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Environmentally Friendly Hybrid Power System for Cultivators

Sang Cheol Kim*, Young Ki Hong, Gook Hwan Kim

Department of Agricultural Engineering, National Academy of Agricultural Science, Rural Development Administration, Jeonju, Korea

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Abstract

Purpose: In this study, a hybrid power system was developed for agricultural machines with a 20-KW output capacity, and it was attached to a multi-purpose cultivator to improve the performance of the cultivator, which was evaluated using output tests. **Methods:** The hybrid system combined heterogeneous sources: an internal-combustion engine and an electric power motor. In addition, a power splitter was developed to simplify the power transmission structure. The cultivator using the hybrid system was designed to have increased fuel efficiency and output power and reduced exhaust gas emissions, while maintaining the functions of existing cultivators. **Results:** The fuel consumption for driving the cultivator in the hybrid engine vehicle (HEV) mode was 341 g/KWh, which was 36% less than the consumption in the engine (ENG) mode for the same load. The maximum power take off output of the hybrid power system was 12.7 KW, which was 38% more than the output of the internal-combustion engine. In the HEV mode, harmful exhaust gas emissions were reduced; i.e., CO emissions were reduced by 36~41% and NOx emissions were reduced by 27~51% compared to the corresponding emissions in the ENG mode. **Conclusions:** The hybrid power system improved the fuel efficiency and reduced exhaust gas emissions in agricultural machinery. Lower exhaust gas emissions of the hybrid system have considerable advantages in closed work environments such as crop production facilities; therefore, agricultural machinery with less exhaust gas emissions should be commercialized. However, the high manufacturing cost and complexity of the proposed system are challenges which need to be solved in the future.

Keywords: Cultivator, Energy cost, Environmentally friendly, Harmful exhaust gases, Hybrid power system

Introduction

Power generation systems that reduce energy cost and are environmentally friendly have emerged as major competitive variables in the fields of agriculture and agricultural machinery. In addition to reducing greenhouse-gas emissions in agricultural production and improving energy efficiency, constructing a clean production system is a method to ensure environmental sustainability in the future. The use of a hybrid power system in agricultural machinery has important implications for constructing clean agricultural production systems.

Hybrid power systems drive a machine or equipment by combining two different types of power sources efficiently. A hybrid electric vehicle combines a conventional internal-combustion engine propulsion system with an electric propulsion system to reduce fossil fuel consumption and exhaust gas emissions. In the hybrid vehicle, the power by a generator produces the electricity which rotates the motor (series hybrid), or the engine load is reduced by using electricity to assist the motor (parallel hybrid). The overall efficiency of electric vehicles is known to be 21%, including the efficiency of thermal power generation, battery charging/discharging efficiency, motor efficiency, and charger efficiency. On the other hand, the overall efficiency of gasoline vehicles is known to be 14%. The low efficiency of gasoline vehicles is attributed to the fact that the vehicle is not always operated at the optimal thermal efficiency (maximum 30%) because the load varies

***Corresponding author:** Sang Cheol Kim
Tel: +82-63-238-4033; **Fax:** +82-63-238-4035
E-mail: sckim7777@korea.kr

during actual driving (Bae, 2002). In the automotive industry, parallel hybrid systems have been used commercially because they increase the fuel efficiency in the idle state or during the initial startup and reduce exhaust gas emissions. In the agricultural machinery industry, United States and Europe have been conducting research on electric tractors since the 1990s, and companies such as John Deere and Case IH have promoted the development of hybrid tractors. The first hybrid tractor was a 15-KW utility tractor for weed control developed by John Deere in 2002. Since the launch of this product, many other companies have joined the competition to develop hybrid power farm machinery. Patent applications for high-mobility hybrid electric vehicles have been filed actively by Hyundai Motors in Korea, Toyota Motor Company and Honda Motor Co., Ltd. in Japan, General Motors in the USA, and Mercedes-Benz and other companies in Europe (The Korean Intellectual Property Office, 2009). However, developing a reasonably priced commercial model has been difficult because of complexities in the electric power transmission structure caused by high torque in the power take off (PTO) output, limitations of high power motors, limited battery performance, and factors that increase cost.

