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Article

Performance and Thermoeconomic Analysis of a Biogas Engine Powered Ventilation System for Livestock Building

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Abstract. In this study, a biogas engine powered ventilation fan of a small swine farm was proposed. The research objective was to evaluate performance of, and apply a thermoeconomic analysis to an active ventilation system powered by a small biogas engine. Comparison was made against a gasoline engine and an electric motor. The engine used was a single-cylinder, four-stroke, spark ignited engine with capacity of 118 cm^3. The biogas engine was found to be practically able to drive the ventilation fan with acceptable operation over a range of speeds and loads. At null price for biogas, the biogas engine proved to offer the lowest cost per product exergy unit at $0.054/MJ, which was considerably lower than the gasoline engine and electric motor.

Keywords: Biogas, exergy costing, gas engine, ventilation.

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Nomenclature

BSFC	brake specific fuel consumption (g/kWh)
bTDC	before top dead center (-)
$\dot{C}_f$	cost rate associated with fuel exergy ($/h)
c_f	cost per exergy unit of fuel ($/MJ)
$\dot{E}_f$	exergy rate of fuel (MJ/h)
$\dot{C}_w$	cost rate associated with product exergy ($/h)
c_w	cost per product exergy unit ($/MJ)
LHV_f	lower heating value (kJ/m³)
$\dot{m}_a$	mass flow rate of air (kg/s)
P_{engine}	power output from biogas engine (kW)
P_{motor}	power output from electric motor (kW)
v_a	velocity of air (m/s)
V_f	volumetric flow rate (m³/s)
$\dot{W}$	exergy rate of product (MJ/h)
$\dot{Z}_{eng}$	cost rate of the capital investment of the engine ($/h)
$\dot{Z}_{fan}$	cost rate of a fan ($/h)
$\dot{Z}_{o\&m}$	cost rate of operating and maintenance ($/h)
η	engine thermal efficiency (%)

1. Introduction

Proper ventilation is of paramount importance for animal husbandry to maintain the health and comfort of farm animals. Normally, natural ventilated building design is not usually able to allow prevailing winds to bring sufficient fresh air into the buildings. Ventilation requirement of these buildings are often compromised by the need to avoid livestock stressing from uncomfortable environments. Sufficient ventilation rate is required to primarily provide optimal thermal indoor environment. Ventilation rate is also connected with environmental issue in terms of distribution or removal of airborne contaminants and gas emissions [1-2]. To provide adequate indoor conditions for farm animals, an understanding of climate distribution in the building and its relation to the ventilation configuration and ambient outdoor environment is required. Furthermore, recent outbreaks of various diseases like avian and swine flu have induced concern of general public about the way animals are being kept [3], forcing many farmers to adopt modern closed farming system. Prevention of outbreaks among the farm animals requires the ability to maintain ventilation and thermal comfort as homogeneous as possible and within pre-specified thresholds in occupied zones. This can be achieved by forced ventilation system. Normally, active ventilation system has fans mounted at suitable locations to induce fresh air and circulate room air. Proper environmental control inside the livestock house relies on the fan capacity to supply the required volume of air at the static pressure differential chosen for the building as well as properly configured and operated inlets for fresh air distribution [4]. In tropical climate like in Thailand, farm buildings normally operate in tunnel ventilation mode in which air is drawn through evaporative cooling pads at one end of the building and exhausted by large capacity fans at the opposite end. Typically, these fans are powered by electric motors or gasoline engines which account for considerable energy consumption, hence operating cost.

