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Effect of a semi electro-mechanical engine valve on performance and emissions in a single cylinder spark ignited engine*

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Abstract: In this study, an electro-mechanical valve (EMV) system for the intake valve of a four stroke, single cylinder, overhead valve and spark ignition (SI) engine was designed and constructed. An engine with the EMV system and a standard engine were tested to observe the effects of the EMV on engine performance and emissions at different speeds under full load. The EMV engine showed improved engine power, engine torque and break specific fuel consumption (BSFC). A 66% decrease in CO emissions was also obtained with the EMV system, but hydrocarbons (HC) and NO_x emissions increased by 12% and 13% respectively.

Key words: Semi electro-mechanic, Camless engine, Electro-mechanic engine valve, Engine performance, Emissions
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1 Introduction

All internal combustion engines (ICE) have mechanically actuated systems for opening intake and exhaust valves. Traditional valve systems have constant valve timing which restricts engine performance especially at low and at high engine speeds. Controlling valve operation in ICE's is an effective method for improving engine performance and emissions over a range of engine speeds. Parameters such as cam shape, valve timing, valve opening duration and valve lifting have a major impact on engine performance and emissions (Barkan and Dresner, 1989; Krauter *et al.*, 1992; Hatano *et al.*, 1993; Çınar, 1998; Akbaş, 2000; Pischinger *et al.*, 2000; Stein *et al.*, 1995).

To increase torque and reduce fuel consumption in gasoline engines, manufacturers are increasingly using variable valve timing systems in production engines. Most valve timing systems used for improving engine performance are dependent on the camshaft. The mechanical variable valve timing systems are complex but greatly reduce the limitations of traditional valve systems, especially in regard to volumetric efficiency (Barkan and Dresner, 1989). However, except for BMW's Valvetronic system, they cannot control all parameters such as valve timing, valve lifting and valve opening duration simultaneously, continuously and completely independently. Lotus Engineering has developed research and production versions of their fully variable valve system that are not dependent on camshafts. The Lotus system can also independently control valve timing, valve lifting and the duration of valve opening.

The power and torque increase obtained by using variable intake valve timing is between 5% and 21% The improvement in fuel consumption obtained by variable intake valve timing is between 6% and 30% (Ahmad and Theobald, 1989; Barkan and Dresner, 1989; Dresner and Barkan, 1989; Asmus, 1991; Demmelbauer *et al.*, 1991; Gould *et al.*, 1991; Hatano *et al.*, 1993; Urata *et al.*, 1993; Lee *et al.*, 1995; Levin and Schlecter, 1996; Moriya *et al.*, 1996; Pischinger *et al.*, 2000). The improvement in CO emissions ob-

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tained using variable intake valve timing is between 5% and 60% (Dresner and Barkan, 1989; Gould *et al.*, 1991; Lee *et al.*, 1995; Moriya *et al.*, 1996). In some studies, hydrocarbon (HC) emissions were shown to increase with the use of variable valve timing (e.g., Lee *et al.*, 1995). Other studies showed that HC emissions were reduced by between 4% and 40% (Dresner and Barkan, 1989; Gould *et al.*, 1991; Lancefield *et al.*, 1993; Moriya *et al.*, 1996). NO_x emissions were reported to decrease by from 30% to 90% (Dresner and Barkan, 1989; Gould *et al.*, 1991; Lee *et al.*, 1995; Moriya *et al.*, 1996). The opening speed of the valve increases the volumetric efficiency of the engine and the reduction in valve lifting decreases the friction arising in the valves (Levin and Schlecter, 1996). With a variable valve timing system employing the EMV system, all relevant parameters can be controlled simultaneously and completely independently. Therefore, in addition to improvements in fuel economy and emissions, engine performance is greatly improved (Levin and Schlecter, 1996; Pischinger *et al.*, 2000).

