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SI ENGINE INTRACYCLE SPEED PROFILE MODULATION FOR MAXIMIZING INDICATED EFFICIENCY UNDER VARIOUS INTAKE MANIFOLD PRESSURE AND SPEED CONDITIONS

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ABSTRACT

Improving the efficiency of the internal combustion engine is important for reducing carbon dioxide emissions in the transport sector. Various types of hybrid electric vehicles have been proposed to increase the fuel economy of the internal combustion engine-based vehicle. In a series hybrid electric vehicle, the shaft of the internal combustion engine is separated from the vehicle drive shaft. This means that even if the engine rotation speed changes within a single cycle, the vehicle power transmission is not greatly influenced by the internal combustion engine drive shaft. Therefore, it is possible to improve efficiency by modulating the speed in a single cycle of the engine. To investigate the effect of speed profile modulation on SI engine net indicated efficiency, we have optimized the intracycle speed profile of the SI engine through simulation. Simulation results show that the net indicated efficiency is improved under various speed and intake manifold pressure conditions due to combustion phasing enhancement under a high intake manifold pressure and low speed condition and improvement of heat loss and pumping work in a low intake manifold pressure condition.

Keywords: Energy analysis, SI engine, series HEV, Trajectory optimization, Zero-dimensional model

NOMENCLATURE

Abbreviations	
BMF	Burned Mass Fraction
EVC	Exhaust Valve Closing
EVO	Exhaust Valve Opening
HEV	Hybrid Electric Vehicle
IVC	Intake Valve Closing
IVO	Intake Valve Opening
LHV	Lower Heating Value
SI	Spark Ignition
WOT	Wide Open Throttle
Symbols	
K	Mean kinetic energy
L_g	Geometric length scale
S_{ij}	Strain rate
V	Cylinder volume
$\dot{X}_b$	Burn rate
Δ	Difference between the optimum profile and conventional profile
η_{net}	Net indicated efficiency
η_p	Pumping work efficiency
ρ	Density

1. INTRODUCTION

To reduce carbon dioxide emissions in the transportation sector, regulations on vehicle fuel economy or carbon dioxide emissions have been imposed and strengthened globally [1]. Automakers are researching and developing new powertrains or improving the efficiency of existing powertrains to meet enhanced standards.

It is predicted that fossil fuels will be the main energy source for the transport sector in the future [2]. To satisfy future standards, it is essential to improve the efficiency of the internal combustion engine, which uses fossil fuel in various automotive vehicle powertrains.

HEVs were introduced to increase the fuel economy of internal combustion engine-based vehicles, and the sales volume of HEVs has increased. The series HEV uses the engine only for electric generation, so traction force of the vehicle is transmitted from an electric motor instead of the internal combustion engine. This leads to the elimination of constraints on intracycle speed variation in the engine operation.

Engine speed is a factor that affects internal combustion engine efficiency. Therefore, additional efficiency could be obtained by modulating the rotational speed of the internal combustion engine within a single cycle. Furthermore, this speed control could be applied in the series HEV powertrain architecture.

Therefore, in this paper, we discuss the possibility of an efficiency increase through speed profile modulation under various operating conditions by simulating an SI engine.

2. METHODS

2.1 *SI engine modeling*

The SI engine model used in this study is a two-zone zero-dimensional SI engine model [3]. Since the speed profile of the gas exchange process also affects the efficiency, modeling was carried out including the gas exchange process [4].

The Poulos heat transfer model [5] and turbulent flame model [6] were used to reflect the effect of the speed profile modulation. The flow properties required for the heat transfer and turbulent flame models were calculated using a zero-dimensional k-epsilon model [7], [8]. In the zero-dimensional k-epsilon model, the product of the strain rate tensor is modeled as equation (1), considering the compression effect of the piston.

$$S_{ij}S_{ij} = C_{shear}\frac{2K}{L_g^2} + \left(-\frac{\dot{\rho}}{\rho}\right)^2 \quad (1)$$

The Livengood-Wu integral method was used to estimate knock onset timing [9]. The ignition delay of the unburned mixture was calculated under various temperatures, pressures and dilution concentrations based on the reduced chemical reaction mechanism of the previous research [10]. We assumed the SI engine could stably operate when the remaining unburned mass was below 1.5% [11] at a Livengood-Wu integral value of 1.

2.2 *Optimization*

Using the developed SI engine model, trajectory optimization was performed to find the optimum speed profile for maximizing the net indicated efficiency. Among the various possible methods for solving the trajectory optimization problem, we used the direct method to change the trajectory optimization problem to a parameter optimization problem [12]. The patternseach method was used to solve the parameter optimization problem.