Direct on-farm energy usage involves fossil fuels and electricity. Farming practices and energy usage have changed in the past decade with increasing concern for fuel cost and energy conservation. Improvement in energy efficiency and renewable energy use can reduce farm operating cost [5]. In Thailand, biogas technology has been a reasonably successful renewable energy technology developed and widely disseminated. Farms normally use biogas for heating, electricity generation and shaft work [6-8]. Adoption of biogas engine, in place of gasoline engine or electric motor has great potential to reduce ventilation energy cost. Such strategy would require full assessment of energy and cost, whether the energy saving would offset the installation cost. There have been a number of literatures on biogas fueled spark ignited engine. However, most studies have been on relatively large engines [9-12]. Reports on small biogas engine were rather limited. Additionally, exergy and thermoeconomic analysis methods have been used widely in assessments of various energy systems, including engines [13-15]. Thermoeconomics combines the second law of thermodynamics and economics by applying the concept of cost to energy in order to achieve a better production management and more cost effective operation [16]. Exergy is a potential or quality of energy used to evaluate inefficiencies associated with various processes. Exergoeconomic cost is defined as the amount of money consumed to generate an energy flow. Thermoeconomic analysis is a powerful tool to analyze and improve the design of energetic systems. There have been a number of reports on thermoeconomic analysis of complex energy systems [17-20]. However, there has been relatively modest work in the existing literature reported on small biogas engine, and no report about its exergy costing analysis. The idea was to use biogas as an alternative energy source for driving the farm ventilation system. The main objective of this work was to evaluate biogas engine performance and compare the exergy cost against existing prime movers used in active ventilation system for animal husbandry.

2. Performance Evaluation

Experimental evaluation of the performance of different prime movers used to drive a ventilation fan was carried out. Biogas engine, electric motor and gasoline engine were tested separately for individual performance. Afterward, tests were performed for each of the three prime movers coupled to the ventilation fan.

In this work, biogas was used as alternative fuel in place of gasoline. The research engine used in this work was a Honda GX-120. It was a single-cylinder spark ignited engine with overhead valve. Bore and stroke were 60 and 42 mm, respectively. The displacement volume was 118 cm^3. The combustion chamber is cylindrical in shape with the compression ratio of 7.5:1. The ignition timing was set at 25° before TDC. The four-stroke, naturally aspirated, air-cooled, gasoline fueled engine is a widely used engine model for various applications in Thailand. It was modified to accommodate the use of biogas. Consequently, its carburetor was replaced with a venture gas-air mixer. The engine compression ratio was adjusted from 7.5:1 to 10:1. Biogas was supplied through a plastic pipe and mixed with inlet air in the mixer. Change in airflow quantity and velocity causes a change in pressure at the channel contraction which in turn affects a change in biogas flow to mix with the main airflow in the required proportion, prior to intake of the engine cylinder. The modified engine was coupled to a Fabric TL170 dynamometer for speed and load control. Simplified schematic diagram of the experimental test rig is shown in Fig. 1. It consists of the biogas engine, the ventilation fan, a test bed, various sensors for measuring flow rates, temperatures, velocity, and a data acquisition system. Biogas used in the experiment was obtained from a continuously stirred reactor located at the Energy Research and Development Institute, Chiang Mai University, Chiang Mai, Thailand. It was stored in a closed, collapsible rubber dome from where it was fed to an engine intake port at a pressure of 64 Pa. The biogas was regularly sampled and analyzed for its properties and composition. The properties of the biogas used were found to remain nearly unchanged during the course of experimental run. With average relative humidity of 80% and methane content of 59% by volume, lower heating value of the biogas was 17.2 MJ/m^3. Since the heating value and the flame speed of biogas is smaller than those of gasoline, proper ignition timing must be considered. Consequently, a series of tests were conducted to evaluate biogas engine performance on stand-alone mode of operation with varying speeds and ignition timing before top dead center (bTDC). In the test, engine speed was varied between 2000 to 3000 rpm. Measurements on engine torque, power output, brake specific fuel consumption (BSFC), and efficiency were performed at ignition timing of 45°, 50°, 55°, 57°, and 59° bTDC. The flow rate of the biogas was measured by gas meter. Ignition timing and speed were measured by a SINCRO 105 and a digital tachometer, respectively. Efficiency of the biogas engine, defined as the ratio of the engine power output to input power from the biogas, was derived from the following expression:

$$\eta = \frac{P_{engine}}{V_f LHV_f} \tag{1}$$

Electric motor used in the experiment was a Toshiba DC motor. It was connected to a TERCO DC dynamometer to evaluate the performance in terms of torque and current. For a gasoline engine, the original engine of the same type and model to that used with biogas was used. The unmodified engine was coupled to a Fabric TL170 dynamometer to investigate the engine performance in terms of engine power output, torque, BSFC, and brake thermal efficiency. This was conducted to investigate if the gasoline engine could run at optimum speed and give the required torque for driving the ventilation fan. The motor and gasoline engine performances were used to compare with those obtained from biogas engine testing.

