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Thermoeconomic Assessment of a Trigeneration System for a Typical Indian Hospital an Assessment Considering Compulsory load Management Scenario

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Abstract – In India, Hospitals like other large consumers operate a standby Diesel Generator to deal with the load shedding hours. The paper first discusses the selection of engine for trigeneration system for a typical hospital. In trigeneration system, engine exhaust based absorption chiller offsets some of the cooling demand for the hospital wh0ile the thermal energy recovery from the jacket meets the heating load. Selection of diesel generator for trigeneration is done using the energy balance. In energy analysis using first law of thermodynamics, the limits caused by irreversibilities are neglected. Exergy analysis facilitates locating and quantifying the lost exergy. However reduction in exergy losses requires additional capital investment. Thermoeconomic analysis by allocating costs to the exergy streams integrates the second law analysis with exergy analysis. In this study, this proposed plant for meeting the cooling, heating and power demand selected by energy analysis is re-examined using thermoeconomic analysis tool. Sensitivity analysis examines the effect of change in load shedding hours and fuel prices on the thermoeconomic parameters of the trigeneration system.

Index Terms — Load shedding, Cogeneration Cooling, Trigeneration, Exergy analysis, Thermoeconomic Analysis.

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1. INTRODUCTION

Compulsory Load management or load shedding by the utilities for few hours is a common load management strategy in India. Consumer's response to this load shedding could be time management of their load and or having a standby captive power generation facility. Diesel generators are commonly used as a standby power source. However significant energy is lost from these engines. About 40% to 45% of the thermal energy is lost with the engine exhaust. This waste heat could be useful for applications involving heating and cooling load. Cogeneration is an important strategy for waste heat recovery. Cogeneration cooling involves recovering exhaust energy for operating an absorption chiller. This chiller can meet the cooling demand partially or completely depending on the load profile. Similarly combined production of electrical, heating and cooling energy also known as trigeneration are economically viable for applications involving heating cooling and power load. Andrea Costa et al (2005) report an economic analysis of a cogeneration and trigeneration system for a Kraft pulp mill. They test the economic viability using simple payback and net present value method. Bassols et al (2001) cite examples of natural gas engine and gas turbine driven cogeneration systems used in food industry and suggest linking absorption refrigeration plant to these cogeneration units. Some studies like E. Cardona et al (2003) restrict the investigation to the matter of economic profitability of investments made for trigeneration systems .While suggesting trigeneration options for hotel sectors in Europe; they claim that trigeneration would yield the maximum energy savings by primary energy saving management strategy. Joel Hernandez et al (2003) discuss the gas turbine based trigeneration systems where addition of absorption chillers results in higher efficiency and led to reduction in fuel consumption. Ziher et al (2005) report the economics of installing a trigeneration system at Slovenia's biggest hospital. Hospitals are large consumers of electrical, heating and cooling energy in India too. Moreover diesel generators are used by hospitals during load shedding hours. For this reason trigeneration could be feasible and economically attractive when load shedding demands the use of captive power generation through diesel generator sets.

2. HOSPITAL LOAD STUDY

First a load survey for the hospital was done. A daily load curve was estimated from the data obtained. Loads which are to be met even during load shedding hours (we use the term critical loads for convenience) were identified. This means these loads need to be met by diesel generator with or without waste heat recovery. Based on this, diesel generator was selected for standalone and trigeneration option. The hospital load can be distributed as heating, cooling and electrical load. The estimated load curve is shown in Fig 1. Heating load comprises of the hot water requirements for bathing .Hot water needs to be supplied in the morning. Another heating load is from two auto-claves which are used for sterilization of surgical instruments. The autoclaves are operated for few hours in the morning. Cooling load is basically of air-conditioning. Operation theatres, special and deluxe rooms and OPDs (out patient department) are air conditioned. The hospital has twelve operation theatres, one intensive care unit and fifty special and deluxe rooms. Seasonal variation of the air-conditioning load is neglected. Refrigerators are used for storing of medicines, whose energy consumption variation is insignificant and hence neglected. Moreover refrigeration load is basically met by small refrigerators dispersed at different rooms and which are operated by electric power. We therefore consider the refrigeration load as power demand instead of cooling demand. The electrical power demand is also for pumps which constitute a significant connected load in the morning as seen in the Fig 1.The other power loads like that for electric lifts, lighting, fans and medical equipments are estimated and shown in the load curve. Based on the load curve a standby diesel generator of 240 kW can be selected.