In this study, a 20-KW agricultural hybrid power system was developed, and it was attached to a multi-purpose cultivator. The hybrid power system was designed to combine heterogeneous power sources (an internal-combustion engine and an electric power motor) and to simplify the power transmission structure. Moreover, the cultivator running on hybrid power was designed to increase fuel efficiency and output power and to reduce exhaust gas emissions while maintaining the functions of a conventional cultivator.

Materials and Methods

Hybrid power system for a multi-purpose cultivator

The hybrid power system for a multi-purpose cultivator was composed of an internal-combustion engine, an electric motor, a battery, and a generator in Figure 1. A power splitter was developed for the cultivator to combine heterogeneous power systems efficiently. The power splitter used a method based on an operation map, suggested by Lee et al. (2008), and it transmitted power selectively, as needed. The splitter contained a hybrid power combination mechanism with belt transmission based on an electric clutch, which measured real-time dynamic torque. In addition, the splitter employed parallel hybrid power transmission, suggested by Delpart et al. (2004).

The hybrid system consisted of a 48-V 5-KW BLDC motor, a gasoline engine with a maximum output of 14.6 KW, and a 5.5-KVA generator connected to the same shaft, and each power source was driven selectively through the electric clutch in Figure 2. A potentiometer was attached to the throttle pedal to control the gasoline engine throttle and motor speed. Based on the operating mode, a hybrid power control unit (HCU) controlled the opening and closing of the engine throttle and motor throttle, receiving feedback signals from the speed sensor and torque sensor; the HCU also controlled the rotational speed of the motor. The

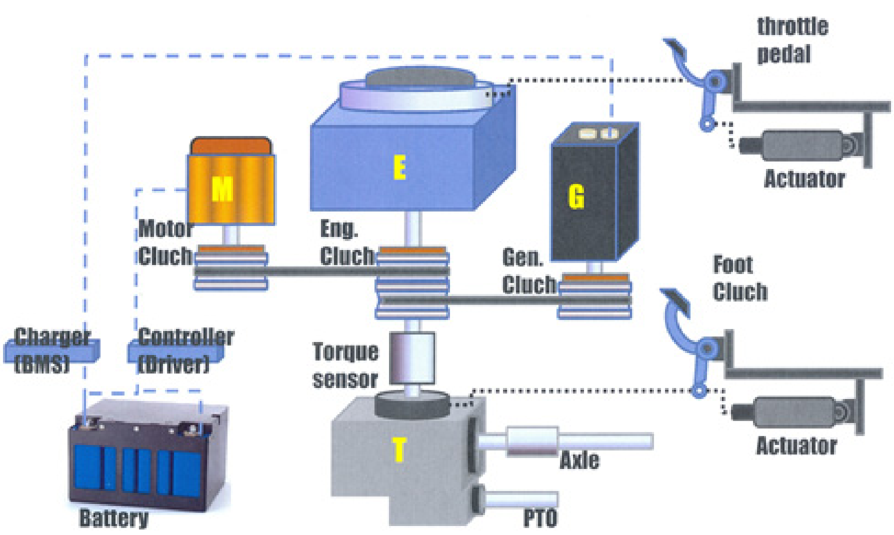

Figure 1. Diagram of hybrid power system for cultivator.

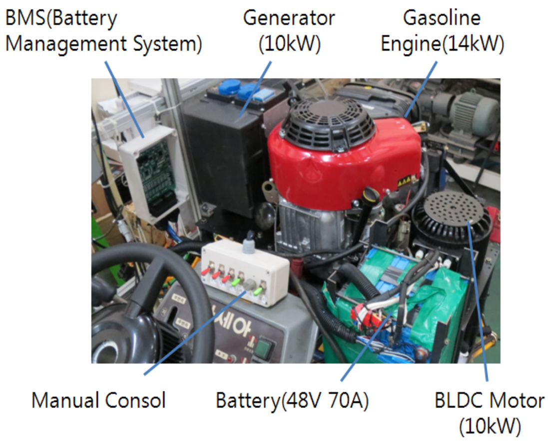

Figure 2. Hybrid power system.

Figure 3. Cultivator running on hybrid power.

