Article

Effect of a Geothermal Heat Pump in Cooling Mode on the Housing Environment and Swine Productivity Traits

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Abstract: This study compared the effects of the cooling mode of a geothermal heat pump (GHP) system with those of a traditional cooling system (ventilation fans) inside a pig house on the internal house temperature, harmful gas emissions, and the growth performance of the pigs. During the 19-week experimental period, the temperature inside the house connected to the GHP cooling system was significantly lower ($p < 0.05$) than that of a house with a conventional cooling system. Similarly, the temperature–humidity index (THI) was significantly reduced ($p < 0.05$) in the GHP cooling system-connected pig house. Furthermore, the concentrations of ammonia (NH_3) and hydrogen sulfide (H_2S) were also decreased significantly in the GHP-installed pig house ($p < 0.05$). However, no differences were observed in the concentrations of particulate matter ($\text{PM}_{2.5}$) and formaldehyde ($p > 0.05$). The pigs reared in the GHP-equipped pig house gained significantly more weight ($p < 0.05$) by the end of the experiment. The GHP cooling system can therefore be implemented as a renewable, environmentally friendly energy source in pig farms for sustainable swine production without adversely affecting the productivity parameters.

Keywords: geothermal heat pump; ammonia; temperature–humidity index; renewable energy source; pigs

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1. Introduction

Energy, as a topic, is gaining attention in the livestock sector because the consumption of energy in the rearing of animals will play a vital role in the future. According to UN research [1], the world population will reach 9.15 billion by 2050, thus increasing the demand for food. This will lead to an increase in the consumption of livestock products by 40–80%, compared with the consumption in 2010 [2]. As a result, the energy required to sustain the demand for animal protein will increase in the near future. Against the background of decreasing fossil energy resources due to their high demand and price, the use of renewable energy resources is an important alternative to energy from fossil fuels in the agriculture sector [3].

The use of energy in livestock production has gained attention recently because of its harmful impact on the environment [4]. In pig housing, it is necessary to provide an adequate housing environment for optimum production, and to satisfy the legislation regarding animal welfare demands [5]. Temperature, moisture, and indoor air quality are important parameters for indoor housing environments. Temperature control is crucial for

pigs, and a slight variation in the inside temperature has a negative impact on their health, growth, and performance [6]. A pig house contains a large variety of air pollutants—such as NH_3 , CO_2 , fine particles, microbes, and endotoxins—which cause environmental pollution and global warming [7]. Therefore, it is time to utilize renewable energy resources which reduce environmental pollution for the maintenance of indoor housing environments.

GHP systems have been successfully utilized as alternative renewable energy sources [8] in many countries [9]. They are environmentally friendly, and can reduce electricity consumption [10]. In a GHP system, the internal air quality improves owing to the supply of fresh air, and there is also no direct combustion that produces pollutants [11]. Similarly, GHP can reduce electricity consumption by consuming one unit of electricity to provide three units of geothermal energy [12]. The use of renewable energy sources is relatively low in Korea compared to other developed countries; however, GHP systems have been gaining popularity for cooling and heating. The Korean government is taking steps to increase the use of new and renewable energy from 2.1% in 2004 to 11% in 2030. In Korea, the energy acquired will be 200 times the main energy consumption if 2% of the geothermal energy resources to a depth of 5 km are used [13]. These energy resources can be used at a depth of 100–500 m to operate a GHP for livestock [14]. Several authors [4,7,14,15] have reported the beneficial effects of a heating system using a GHP on environmental pollution, energy consumption, and production performance in livestock farms. However, to the best of our knowledge, the cooling effects of GHP systems in pig farms during summer have not yet been reported. Therefore, the aim of this experiment was to assess the effects of the GHP cooling system on pig growth performance, housing conditions, and the emission of noxious gases.

2. Materials and Methods

2.1. Ethics

This study was performed at the experimental farm of Sunchon National University, 57922 Suncheon, South Korea. All of the experimental protocols and the rearing of the animals were in line with the guidelines of the Animal Care and Use Committee (SCNU IACUC 2020-09).

