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Original Research Article

Energy balance and efficiency analysis for power generation in internal combustion engine sets using biogas

Li Yingjian [a,*], Qiu Qi [a], He Xiangzhu [b], Li Jiezhi [c]

[a] College of Chemistry & Chemical Engineering, Shenzhen University, Shenzhen 518060, PR China
[b] Hunan Energy Conservation Center, Changsha 410007, PR China
[c] Ecole Centrale de Lyon, Lyon 69130, France

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ABSTRACT

This paper presents an example of the energy balance and the efficiency analysis for power generation in internal combustion engine sets using biogas. Water-cooled engine can effectively reduce the cylinder wall temperature. Therefore, the working conditions of the cylinder components could be improved. Result of energy balance and efficiency calculation show that the engine set can generate electricity of 70.0 kW under a biogas yield of 34.84 m^3/h in the standard state with the energy efficiency of 28.45% and the exergy efficiency correspond to 27.36%. The energy consumption of electricity generated was 432 g coal equivalent (kce) per each kW h. The thermal energy dissipated from the engine exhaust was the greatest of all and it was accounting for 40.34%. Whereas the recoverable thermal energy dissipated from the water in the cylinder jacket was approximately 26.86%. Thermal energy dissipated by radiation and convection from the engine only accounted for 2.99% of total energy input. How to improve the energy efficiency of biogas processed was discussed in this paper, for example, the biogas purification (removal of CO_2 and H_2S) to enrich methane in biogas, can be used for the power fuel, meanwhile, it enhances the efficiency of power generation. A CHP efficiency of over 80% can be achieved if heat of both the exhaust gas and water heated within the cylinder jacket is utilized.

Introduction

The biogas production by industrial wastewater or municipal solid waste through the degradation process of anaerobic digestion could be employed for generating electricity and supplying heat. The above process is an important aspect of the sustainable development of renewable energy [1]. There is a very high efficiency in energy conversion, if the uses exhaust waste heat from thermal machine generates electricity at the same time to produce the amount of heat or cold. When the energy consumption of the power, cooling and heating in the field, the benefits is the most, in particular the use of biogas direct-fired refrigeration is an attractive technology choice [2–4].

The crucial role of heat transfer in the design of engines affects the performance, efficiency, and emission from the engine. In cylinder regions of the engine that has high heat flux values, the surface temperature must be kept below certain level that may cause cylinder failure. The gas-side surface temperature of the cylinder wall must be less than 180 °C to prevent deterioration of the lubricating oil film. Besides, spark plug and valves must be kept cool enough to avoid knock and pre-ignition problems [5].

The spark-ignition engine operation with biogas containing a large share of the inert gases such as CO_2 and N_2, exhibits penalties of performance compared with the engine operated by natural gas or gasoline. Overcoming this by raising compression ratio could lead to increase in the emission of NOx. The presence of the inert gases tends to offset this emission effect. Consequently, the optimum conditions could be determined for satisfactory operation [6].

The same amount of biogas production can also produce 100 kW electricity by using a gas turbine. We may use gas turbine exhaust to heat air and create a recuperative cycle, so that heat from the exhaust gas of high-temperature turbine is transferred to the colder compressed air in a heat exchanger between the compressor and combustor. Due to the preheating of the air, the thermal efficiency increases and the less fuel is required. The gas turbine exhaust which preheats of the air is very suitable for decentralized CHP units, contributing to minimizing CO_2 emission. Moreover, the thermal cycle can be operated more economically if waste biomass is used [7].

Experimental results were collected by the spark ignition engine of Ricardo E6 single cylinder with a variable compression ratio, using the biogas simulated by natural gas and carbon dioxide in different ratio. The above experimental results showed that: when running with lean fuel mixtures, the engine showed low

* Corresponding author. Tel.: +86 755 26538802; fax: +86 755 26536141.
E-mail address: szulyj@sohu.com (L. Yingjian).

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Nomenclature

A_s	engine surface area, m^2
CCHP	combined cold, heat and electricity
CHP	combined heat and electricity
c_{pa}	specific heat capacity of air, kJ/kg K
c_{pL}	specific heat capacity of water, kJ/kg
d	engine height, m
E_{fuel}	chemistry exergy of biogas fuel, kW
$E_{th,heat}$	heat exergy of water heated by cylinder, kW
$E_{th,ava}$	heat exergy of exhaust availability, kW
E_e	machine exergy, kW
Gr	Grashof number
H_y	exhaust enthalpy per unit fuel, kJ/m^3 biogas
ΔH	enthalpy difference of exhaust, kJ
HP	heat pump technology
L_0	amount of theory air, m^3 air/m^3 biogas
m_w	mass flow rate of water, kg/s
Nu	Nusselt number
Pr	Prandlt number
Q_{ava}	exhaust thermal availability, kW
Q_{con}	dissipated heat by convection, kW
Q_{heat}	dissipated heat by cylinder, kW
Q_{ex}	dissipated heat by exhaust, kW
Q_{fuel}	input heat of biogas fuel, kW
Q_H	high heat value of biogas, kJ/kg or kJ/m^3
Q_{rad}	dissipated heat by radiation, kW
T	thermodynamics temperature, °C
t	temperature, °C
$\bar{T}$	average temperature of thermodynamics, °C
ΔT	temperature difference ($\Delta T = T_s - T_f$), °C
V_0	amount of theory smoke, m^3 smoke/m^3 biogas
W_e	power of generating electricity, kW