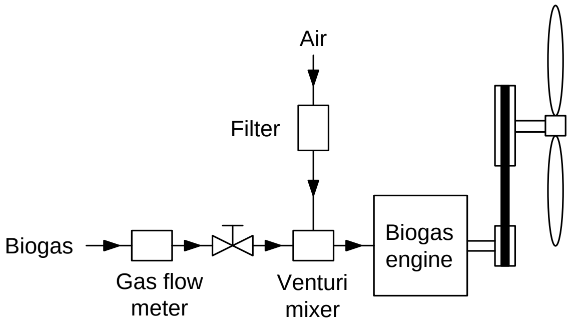

Fig. 1. Schematic of a ventilation fan driven by biogas engine.

3. Exergy Costing Analysis

This section is concerned with the potential of each prime mover to generate energy to drive the ventilation fan in the swine farm. Therefore, exergy costing analysis on each of the prime movers was conducted. Comparison was made between the energy cost obtained from biogas with those from gasoline and electricity. In the analysis of exergy costing, each cost was associated with each rate of exergy stream [21-22]. Thus, the cost rates related to the entering and exiting exergy stream can be written as

$$\dot{C}_f = c_f \dot{E}_f \tag{2}$$

$$\dot{C}_W = c_W \dot{W} \tag{3}$$

where c_f and c_W denote the cost per exergy unit of fuel and generated power, respectively, while $\dot{E}_f$ and $\dot{W}$ denote the exergy transfer rates of fuel and work, respectively. Exergy rate of electric motor is given by Eq. (4), while exergy rates of gasoline and biogas engines are given by Eq. (5). Exergy rates of ventilation fan driven by electric motor, gasoline engine, and biogas engine are computed using Eq. (6).

$$\dot{E}_{f,motor} = P_{motor} \tag{4}$$

$$\dot{E}_{f,engine} = V_f LHV_f \tag{5}$$

$$\dot{W}_i = \frac{\dot{m}_{ai} v_{ai}^2}{2} \tag{6}$$

where subscripts i = 1, 2, 3 which denote motor, gasoline engine, and biogas engine, respectively.

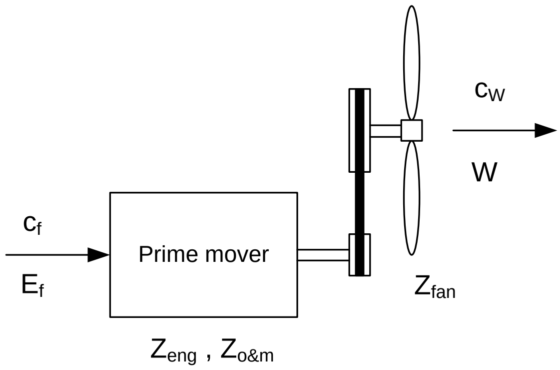

Fig. 2. Exergy stream of the system.

Exergy costing involves the balance of cost expressed for each component separately. A cost balance applied to a component, shown in Fig. 2, was expressed as the equal sum between the sum of cost rates associated with all exiting exergy streams ($\dot{C}_W$) and the sum of cost rates of all entering exergy streams ($\dot{C}_f$)

plus the appropriate cost rates due to the capital investment of the engine ($\dot{Z}_{eng}$), fan ($\dot{Z}_{fan}$), and operating and maintenance expense ($\dot{Z}_{o\&m}$). For a particular system considered, the cost rate associated with the inlet air induced into the engine, flue gas loss, and heat removed from the engine were neglected. Thus, the cost rate balance can be generally written as

$$\dot{C}_W = \dot{C}_f + \dot{Z}_{eng} + \dot{Z}_{fan} + \dot{Z}_{o\&m} \tag{7}$$

Substituting the cost rates of Eqs. (2) and (3) into (7) yielded

$$c_W \dot{W} = c_f \dot{E}_f + \dot{Z}_{eng} + \dot{Z}_{fan} + \dot{Z}_{o\&m} \tag{8}$$

Thus, the cost per exergy unit of the generated power was obtained as follows:

$$c_W = \frac{c_f \dot{E}_f + \dot{Z}_{eng} + \dot{Z}_{fan} + \dot{Z}_{o\&m}}{\dot{W}} \tag{9}$$

To investigate and compare the energy costs between biogas, gasoline, and electricity, all variables must be obtained. Table 1 presents required data of cost per product exergy unit and exergy rate associated with each of the prime movers. Table 2 shows cost rates due to the capital investment of the prime movers, fan, and operating and maintenance.

