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A heating system for piglets in farrowing house using waste heat from biogas engine

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Abstract: The aim of this study is to design and test a heating system for piglets in farrowing house by utilising the waste heat from a biogas engine as a heat source. The study was separated into three parts: the study on the biogas combined heat and power plant, the investigation on the properties of the heat panel, and the installation and testing of the heating system. From the experiment, the condition producing 60 kW of electrical power was a proper one, in which electrical efficiency and specific fuel consumption were 14% and 1.22 m^3/kWh respectively. Generating both electricity and heat increased the overall efficiency to 37.7% and decreased the specific fuel consumption to 0.45 m^3/kWh. The heat panel, which was made of a plastic material, had a thermal conductivity of 0.58 W/m°C and the maximum compressive force and operating pressure of 8.1 kN and 0.35 bar respectively. The surface temperature of the panel was dependent on the inlet water temperature. When hot water of 44°C was supplied into the farrowing house with room temperature of 26°C, the average surface temperature was 33°C. The developed heating system could provide heat for 4.3 farrowing houses. The payback period of this project was 2.5 years.

Keywords: piglet, heating system, heat panel, waste heat, biogas engine

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Introduction

Heating system plays a crucial role in nurturing of piglets in the farrowing house because of the difference in heat requirement between sows and their piglets. The sows feel comfortable at temperatures between about 18°C and 21°C while the piglets prefer higher temperatures of at least 30-

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 50- 60

32°C in resting area [1]. Many researches have reported that a heating system could alleviate piglet mortalities stemming from crushing by the sows [2-4].

The heating system with heat lamp as a heat source has been commonly used for warming the piglet resting area. However, since the heat lamp has many limitations such as high energy consumption and short lifetime, the heat panel is increasingly promoted as an alternative, energy-efficient heat source. A heating system with heat panel has a homogeneous surface temperature, and therefore every piglet gets the same temperature in the resting area [2,5].

The heat panel is generally made of insulated composite material with heating wire or hot-water pipe inside. It can be used not only as a heat source but also as the floor of the farrowing house. Nowadays, the heat panel is produced as a commercial product and widely used in developed countries. In Thailand, however, the heat panel is rarely used because of the fact that there is neither domestic panel-making company nor suitable technology for the existing pig houses. Nevertheless, there are few swine entrepreneurs utilising the heat panel for warming the piglets in the weaning house by constructing a concrete floor with hot water pipes inside and employing biogas to boil the water [6]. As the temperature in the house is wholly similar, however, this novel idea is still not appropriate to the farrowing house.

Presently, swine producers in Thailand have utilised private electricity generation employing biogas as an energy source for lowering energy cost as well as waste in their farms. The electricity generation system consists mainly of a biogas engine and an induction motor [7]. In general, a great amount of heat generated from the biogas engine is removed to the cooling system and exhaust gas as waste heat in order to maintain an optimum engine operating temperature. The main aim of this research is to design and test a heating system for piglets in the farrowing house by utilising the waste heat from a biogas engine in order to reduce energy cost in swine production.

Materials and Methods

Biogas combined heat and power plant system

In this research, a small-scale biogas combined heat and power plant (biogas CHP plant) at SPM Feed Mill Co., Ltd., a commercial swine farm located in Ratchaburi province, Thailand, was tested. The principal components of the biogas CHP plant were comprised of a biogas engine, an induction motor, a heat exchanger and two insulated water tanks, as depicted in Figure 1. The biogas CHP plant produced both electricity used within the farm and hot water for warming the piglets in the farrowing house. The hot water was produced by employing the waste heat recovered from the cooling water and the exhaust gas of the biogas engine, and stored in tanks.

The biogas engine was modified from a six-cylinder diesel engine by altering the ignition system from the self-ignition of the air-fuel mixture due to high temperature in the combustion chamber caused by high compression, the so-called compression ignition, to the ignition of the air-biogas mixture in the combustion chamber by use of a spark plug, the so-called spark ignition. The biogas engine was equipped with a 110 kW three-phase four-pole induction motor in order to generate the electricity. The cross-flow heat exchanger, which was made of copper ducts, 19.05 mm in diameter, with a total heat exchanging area of about 2.92 m^2, was used to recover the waste heat from the biogas engine.