2.2. Experimental Design

The performance of the GHP cooling mode was evaluated in a pig house during the summer season. The pigs were reared for 19 weeks, from 29 May 2020 to 9 October 2020. The growth period was further divided into four phases, as follows: 5 weeks for weaning, 4 weeks for growing, 5 weeks for early finishing, and 5 weeks for the late finishing phase. The pig house was divided into two separate rooms (3 m wide $\times$ 8 m long), which were further divided into 10 individual pens for replication (Figure 1).

Figure 1. Schematic view of the experimental pig house.

Both rooms were environmentally controlled and were orientated similarly; the first was installed with a conventional cooling system (ventilation fans) and served as a control, while the other room was connected to the ground water source geothermal heat pump in cooling mode. The control pig house was equipped with one big fan and two small fans operating at 1150 and 1700 rpm, respectively. The ventilatory volume of the large

fan ranged from 677 cubic feet per minute (CFM) to 1574 CFM, while that of the small fan ranged from 451 to 1097 CFM. The ventilation rate was regulated at 75 CFM/unit for the early and late finishing pigs, 35 CFM/unit for growing pigs, and 25 CFM/unit for weaning piglets. The pigs were reared on slatted floors, and were offered water and commercially available phase-appropriate feed ad libitum. The feed formulation and chemical composition of the diets are presented in Table 1.

Table 1. Diet formulae and chemical composition of the experimental diets.

	Weaning Pigs 0–5 Weeks	Growing Pigs 5–9 Weeks	Finishing Pigs 10–19 Weeks
Ingredients (% as fed basis)			
Yellow corn	47.85	51.34	54.00
Rice bran	14.00	7.00	9.00
Rapeseed oil	0.00	1.72	3.00
DDGS	0.00	6.00	6.00
Soybean meal	22.10	21.80	18.00
Limestone	0.70	0.86	1.00
Calcium Phosphate	0.70	0.10	0.20
Salt	0.15	0.30	0.30
Vit-min premix ¹	0.50	0.45	0.20
Animal fat	7.00	6.78	4.86
Molasses	2.00	2.50	2.50
Amino Acid additive	5.00	1.15	0.94
Analyzed composition (g/kg dry matter)			
Dry matter	879	876	881
Crude protein	190	180	170
Crude fat	43	44	44
Crude fiber	39	38	38
Ca	7.0	8.0	8.0
Available P	4.4	3.4	3.4
Lysine	10.35	10.20	10.10
Methionine	5.3	3.7	3.1

¹ Vit-min premix contained following nutrients/kg: vitamin D₃, 800 IU; vitamin A, 6000 IU; vitamin K₃, 2 mg; vitamin E, 20 IU; thiamin, 2 mg; riboflavin, 4 mg; vitamin B₁₂, 1 mg; niacin, 10 mg; pantothenic acid, 11 mg; biotin, 0.02 mg; vitamin B₆, 20 IU; manganese, 90 mg; copper, 21 mg; iron (ferrous), 100 mg; zinc, 60 mg; iodine, 1.0 mg; cobalt, 0.3 mg; selenium, 0.3 mg.

2.3. Description of the GHP System

The heat pump unit (DHGW 5N-C4-02, Daesung Heat Enersys, Seoul, Korea) was installed in the pig house (Figures 2 and 3). The system consisted of a 150 m-deep double U-tube borehole exchanger (BHE), a fan coil unit (FCU), water-circulating pumps, and a water tank. The cooling ability of the heat pump was 20.59 kW, with a 4.93 kW rating of electric power consumption. The freezing capacity of the system was 2.1 RT, and R-410A was used as a refrigerant. The water storage capacity of the tank was approximately 260 L. The FCU can generate different wind speeds, with a temperature range of 5–45 °C. Three circulating pumps (Wilo Pump, Ansan, Korea) were attached to the system: (1) a PH-200M with a flow rate of 136 L/min, which was used for the transfer of ground water to the heat pump; (2) a PH-080M with a flow rate of 75 L/min, which was used for the transfer of water from the heat pump to the tank; and (3) a PB-600MA with a flow rate of 80 L/min, which was used for the transfer of water from the tank to the pig house.