Delfino microcontroller (TMS320F28335, Dallas, TX, USA) was used for the main electric control unit (ECU), and the HCU board had a 32-bit CPU, which had a maximum speed of 150 MHz (cycle time: 6.67-ns). Sensors were connected to the input ports to detect the motor speed, engine speed, load (in the form of torque), voltage, current, and battery charge state. A device to convert amplified strain gage signals to 4~20 mA signals and a F-V conversion device to convert magnet pickup signals to 1~10 V signals were designed. As output devices, a pulse width modulation (PWM) motor drive, a throttle controller, a charge current controller, a signal controller for the electric clutches of the motor, engine, and, generator, and a signal transmission device for the monitored information were designed by applying the motor control algorithms proposed by Kim et al (2009).

Hybrid power control unit software

The hybrid power system was operated by selecting a mode depending on the load condition and battery charging state. Based on the state of charge (SOC) suggested by Kim et al. (2011), the drive mode was selected depending on the load. Five types of drive modes were selected manually or by using an algorithm. In manual selection, the switching of modes depended on the select switch, and in automatic selection, it depended on the control command from the HCU (Table 1).

The hybrid emission vehicle (HEV) mode was a drive mode which combined electric power and gasoline engine. The HEV mode had two options: the zero emission vehicle (ZEV) first mode and the engine (ENG) first mode (Table 1); the ZEV first mode used the electric motor as the main power source and used the gasoline engine as reinforcement, whenever needed. This mode was used in situations such as when over 50% of the battery SOC was used for traveling on the field, a light load was to be carried, or work was to be done in crop production facilities. The ENG first mode used the gasoline engine as the main power source and used electric motor as reinforcement, whenever needed. This mode was used in situations such as when less than 50% of the battery SOC was used, heavy load was to be carried, the vehicle was to be used outdoors, or work was to be done on terraced fields to produce the maximum output. The ZEV mode used the electric motor only as the power source, and it was used in situations such as when sufficient battery charge was available, the vehicle was traveling on fields, or work involved only light loads(e.g., during soil preparation, weeding, ridging, mulching, and culturing crops (Table 1). The ZEV mode can be used when the battery SOC is less than 30% through the emergency battery mode in case of engine failure in Figure 2. A fuzzy algorithm suggested by Yang et al. (2010) was used for mode switching according to the SOC.

The ENG mode used the gasoline engine only as the power source (Table 1). This mode was suitable for working under medium load, and the generator produced extra output, controlling the power generation according to the load, to increase fuel efficiency. The ENG mode automatically switched to the engine mode in case of motor failure or electric system failure, or if the charge was insufficient.

Table 1. Specifications of drive mode of hybrid system

Mode		Specification
*HEV mode	ZEV first	The electric motor was used as the main power source, and gasoline engine power was used as reinforcement, whenever needed. Used for traveling, carrying, or working in crop production facilities.
	ENG first	The gasoline engine was used as the main power source, and electric power is used as reinforcement, whenever needed. Used for working under heavy load, outdoor working, or working on terraced fields.
ZEV mode		Only the electric motor was used as the power source. Used for traveling or working under light load, or during engine failure.
ENG mode		Only the gasoline engine was used as the power source. Used during motor failure or electric system failure.
Battery charging mode		The battery was charged regularly by driving the generator with extra output. If necessary, the battery can be charged when the engine is running.