The variable valve timing system, which is a completely electro-mechanical system, does not need a camshaft and therefore enables the production of a camless engine. A semi electro-mechanical camless engine is one in which only intake or only exhaust valves are driven electro-mechanically. Camless engine systems have a great potential as they have the advantages of a mechanically working variable valve timing system and because the control of valve performance parameters is easier. There is a considerable collection of literature on camless engines. Recent studies have focussed on the control of the solenoids used in the EMV system and computer modeling of such control systems (Stubbs, 2000; Boie, 2001; Wang, 2001; Chang *et al.*, 2002; Tai, 2002; Wang *et al.*, 2002; Hoffmann and Stefanopoulou, 2003; Nitu *et al.*, 2004; Peterson and Stefanopoulou, 2004; Kamış and Yüksel, 2005; Cope *et al.*, 2008). However, a mass production camless engine has not yet been produced.

In this study an EMV system was designed based on systems built by other engineers. The EMV engine (a semi electro-mechanical camless engine), which enables electro-mechanical operation of the intake valve, and a standard engine were tested to understand the effect of EMVs on engine performance and emissions at different engine speeds under load. During the engine tests engine valve timing, valve opening duration and ignition timing were kept constant to observe the effects of the EMV system alone.

2 Electro-mechanical valve system

The components that comprised the electro-mechanic valve actuator (EMVA) were similar to those of other systems (Stubbs, 2000; Boie, 2001; Wang, 2001; Chang *et al.*, 2002; Tai, 2002; Wang *et al.*, 2002; Hoffmann and Stefanopoulou, 2003; Nitu *et al.*, 2004; Peterson and Stefanopoulou, 2004; Kamış and Yüksel, 2005; Cope *et al.*, 2008). They included an engine valve, two electro-magnets, an actuator spring and a valve spring. The diagram of an EMVA that is commonly used is given in Fig. 1.

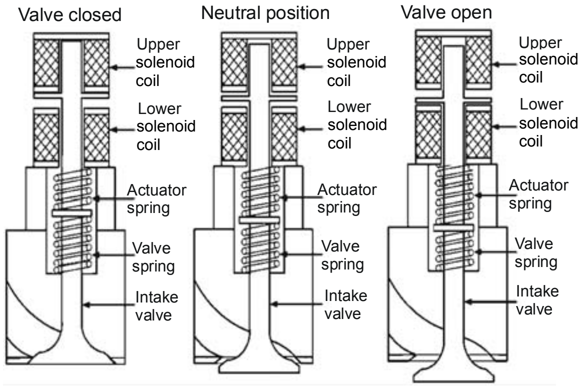


Fig. 1 Electro-mechanic valve actuator (EMVA) system

Principally, the actuator is like an oscillating mass-spring combination and is activated by an electro-magnetic force. The potential energy is transferred between two springs via the core and the valve throughout normal operation. The voltage is applied to the relevant coil during the transition. The magnetic force formed overcomes the spring, friction and gas flow forces.

The upper coil closes the valve and the lower coil opens it. The EMV system works in three different positions: voltage is applied to the lower coil to open the valve. The magnetic traction force formed moves the core and opens the valve. When no voltage is applied to the coils, the core is centered exactly in the middle of two coils and in a neutral position. In this position, the valve spring and the actuator spring are compressed equally and the valve is half open. Voltage is applied to the upper coil to close the valve. The core moves upwards under the effect of the magnetic force and closes the valve.

In some studies, the electrical power requirement of the EMV system is given as about 3 kW and the operating voltage that can meet this requirement would be 42 V (Trevett, 2002; Kassakian *et al*., 2005). An E-shaped electro-magnet is recommended as the most suitable magnet type for the EMV driving system (Nitu *et al*., 2004). The springs are very important to the continuous operation of the valve and they also influence the valve transition time (Wang *et al*., 2002; Kamış and Yüksel, 2003). The moving core completes most of its movements with the help of the energy stored in the springs. The spring force adds to the magnetic force until the point at which half of the movement length is reached for the effective coil. After that point, it imposes a force against the magnetic force. Therefore, the selection of the springs in EMV systems is of paramount importance.

