Energy and Buildings 43 (2011) 3074–3081

Contents lists available at ScienceDirect

Energy and Buildings

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

Exergy based performance analysis of high efficiency poly-generation systems for sustainable building applications

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ARTICLE INFO

Article history:
Received 18 March 2011
Received in revised form 30 June 2011
Accepted 29 July 2011

Keywords:
Co-generation
Poly-generation
Combined heat and power
Energy analysis
Exergy analysis
Rational exergy management model
Internal combustion engine
Building applications

ABSTRACT

In this study, first and second laws of thermodynamics, accompanying with Rational Exergy Management Method (REMM) were employed in developing a MATLAB based algorithm for natural gas fired, internal combustion engine (ICE) driven poly-generation systems. Two systems were studied based on a tri-generation plant built within the framework of the EU-FP6 HEGEL Project, tested at METU MATPUM (RICBED) building. This study introduces a better set of metrics for rating, evaluating, and optimizing poly-generation systems in order to minimize emissions, maximize fuel savings, and thus to accomplish an optimum sustainability metric among the factors of environment, energy, human needs and economics. Results show that with ICE poly-generation systems, exergy efficiency may increase beyond 60%. Even at part loads, minimum values of Primary energy savings (PES) are 12.4% for Case-1 and 17.7% for Case-2 (compared to minimum allowed 10%). REMM efficiency and Exergy Embedded PES (PES_R) evaluated by REMM are proven to be better indicators of the performance. When exergy destruction is lower, (waste heat is recovered) PES_R increases significantly. PES_R values are minimum 18.2% for Case-1 and 42.4% for Case-2, which reveals that both systems provide high performance energy generation and considerably lower emissions.

1. Introduction

The rising cost of energy and power, depleting nature of natural resources, and the recent global warming issues have all led to the urgent need for developing advanced energy systems. In this respect, high-efficiency poly-generation systems are gaining more attention, due to their additional advantages in terms of increasing efficiency and reducing harmful emissions [1].

The increasing demand for electrical power as well as energy for heating and cooling of residences, commercial buildings, shopping malls, schools, hospitals, governmental buildings etc., led to application of poly-generation systems for decentralized electricity generation coupled with thermally activated components in buildings. Poly-generation applications in buildings have to satisfy either all or part of both the electrical and thermal demands depending on the magnitude of the electrical and thermal loads, and the operating strategy [2].

Poly-generation systems are often coupled to a district energy system, especially with low-exergy, net-zero energy, and green buildings (sustainable buildings). Sustainable buildings is a widely used multi-criteria subject related to parameters like economics, technical and environmental issues, and social parameters. Sustainable buildings are designed to reduce the overall impact of the built environment on human health and the nature by efficiently using energy sources and water, protecting health, improving productivity, reducing waste, pollution and environmental degradation. In such cases, these systems may stimulate the economy, ensure reliability of energy supplies, reduce transmission and distribution losses of the electrical power grids, and enhance carbon emission reduction. The key issue is often to make the buildings energetically sustainable for better performance in terms comfort while ensuring economical and environmental issues [3].

For poly-generation systems, it is important to rate their energy savings and exergy performance, estimate the system efficiencies and emissions. In order to demonstrate how a poly-generation system should be properly rated and evaluated, a complete first and second law (exergy) analysis of a NG fired ICE powered medium sized co-generation system for building applications was performed with special emphasis on exergy rationale. The latter

Abbreviations: CHP, combined heat and power; HEGEL, high efficiency combined-cycle gas poly-generator for ecological local generation; MATPUM, research and implementation centre for built environment and design at middle east technical university.

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doi:10.1016/j.enbuild.2011.07.029

Nomenclature

c_i	carbon content of the fuel (kg CO_2/kW h)
C	power to heat ratio, dimensionless
$CHPE_\eta$	electrical efficiency of CHP defined as annual electricity from CHP divided by the fuel input used to produce the sum of useful heat output and electricity from CHP, dimensionless
$CHPH\eta$	thermal efficiency of CHP defined as annual useful heat output divided by the fuel input used to produce the sum of useful heat output and electricity from CHP, dimensionless
e_{fuel}	specific flow exergy of fuel (kJ/kg)
e_{in}	specific inflow exergy (kJ/kg)
e_{out}	Specific outflow exergy (kJ/kg)
$\dot{E}$	exergy rate (kW)
$\dot{E}_{dest}$	exergy destruction rate (kW)
$\dot{E}_{exhaust}$	exergy rate of exhaust gases (kW)
EUF	energy utilization ratio/factor, dimensionless
h_{sat_l}	saturated liquid enthalpy (kJ/kg)
h_{sup}	superheater enthalpy (kJ/kg)
h_{w_in}	inlet water enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
$\dot{m}_{fuel}$	fuel mass flow rate (kg/s)
$\dot{m}_{wc}$	mass flow rate of cooling water (kg/s)
P_{net}	net power of the system (kW)
P_{pumps}	pump power (kW)
$\dot{Q}$	heat power (kW)
$\dot{Q}_{ICE}$	heat power of ICE (kW)
$\dot{Q}_{EXCH}$	heat power of HEX (kW)
$\dot{Q}_{COND}$	heat power of condenser (kW)
$RefH_\eta$	efficiency reference value for separate heat production, dimensionless
$RefE_\eta$	efficiency reference value for separate electricity production, dimensionless.
s_0	dead state entropy, kJ/kg K
T_0	dead state surroundings temperature, K (°C)
T_a	indoor dry-bulb air temperature, K (°C)
T_{app}	application inlet temperature, K (°C)
T_E	minimum source temperature that electricity can be generated, K (°C)
T_f	flame temperature of the fuel spent in System (i), K (°C)
T_{ref}	reference temperature of the environment that any process tends to become in equilibrium, K (°C)
T_{fuel}	flame temperature of the fuel K (°C)
T_{sat}	saturation temperature at a given pressure, K (°C)
$\dot{W}_{net}$	net electrical power rate (kW)