The heat pump unit had a rolling compressor piston, a thermostatic expansion valve, and a copper tube with tube heat exchangers. The exchangers increased (in heating mode) and decreased (in cooling mode) the temperature of air, and distributed it through the pig house via plastic ducts. The air inside the pig house was replaced with incoming air. The volumetric flow of air through the heat pump was 700 m³/min.

Figure 2. Schematic view of the geothermal heat pump and geothermal monitoring system. The red coloured pipes show hot water and the blue colour shows cold water. * Emergency water supply.

Figure 3. GHP system with a water tank and pipes installed at the pig farm.

2.4. Internal House Temperature and Temperature–Humidity Index (THI)

The temperature and humidity were measured using T-type thermocouples and thermistors with sensors with a range of -20 to $80\text{ }^{\circ}\text{C} \pm 0.2\text{ }^{\circ}\text{C}$ for temperature and 0 – 100% for humidity.

The temperature–humidity index (THI) was calculated from the relative humidity and temperature as an indicator of the heat stress using the following equation [16]:

$$\text{THI} = 0.8T + (\text{RH}/100) \times (T - 14.3) + 46.4, \quad (1)$$

where T = temperature ($^{\circ}\text{C}$), and RH = relative humidity (%).

2.5. Coefficient of Performance (COP) and the Heat Pump Outflow and Inflow Temperatures

The temperature of the inflow and outflow water (hot and cold) of the GHP was measured using a GPT-1000 pipe temperature sensor (Ginice, Korea), which is equipped with a high-grade thermistor sensing element with a temperature ranging from $-50\text{ }^{\circ}\text{C}$ to $150\text{ }^{\circ}\text{C}$.

The COP of the system in cooling mode was calculated using equation [9]:

$$\text{COP} = \frac{\text{Cooling capacity}}{\text{Power input}} \quad (2)$$

$$\text{COP} = \frac{QH - W}{W}$$

where QH = heat transferred to the ground (kW), and W = total electricity consumption (kWh)

2.6. Concentration of Ammonia (NH_3) and Hydrogen Sulfide (H_2S)

The concentration of NH_3 was measured by installing a sensor (City Technology NH_3 3E 100 SE, Bonn, Germany) at a height of 1.9 m in the middle of the swine house, with a range of 0–50 ppm. Similarly, the concentration of H_2S was measured by installing a sensor (Alphasense Ltd. H_2S -B4 sensor, Great Notley, UK). Every week, the concentrations of both gases were also measured manually using a gas sampling pump (Gastec Corp, GV-100, Ayase-Shi, Japan) and gas detection tubes (3 L for NH_3 and 4LT for H_2S) to validate the values from the sensors.

2.7. Formaldehyde (FA) and Particulate Matter ($\text{PM}_{2.5}$)

The FA and $\text{PM}_{2.5}$ levels were measured daily by placing a sensor (Smart Air quality meter AR830A, Dongguan, China) in the middle of the pig house. The range of the sensor was 0–150 $\mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$ and 0–50 ppm for formaldehyde.

2.8. Growth Performance Measurement

The body weight gain (BWG), feed intake (FI), and feed conversion ratio (FCR) were measured. The animals were weighed at the start and end of each phase individually (weaning, growing, finishing, and late-finishing), and the BWG was calculated weekly. The FI was determined weekly by subtracting the remaining feed from the total amount of feed offered. The FCR was calculated by dividing the FI by the BWG.

2.9. Statistics

Statistical Analysis System software (SAS 2011, Cary, NS, USA) was used to analyze the data, and the results are shown as the mean values and the standard error of the mean (SEM). The analysis of variance (ANOVA) was used to compare the parameters in the groups, and Duncan's multiple range test was used to compare the means. Tendencies were identified when $0.05 < p < 0.10$, and differences were considered significant at $p < 0.05$.