3 Electro-mechanical valve system design

The appearance of the designed EMV system on the engine cylinder head is given in Fig. 2 and a block diagram of the system in Fig. 3. The EMV control system consists of a timing disc installed on the camshaft, an inductive sensor used for sensing the valve timing on the timing disk, a control unit that controls the actuator with sensor signals, a power supply that feeds the EMV control unit (18 V), an actuator that opens and closes the valve by forming magnetic force, an actuator spring and a valve spring, and a power supply with 33 V rated voltage, which feeds the EMV system (Fig. 4).

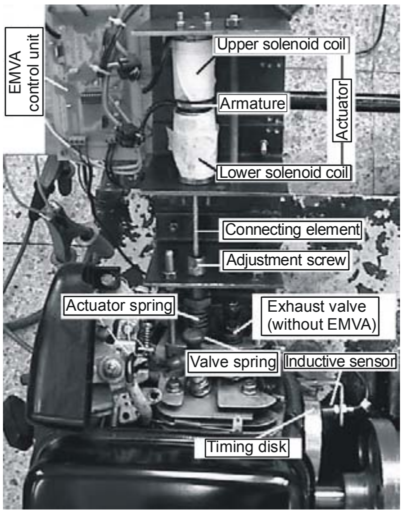


Fig. 2 EMV system on a cylinder head

The sensor that senses the valve timing on the disc which rotates with the camshaft, transmits the signal to the EMV control unit. In accordance with the signals received from the sensor, the EMV control unit directs the 33 V voltage to the lower solenoid coil. With the activation of the lower solenoid coil, the core (armature) inside the solenoid coil overcomes the valve spring force with the help of the magnetic force and opens the valve completely (Fig. 3). Thus, the EMV control unit provides opening and closing of the valve according to the timing signals received from the sensor.

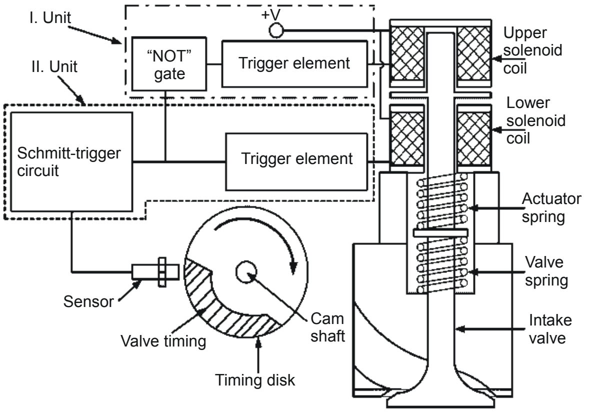
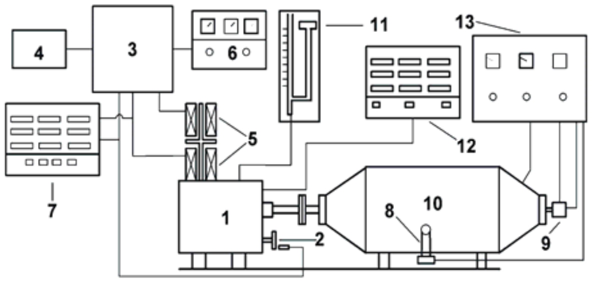


Fig. 3 Block schema of the EMV control system



1: IC engine
2: timing disc and sensor
3: EMVA control unit
4: EMVA control unit power supply (18 V)
5: electro-mechanic valve actuator (EMVA)
6: power supply (33 V)
7: automotive diagnostic instrument
8: load cell
9: tachometer
10: IC engine dynamometer
11: fuelmeter
12: exhaust gas analyzer
13: IC engine dynamometer control unit

Fig. 4 Experimental set-up

The EMV control system consists of two units that have the same structure: one of the units controls the lower solenoid coil, the other controls the upper solenoid coil. Upon receiving the sensor output signal, the unit that controls the solenoid coil switches the current by saturating the Darlington connected transistors and transmits the current to the lower solenoid coil via the power transistor. The same signal is used for the control of the upper solenoid coil. After the sensor output signal is inverted by a “NOT” gate, the upper solenoid coil is activated via a power transistor, as described above.