* Combination of electric power and gasoline engine

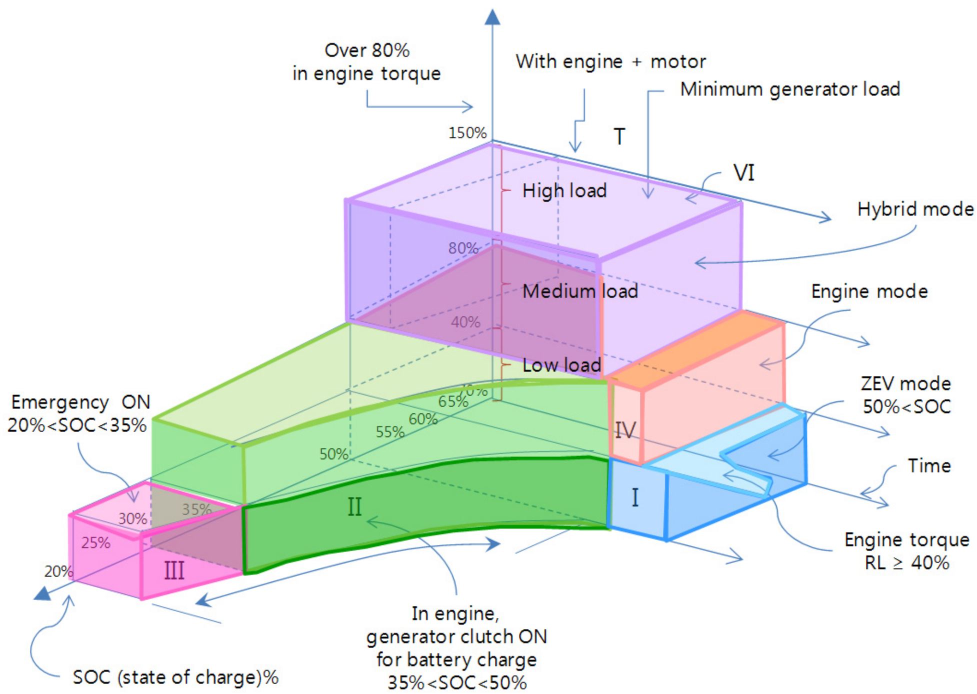

Figure 4. Diagram of hybrid power control.

The battery charging mode prioritized battery charging over load control (Table 1). The mode was switched to the battery charge mode when the SOC was less than 50%, and battery charging was possible when the engine was running, if necessary in Figure 4.

Performance testing of hybrid cultivator

The hybrid cultivator was mounted on a PTO dynamo system for dry fields and the output of the system was measured to evaluate the performance of the hybrid system at the Foundation of Agri. Tech. Commercialization & Transfer, located in Suwon, Gyunggi province, in 2013. Each mode was tested using the PTO dynamo system, and operating characteristics based on the break load were evaluated in each operation mode. The eddy current PTO dynamometer had a maximum measurement capacity of 250 KW with a maximum engine speed of 7,000 rpm and a maximum torque of 405 Nm (Table 2). In addition, incidental equipment such as a fuel oil flow meter for measuring fuel consumption, a fuel temperature controller for maintaining a constant engine state during the test, a lubrication oil temperature controller, a cooling water

Table 2. Specifications of eddy current PTO dynamometer

Maximum output	250 KW
Maximum engine speed	7,000 rpm
Maximum torque	405 Nm
Measurement range of engine speed	1,000 ~ 7,000 rpm
Incidental equipment: fuel oil flow meter, fuel temperature controller, lubrication oil temperature controller, cooling water temperature controller, suction air flow meter, exhaust gas analyzer, and smoke meter	

Table 3. Test results in ZEV mode

Motor speed (rpm)	PTO output (KW)	PTO torque (Nm)	Current(A)			Voltage (V)	Theoretical output (KW)
			Min.	Max.	Ave.		
3,560	0.02	0.07	0.8	1.0	0.9	55.9	0.1
3,550	0.11	0.31	47.2	61.0	54.1	53.4	2.9
3,530	0.68	1.84	52.6	70.2	61.4	53.1	3.3
3,490	1.45	3.99	67.4	81.7	74.6	52.2	3.9
3,450	2.13	5.93	76.4	97.2	86.8	51.5	4.5
3,430	2.34	6.54	98.7	109.9	104.3	50.6	5.3
3,410	2.75	9.61	103.5	116.3	109.9	49.8	5.5
3,400	3.09	11.55	117.4	128.9	123.2	47.5	6.0