Greek symbols

α	excessive air coefficient
α_c	convection heat transfer coefficient, W/m^2 K
α_r	radiation heat transfer coefficient, W/m^2 K
α_T	combined heat transfer coefficient, W/m^2 K
β	content expand coefficient, 1/K
ε	emissivity
η_{th}	thermal efficiency, %
η_e	electricity efficiency, %
λ	air thermal conductivity, W/m K
μ	air dynamic viscosity, kg/m s
v_0	biogas output under standard state, Nm^3/h
ρ	air density, kg/m^3
υ	air kinematic viscosity, m^2/s
σ	radiation constant, 5.67×10^{-8} W/m^2 K^4
φ	appropriate constant of fuel
Ψ_e	electrical efficiency of second law, %
ψ_{th}	thermal efficiency of second law, %

Subscripts

a	ambient
air	inside room
ave	average
b	biogas
c	combine
f	film layer of air
s	engine surface
N	standard state
w,1	input water of cylinder
w,2	output water of cylinder
w,3	output water of heat exchanger

emission of CO and little change in CO with varying CO_2 fraction in the biogas; when running with rich, the CO emissions went up rapidly, and the CO_2 fraction increased above 30% due to incomplete combustion. The CO emissions correlated with the relative air to fuel ratio and were almost unaffected by compression ratio and engine speed [8]. Compared with gasoline, lower stoichiometric fuel–air ratio of natural gas reduces NOx emissions. The engine can run at a lower equivalence ratio, especially at high load, using the engine exhaust gas recirculation (EGR) to reduce NOx emission. However, EGR rate above a maximum value resulted in an engine misfire and erratic engine operation [9].

The advanced injection timing is intended to compensate for longer ignition delay or slower burning rate of natural gas-fuelled engine. The test results with advanced injection timing showed that each alternative fuel requires injection in advance appropriate to its delay period. It was found that advanced timing tended to incur a slight increase in the fuel consumption accompanied with reduced emission of CO and CO_2 [10].

Smith et al. [11] introduced an innovative domestic scale combined heat and power (CHP) plant incorporating a heat pump (HP). The heat pump incorporated enhanced the economy efficiency of the domestic use of CHP equipment and it also satisfied with the flexibility of the family energy requirements. Owing to the experimental nature of the prototype plant, relatively high convective and radiative losses were experienced. However, these did not compromise the comparative nature of the analysis.

The clean fuel is indispensable for the moving parts of engine and gas turbine because of their direct contact with the combustion gas. Biogas has the advantage of high transformation efficiency and low emission rate. Especially, the technology of controlling carbon dioxide emissions from flue gas are applicable to small to medium scale CHP, CCHP and the HP/CHP technology. Considering the high exhaust temperature of small/medium scale units, the afterheat utilization of exhaust is advantageous in increasing the heat output and the overall set efficiency.

In order to increase the heat value and improve the combustion characteristics of biogas, the methane (CH_4) in the biogas must be enriched and pollutants in the biogas eliminated. This means that all gases except for methane must be removed [12]. The use of pressurized water as an absorbent is the simplest and least expensive method of CO_2 removal from biogas, and simultaneously also removes H_2S. After removal of CO_2, biogas can be equivalent to natural gas with thermal value [13].

This paper introduces an engineering example of a biogas power generation project. The project conducted energy balance testing, computation and efficiency analyses within a beer wastewater processing station. Through this paper, we could obtain the power generation efficiency of the biogas engine as well as distribution of each energy loss on the units by measuring and reckoning. Finally, the biogas purification (removes CO_2 and H_2S) and the afterheat recycling way of the engine exhaust were discussed.

The technology combining cooling, heating and power (CCHP) or integrated energy system (IES) by coal, heavy oil, and natural gas as fuel is relatively mature. However, because of the impact of biogas on physical chemistry properties, combustion characteristic, as well as transportation, storage, working load after energy conversion and devices equipment, etc., there is big difference between the technology of combine cooling, heating, and power using biogas and the fossil energy technology. Consequently, this