4 Experimental studies

An experimental study was performed to compare the performance and emissions of a spark ignited engine (SI) containing an EMV system and an electro-mechanically controlled intake valve with an engine containing a traditional valve system (standard engine). We also aimed to test the efficiency of the EMV system. The experimental conditions included six engine speeds (1600, 2000, 2400, 2800, 3200 and 3600 r/min) under full load and other relevant parameters (Table 1).

Table 1 Engine specifications

	Standard engine	EMV engine	Variety
Model	Briggs & stratton vanguard	Briggs & stratton vanguard	Constant
Fuel system	Gasoline/ Carburetor	Gasoline/ Carburetor	Constant
Cylinder number	1	1	Constant
Engine power (kW)	3.2 (3600 r/min)	3.3 (3600 r/min)	X
Cylinder volume (cm^3)	181	181	Constant
Cooling system	Air cooled	Air cooled	Constant
Ignition system	Magneto	Magneto	Constant
Ignition advance (°)	BTDC 12	BTDC 12	Constant
Valve system	OHV	EMV	X
Intake valve timing (CA°)	12°BTDC-ABDC 40	12°BTDC-ABDC 40	Constant
Exhaust valve timing (CA°)	56°BBDC-ATDC 12	56°BBDC-ATDC 12	Constant
Maximum valve lift (mm)	6.5	4.5	X

X means EMV specifications which are different from standard engine

The experimental set-up (Fig. 4) consisted of a test engine, dynamometer (DC dynamometer), fuel flow meter, exhaust gas analysis system, EMV system and EMV system test apparatus. The technical specifications of the test engine used in the experiments are given in Table 1. The test engine was first tested without EMV under full load, at various engine speeds. Then the same engine was equipped with the EMV system and tested under the same conditions for comparison. To test the EMV control unit and electrical parts, a Picoscope ADC 212 general purpose PC oscilloscope (UK) was used. The measurements of the EMV system and those of the engine performance were obtained simultaneously.

Emissions were measured with an MRU DELTA 1600 L exhaust gas analyzer (Germany). The specifications of the exhaust gas analyzer are given in Table 2.

Table 2 Specifications of the exhaust gas analyzer

	Measurements range	Accuracy
CO (%, v/v)	0~15	0.01
HC ($\times10^{-6}$)	0~20000	1
NO_x ($\times10^{-6}$)	0~4000	1

Data were collected for engine torque, engine power, specific fuel consumption, excess air factor (λ), CO, HC and NO_x emissions. In addition, the variation in the current flowing through the lower and upper coils and sensor signal data were recorded.

5 Results and discussion

5.1 Engine performance

Fig. 5 shows the torque changes for the EMV engine and the standard engine. Compared with the standard engine, the EMV engine achieved a 6.4% higher torque at 1600 r/min, a mean increment of 9% between 2000 and 3200 r/min engine speed, and 2.8% higher torque at 3600 r/min.

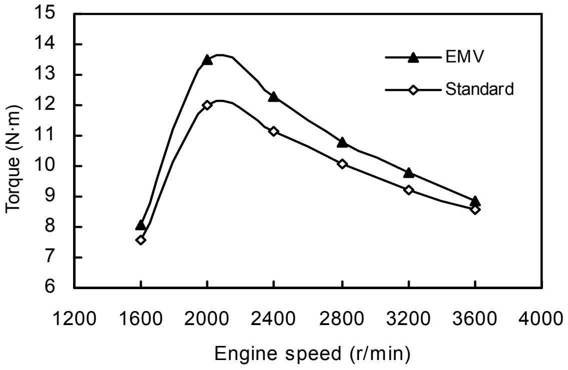


Fig. 5 Variation in engine torque

The valve opening and closing speed depends on several conditions, especially the control algorithm. However, valve opening and closing profiles are more square-shaped in EMV applications. The intake valve is fully open for a longer time in the operation of an EMV engine because the intake valve opens faster. In addition, differences in the valve cross-sectional areas have a considerable influence on engine performance and emissions (Ergeneman *et al.*, 1998). The computed cross-sectional area under the intake valve lift curve of the standard engine used in this study was 17.7% lower than that of the EMV engine (Fig. 6). An increased valve cross-sectional area in the first half of the induction stroke has significant importance for many reasons. For example, it produces a greater flow area as the piston starts to pull in a fresh charge.