3. Results

3.1. Pig House Temperature and THI

The inside temperatures of the control and GHP cooling system houses are presented in Table 2. The setting temperature during the weaning phase was maintained at $26\text{ }^{\circ}\text{C}$, and was then gradually reduced at a rate of $1\text{ }^{\circ}\text{C}$ every week until it reached $20\text{ }^{\circ}\text{C}$. The temperature during the weaning and growing phases did not decrease ($p > 0.05$). However, the inside temperature was reduced ($p < 0.05$) in the early and late finishing periods. The temperature during early finishing and late finishing was decreased by 17% and 9%, respectively, in the GHP cooling system relative to the temperature of the control house. Similarly, the THI of the GHP-installed pig house was decreased ($p < 0.05$) over the 19-week trial (Figure 4).

Table 2. Effect of the GHP cooling mode on the inside temperature of the pig house.

Items	Outside	Control	GHP	SEM	<i>p</i> -Value
Weaning	28.70	25.85	25.32	0.21	0.0495
Growing	27.31	24.31	23.85	0.21	0.2134
Early Finishing	31.12	27.76 ^a	22.93 ^b	0.15	<0.0001
Late Finishing	26.49	22.20 ^a	20.28 ^b	0.17	<0.0001
Average	28.40	25.07 ^a	23.84 ^b	0.22	<0.0001

^{a,b} Values within the same row with different letters differ significantly.

Figure 4. Effect of the GHP cooling mode on the temperature–humidity index (THI). The data are presented as the mean ± SEM. ^{a,b} Values with different superscripts within the same bars differ significantly ($p < 0.05$).

3.2. Heat Pump Outlet and Inlet Temperature and COP

The outflow water temperature from the heat pump decreased by 7.44, 14.74, and 11.83 °C during the weaning, growing, and finishing phases, respectively, compared to the inflow water temperature. The maximum and minimum COP calculated were 4.50 during the early finishing and 4.10 during the weaning phase, respectively (Table 3).

Table 3. Heat pump water flow temperature and the coefficient of performance (COP) of the GHP cooling mode.

Periods	Heat Pump Water Flow Temperature (°C)		Difference	Heat Pump Consumption (kWh)	COP
	Outflow	Inflow			
Weaning	26.11	33.55	7.44	44.80	4.10
Growing	20.22	34.96	14.74	44.20	4.46
Early Finishing	19.92	31.75	11.83	48.20	4.50
Late Finishing	20.16	29.30	9.14	44.60	4.40
Average	21.60	32.39	10.79	45.45	4.36

3.3. Particulate Matter (PM_{2.5}), Formaldehyde, NH₃ and H₂S Concentrations

The concentration of FA in the pig house was not affected ($p > 0.05$) by the cooling system during the experiment (Table 4). Similarly, the concentration of PM_{2.5} remained unaffected ($p > 0.05$), except during the early finishing phase. On the other hand, the concentration of noxious gases (NH₃ and H₂S) decreased ($p < 0.05$) in the GHP-connected pig house compared to the control (Figure 5).

Table 4. Effect of the GHP cooling mode on the formaldehyde (ppm), PM_{2.5} (µg/m³) and hydrogen sulfide (H₂S) (ppb) in the pig house.

Items	Control	GHP	SEM	p-Value
Particulate matter (PM _{2.5} µg/m ³)				
Weaning	22.51	21.86	2.44	0.8610
Growing	16.25	15.32	2.39	0.7932
Early Finishing	34.17	31.97	4.90	0.7514
Late finishing	25.49	24.94	3.67	0.9223
Average	25.05	24.07	1.90	0.7163
Formaldehyde (ppm)				
Weaning	0.07	0.10	0.01	0.0611
Growing	0.08	0.10	0.01	0.2638
Early Finishing	0.11 ^a	0.05 ^b	0.02	0.0431
Late Finishing	0.08	0.13	0.01	0.0595
Average	0.09	0.09	0.01	0.5051
Hydrogen sulfide (ppb)				
Weaning	13.00 ^a	0.14 ^b	0.01	0.0002
Growing	7.00 ^a	0.03 ^b	0.02	0.0325
Early Finishing	5.00 ^a	1.28 ^b	0.01	0.0199
Late Finishing	16.00 ^a	0.21 ^b	0.10	0.0341
Average	10.00 ^a	0.44 ^b	0.01	0.0011

^{a,b} Values within the same row with different letters differ significantly.