Table 1. Cost per product exergy unit and exergy rate associated with prime movers.

Prime Mover	c_f **($/MJ)**	$\dot{E}_f$ **(MJ/h)**	$\dot{W}$ **(MJ/h)**
Motor	0.029	2.83	0.602
Gasoline engine	0.027	21.76	0.916
Biogas engine	0	36.35	0.676

Table 2. Cost rates associated with prime movers.

Prime Mover	$\dot{Z}_{eng}$ **($/h)**	$\dot{Z}_{fan}$ **($/h)**	$\dot{Z}_{o\&m}$ **($/h)**
Motor	0.00453	0.00457	0.000168
Gasoline engine	0.00557	0.00457	0.012
Biogas engine	0.01960	0.00457	0.012

4. Results and Discussion

4.1. Biogas Engine Performance

The experimental evaluation of the biogas engine, taken at a mean ambient temperature of 30°C, provides the performance curves in terms of torque, power, BSFC and efficiency with respect to the engine speed and ignition timing between 45° and 55° bTDC against the gasoline engine, shown in Figs. 3 to 6. For all cases of biogas engine considered, the engine torque, power output, and efficiency were found to initially increase with speed until they reached their maximum, and decline as the speed approached 3000 rpm. On the other hand, the BSFC was found to initially decrease with speed until it reached the minimum, and then increased with increasing engine speed. It was clear that the gasoline engine gave better performance than the biogas engine for the range of engine speed considered. The biogas engine was found to perform best at ignition timing of 55° bTDC. An increase in advanced ignition timing appeared to improve the overall performance of the biogas engine. However, limited tests at 57° and 59° bTDC showed slight drop in torque, BSFC and efficiency. At ignition timing of 55° bTDC, torque was higher than the required torque used to drive the ventilation fan over a range of speeds. The electric motor used in the experiment was employed to drive the ventilation fan. The current was measured to be 4.33 A during the operation of the fan at 1450 rpm. The corresponding torque required to drive the fan was found to be 1.95 Nm. The biogas engine torque was initially found to be 2.6 Nm at 2024 rpm and increase with engine speed, reach its maximum of 4.5 Nm at 2415 rpm, and decline to 3.0 Nm as the speed approached 3000 rpm. For a fixed ignition timing, similar characteristics were observed for the engine efficiency and the power output. The efficiency of the engine was 6.3% at 2024 rpm and reached its maximum of 11.5% at 2415 rpm and

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declined to 9.3% as the speed approached 3000 rpm. While the power output was 0.55 kW at 2024 rpm and reached its maximum power output of 1.15 kW at 2617 rpm, and declined to 0.95 kW as the speed approached 3000 rpm. BSFC was estimated from the power output and the measured volume flow rate of biogas. The highest BSFC was 4000 g/kWh at 2024 rpm, while the lowest BSFC of 2190 g/kWh was observed at 2415 rpm.

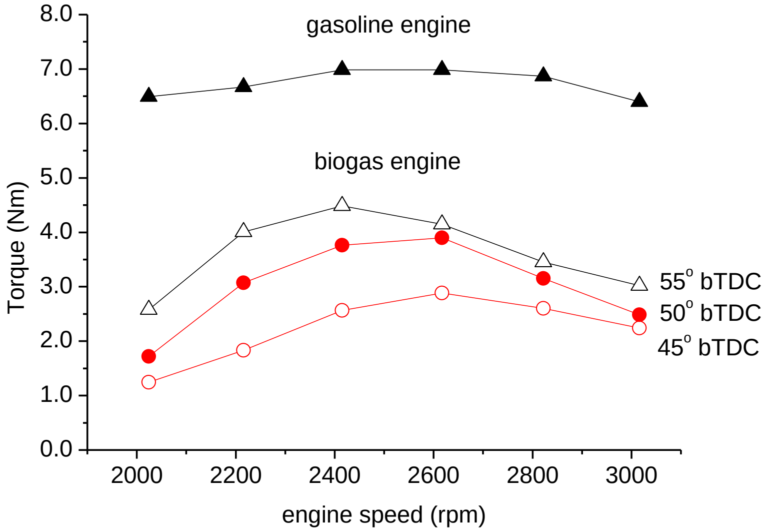

Fig. 3. Variation of torque with engine speed for biogas and gasoline engines.

