Sustainable Energy Technologies and Assessments 13 (2016) 60–67

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

journal homepage: www.elsevier.com/locate/seta

Original Research Article

Thermodynamic and economic analysis of diesel engine based trigeneration systems for an Indian hotel

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ARTICLE INFO

Article history:
Received 7 May 2015
Revised 24 November 2015
Accepted 25 November 2015

Keywords:
Trigeneration
Thermodynamic model
Hotel
Economic analysis

ABSTRACT

The paper proposes an engine based trigeneration system that would aid in harnessing the energy from engine jacket water and engine exhaust gases for cooling loads via an absorption chiller. A thermal stabilizer is proposed for stabilizing the temperature fluctuations at the desorber inlet of absorption chiller. Two systems are considered for meeting variable thermal and power demand. One configuration includes only absorption chiller with an auxiliary water heater while the other has a compression chiller in addition to absorption chiller and the auxiliary water heater. A comparison of both these alternative options is attempted on thermodynamic and annualized life cycle costing basis for a typical hotel. It is seen that trigeneration systems with compression chillers are more efficient than trigeneration systems without the use of compression chillers for a hotel located in inland peninsular region of India.

Introduction

Grid electricity from centralized power utilities is the cheapest option in India because of economies of scale and availability of coal. However, grid electricity is often unreliable and comes costly to non-residential and non-agricultural consumers. With electricity act 2002 in place and other reforms in energy sector, it is possible for consumers to opt for captive power generation. It is therefore likely that consumers like hotels and hospitals may opt for engine generators for their needs. Both hotels and hospitals require a simultaneous supply of power, heating and cooling energy which means the engine based trigeneration system could make sense. Considerable literature and some practical case studies on engine based trigeneration are available. Engine based trigeneration systems involve recovering heat from an engine that is used to meet the thermal demand (heating and cooling) while the engine generator meets the power demand. Literature exists on diesel generator based trigeneration systems where waste heat energy is recovered. Huang et al. [1] in their paper proposes a system with a biomass gasifier integrated with engine, absorption chiller and heating system with storage, but does not detail the heat recovery system as well as operating issues associated with thermal storage. The authors, after mathematical modeling and simulation predict an increase in plant efficiency from 22% to 53% when energy is recovered from exhaust gases and engine jacket water in trigeneration mode. Espirito Santo [2] in his paper simulates an engine based trigeneration recovering engine jacket water heat for hot water absorption chiller and exhaust energy for steam demand. An auxiliary boiler is introduced to take care of the additional steam demand. The author arrives at efficiency values between 65% and 81%, depending upon the loading conditions and operating strategy. Hospital load curve is considered for analysis. Lee et al. [3] reports experimental findings of their efforts for increasing the efficiency of cogeneration systems. The recombustor is installed at the exhaust gas outlet to perform secondary burning of the exhaust gases. The cogeneration efficiency improves to 85% and the emissions are drastically reduced according to the paper. However they have considered cogeneration system. Efficiency of the whole plant after introduction of absorption chiller is more relevant in trigeneration applications. Authors have not considered recovery from engine jacket water which when utilized improves the system efficiency. Pierro Colonna et al. [4] are a study of engine based trigeneration systems involving ammonia absorption chillers. Mathematical modeling and simulation results for different configurations are reported. One configuration considers recovering heat separately at two temperatures from engine exhaust and jacket water and operating steam driven absorption chiller and superheated water driven absorption chiller. The other configuration discussed in the paper is about recovery of heat to produce superheated water which drives a single absorption chiller. Trigeneration efficiency of 48% is reported. Using two

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http://dx.doi.org/10.1016/j.seta.2015.11.008
2213-1388/