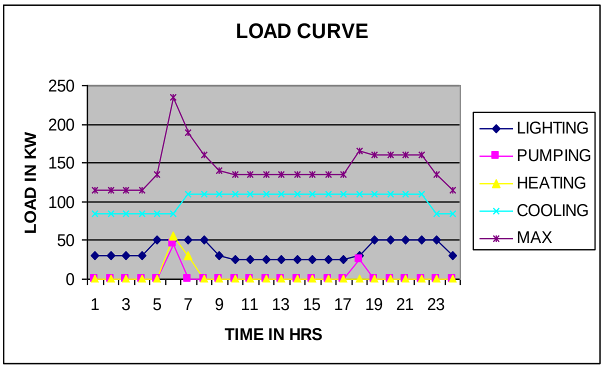

Fig. 1. Estimated load curve before load management

It is seen that some loads like pumping, and autoclave can be managed by load management strategy. This means that these loads are met when the grid supply is available. This strategy will reduce the size of generator. The revised load curve for the hospital after considering the load management strategy is estimated. This load curve is shown in Fig. 2.

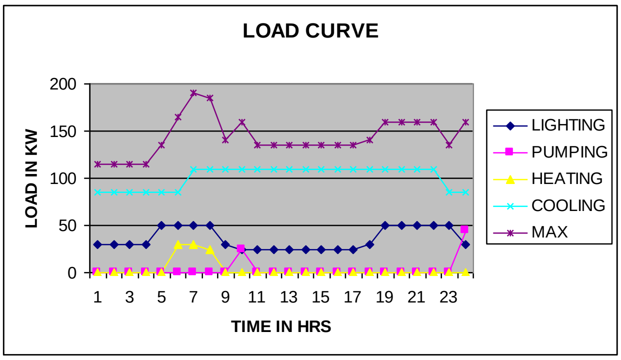

Fig. 2. Revised load curve after load management

A diesel generator can now be chosen to satisfy the load demand shown in Fig. 2.To meet this load a diesel generator of capacity 190kW can be selected. This is reference case against which the waste heat recovery options needs to be evaluated. Without heat recovery a maximum load of 190 kW has to be met. With waste heat recovery some of the cooling load and or heating load can be offset.

3. LOAD MANAGEMENT WITH TRIGENERATION

Presently the hospital has selected the diesel generators to meet its load depicted in Figure1.However we consider that a smaller sized diesel generator can be selected to met the demand depicted in Figure2.This is the first option with no waste heat utilization from the diesel generator This option requires the diesel generator generates electricity to satisfy the cooling, heating and power demand of the hospital. Cooling demand is met by operating the existing vapour compression cycle based chiller.

In the proposed Trigeneration, the cooling demand is met partially by exhaust gas energy while heating demand is satisfied from jacket cooling water. Waste heat recovery from diesel exhaust is possible to meet the cooling load partially by using an exhaust based steam fired Libr-H_2O Vapour absorption machine. We cannot select a Diesel generator to meet the entire cooling load on waste heat for this hospital having lower power demand as this leaves the generator unloaded. So the option is to select the diesel generator such that it meets the cooling demand by both vapour compression system and vapor absorption machine. This requires additional investment on the waste heat based vapour absorption machine and waste heat recovery boiler. To meet the heating load, waste heat recovery boiler for jacket cooling water is proposed.

Thus, during load shedding hours, the present load can be alternatively meet by standalone diesel generator set, or diesel generator in trigeneration mode.