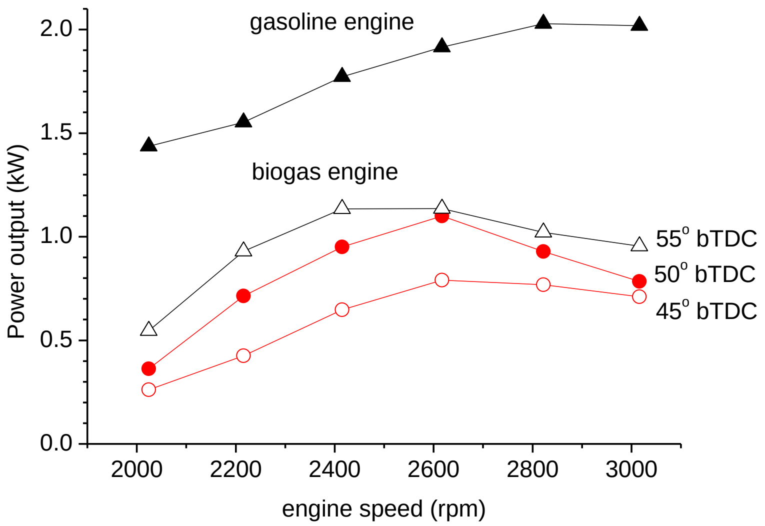

Fig. 4. Variation of power output with engine speed for biogas and gasoline engines.

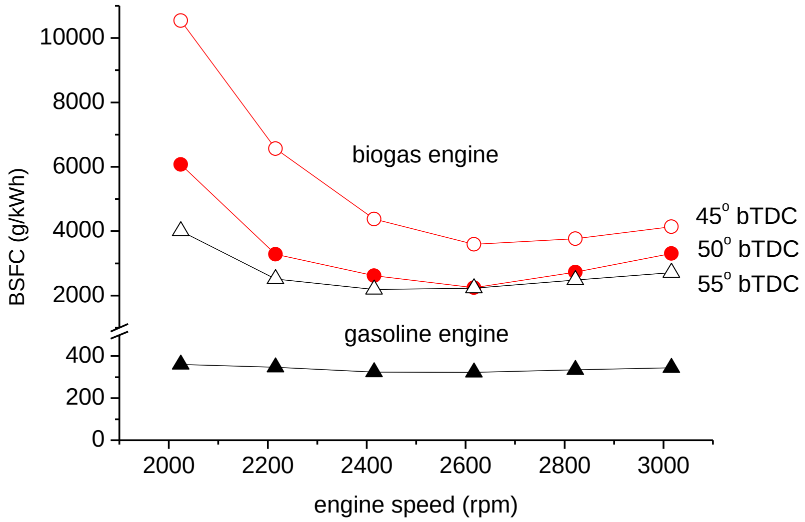

Fig. 5. Variation of BSFC with engine speed for biogas and gasoline engines.