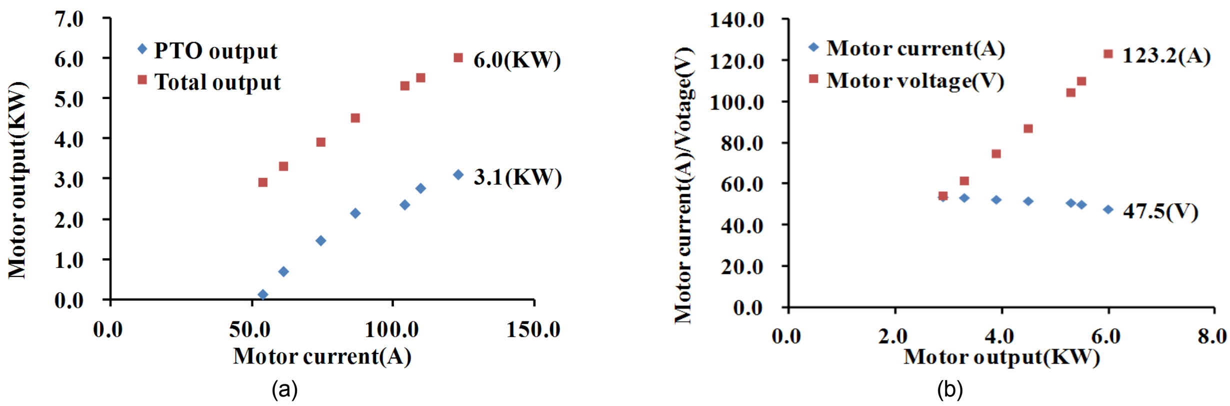

Figure 5. Motor output current/voltage in ZEV mode.

temperature controller, a suction air flow meter, an exhaust gas analyzer, and a smoke meter were used. The connection gear ratio was 4.89. The fuel specific gravity was 0.745.

While the hybrid cultivator connected to the eddy current PTO dynamometer ran under the variable load condition, the fuel consumption and exhaust gas emissions (NO_x, CO, CO_2, etc) were measured for different combinations of the PTO speed and torque in each mode (HEV, ZEV, and ENG modes). In the ENG mode, a full load test was conducted for engine speeds in the range of 1,800 ~ 3,500 rpm at intervals of 100 rpm. However, in the HEV mode, the test was conducted for motor speeds in the range of 3,300 ~ 3,500 rpm considering the rated motor speed.

Results and Discussion

Performance testing of hybrid cultivator

Output characteristics in ZEV mode

Figures 5(a) and (b) show the motor output current and motor output voltage, respectively, in the ZEV mode. The PTO output showed a linear relationship to the current, as shown in Figure 5, and the maximum output could handle loads up to 6.0 KW, which was 20% higher than the rated output. The battery voltage (47.5 V) at the maximum output dropped by 11% compared with the voltage (54 V) of the battery in the unloaded condition. The motor speed was 3,400 rpm, and the amount of current

Table 4. Test results in ENG mode

ENG speed (rpm)	PTO torque (Nm)	ENG torque (Nm)	Fuel consumption (L/h)	PTO fuel consumption (g/KWh)	PTO output (KW)
3,519	1.00	0.20	2.60	2,110.8	0.9
3,450	31.00	6.34	4.20	1,350.7	2.3
3,400	55.00	11.25	4.90	920.1	4.0
3,350	78.00	15.95	5.50	737.0	5.6
3,300	92.50	18.92	6.00	685.4	6.5
3,250	103.60	21.19	6.40	658.1	7.2
3,200	117.40	24.01	6.60	610.9	8.0
3,150	127.60	26.09	6.60	570.9	8.6
3,090	133.20	27.24	6.70	568.9	8.8
3,000	139.00	28.43	6.70	550.5	9.2
2,900	143.00	29.24	6.50	544.1	8.9
2,800	146.00	29.86	6.20	531.8	8.7
2,700	148.00	30.27	6.00	522.4	8.6
2,600	152.00	31.08	5.80	518.0	8.4
2,500	153.00	31.29	5.60	507.0	8.2
2,400	156.00	31.90	5.40	498.2	8.0
2,300	157.00	32.11	5.10	496.3	7.7
2,200	157.40	32.19	4.90	493.3	7.4
2,100	158.00	32.31	4.70	495.3	7.1
2,000	160.00	32.72	4.50	480.5	6.9
1,900	159.00	32.52	4.40	498.6	6.5
1,800	152.00	31.08	4.30	553.6	5.8