Figure 5. Effect of the GHP cooling mode on the ammonia (NH₃) concentration. The data are presented as the mean ± SEM. ^{a,b} Values with different superscripts within the same bars differ significantly ($p < 0.05$).

3.4. Growth Performance

Table 5 shows the effect of the GHP cooling system on the growth performance of the pigs. From 0 to 19 weeks, the weight of pigs significantly increased in the GHP-connected house relative to that in the control ($p < 0.05$).

Table 5. Effect of the GHP cooling mode on the growth performance parameters.

Parameter	Control	GHP	SEM	<i>p</i> Value
0–5 weeks				
Initial body weight (kg)	6.18	6.17	0.37	0.9910
Final body weight (kg)	23.74	25.84	0.88	0.1250
Weight gain (kg)	17.56	19.67	0.77	0.0850
Feed intake (kg)	26.60 ^b	31.10 ^a	1.26	0.0350
Feed conversion ratio	1.52	1.59	0.06	0.4390
6–9 weeks				
Final body weight (kg)	48.53	51.35	1.66	0.2490
Weight gain (kg)	24.79	25.51	0.91	0.7250
Feed intake (kg)	51.83 ^b	52.71 ^a	2.21	0.0005
Feed conversion ratio	2.11	2.07	0.05	0.6700
10–14 weeks				
Final body weight (kg)	75.61 ^b	82.58 ^a	1.88	0.0220
Weight gain (kg)	27.09	31.23	1.01	0.0840
Feed intake (kg)	81.29 ^b	91.62 ^a	2.42	0.0140
Feed conversion ratio	3.03	2.94	0.14	0.8210
15–19 weeks				
Final body weight (kg)	108.47 ^b	118.17 ^a	2.56	0.0240
Weight gain (kg)	32.86	35.58	0.82	0.2760
Feed intake (kg)	101.16 ^b	120.53 ^a	2.76	0.0008
Feed conversion ratio	3.10 ^b	3.39 ^a	0.13	0.0280
0–19 weeks				
Final body weight (kg)	108.47 ^b	118.17 ^a	2.56	0.0240
Weight gain (kg)	102.29 ^b	111.99 ^a	2.47	0.0170
Feed intake (kg)	260.88	295.96	6.96	0.0780
Feed conversion ratio	2.56	2.64	0.05	0.4390

^{a,b} Values within the same row with different letters differ significantly.

4. Discussion

The ambient temperature inside a pig house is a crucial parameter for pig farming, and variation in this parameter may have a negative impact on pig productivity [17]. In Korea, heating pig houses is essential during the winter season, whereas they need to be cooled in hot weather. Research has shown that heat shock or cold stress substantially affect the growth and reproduction performance, welfare, and health of animals [18,19]. In general, cold stress is common in weaning pigs, while the effects of heat stress are more of a concern in finishing pigs. Therefore, a major proportion of the total cost involved in pig farming is spent on maintaining the optimum temperature for pigs [20]. Similarly to our study, various experiments conducted in other countries have also reported the cooling and heating efficiencies of GHPs in broiler houses and swine farms [4,15,21]. In the current study, the decrease in temperature in the GHP-installed house might be because of the efficient degree change per unit of energy consumption of the GHP system [9]. Additionally, a direct heat exchange system in a single-loop configuration increases the efficiency of the GHP system [22], which can efficiently increase or decrease the temperature of the pig house depending on the season. THI is considered as a basis for the safety index to explain the categories of heat stress in animals. Myer and Bucklin [19] reported that humidity is not harmful for swine unless a high temperature is combined with a high humidity. According to the National Atmospheric and Oceanic Administration [23], $\text{THI} \geq 84$ is classified as an emergency, $\text{THI} \leq 74$ is safe, and $74 < \text{THI} < 79$ is considered as an alert for animal welfare. In the present study, the THI of the GHP-connected pig house fell within the safety zone for all of the phases of growth.