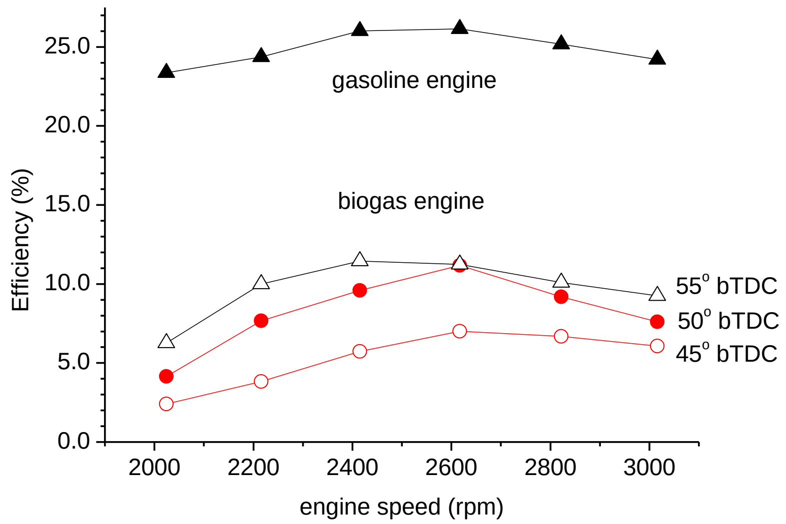

Fig. 6. Variation of thermal efficiency with engine speed for biogas and gasoline engines.

4.2. Exergy Costing

4.2.1. Choice of prime movers

In this work, three different types of prime movers were used to drive a ventilation fan. Electric motor, gasoline engine, and biogas engine were run at 1450, 1850, and 2440 rpm, respectively. When the fan was driven by the electric motor, a product stream of the system was the power generated by a fan driven by the motor. Exergy entered the motor at a rate of 2.83 MJ/h with a unit cost c_{f1} = \$0.029/MJ. Exergy rate of work generated by a fan was 0.602 MJ/h. In addition, the capital and other expenses for the system were shown in Table 2. The capital for the motor and fan were \$0.00453/h and \$0.00457/h, respectively. The operating and maintenance cost of the system was \$0.000168/h. Therefore, the cost per exergy unit of the system was \$0.152/MJ.

When the prime mover was changed to a gasoline engine, exergy entered the gasoline engine at a rate of 21.76 MJ/h with a unit cost c_{f2} = \$0.027/MJ. Exergy rate of work generated by a fan was 0.916 MJ/h. Table 2 provides all other expenses related to the system. The capital for the gasoline engine and fan were

$0.00557/h and $0.00457/h, respectively. The operating and maintenance cost of the system was $0.012/h. The cost per exergy unit of the system using a gasoline engine as a prime mover was $0.668/MJ.

For a biogas engine, the exergy entered at a rate of 36.35 MJ/h with a unit cost c_{f3} = $0/MJ. Exergy rate of work generated by a fan was 0.676 MJ/h. The capital for the biogas engine and fan were $0.0196/h and $0.00457/h, respectively. The operating and maintenance cost of the system was $0.012/h. The cost per exergy unit of the system was $0.054/MJ.

4.2.2. Assessment of cost rate

The results of cost rates associated with all exergy stream plus cost rates due to the engine capital investment and operating and maintenance are discussed. The cost rate associated with the entering exergy stream, $\dot{C}_f$, can be computed using Eq. (2) with the data given in Table 1. As a result, fuel cost rates associated with motor, gasoline engine, and biogas engine were computed using Eq. (10).

$$\dot{C}_{fi} = c_{fi}\dot{E}_{fi} \tag{10}$$

where subscripts i = 1, 2, 3 which stand for motor, gasoline engine, and biogas engine, respectively.

The results are shown in Fig. 7. It was noticeable that there was no cost rate associated with energy from biogas engine since the biogas was freely available in the farm, while the other two sources of energy, electricity and gasoline fuel, the energy must be paid for. It was comprehensible that the cost rate of $0.590/h associated with gasoline was the highest among all energy sources due to a recent high oil price. The cost rate associated with electric motor was $0.082/h, approximately seven times smaller than that associated with gasoline engine. Among the three types of prime movers, the biogas engine was found to provide the lowest cost rate. However, if the biogas cannot be sufficiently produced to run the biogas engine, the electric motor may temporary be used to drive the fan. The capital investment on the electric motor, gasoline engine, and biogas engine were $0.00453/h, $0.00557/h, and $0.01960/h, respectively. It was obvious that the capital investment on biogas engine was the highest among the three prime movers. This was due to the high cost of the engine and its modification requirement. However, the biogas engine offered no payment on fuel. This provides a great opportunity in a long term operation to any swine farms that are capable of producing the biogas to utilize it as a fuel. On a contrary, the electric motor and gasoline engine offered a low capital investment, but the energy costs can be expensive.