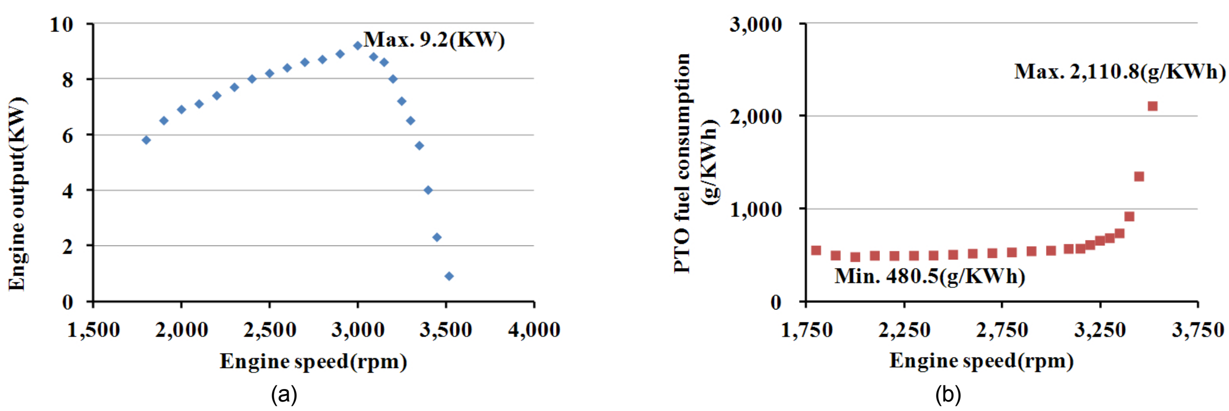

Figure 6. PTO output and fuel consumption in ENG mode.

was 123.2 A at the maximum output (Table 3).

Output characteristics in ENG mode

For the measurement of the PTO output in the ENG mode, the maximum output, fuel consumption, and exhaust gas at each engine speed were measured simultaneously, while increasing the load torque for a fully open throttle. Figure 6(a) shows the PTO output curve for a fully open throttle and variable loads, and Figure 6(b) shows the fuel consumption at variable loads and speeds in the ENG mode. The maximum engine speed was 3,519 rpm as shown in Figure 6(a), and the speed was decreased as the load torque increased. The maximum PTO output was 9.2 KW at 3,000 rpm, and the maximum torque was 32.7 Nm at 2,000 rpm (Table 4). For the engine at full load, the fuel consumption was 550 g/KWh up to 3,000 rpm, as inferred

Table 5. Test results in HEV mode

ENG speed (rpm)	PTO torque (Nm)	ENG torque (Nm)	Fuel consumption (L/h)	PTO fuel consumption (g/KWh)	ENG PTO output (KW)	HEV PTO output (KW)
3,560	0.07	Electric mode			0.0	Electric mode
3,550	0.31				0.1	
3,530	1.84				0.7	
3,490	3.99				1.5	
3,450	5.93				2.1	
3,430	6.54				2.3	
3,410	9.61				3.4	
3,400	55.00	11.25	4.94	930.0	4	6.1
3,350	78.00	15.95	5.54	735.0	5.6	7.7
3,300	92.50	18.92	5.98	685.0	6.5	8.6
3,490	96.10	19.66	6.36	408.0	7.1	9.3
3,450	110.20	22.54	6.56	394.0	8.0	10.1
3,450	117.40	24.01	6.59	379.0	8.6	10.7
3,430	126.30	25.82	6.72	360.0	8.8	10.9
3,400	131.10	26.80	6.65	341.0	9.2	11.1
3,380	139.00	28.43	5.09	379.0	10.0	12.1
3,330	160.00	32.71	5.60	379.0	11.0	13.1
3,310	180.80	36.98	6.55	384.0	12.7	14.8