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 50- 60

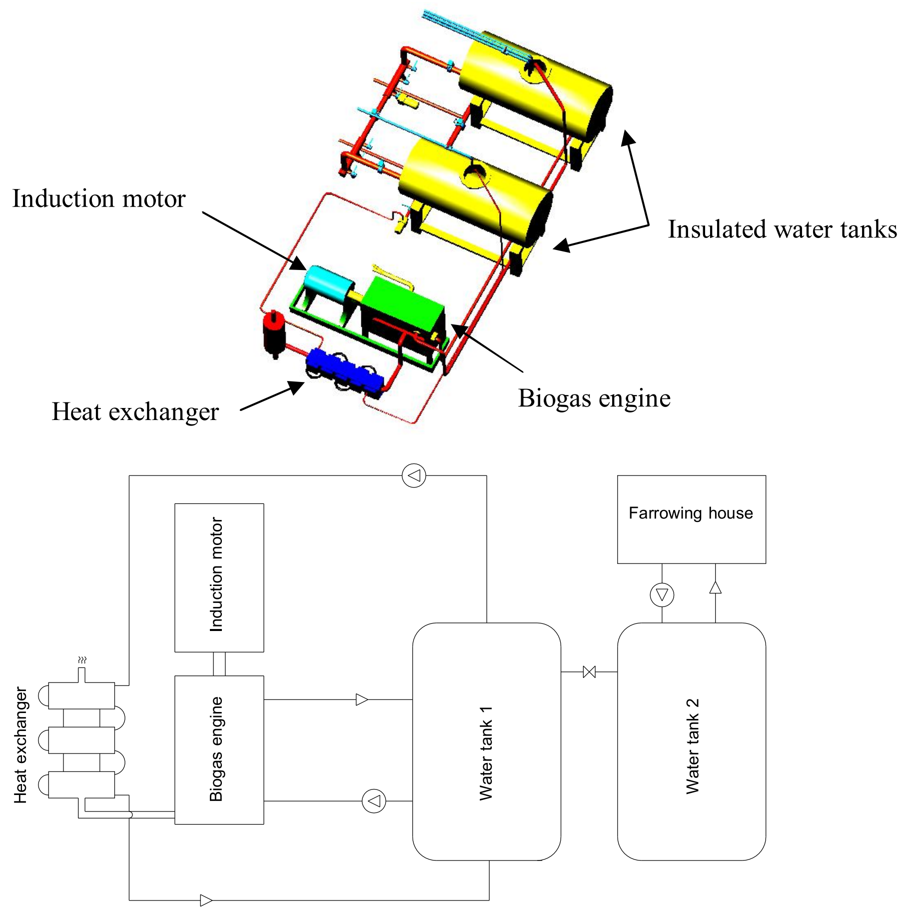

Figure 1. Schematic diagram of the biogas CHP plant

Heat transfer in the biogas engine

The total energy of the tested biogas engine can be derived from the electricity generation with waste heat recovery. From the principle of energy balance, the total energy (Q_{fuel}) derived from biogas is equal to the summation of produced electrical energy ($Q_{electrical}$), heat removed to cooling water ($Q_{coolant}$), heat recovered from the exhaust gas (Q_{EGR}), and heat losses (Q_{loss}), as shown in the following equations.

$$Q_{fuel} = Q_{electrical} + Q_{coolant} + Q_{EGR} + Q_{loss} \quad (1)$$

$$Q_{fuel} = HHV_g \dot{m}_g \quad (2)$$

$$Q_{electrical} = \sqrt{3} VI \cos\phi \quad (3)$$

$$Q_{coolant} = \dot{m}_C C_w (T_{Cout} - T_{Cin}) \quad (4)$$

$$Q_{EGR} = \dot{m}_E C_w (T_{Eout} - T_{Ein}) \quad (5)$$

where HHV_g is the biogas high heating value; $\dot{m}_g$ is the biogas consumption rate; $\dot{m}_C$ and $\dot{m}_E$ are the mass flow rates of the cooling water and the heat-transfering water in heat exchanger respectively; V, I and $\cos\phi$ are the electrical voltage, current and power factor respectively; C_w is the specific heat of

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 50- 60

water; T_{Cin} , T_{Cout} , T_{Ein} and T_{Eout} are the temperatures at inlet and outlet of the engine and the heat exchanger respectively.