4. SELECTION OF DIESEL GENERATOR FOR TRIGENERATION

Waste heat recovery from diesel generator exhaust is a function of mass flow rate of engine exhaust and exhaust gas temperatures. The diesel generator parameters including its capacity, fuel consumption, exhaust gas temperature, exhaust gas flow rate and coolant temperature are taken from the supplier's specification sheet. (Table 1). These parameters were used to arrive at the actual heat recovery potential and actual heat input for the vapour absorption machines (VAM). The maximum possible VAM capacities for different generator sizes are then estimated. The equivalent cooling capacity of VAM expressed in kWe is calculated for various generator configurations. Load that can be met by this generator inclusive of VAM is then calculated. Considering the heat recovery from jacket water for meeting the hot water needs, the maximum load to be met under trigeneration is estimated. The methodology is illustrated in the flowchart shown in Fig.3.The peak demand to be met under trigeneration is reduced to 160 kWe and 200kVA generator meets this demand.

The cooling demand in kWe (Ce) has to be met jointly by VCRS and VAM.

If VCRS capacity in kWe is Cce and VAM capacity in KWe is Cae then,

Ce=Cce+Cae (1)

So the cooling load to be shared by VCRS for a given DG capacity depends on the maximum power demand that can be met (Pe) by DG of capacity (DGe) and maximum VAM capacity that can be operated on waste heat for the given DG capacity.

Cce=DGe-(Pe+Cae) (2)

For available DG ratings maximum VAM capacities in TR can be estimated using equation 3 and a plot of DG Rating versus VAM TR can be obtained. This can be further expressed as equivalent kWe(Cae) by considering the COP of VCRS.

Ca=mcp (te-ta) ×COPa/3.5 (3)

Cae= (Ca/COPc) ×3.5 (4)

Where m=mass flow rate of exhaust, Cp=specific heat of exhaust gas, te=exhaust gas temperature and ta=ambient temperature. COPa and COPc=coefficient of performance of vapour absorption machine and VCRS respectively.

The decision making for selection is done using the flowchart in Fig 3.

Table 1. Diesel Generator Parameters

Capacity kVA	180	200	225	250
Capacity kW	150	160	180	225
Specific fuel consumption in kg/h	29.9	31.5	35	40
Exhaust gas temp in degree Celsius	450	450	450	450
Exhaust gas flow rate in kg/min	14.6	14.7	15	15
Coolant flow rate lpm	200	250	300	350
Coolant temperature difference in degree Celsius	5	5	5	5
Typical capital Cost Indian Rupees	11,00,000	12,00,000	12,50,000	13,00,000

Vapour absorption machines of Lithium Bromide water type are commercially available from 40 TR capacities. Industry sources indicated to provide for customized 12- 15 TR absorption chillers. We have assumed a typical cost of one lakh Indian rupees per TR for these systems. Single effect VAM systems have a COP in the range of 0.6 to 0.7 and double effect systems have COP of about 1.We have assumed a COP of 0.7. Diesel exhaust based steam fired vapour absorption chillers of larger capacities are commercially available.

5. THERMOECONOMIC ANALYSIS OF THE SELECTED COGENERATION AND TRIGENERATION SYSTEM

Assumptions:

1. Air is an ideal gas.
2. Dead state is environment state (T_0=298 K and p_0=1.013 bar).
3. Air molar analysis (%) is : 77.48 N_2, 20.59 O_2, 0.03 CO_2 and 1.90 H_2O (g).
4. The gain and loss of heat and pressure in the pipe connections have been neglected.
5. Diesel has a typical chemical formula C14.4H24.9.For lean combustion in diesel generator; we will assume no product CO and H_2.

The schematic diagram for the trigeneration system selected based on the methodology discussed in the earlier section and which is further analyzed using thermoeconomic analysis is shown in Fig.4. The mass flow rates and the temperatures at the salient points are tabulated in Table 2.

In exergy analysis, it is necessary to identify both a product and a fuel for the thermodynamic system being analyzed. The product represents the desired result produced by the system. The fuel represents

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the resources expended to generate the product and is not necessarily restricted to being an actual fuel. For engine generator the fuel is the air fuel mixture while the products are work and exhaust gases. For waste heat recovery boiler, the product is the heat gained by feed water which in turn becomes the fuel for absorption chiller. For the absorption chiller unit, the product is the chilled water

Table 2. Monetary expenditures related to Trigeneration components.