We set the objective function to the net indicated efficiency. To consider the knock, the remaining unburned mass fraction when the Livengood-Wu integration is 1 was used as a constraint. To optimize the various target speeds, the average speed was also constructed with constraints. A tolerance of ± 1% of the target speed was allowed for the reproducibility of results. Upper and lower bounds of speed were set at 6,000 RPM and 500 RPM, respectively.

2.3 *Simulation results analysis*

Energy analysis was performed to compare the optimized profile operation results with the conventional profile operation results. From the energy analysis results of the SI engine [13], the factors affecting the efficiency are summarized in three major categories.

The first factor is the combustion phasing. CA 50 timing was used in many studies to compare the combustion phasing [14]. In this paper, CA 50 timing is not representative of combustion phasing because of the large speed variation during the combustion process. Therefore, we use the burn rate weighted average cylinder volume during the combustion process. The cylinder volume at the EVO timing was divided into an average cylinder volume during the combustion process as equation (2) was used to compare combustion phasing. It was used as an indicator of the work extraction from the chemical energy through the combustion process.

$$ER_{EFF} = V_{EVO} \Big/ \left(\int_{\mathrm{SOC}}^{\mathrm{EOC}} V_{cyl}(t)\dot{X}_b \, \mathrm{d}t \right) \quad (2)$$

The second factor is heat loss. Heat transfer from the in-cylinder gas to the cylinder wall reduces the pressure of the gas and the pressure-volume work. Heat loss during the gas exchange process was not considered because even if heat transfer occurs during the gas exchange process, the gas pressure is not significantly affected because the in-cylinder gas pressure and manifold pressure are equilibrated through the mass transfer.

The last factor is pumping work. In this paper, pumping work is defined as the pressure-volume work from EVO timing to IVC timing and normalized to LHV at IVC timing. This approach is used since the pressure-volume work of the open system is affected differently from the closed system as described in the heat loss section.

3. RESULTS AND DISCUSSION

3.1 *Optimum speed profile*

Engine operating conditions used in this paper are summarized in Table 1.

Table 1 Simulation condition

Simulation condition	
Stroke [mm]	77
Bore [mm]	85.4
Fuel Anti Knock Index	87
IVO [cad]	bTDC 16
IVC [cad]	aBDC 48
EVO [cad]	bBDC 52
EVC [cad]	aTDC 12

Setting the average cycle speed to 1,000 RPM, we varied the intake manifold pressure and found the optimum speed profile. Intake manifold pressure was varied from 0.4 atm to 1.0 atm in 0.2 atm increments. Fig 1 shows the optimum speed profiles in this simulation condition.

The speed profile of the compression, exhaust, and intake process varied with the intake manifold pressure. As the intake manifold pressure increased, the speed of compression and intake process increased. Under high intake manifold pressure conditions, combustion duration is important for knock mitigation. High speed during the compression and intake process could enhance burn rates and assist knock mitigation. Under low intake manifold pressure conditions, burned gas could be transferred from the exhaust manifold to the intake manifold during the valve overlap interval. The

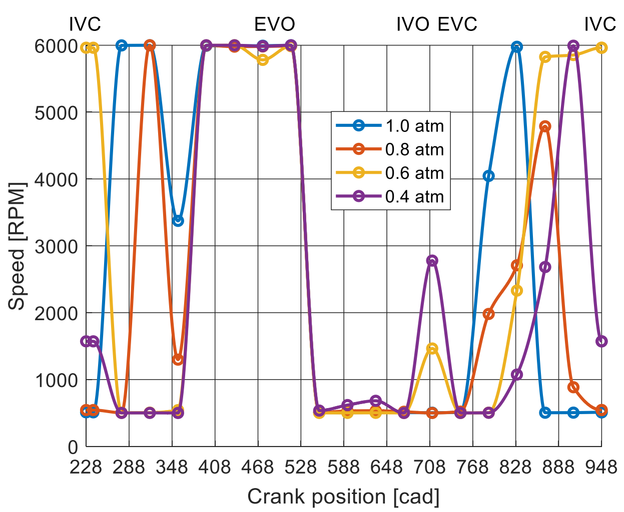

Fig 1 Optimum speed profiles with variation in intake manifold pressure

high residual mass fraction at IVC timing could reduce LHV of in-cylinder gas, leading to a relative increase in pumping loss. High speed of valve overlap interval could reduce backflow to the intake manifold.