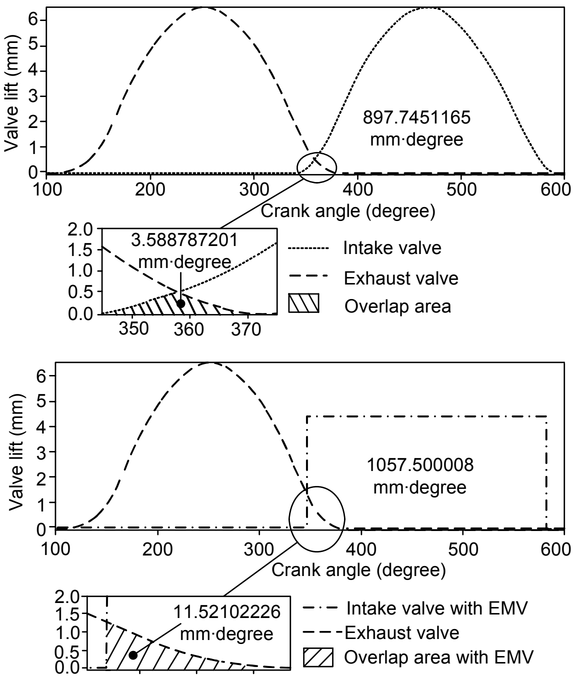


Fig. 6 Variation in valve cross-sectional areas

The opening of the intake valve occurs faster with the EMV system, enabling the engine to have an increased valve overlap area. Valve overlap is the point near the piston top dead center (TDC) in the 4-stroke cycle where both the intake and the exhaust valves are open at the same time. In this study, the computed valve overlap cross-sectional area of the EMV engine was about 310% greater than that of the standard engine (Fig. 6).

The negative work necessary to suck air into the cylinder is reduced by increased valve overlap. Also, an increase in the valve overlap amount implies an increase in the intake manifold pressure (Hammarlund, 2008; Leroy *et al.*, 2008). The increase in the valve overlap cross-sectional area is equivalent to extending the valve overlap period in a standard engine (Ergeneman *et al.*, 1998). At low speed, the effect of valve overlap is to re-introduce exhaust gasses into the combustion chamber. This is known as generating internal exhaust gas re-circulation (EGR) or internal EGR. Extending the valve overlap period facilitates an internal EGR. However, extending the valve overlap period at low speeds causes a decrease in engine performance (Çınar, 1998; Akbaş, 2000).

When the engine speed was near 2000 r/min in the operation of the standard engine, the excess air factor was determined as $\lambda<1$ (Fig. 7). The reason that the excess air factor was higher in the EMV engine than in the standard engine at the same engine speed, was that the air mass increased because of the more rapid opening of the intake valve. Because the remaining fuel mass was the same in both engines, the mixture became poorer in the EMV engine.

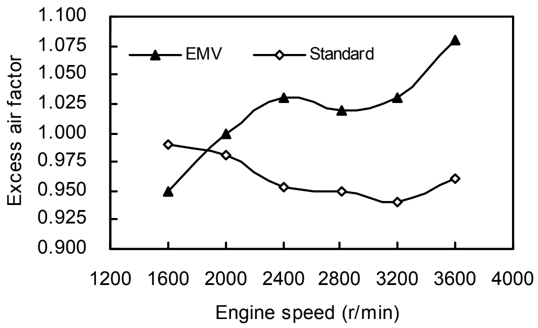


Fig. 7 Variation in the excess air factor

The torque increase attained by the EMV system was reduced at low and high engine speeds because the fresh air-fuel mixture taken inside the cylinders mixes with the exhaust gases. Some of the fresh air-fuel mixture is exhausted together with waste exhaust gases in the operation of the standard engine. However, the torque increase was minimized because of the decrease in power lost as a result of friction in the valve system.