	DG	WHR_1	ACU	WHR_2
Investment cost	1200000.00	60000.00	1500000	60000
Fuel cost /yr	2759400	0	0	0
Yearly oil consumption expenditure (Rs/year)	3000	0	0	0
Cost of spare parts (Rs/year)	10000.00	2000.00	15000.00	2000
Personnel costs (Rs/year)	60000.00	0.00	0.00	0
Electricity consumed by the gas engine(Rs/year)	0.00	0.00	0.00	0
Municipality tax and insurance (Rs/year)	15000.00	6000.00	5000.00	6000
Total monetary expenditure per hour(Rs/hr)	21.0000	1.5000	15.0000	1.5000

Table 3. Temperature (T), specific exergy (e) and average cost per unit of exergy(c) values of the states of the system studied.

Sr No	Temp (K)	e	m	E (KJ/s)	c (Rs/GJ)
1	298	42265	0.00875	369.81875	21.41117
2	723	238.1646277	0.245	58.35033378	7.586254
3	353	19.1456	4.16	79.645696	21.41117
4	363	26.1506	4.16	108.786496	21.41117
5	473	98.64103821	0.245	24.16705436	7.586254
6	393	586.094	0.023	13.480162	63.48742
7	378	38.5824	0.023	0.8873952	63.48742
8	285	1.1062	2.34	2.588508	3792.261
9	280	0.4074	2.34	0.953316	3792.261
10	305	0.1852	2.9	0.53708	63.48742
11	313	1.5504	2.9	4.49616	63.48742
12	298	0	0.6	0	101.7593
13	353	19.0662	0.6	11.43972	101.7593

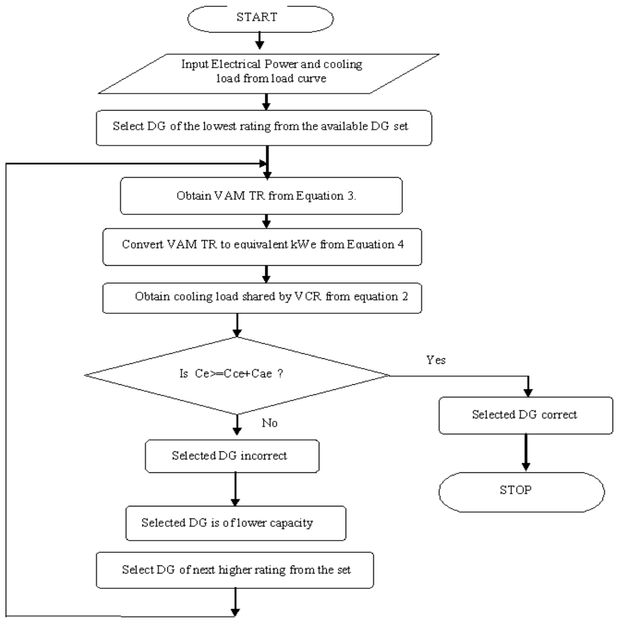

Fig. 3. Flowchart showing selection methodology of Diesel generator for Trigeneration.

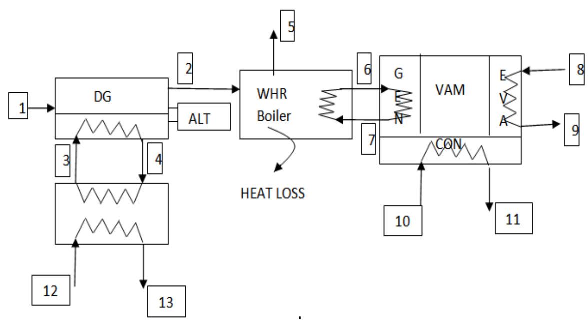

Fig. 4. Schematic of proposed Trigeneration System

6. DISCUSSION

Table 4 summarizes the thermoeconomic variables calculated for each component. The values of the rates of exergy loss and exergy destruction provide the thermodynamic measures of the system inefficiencies. The summation of rate of exergy destruction and exergy losses in the component is compared with the exergy rate of the fuel provided to obtain the parametery.