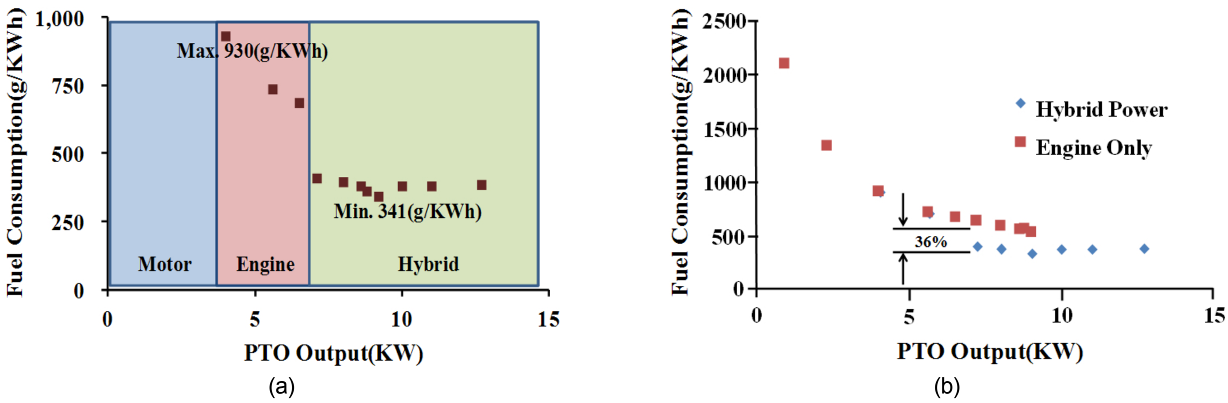

Figure 7. PTO output-fuel consumption relationship in HEV mode.

from the PTO output shown in Figure 6(b). However, the fuel consumption increased rapidly to approximately 3.8 times (2,110.8 g/KWh) at 3,519 rpm when the engine speed was increased and the load was reduced (Table 4).

Output characteristics in HEV mode

The electric motor was used for a PTO output stage load of less than 3 KW, and the gasoline engine was used for the load range of 3~7 KW in the HEV mode. In addition, both the engine and motor were used with loads of more than 7 KW. Figure 7(a) shows the PTO output-fuel consumption relationship, and Figure 7(b) shows the difference between the hybrid and engine modes in the HEV mode. When comparing the fuel consumption between the HEV and ENG modes, it was found that driving the cultivator in the HEV mode with a load of over 9 KW reduced the fuel consumption by 36% in Figure 7(b). For the same load, the HEV mode used 341 g/KWh, whereas the ENG mode used 550.5 g/KWh (Table 4).

The maximum PTO output in the HEV mode was 12.7 KW (Table 5), which was 38% more than that in the ENG mode (9.2 KW) (Table 4). The output increase was due to the addition of electric motor output into the existing engine power, and fuel was saved because of motor control during

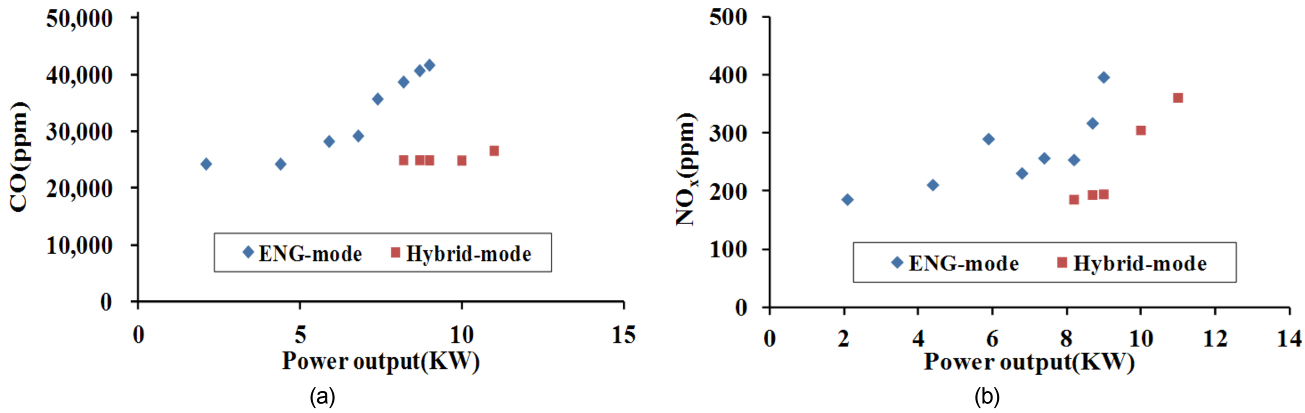

Figure 8. Comparison of exhaust gas emissions in ENG and hybrid modes.