Greek letters

η	energy efficiency, dimensionless
η_{cogen}	co-generation energy utilization (first law) efficiency, dimensionless
$\eta_{cogen,II}$	co-generation second law efficiency, dimensionless
$\eta_{CONDENSER,II}$	condenser second law efficiency, dimensionless
$\eta_{heat\,exh,II}$	second law efficiency of HEX, dimensionless
η_{HEX}	HEX efficiency, dimensionless
$\eta_{HRSG,II}$	HRSG exergy efficiency, dimensionless
$\eta_{ice,II}$	second law efficiency of ICE, dimensionless
$\eta_{PUMP,II}$	pump second law efficiency, dimensionless
η_{SE}	SE first law (energy) efficiency, dimensionless
$\eta_{SE,II}$	SE second law (exergy) efficiency, dimensionless
$\eta_{thermal,ice}$	thermal efficiency, dimensionless
ψ_{RE}	rational exergy efficiency of electrical energy generation of CHP, dimensionless
ψ_{RH}	rational exergy efficiency of thermal energy generation of CHP, dimensionless
ψ_{RCHP}	overall rational exergy efficiency of the CHP system, dimensionless
ε	useful work (exergy) that a unit thermal energy flow (fuel) can accomplish, dimensionless
ε_{max}	unit exergy of the fuel input ($\varepsilon_{max} = \varepsilon_{Emax} + \varepsilon_{Hmax}$) to CHP, dimensionless
ε_{Emax}	unit exergy spent in providing electricity from CHP, dimensionless
ε_{Hmax}	unit exergy spent in providing heat from CHP, dimensionless
ε_{Emin}	minimum unit exergy that could provide the same electricity, dimensionless
ε_{Hmin}	minimum unit exergy that could provide the same heat for a given application, dimensionless

was carried out by using the new Rational Exergy Management Model [4], which is a linking procedure between exergy supply and demand in a thermodynamic system for optimizing CHP for lower exergy destruction.

With exergy analysis, locations, types and true magnitudes of wasted energy (as exhaust, losses from heat exchangers or imperfections of system equipment) can be determined more efficiently [3].

Cogeneration represents a well-established technology in small size applications. CHP units based on reciprocating internal combustion engine are at the moment available on the market and they allow to reduce primary energy consumption and polluter emissions in comparison to conventional systems [5]. Reciprocating engines are mostly employed in low and medium power poly-generation units (50 kW to 10 MW) for NG [6]. Mainly, sources of usable waste heat from the reciprocating engine are exhaust gas and engine jacket cooling water. Recovered heat is generally in the form of hot water, low/high pressure steam which is suitable for building applications.

The choice of ICE over conventional gas turbine system is due to ICE properties such as; high electrical power generation efficiency, high energy and exergy efficiencies, uniform constant part load efficiency; low pollutant emissions, high flexibility and easy integration with the energy grid. For ICE co-generation systems, components are an Otto cycle engine and heat exchangers (HEX) for the topping cycle and for the bottoming Rankine cycle, a waste heat exchanger (usually a heat recovery steam generator-HRSG), a steam turbine (ST) or a steam engine (SE), a condenser, a feed water pump (FWP) and other auxiliary equipment.

In the study, the choice of steam engine over conventional steam turbine is due to its higher electrical power generation efficiency, high flexibility, reliability and low flame temperatures causing very little nitrogen oxide, thus protecting the environment [7].

The current study is different from the previously conducted ones since energy, conventional exergy or both methods were utilized to evaluate the performance of poly-generation systems before, but in this study, PES_R indicator is also involved besides the PES calculations, and these show clearly the effects of the lowest, highest temperatures in the system which will contribute to overall exergy destruction, thus reveal whether or not and by how much it is possible to design more efficient energy systems and improve existing systems. Improvements can be done on parameters regarding less carbon emissions and high utilization of energy resources, as well as human comfort and health.