Changes in the power of the EMV and standard engines are shown in Fig. 8. The power of the EMV engine relative to the standard engine increases in parallel with the increase in torque. The volumetric efficiency increases because of rapid valve opening and because of the increase in the valve opening cross-sectional area (Fig. 6). The valve overlap cross-sectional area has a negative impact on engine power at low speeds, inhibiting the proportional increase in engine power.

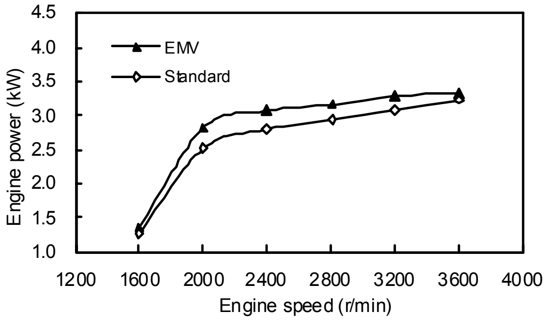


Fig. 8 Variation in engine power

At high engine speeds, the power supplied from the operation of the EMV engine and that supplied from the standard engine are almost the same. This is because when the EMV engine is operating at maximum speed, the air-fuel mixture ratio becomes leaner. However, the EMV engine power showed a small increase because of the lower number of mechanical parts in the EMV engine. Thus, the power consumed by valve friction contributes to engine performance.

Fig. 9 shows the changes in the break specific fuel consumption (BSFC) for the EMV and standard engines. The EMV engine achieved an improvement in BSFC of 18.9% at 1600 r/min, a mean improvement of 26.9% between 2000 and 3200 r/min , and an improvement of 32.2% at 3600 r/min engine speed, compared to the standard engine.

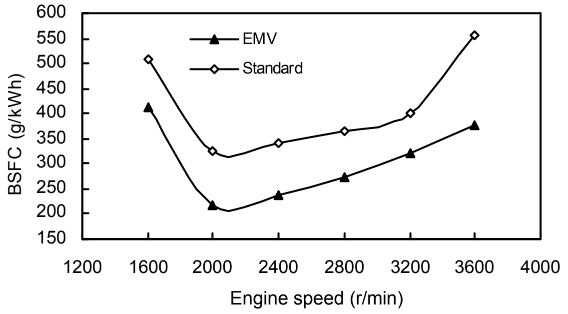


Fig. 9 Variation in break specific fuel consumption (BSFC)

Since the friction losses in the operation of the EMV engine are less than those of a standard engine, the torque increase is better. Also, as a result of a leaner fuel mixture arising from the differences in valve cross-sectional area compared to the operation of a standard engine, the BSFC is improved. The decrease in the number of mechanical parts leads to an increase in mechanical efficiency and improves engine performance and fuel consumption, especially at high engine speeds.

5.2 Engine emissions

The exhaust emissions were examined with respect to four parameters: excess air factor (λ), carbon monoxide (CO), HC, and nitrogen-oxides (NO_x).

Changes in CO emissions for the EMV and standard engines are shown in Fig. 10. Reductions were obtained in CO emissions of 11% at 1600 r/min, 94% between 2000 and 3200 r/min, and 84% at 3600 r/min engine speed in the operation of an EMV engine compared to that of a standard engine. Decreases in CO emissions are observed because the excess air factor is greater in the operation of an EMV engine compared to that of a standard engine. This is because the intake valve is fully open for a longer time in the operation of an EMV engine. The changes in valve cross-sectional area also influence the emissions formed (Ergeneman *et al.*, 1998).