Table 6. Harmful exhaust gas in ENG and HEV mode

Output(KW)	CO(ppm)		NOx(ppm)	
	ENG mode	Hybrid mode	ENG mode	Hybrid mode
2.1	24,223	.	185	.
4.4	24,202	.	210	.
5.9	28,180	.	289	.
6.8	29,157	.	230	.
7.4	35,650	.	256	.
8.2	38,647	24,883	253	185
8.7	40,640	24,892	316	193
9	41,615	24,864	395	194
10	.	24,829	.	304
11	.	26,532	.	360

loading. Load variation was more substantial using the cultivator in actual farm fields. Therefore, if the hybrid controller was used to control the operation, the driving mode could be switched appropriately in real time depending on the scope of the workload and hence farmers could take advantage of the hybrid power. Fuel savings would be improved if the cultivator is operated with real-time switching, e.g., using the ZEV mode for load ranges of 0~3 KW, the ENG mode for load ranges of 3~7 KW, and the parallel hybrid mode for load ranges of 7~12.7 KW in Figure 8.

Harmful exhaust gas

Figures 8(a) and (b) showed the CO and NO_x emissions, respectively, in the ENG and hybrid modes. Harmful exhaust gas emissions were reduced in all modes for different values of the output power, and the total amount of exhaust gases was also reduced (Table 6). Moreover, the emissions were reduced during the combined electric motor-gasoline engine operation because the motor produced output power for some duration of the operation. The motor was replaced with the engine when the driving was inefficient; therefore, driving the cultivator in the HEV mode reduced CO emissions by 36~41% and NO_x emissions by 27~51% in Figure 8.

Conclusions

In this study, a hybrid power system was developed for agricultural machines with a 20-KW output capacity, and it was attached to a multi-purpose cultivator. The hybrid system simplified the electric power transmission structure and combined heterogeneous power sources: an internal-combustion engine and an electric power motor. The cultivator using the hybrid system was designed to have increased fuel efficiency and output power and reduced exhaust gas emissions, while maintaining the functions of existing cultivators.

The fuel consumption for driving the cultivator in the HEV mode was 341 g/KWh, which was 36% less than the consumption in the ENG mode for the same load. The maximum PTO output of the hybrid power system was 12.7 KW, which was 38% more than the output of the gasoline engine. In the HEV mode, harmful exhaust gas emissions were reduced; i.e., CO emissions were reduced by 36~41% and NO_x emissions were reduced by 27~51% compared to the corresponding emissions in the ENG mode.

The hybrid power system improved the fuel efficiency and reduced exhaust gas emissions in agricultural machinery. Lower harmful exhaust gas emissions have considerable advantages in closed work environments such as crop production facilities; therefore, agricultural machinery with less exhaust gas emissions should be commercialized. However, the high manufacturing cost and complexity of the proposed system are the challenges that need to be solved in the future.

Conflict of Interest

The authors have no potential conflict of interest relevant to this study.

Acknowledgement

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References

Bae, C. W. 2002. Hybrid vehicle technology development and background. Korea Advanced Institute of Science and Technology. pp 1-2 (In Korean).

Delprat, S., L. Jimmy, T. M. Guerra and J. Rimaux. 2004. Control of a parallel hybrid powertrain: Optimal control. IEEE Transactions on Vehicular Technology 53(3):872.

Kim, J. E., J. H. Oh and J. S. Ye. 2011. The flexible EV/HEV and SOC band control corresponding to driving mode, Driver's propensity and environmental circumstances. The Korean Society of Automotive Engineers. pp 2799-2809 (In Korean, with English abstract).

Kim, J. M., J. Y. Kang, Y. H. Kim and H. S. Kim. 2009. Motor control for optimal engine operation of a power split type HEV. KSAE 2009 Annual Conference. pp 2854 (In Korean, with English abstract).

Lee, D. E., I. G. Whang, D. I. Jun and S. S. Park. 2008. Development and optimization of the hybrid engine system model to improve the fuel economy. Transactions of KSAE 16(6):65-73 (In Korean, with English abstract).

Report of Partent Analysis for Special Task Hybrid Vehicle. 2009. The Korean Intellectual Property Office. p8 (In Korean).

Yang, S., L. Ming, W. Haoyu, L. Bao, L. Qiang, Z. Yongli and L. Xiu. 2010. Research on genetic-fuzzy control strategy for parallel hybrid electric vehicle. World Electric Vehicle Journal 4:224.