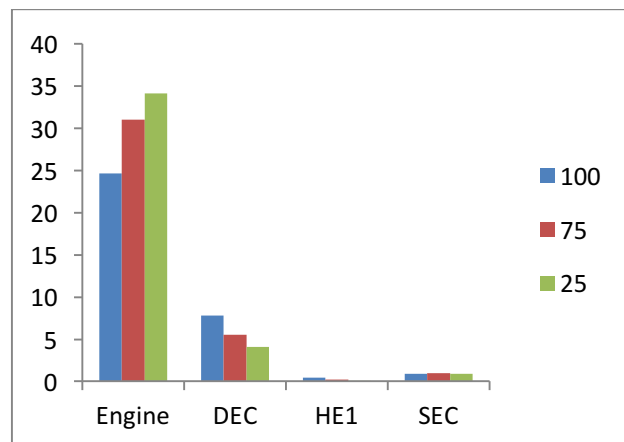


Fig. 3. \dot{E}_D (kW) for different components at various loads

Fig. 4. η for different components at various loadsFig. 5. y^* for different components at various loadsFig. 6. y for different components at various loads

6. Thermodynamic performance of Trigeration system with single chiller

Thermodynamic properties for system represented in Fig. 2 are included in Table 7. These properties are obtained similar to those in Table 2. Analysis of the trigeration system involves calculation of the parameters defined earlier in the text .The calculated values are summarized in Table 8. Exergy destruction in engine and exhaust heat exchanger contribute significantly to the total exergy destruction. Exergy destruction values are larger because of the temperature mismatch of the flue gas with that of hot water in the heat exchanger. The heat exchanger can be designed to minimize energy losses but the exergy destruction is unavoidable. Combining the recovery of exhaust gases (high grade energy) with that of jacket water (low grade energy) results in exergy destruction which effects the performance of trigeration system. The exergy destruction per ton of refrigeration for a single chiller indicates this inefficiency of the system vis a vis trigeration system with two chillers. Trigeration system with single chiller would entail lower initial costs, however the exergetic and energetic performance of the system is inferior to that of a system with two chillers. It would be interesting to investigate the economic performance of the two systems. Fig. 7 is a comparative picture of the life cycle cost of energy per kWh for the two systems for different hours of operation per year. Trigeration system with two chillers appears economically attractive.

Table 7. Thermodynamic properties of state points in Fig. 2 at full load

State no.	Fluid	Pressure (bar)	Temperature (°C)	Mass flow rate (kg/s)	Enthalpy (kJ/s)	Entropy (kJ/kg0C)	Specific Exergy (kJ/kg)	Exergy rate (kW)
i	Fuel	1.00	27	0.011			44730	447.3
ii	Air	1.00	30	0.24	303.5	5.712	0.0	
1	Water	3.1	90.0	6.69	376.9	1.193	25.95	173.60
2	Water	3.0	91.42	6.69	383.2	1.209	27	180.63
2'	Water	3.1	95	6.69	398	1.25	30.06	201.10
3	Water	3.0	90.0	6.69	376.9	1.193	25.95	173.60
4	Water	2.9	85.0	6.69	355.9	1.134	22.54	150.79
5	Exhaust	1.1	540.0	0.25	817.07	1.001	522	130.5
6	Exhaust	1.1	200.0	0.25	475.36	0.4575	343.7	85.92
7	Water	3.0	12	4.68	50.4	0.181	1.02	4.77
8	Water	2.9	7	4.68	29.4	0.091	2.37	11.09

Table 8. Energetic and exergetic evaluations of the components of diesel engine trigeration system at full load for system with single effect chiller

Components	Q (kW)	W(kW)	\dot{E}_f (kW)	\dot{E}_p (kW)	\dot{E}_D (kW)	γ (%)	γ (%)	η_e (%)	\dot{E}_D/TR (KW)
Engine	441	180	469.66	350.20	119.46	72.50	25.43	74.56	5.97
Exhaust	100	0.0	311.13	287.02	24.11	14.63	5.13	92.25	-
heat exchanger									
Heat exchanger (HE1)	0.0	0.0	351.89	347.2	4.69	2.84	0.99	98.66	-
Single effect chiller		0.0	22.81	6.32	15.05	7.26	3.20	27.70	0.75
Overall system		180	1155.49	990.74	164.75	100	34.75	64.92	8.23