In the electricity generation, the induction motor must be driven to a speed higher than its synchronous speed in order that the motor acts as induction generator. This electricity generation system can operate in parallel with the electricity grid by deriving the phase, frequency and voltage from the grid. In the experiment, the synchronous speed of the motor was 1,500 rpm, thus keeping the biogas engine at a speed of 1,520 rpm. At this operation, the flow rates of the cooling water and water in the heat exchanger were found to be about 136.7 L/min and 78 L/min respectively.

The electrical efficiency can be calculated from the following equation,

$$\eta_{electrical} = \frac{Q_{electrical}}{Q_{fuel}} \tag{6}$$

The specific fuel consumption for generating electricity is defined,

$$sfc_{electrical} = \frac{\dot{m}_g}{Q_{electrical}} \tag{7}$$

The amount of heat utilised for piglet heating is the sum of $Q_{coolant}$ and Q_{EGR}. Therefore, the heating efficiency can be calculated,

$$\eta_{heating} = \frac{Q_{coolant} + Q_{EGR}}{Q_{fuel}} \tag{8}$$

Finally, the biogas CHP efficiency and specific fuel consumption can be defined by the following equations,

$$\eta_{CHP} = \eta_{heating} + \eta_{electrical} = \frac{Q_{coolant} + Q_{EGR} + Q_{electrical}}{Q_{fuel}} \tag{9}$$

$$sfc_{CHP} = \frac{\dot{m}_g}{Q_{electrical} + Q_{coolant} + Q_{EGR}} \tag{10}$$

Testing of heat panel

The heat panel was made of a high-density polyethylene (HDPE) thermoplastic with the size of 40 cm x 40 cm. It was designed not only for piglet heating but also for displacing concrete floor in the piglet resting area. The bottom side of the panel was lined with a thermal insulator to lessen heat loss. The properties of the panel such as compressive strength, maximum operating pressure and thermal conductivity, and the relationship between hot water flow rate and surface temperature of the panel were examined at The Centre for Scientific and Technological Equipment (CSTE), Suranaree University of Technology.

Installation and efficiency test of heating system

The heat panel was installed in a farrowing house with 56 pens. Two pens were fitted with a group of six heat panels, and thus 168 heat panels were used. Figure 2 shows a schematic diagram of the heat panel installation and piping system in the farrowing house. The hot water was circulated in the

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 50- 60

piping system by means of gravity from the water tank elevated to three metres in order to create a sufficient distributing pressure. A water pump was used to feed water back to the tank. The biogas CHP plant was operated 21 hours a day while the heating system was utilised throughout the day.

An efficiency test was carried out by operating the heating system continuously for 12 hours. In this trial, the hot water flow rate and the temperatures of the hot water at inlet and outlet of the farrowing house as well as the panel surface temperature were observed.