Nomenclature

A_{st}	surface area of the insulated storage tank (m^2)
C_0	capital investment (INR)
C_{pw}	specific heat of water (kJ/kg K)
C_{pg}	specific heat of flue gases (kJ/kg K)
C_v	lower calorific value of fuel (kJ/kg K)
C_e	total equivalent electrical cooling load (kW_e)
C_{ce}	equivalent cooling demand met by compression chiller (kW_e)
C_{ae}	equivalent electrical cooling load met by absorption chiller (kW_e)
$\cos\phi$	power factor
D	diameter of storage tank (m)
H	height of storage tank (m)
k	factor accounting for change in efficiency with part loading
K_p	loading of diesel generator (%)
m_a	mass flow rate of air supplied to diesel generator (kg/s)
m_f	fuel consumption rate of diesel generator (kg/s)
m_{fa}	fuel consumption rate of auxiliary hot water generator (kg/s)
m_g	mass flow rate of flue gases released by diesel generator (kg/s)
m_w	mass flow rate of water circulated through engine jacket (kg/s)
m_s	mass flow rate of water circulated through exhaust gas heat exchanger (kg/s)
m_{sr}	mass flow rate of water circulated through low temperature desorber of chiller (kg/s)
m'_{sr}	mass flow rate of water circulated through high temperature desorber of chiller (kg/s)
m_h	mass flow rate of water from mixer to the heating load (kg/s)
m'_h	mass flow rate of water dependent on the heating load (kg/s)
m_m	makeup water to adiabatic hot water mixer (kg/s)
P_R	rating of diesel generator (kV A)
P_e	electrical power output of diesel generator (kW_e)
P_{he}	total equivalent electrical heating load (kW_e)
P_h	total heating load after load management (kW_{th})
P'_h	heating load before load management (kW_{th})
P_c	total cooling load (kW_{th})
P_o	power demand other than cooling demand (kW_e)
P_{ca}	cooling demand met by absorption chiller due to energy recovered from diesel generator (kW_{th})
P_{cm}	cooling demand met by compression chiller (kW_{th})
q_{stl}	surface heat losses from storage tank
Q_L	engine thermal losses (kW_{th})
Q_a	heat energy input for an absorption chiller (kW_{th})
T_r	desired temperature to be maintained at the low temperature desorber inlet
(ΔT_r)	temperature drop of hot water across low temperature desorber
$(\Delta T_r)'$	temperature drop of hot water across high temperature desorber
ΔT_j	temperature gain across engine jacket
T_g	temperature of flue gases exiting the diesel generator (°C)
T_a	temperature of ambient air (°C)
T_s	temperature of water in low temperature storage tank (°C)
T'_g	temperature of flue gases at exit of exhaust heat recovery unit (°C)
T_{w2}	temperature of water (°C)
T_h	temperature of water in high temperature storage tank (°C)
t	time in seconds
U_{st}	overall heat transfer coefficient of storage tank (W/m K)
V	thermal stabilizer volume

Greek symbols

ρ	density of water (kg/m^3)
η_e	electric efficiency of diesel engine generator at rated conditions (%)
η_{te}	trigeneration efficiency of diesel engine generator on electrical equivalent basis (%)
η_t	efficiency of trigeneration system (%)
η_a	efficiency of auxiliary heater (%)

Subscripts

st	storage tank
w	water
g	engine exhaust gases
th	thermal
e	electrical

Abbreviations

ALCC	annualized life cycle cost
Aux	auxiliary diesel fired hot water heater
COP	coefficient of performance
CRF	capital recovery factor
DG	diesel engine generator
RC	running cost
TR	tons of refrigeration
VAM	vapor absorption chiller
VCR	vapor compression chiller
INR	Indian national rupees

absorption chillers would however be a costly option, especially for lower capacities. Cardona et al. [5] model a reciprocating engine driven trigeneration system involving two heat exchangers, one recovering energy from jacket water (low temperature heat exchanger) and the other recovering energy from exhaust gases. The hot water is used to fire hot water based single effect lithium bromide water vapor absorption unit. Auxiliary boiler and auxiliary compression chiller are also proposed to take care of additional thermal and cooling demand. However, thermal storage is not introduced. The focus of the study was to formulate an exergy economic analysis methodology. Trigeneration efficiency values possible with this arrangement are therefore not specified. Practical Issues like constraints in energy recovery, especially from jacket water when its temperature increases were not considered. Moreover the part load performance of the engine and its implications are not dealt with in the paper. Cardona et al. [6] discusses sizing of trigeneration plant for the hotel sector in the Mediterranean region. Sizing means deciding prime mover and absorption chiller capacity. They highlight the role of trigeneration plant management in sizing plant components. They consider grid connected trigeneration plant where excess electricity produced can be sold to the grid while excess thermal energy has to be discarded. The authors argue that primary energy savings strategy of load management is better. This study is unique in considering load management strategy in details which many researchers have neglected. Ziher [7] suggest a trigeneration system with chilled water storage for