The COP is measured by dividing the heat output (kWh) by the electrical input (kWh), and it indicates the performance of the cooling system. The calculated COP-day average in this study was 4.36, with the COP ranging from 4.10 to 4.50. The calculated COP of the GHP cooling system was the same as the COP of 4.38 observed by Chokchai et al. [9] for a GHP cooling system. On average, the COP of a ground-source GHP lies within the range

of 4.19 to 4.57 in cold weather and 3.9 to 4.53 in the summer season [24]. The results of the present study also fall within the optimum parameters, indicating the performance index and efficiency of the GHP cooling system. Aikins et al. [25] also reported that water–water-type GHP systems are popular in Korea because of their ability to heat and cool, and their better COP values. The decreased water outflow temperature from the heat pump demonstrates the efficiency of the GHP cooling system [15] in maintaining the optimum temperature of the swine house.

In the present study, the reduction in the concentration of noxious gases is in agreement with the studies of Choi et al. [21] and Mun et al. [15], in which the cooling and heating effects of the GHP decreased the concentration of particulate matter and ammonia inside the swine house. This is because GHPs can provide fresh air continuously, which dilutes the harmful gases and improves the air quality [7]. NH_3 and H_2S gases are harmful to animal health and also have harmful effects on the health of farmers and the environment [26]. Generally, the concentration of H_2S is less than 2 ppm, and the NH_3 concentration is in the range of 0 to 40 ppm on swine farms [27]. Similarly, $\text{PM}_{2.5}$ and the release of formaldehyde have harmful effects on the respiratory systems of humans and animals, and have a detrimental impact on the environment [28]. Particulate matter includes airborne particles with an aerodynamic diameter of 2.5 μm or less. $\text{PM}_{2.5}$ has become a threat to public health in South Korea, and can damage the lungs and penetrate the blood–brain and placental barriers. Formaldehyde is classified as a carcinogenic compound, and can cause irritation to the skin and eyes. No significant differences were observed in the concentration of $\text{PM}_{2.5}$ and formaldehyde (except in the early finishing period in the case of $\text{PM}_{2.5}$), and the values of $\text{PM}_{2.5}$ and formaldehyde were in line with ambient air quality standards (AQS) in South Korea. The AQS safety range of $\text{PM}_{2.5}$ is 50 $\mu\text{g}/\text{m}^3$, and formaldehyde has no harmful effects at concentrations of 0.10–0.11 ppm [29,30]. Geothermal energy is popular worldwide as an environmentally friendly and renewable energy source that has a significant impact on the reduction of global climate change, protects public and animal health, and enhances energy security [31]. While conducting several experiments [4,14,26] using GHP cooling and heating systems in poultry and swine houses, different scientists have reported the beneficial effects of the economically effective GHP cooling and heating system on the environment.

The important economic drivers for pig farmers are market weight and FCR [32], which cannot be ignored while introducing any of the latest innovations and technologies. In this study, the final BWG at the end of the experiment was significantly increased in the GHP-installed pig house. This might be due to the weight gain in the finishing period because the GHP cooling system maintained the internal temperature of the pig house within the thermoneutral zone. It has also been reported that heat stress negatively affects growth performance by decreasing FI, which eventually decreases the weight of pigs [33]. Therefore, a GHP cooling system can be installed in pig houses to reduce heat stress whilst having a positive impact on the growth performance parameters.

5. Conclusions

The implementation of a GHP cooling system in pig farms can improve the housing environment and growth performance parameters. Furthermore, GHPs are an environmentally friendly, renewable energy resource that can reduce the emission of noxious gases. Because of the high installation cost at animal farms, government assistance through subsidies is necessary for farmers to protect the environment and save energy. Further studies are recommended at commercial swine farms to evaluate the heating and cooling effects of the GHP system.

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