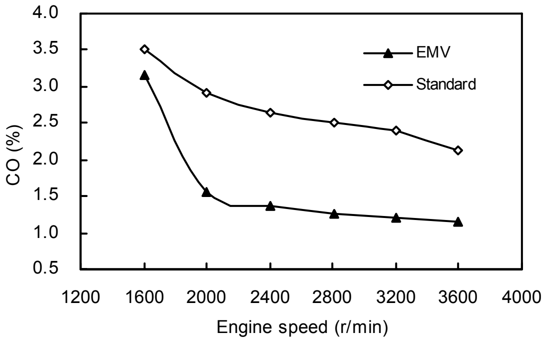


Fig. 10 Variation in CO emissions

Changes in HC emissions for the EMV and standard engines are shown in Fig. 11. Relative to the standard engine, HC emissions from the EMV engine increased by about 23% at 1600 r/min and 11% between 2000 and 3200 r/min, whereas 1% less HC emission formation was observed at 3600 r/min. Although the increase in the air-fuel mixture taken in should reduce HC emissions, we found that emissions increased, especially at low engine speeds, because of higher valve overlap cross-sectional area. HC emissions are influenced mainly by the amount of valve overlap (Zhaoda *et al.*, 2000). With the increase in the engine speed, as a result of better utilization of the valve overlap cross-sectional area by the EMV engine and thus the presence of sufficient oxygen in the environment, the HC emissions improve. However, at all speed intervals, more HC emissions were observed from the operation of the EMV engine.

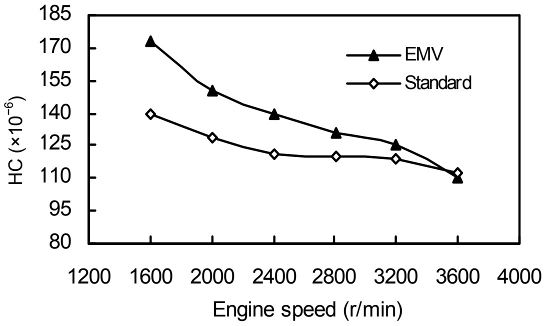


Fig. 11 Variation in HC emissions

In spite of the fact that the excess air factor in the operation of the EMV engine is higher than that of the standard engine, HC emissions from the EMV engine were found to be higher than those from the standard engine because the EMV engine has a larger valve overlap cross-sectional area (Fig. 6). This negative impact can be eliminated with the use of variable valve timing.

Fig. 12 shows the changes in NO_x emissions for the EMV and standard engines. An improvement of 36.1% was observed in the EMV engine relative to the standard engine at 1600 r/min. However, NO_x emissions from the EMV engine were higher by 25.1% between 2000 and 3200 r/min, and by 81.9% at 3600 r/min engine speed.

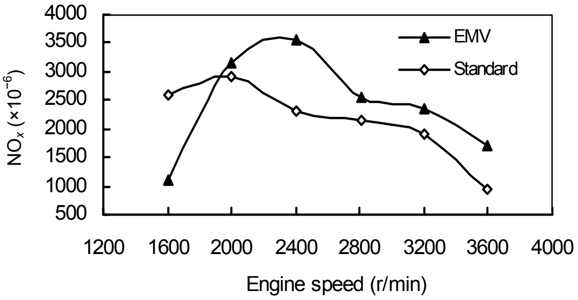


Fig. 12 Variation in NO_x emissions

NO_x emissions are found to decrease at low speeds because of the effect of internal EGR of a higher valve overlap cross-sectional area. Combustion in the cylinder becomes more uniform with the positive utilization of the valve overlap cross-sectional area at intermediate speeds. The increase in excess air factor, and thus the amount of oxygen that can go into reaction, leads to an increase in the formation of NO_x emissions at high speeds.

5.3 Testing the EMV system

The signals received from the EMV system were used to determine whether the system worked efficiently, and to provide information on the behavior of the system. The inductive sensor used in the EMV system generates signals at the moment that it senses the valve timing on the timing disc. The signals generated on the timing disc also represent the valve timing. Figs. 13a and 13b show the changes in the lower and upper solenoid coil currents over time and the changes in sensor output signals at 1600 and 3600 r/min, during the operation of the EMV engine.