Next, optimization in WOT condition was performed by varying the average speed from 1,000 RPM to 5,000 RPM at 1,000 RPM intervals. Fig 2 shows the optimal speed profiles at various average speeds.

With a variation in target speed, the speed profile change around compression, expansion, and firing TDC was not large, and the speed profile of the exhaust process mainly changed. This is because the speed near the firing TDC has a greater effect on the efficiency than the speed of the exhaust process. Exhaust process speed cannot significantly change in-cylinder flow dynamics from IVC timing to EVO timing. Heat loss and combustion phasing were not significantly changed as the average speed increased with modulating exhaust process speed. Therefore, the average speed was adjusted to the target speed by controlling the exhaust process speed.

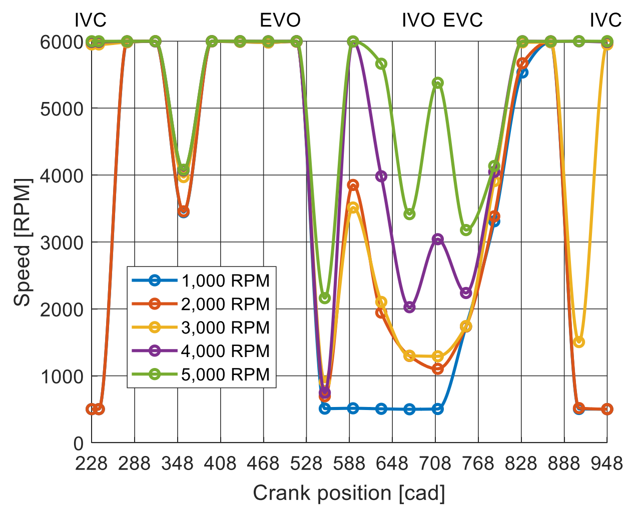

Fig 2 Optimal speed profiles with variation in average speed

3.2 *Variation in intake manifold pressure*

Fig 3 shows the net indicated efficiency difference and energy analysis results when operating with the optimum speed profile obtained in section 3.1 and operating with the conventional profile. Average speed was fixed at 1,000 RPM and only the intake manifold pressure was changed. The efficiency difference increased as the intake manifold pressure was increased.

To study the cause of the efficiency difference, factors affecting the efficiency were analyzed in terms of combustion phasing, heat loss, and pumping work. First, we examined the combustion phasing. Combustion phasing improved under all intake manifold pressure conditions. The operating condition in which combustion phasing was the most improved was the high intake manifold pressure condition. This condition is the retarded spark timing operating condition for knock mitigation in conventional engine operation. Speed profile modulation operation could improve combustion phasing by knock mitigation using not only spark timing but the intake, compression, and firing TDC speed profile modulation.

Second, heat loss analysis was performed. The amount of heat loss between IVC and EVO timing was normalized to the in-cylinder gas LHV at IVC timing. The improvement of heat loss increased as the intake manifold pressure decreased. Expansion process speed in the optimum speed profile was faster than in conventional operation, so heat loss was reduced.

Finally, pumping work was compared. Pumping work showed greater improvement when the intake manifold pressure was lower. In the conventional speed profile, there was a large loss due to the difference between the exhaust manifold and intake manifold pressure when throttled conditions. Exhaust process operation at a low rotating speed reduced pumping loss. In addition, the high speed of valve overlap interval could reduce backflow to the intake manifold.

3.3 *Variation in average speed*

Fig 4 shows the net indicated efficiency difference and energy analysis results when operating with the optimum speed profile with variation in average speed and operating with the conventional profile. Intake manifold pressure was fixed at 1.0 atm and cycle average speed was varied. Net indicated efficiency increased at all average speeds compared to conventional engine operation. The greatest improvement of net indicated efficiency occurred at a low average speed.

The reasons for efficiency improvement were analyzed as in section 3.2. Combustion phasing was improved under all average speed conditions. Knock occurred mainly under low engine speed operating conditions because time-based combustion duration is increased as the engine speed decreases. Speed profile modulation of the intake and compression process leads to enhanced burn rates, so combustion phasing improved with speed profile modulation at the low average speed condition.

Next, heat loss was analyzed. In WOT condition, retarded spark timing for knock mitigation led to reduced time in high temperature and pressure gas states under low speed conditions. Under high average speed operating condition, the expansion process speed difference between the optimum speed profile and conventional operation was not large. Thus, the improvement in heat loss was modest.