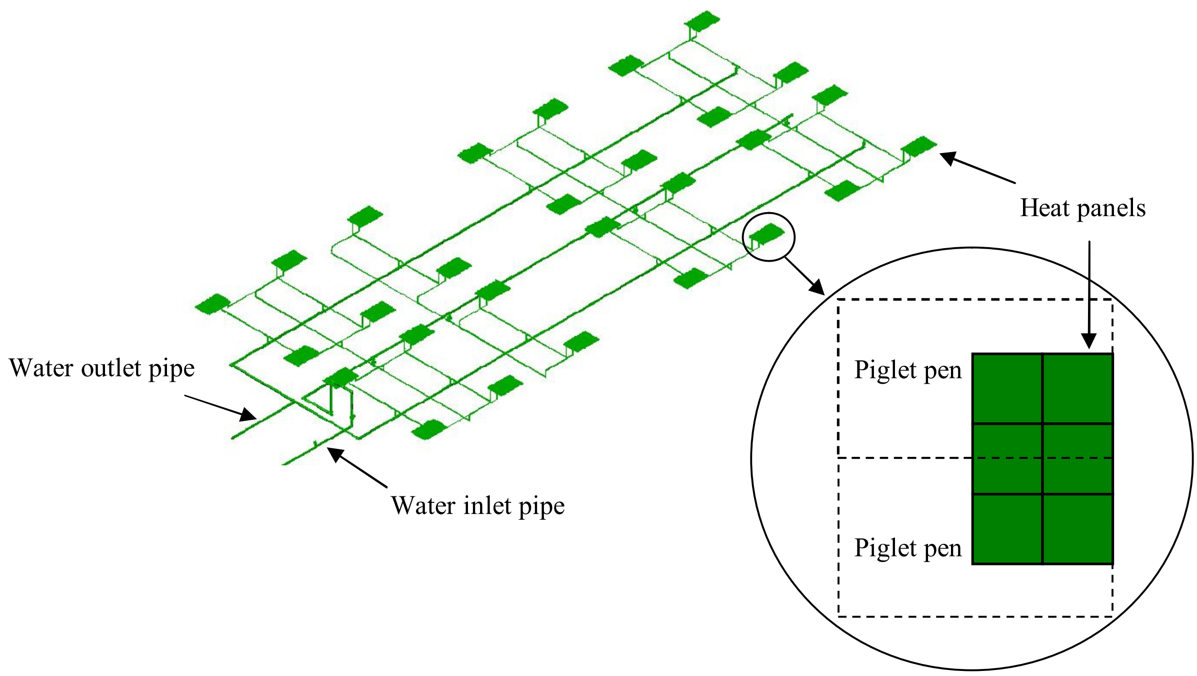

Figure 2. Schematic diagram of the heat panel installation and piping system in the farrowing house

Results and Discussion

Efficiency of the biogas CHP plant

The biogas CHP plant was capable of producing a maximum electrical power of 75 kW with biogas consumption rate of 2.17 m^3/min. The minimum power was found to be about 40 kW while the biogas engine shut itself down at a lower fine-tuned flow rate of the gas.

Table 1 shows the efficiency of the biogas CHP plant. When only $\eta_{electrical}$ was taken into account, it was found that the condition producing 75 kW of electrical power was not suitable because the biogas consumption was too high. In this condition, $\eta_{electrical}$ and $sfc_{electrical}$ were 9.9% and 1.73 m^3/kWh respectively. The most efficient condition was found to be at 60 kW of electrical power with $\eta_{electrical}$ and $sfc_{electrical}$ at 14% and 1.22 m^3/kWh respectively. However, when $\eta_{heating}$ was only considered, the condition producing 70 kW of electrical power showed the highest heat recovery with $\eta_{heating}$ at 25.3%.

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 50- 60

The experimental results in Table 1 showed that producing both electricity and heat increased the overall efficiency of the CHP plant. For example, the electrical power production of 60 kW showed $\eta_{heating}$ of 23.7%, which was equal to 101.62 kW of waste heat recovered, thus resulting in increased η_{CHP} up to 37.7% with lowest sfc_{CHP} at 0.45 m^3/kWh. At this condition, the heat transferred to the cooling water and recovered from the exhaust gas were approximately 0.89 and 0.8 kW respectively for each kilowatt of electrical power, as shown in Figure 3.

The $\eta_{electrical}$ producing 50 kW of electrical power was comparable to that producing 60 kW, but the $\eta_{heating}$ of the former case was 7.0% lower than that of the latter. Therefore, the condition at 50 kW was not selected as appropriate for operating the biogas CHP plant. Similarly, the $\eta_{heating}$ at 70 kW was similar to that at 60 kW, but the $\eta_{electrical}$ at 70 kW was only 11.8%.

Generally, 1 m^3 of biogas is capable of generating about 1.8-2.0 kWh and 1.2-1.5 kWh of electrical energy with a biogas engine and a modified biogas engine respectively [8]. However, the modified biogas engine used in this experiment could generate only 0.82 kWh of electrical energy because of the fact that the engine employed had been in use for a long time.