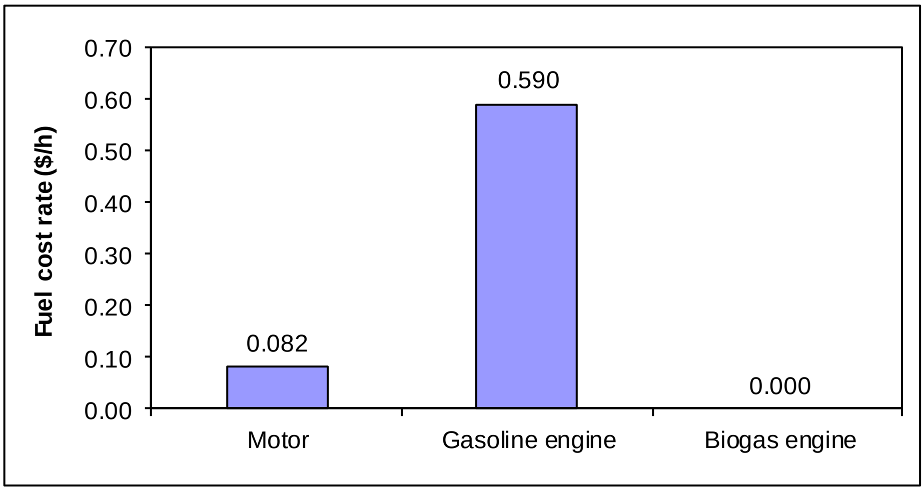

Fig. 7. Fuel cost rates associated with different prime movers.

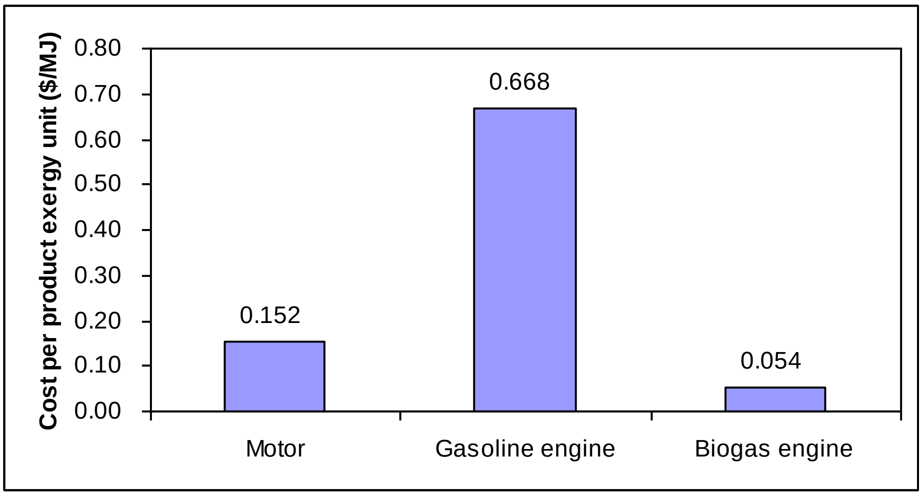

Fig. 8. Cost per product exergy unit over different prime movers.

Figure 8 shows the results of cost per product exergy unit obtained from the analyses of the active ventilation system. Among the three cases, the cost per product exergy unit of gasoline engine was highest, with the price of $0.668/MJ. This was due directly to the very high oil price in the market. The electric motor was found to have the cost per product exergy unit of $0.152/MJ, while the biogas engine showed the lowest cost per product exergy unit of $0.054/MJ, since the biogas was available for free in the farm.

5. Conclusions

Analysis of a ventilation system driven by three different prime movers, i.e. electric motor, gasoline engine, and biogas engine was carried out for their performances. Investigation of the cost-effective system was also carried out in terms of cost per exergy unit and cost rate associated with all exergy streams. Results showed that the biogas engine can provide the lowest cost per product exergy unit of $0.054/MJ, which was estimated to be three and twelve times lower than those from the motor and gasoline engine, respectively. Regarding the fuel cost rate, biogas offered no cost rate, while electricity and gasoline would cost about $0.082/h and $0.590/h, respectively. The biogas engine can be practically employed as a prime mover for driving the ventilation fan in a small swine farm.

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