Table 4 Thermoeconomic values calculated for each component of Trigeneration

Component	Exergetic fuel rate EF kW	Exergetic Product rate EP kW	Exergy Loss-Destruction ratio y %	Levelized Cost rate Z RS/hr	Exergy Economic factor f %
Engine	369.81	247.49	33.07	27.22	74.27
WHR-I	34.18	12.59	5.83	1.94	76.73
ARU	12.59	1.63	2.96	19.44	88.5
WHR-II	29.14	11.43	4.78	1.94	58.76

The highest value of y is seen in engine which indicates possibility of reducing irreversibility. This requires additional investment. However the higher value of exergoeconomic factor f for engine reveals that capital investment and operating and maintenance costs are already high to allow further improvements.

It is seen that waste heat recovery boilers and absorption chillers have very low values of y and much higher values of f. This means it is cost effective to reduce the capital investment at the cost of exergetic efficiency.

The selection of components of trigeneration system done earlier using energy balance does not reveal this. Exergy analysis reveals that the system has lower exergy losses and better exergetic efficiency. However basing the selection on exergy analysis ignores the cost of these components. Thus optimization using thermoeconomic analysis becomes important.

NOMENCLATURE

c - Average cost per unit exergy(Rs/GJ)

C- Cost rate of an exergy stream (Rs/hr)

e- Specific exergy on a mass basis (kJ/kg)

E- Exergy flux (kW)

f- Exergoeconomic factor (%)

m- Mass flow rate

p- Pressure (bar)

R- Universal gas constant (kJ/kg.K)

T- Temperature (K)

y- Exergy loss destruction ratio (%)

Z- Levelized annual cost (Rs/hr)

Subscripts:

D- destroyed

e - outlet

I – inlet

w - work

q - heat

k-the kth component of the system

p - product

r – reactant

Superscripts:

CH-chemical

PH-physical

APPENDIX

Calculation of Physical Exergy:

The physical exergy is the maximum theoretical useful work obtainable as the system passes from initial state where the temperature is T and the pressure is p to the restricted dead state where the temperature is T_0 and pressure is p_0.

The physical component e^{PH} of the exergy transfer associated with stream of matter

$e^{PH} = (h-h_0)-T_0(s-s_0)$

Calculation of Chemical exergy(e^{CH}):

Standard chemical exergies are based on the standard values of the environmental temperature T_0 and pressure p_0. Two alternative standard exergy reference environments have gained acceptance for engineering evaluations these are called here Model 1 and Model 2.

Model 1 satisfies the equilibrium requirement of thermodynamic theory; also the chemical composition of the gas phase of this model approximates satisfactorily the composition of natural atmosphere. On an overall basis, however, the chemical composition of the exergy reference environment of Model 2 is closer. The use of table of a standard chemical exergies generally facilitates the application of exergy principles. For a broad range of engineering applications the simplicity and ease of use of standard chemical exergies generally outweighs any slight lack of accuracy that might result.

Standard chemical exergy of gases and gas mixtures:

A common feature of standard exergy reference environments is a gas phase, intended to represent air, that includes N_2, O_2, CO_2, H_2O (g) and other gases. The kth gas present in this gas phase is at temperature T_0 and the partial pressure $p^e_k = x^e_k p_0$, where the superscript e denotes the environment and x^e_k is the mole fraction of gas k in the environmental gas phase. The kth gas enters at temperature T_0 and pressure p_0 expands isothermally with heat transfer only with the environment and exits to the environment at temperature T_0 and the partial pressure $x^e_k p_0$. The maximum theoretical work per mole of gas k would be developed when the expansion occurs without irreversibilities.

Chemical exergy per mole of gas k is,

$$e_k^{CH} = -RT_0 \ln (x^e_k p_0/p_0)$$

$$e_k^{CH} = -RT_0 \ln (x^e_k)$$

Chemical exergy per mole of mixture ,

$$e^{CH} = -RT_0 \sum x_k \ln (x^e_k/x_k)$$

Expressing the natural logarithm term as $x_k(\ln (x^e_k) - \ln (x_k))$ and using equation 1, we get

$$E^{ch} = \sum X_k e_k^{-Ch} + Rt_0 \sum X_k \ln(x_k)$$

Using standard molar chemical exergy of different exhaust gases,

$$e^{CH} = \sum x_k\, e_k^{-ch} + r\, t_0 \sum x_k \ln(x_k)$$

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