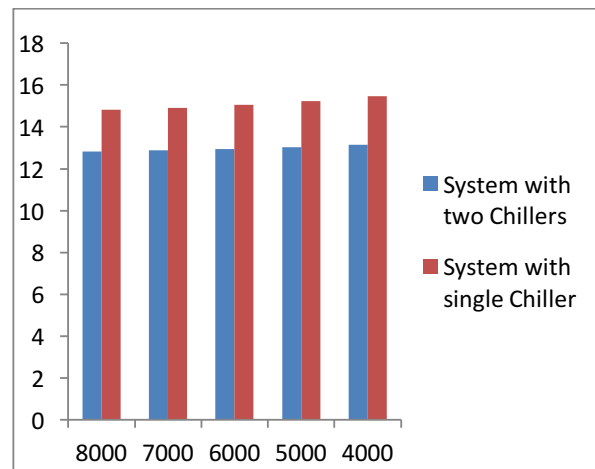


Fig. 7. Annualized life cycle cost (Rs per kWh) versus hours of operation for both systems

7. Conclusions

For a 200 kVA engine the power output at 100% is 180 kW while the energy recovered from jacket water and exhaust gases is 40 kW and 100 kW respectively. This energy when integrated with single effect chiller and double effect chiller would produce a chilling effect of 7TR and 40TR respectively. At part loads the chilling output would reduce as seen from energy analysis. Second law efficiency is maximum for engine system with recovered heat (about 75%) at full load. This efficiency reduces to 65% at 50% loading. The exergy destruction is contributed by engine system in a major way (y^* values are 72% at full load) indicating the importance of engine in total exergy destruction. At part loads this contribution increases to 87 % (at 50% loading)). The second efficiency of double effect and single effect chiller are lower as compared to other components which can attributed to the lower temperature of chilled water. The second law efficiency of double effect chiller is lower as compared to that of single effect chiller. Considering that COP of double effect chiller is higher than single effect chiller a still greater efforts should go in improvements in second law efficiency of double effect chiller. This lower second law efficiency can be attributed to a greater temperature difference between the exhaust gases and water in the desorber section of double effect chiller. It appears that the heat exchanger water tank does not contribute much to the overall exergy destruction as indicated by higher second law efficiency and lower y value. With trigeneration system integrated with only single effect chiller, the exergy destruction per ton is more than twice the corresponding value from system with two chillers. This can be attributed to lower chilling effect as well as increase in irreversibility in a system using a single chiller. This irreversibility is captured by exergy destruction in exhaust heat exchanger that occurs in system with single chiller. Better temperature matching of waste energy source with the application meaning using two chillers would lower this irreversibility. The performance of trigeneration system with two chillers is better than that of a system with a single chiller based on energetic, exergetic as well as economic perspective for the trigeneration system under consideration.

References

- [1] K. F. Fong, C.K Lee, Performance analysis of internal-combustion-engine primed trigeneration systems for use in high-rise office buildings in Hong Kong Energy Procedia 61, 2014, pp. 2319 – 2322.
- [2] N.H.Shekh, B.Saiful, Waste heat recovery from a diesel engine using shell and tube heat exchanger, Applied Thermal Engineering 61,2013,pp. 355-363.
- [3] N.H.Shekh, B.Saiful, Waste heat recovery from the exhaust of a diesel generator using Rankine Cycle, Energy Conversion and Management 75, 2013,pp.141–151.
- [4] K.Herold, S. Klein, R. Radermacher, Absorption Chillers and Heat Pumps, CRC Press, Florida, United States of America,1995.

- [5] D.Gewald, S. Karellas, A. Schuster, H.Spliethoff, Integrated system approach for increase of engine combined cycle efficiency *Energy Conversion and Management* 60, 2012, pp. 36–44.
- [6] Shelar Mahesh, Bagade Sunil , Kulkarni Govind. Trigeneration for a typical Indian Hospital: An assessment considering compulsory load management scenario, *Proceedings of International conference on advances in energy research*, 2009, pp.338-342, IIT Bombay, India.
- [7] D.B.Espirito Santo. Energy and exergy efficiency of a building internal combustion engine Trigeneration system under two different operational strategies, *Energy and Buildings* 53, 2012, pp28-38.
- [8] Aysegul Abusoglu, Mehmet Kanoglu. Exergetic and thermoeconomic analyses of diesel engine powered cogeneration: Part 1- Formulations. *Applied Thermal Engineering* 29, 2009, pp234-241.