Table 1. Efficiency of the biogas CHP plant

$Q_{electrical}$ (kW)	Biogas consumption (m^3/min)	Biogas CHP				
		$\eta_{electrical}$ (%)	$sfc_{electrical}$ (m^3/kWh)	$\eta_{heating}$ (%)	η_{CHP} (%)	sfc_{CHP} (m^3/kWh)
40	1.08	10.6	1.62	17.2	27.8	0.62
50	1.11	12.9	1.33	17.7	30.6	0.56
60	1.22	14.0	1.22	23.7	37.7	0.45
70	1.69	11.8	1.45	25.3	37.1	0.46
75	2.17	9.9	1.73	24.0	33.9	0.50

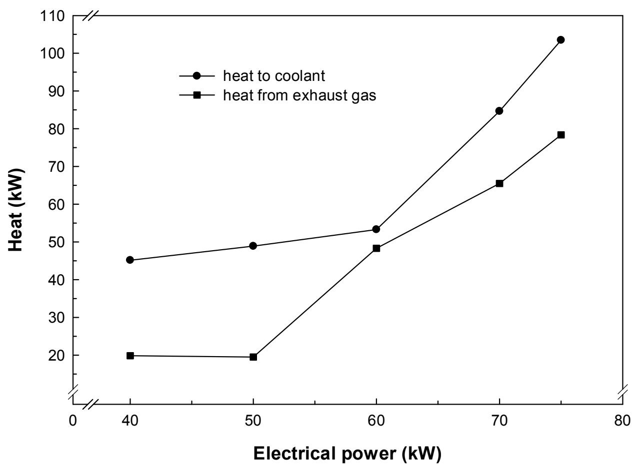

Figure 3. Amount of waste heat recovered from the biogas engine

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 50- 60

Properties of the heat panel

Table 2 shows the experimental results of the property test of the heat panel. Though the panel could resist a maximum compressive force of 8.1 kN, it could only be used for a water pressure of 0.35 bar. When a higher water pressure was applied, the joint between the upper and lower plates of the panel would be split open. This was due to the joint being made by plastic welding with consequent decrease in strength.

The relationship between the hot-water flow rate and the heat panel surface temperature is depicted in Figure 4. It is clear that the flow rate did not significantly affect the panel surface temperature, which was mainly dependent on the inlet water temperature. When hot water with a temperature of 40°C and 50°C was supplied through the heat panels in the room at 25°C, the heat panel surface temperature was 35°C and 43°C respectively.

Table 2. Properties of the heat panel

Item	
Maximum compressive force, kN	8.10
Maximum water pressure, bar	0.35
Thermal conductivity, W/m^2°C	0.58

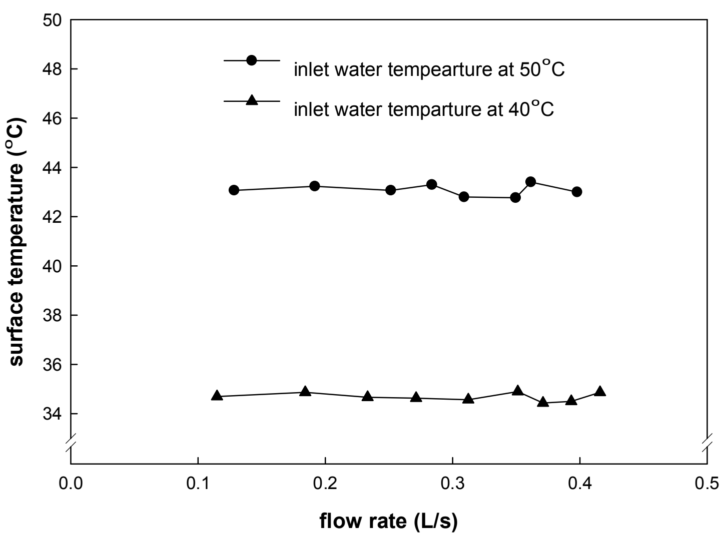

Figure 4. Relationship between hot water flow rate and heat panel surface temperature

Efficiency of the heating system

The efficiency of the heating system can be clarified using the experimental results as shown in Figure 5. At the time the biogas engine was started, the temperature of water at the inlet of the

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 50- 60

farrowing house, the average surface temperature of the heat panel and the average air temperature inside the farrowing house was 36°C, 32°C and 28°C respectively. Thereafter, the temperature of water at the inlet of the farrowing house and the average surface temperature of the heat panel continuously increased. Once the temperature of water at the inlet of the farrowing house was regulated at 44°C, the average surface temperature of the heat panel and the temperature of water at the outlet of the farrowing house was 33°C and 36°C respectively, while the average air temperature was 26°C. The flow rate of inlet water was 0.67 L/s. When the heat transfer in the farrowing house was considered, the heat flux obtained by the heating system was 0.88 kW/m^2 and the heat transfer rate from the hot water to the panel surface was 23.2 kW. Since the condition producing 60 kW of electrical power was capable of recovering about 101.62 kW of waste heat from the biogas engine, this developed heating system could thus procure enough heat for 4.3 farrowing houses.