Finally, pumping work was analyzed. As the average speed increased, the improvement of the pumping work became larger. This was achieved by pressure equilibrium between the manifold and in-cylinder by operating at a slower speed than the operation of the conventional engine.

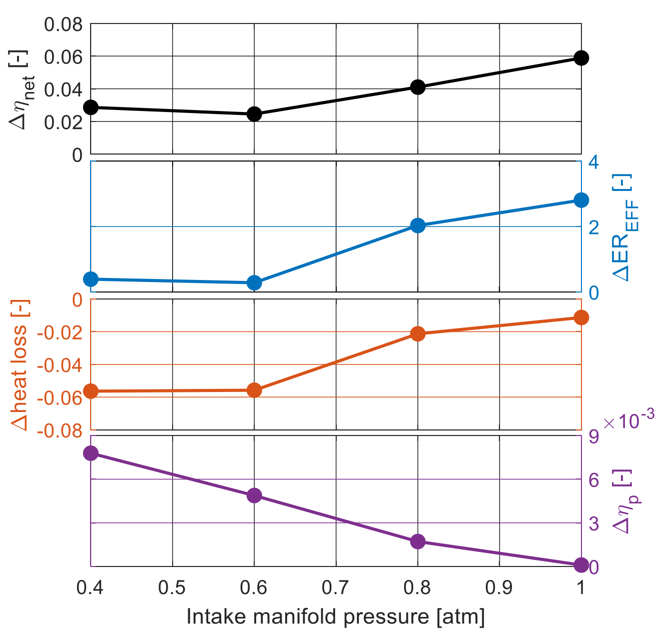

Fig 3 Difference between speed profile modulating operation and conventional operation by varying intake manifold pressure

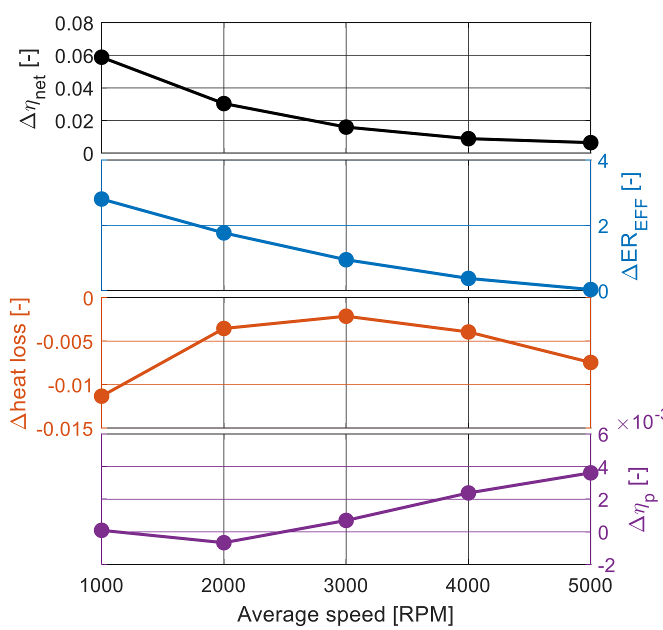

Fig 4 Difference between speed profile modulating operation and conventional operation by varying average speed

4. CONCLUSION

Simulation results show that it is possible to increase the net indicated efficiency under various operating conditions by using intracycle speed profile modulation for the SI engine. The results show that the efficiency is higher than that of the conventional engine operating in all simulation conditions.

Combustion phasing, heat loss and pumping loss of SI engine can be improved by modulating the speed profile of each process. Those improvements could increase the net indicated efficiency of the engine. Improvement of combustion phasing is a major source of efficiency increase in high intake manifold pressure conditions, and improvement of heat loss and pumping work is remarkable under low intake manifold pressure conditions.

The operating condition with the most improved efficiency through the speed profile modulation is a low speed and high intake manifold pressure. In this operating condition, the combustion phasing is worsened due to the knock in the SI engine. In this condition, the net indicated efficiency could be increased by improving the combustion phasing with speed profile modulation.

Intracycle speed profile modulation could be possible through the control of the generator current connected to the SI engine in the series HEV powertrain architecture. This speed profile modulation is expected to enable expansion of the operating conditions of the existing SI engine. The analysis results of the speed profile modulation effect could be applied to the conventional SI engine. In conventional SI engine, factors affecting the piston speed profile, such as connecting rod length, could affect efficiency. Therefore, it is possible to optimize these factors to improve the SI engine efficiency.

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