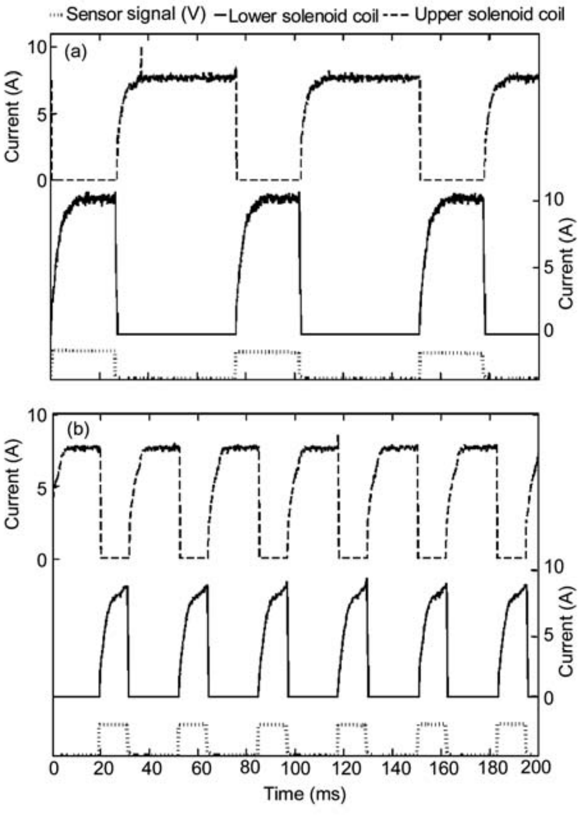


Fig. 13 Lower and upper solenoid coil currents vs. sensor signal. (a) 1600 r/min; (b) 3600 r/min

The currents that passed through the lower and upper solenoid coils were measured as 10 A and 8 A, respectively. These values change depending on the temperatures of the solenoid coils. Since the electrical resistance of the solenoid coils increases with temperature, the current that passes through them decreases as temperature rises.

The sensor frequency of the EMV engine showed an increase relative to that of the standard engine in parallel with the speed increase, when the speed of the EMV engine was 3600 r/min (Fig. 13b). However, despite their increasing frequency, the currents that pass through the solenoid coils do not depend on the rotational speed of the EMV engine, but remain constant. Thus, in the operation of the EMV engine, the current values of the solenoid coils do not change between 1600 and 3600 r/min. However, there may be minor variations in the currents that pass through the upper and lower solenoid coils. Those variations are the result of different electrical resistances in the solenoid coils. The response speed of the actuator used works simultaneously with the engine speed and valve timing.

6 Conclusion

In this study, a system that enables electromechanical operation of the intake valve in a single cylinder SI engine was designed and manufactured, based on published research. The system with EMV was tested with the engine under full load and at various engine speeds. As a result of our experiments, we conclude that, compared with a standard engine, the EMV system has high potential to improve engine torque, can help to reduce BSFC, shows an increase in excess air factor during operation, obtains an overall decrease of 66% in CO emissions, 12% in HC emissions, and 13% in NO_x emissions.

The EMV system designed for this study works with 33 V DC. This operating voltage is 26% lower than that of the 42 V EMV systems. In addition, the maximum engine speed increases by 4% in the operation of an EMV engine. Moreover, the electrical behavior of the components that comprise the EMV system do not change according to the engine load. Also, the response speed of the actuator used works synchronously with the engine speed and valve timing.

With design optimization, especially of the solenoid coils that comprise the actuator, the electrical power requirement of the EMV system can be reduced. The EMV system can be used more efficiently with the use of stronger actuators, sensors and microcontrollers. If the EMV system is used in ICEs, the need for some mechanical parts (camshafts, rocker arms, etc.) can be eliminated. In systems with EMV, with full optimization of the control of the valve performance parameters and of the air-fuel mixture, the improvements in engine performance and emissions can be further enhanced. In future studies, the dependency of the engine on the camshaft will be completely eliminated by driving the exhaust valve as well as the intake valve electro-mechanically.

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