In general, the piglets in farrowing houses require a temperature of at least 30-32°C in their resting area. The postural behaviour of the piglets in the resting area is the best indicator of the environmental adequacy [3,9]. They huddle together when they are feeling cold, and spread out when they are feeling hot. Figure 6 shows the behaviour of the lying piglets on the experimental heat panel. It can be seen that the piglets were comfortable on the panel, stretching their limbs and barely touching their littermates. Therefore, from the experimental results it can be inferred that this developed heating system is a suitable one for warming the piglets in the farrowing house under practical operation.

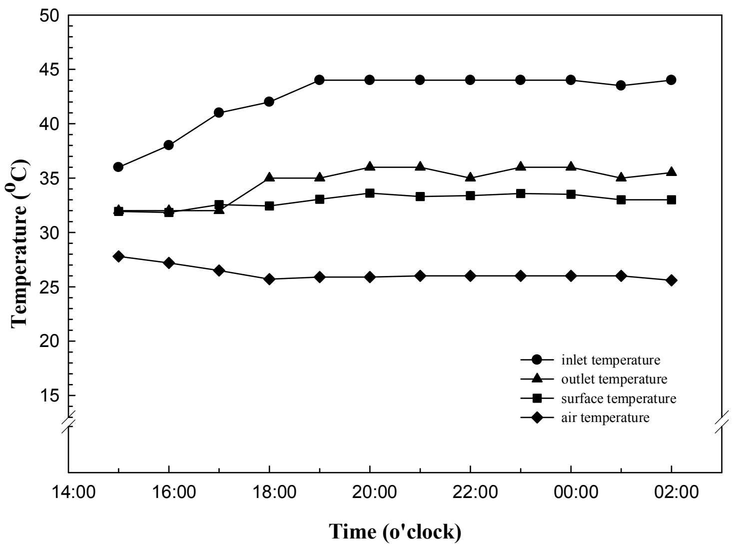

Figure 5. Interrelation of inlet water temperature, outlet water temperature, average surface temperature of heat panel, and average air temperature

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 50- 60

Cost and benefit analysis

- Fabrication cost

Total material and installation costs of the heating system for 4 farrowing houses can be shown as follows:

Figure 6. Postural behaviour of piglets resting on the experimental heat panel

- Heat panels (672 pieces)	672,000	Baht
- Heat exchangers	120,000	Baht
- Insulated water tanks	100,000	Baht
- Pipes, fittings, valves and accessories	80,000	Baht
- Control system	50,000	Baht
- Improvement of farrowing houses	400,000	Baht
Total	1,622,000	Baht

- Piglet heating cost
  - Approximate electricity cost for 4 farrowing houses 650,000 Baht/year

Hence, the payback period of the heating system is about 2.5 years, this considering only making use of waste heat recovery and excluding the benefit of producing electricity.

Conclusions

The following conclusions can be drawn from this study:

1. The condition producing 60 kW of electrical power was the most appropriate operating condition owing to the highest electrical efficiency obtained, with consequent recovered waste heat from the biogas engine of approximately 1.69 kW for each kilowatt of electrical power.

2. The heat panel was resistant to high compressive force but not to high water pressure.

Mj. Int. J. Sci. Tech. **2008**, *1*(Special Issue), 50- 60

3. The flow rate had no effect on the heat panel surface temperature, which was dependent chiefly on the inlet water temperature.

4. The developed heating system was a suitable one for warming the piglets in the farrowing house under practical operation with a satisfactory level of efficiency.

Recommendations

From the results of this work, recommendations are presented as follows:

1. As the amount of recovered waste heat depends on the efficiency of the heat exchanger, a more efficient heat exchanger should be able to recover more useful waste heat.

2. Improvement on strength of the joint between the upper and lower plate of the heat panel should be taken into account in order to prevent a water leakage.

3. Since the electricity generation system is in operation 21 hours a day, which is a condition too heavy for the modified biogas engine, one more engine should be adopted to operate a 12-hour shift. This would result in enhancing the longevity of the biogas CHP plant.

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