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Effect of Breathing Characteristics on the Performance in Spark-Ignition Engines

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Adaptive valve timing control is one of the promising techniques to accomplish the optimized mixture formation and combustion depending on the load and speed, which is needed to meet the future challenges of reducing fuel consumption and exhaust emissions. The behavior and the effect of adaptive valve timing control system has been investigated by computer simulation, which simulates the gas dynamics in engines. These programs are typically one-dimensional including complex flow features as 'special' boundaries. A code adopting 2-step Lax-Wendroff method with artificial damping terms called FCT(Flux Corrected Transport), was developed to investigate the influence of operational and design parameters on the performance of engines.
The effects of adaptive valve timing control system on volumetric efficiency or engine torque, and pumping loss were investigated. It increased low end torque by about 6 %, and reduced pumping loss drastically at low load, high engine speed conditions. The pressure pulsation in intake manifold was affected significantly by adjusting valve timings.

Keywords: Adaptive Valve Timing Control System, Volumetric Efficiency, Reverse Flow

INTRODUCTION

Conventional engines have adopted advanced intake valve opening angle ahead of TC, and retarded closing angle beyond BC, to enhance the volumetric efficiency at higher engine speeds. The inertia of the gas in the intake system, as the intake valve is closing, increases the pressure in the port and continues the charging process as the piston slows down around BC and starts the compression stroke[1]. However, this operation accompanies deterioration of volumetric efficiency at low engine operating speed, caused by reverse flow from cylinder to intake manifold consequently reducing torque and power of engines. Load conditions are controlled by adjusting the opening ratio of throttle plate which also causes most of pumping loss in engine systems.

Adaptive valve timing control system, which can vary valve opening and closing timing to control the amount of charge mixture in cylinders instead of throttle valve system, overcomes these defects of conventional fixed valve timing systems. This system can be constituted by using electromechanical, hydraulic or mechanical valve system. It allows fully variable operation of the intake and exhaust valves and subsequently a completely unthrottled load control of gasoline engines. The adaptive valve timing control system is known to be able to demonstrate the improved fuel economy and high 'low end torque' owing to the unthrottled load control, minimized pumping loss and optimized residual gas fraction[2]. It also leads easy NOx control by residual gas fraction control and substantial reduction of HC emissions during cold start and warm-up operation. Furthermore, minimal residual fraction achieved by optimized valve timings provides high potential for idle speed reduction. Engine loads can

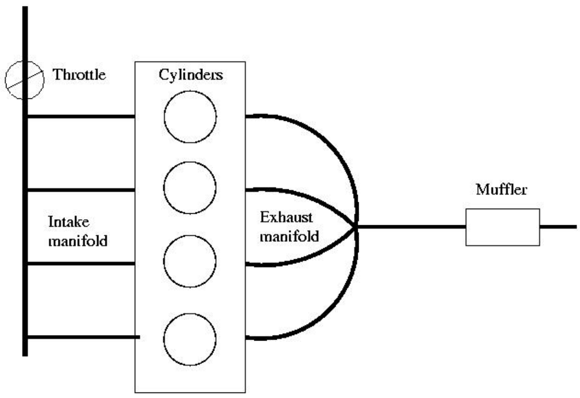

Figure 1. Configuration of the engine to be studied.

Table 1 - Specification of engine

Displacement volume [cc]	1996.8
Compression ratio	9.4
Connecting rod length [mm]	131.9
Piston stroke [mm]	79.5
Number of cylinder	4
Valve timing (fixed), lift [mm]	
IVO(Intake Valve Open)/IVC(Intake Valve Close)	340 / 608 (9.4)
EVO(Exhaust Valve Open)/EVC(Exhaust Valve Close)	118 / 398 (9.4)

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be controlled by adopting early intake valve closing strategy, which enables the gas exchange pumping losses to be minimized. Engine loads can also be controlled by late intake valve closing strategy. The early valve closing is said to be preferable to avoid possibility of cylinder to cylinder and cycle to cycle variation due to the existence of the exhaust gas in intake manifolds[3].

There have been efforts to make adaptive valve timing control system work[3-5]. Adaptive valve timing control system can be classified into three categories. One is an electro-magnetically operating system[3], another is with hydraulic valve lifting mechanism[4], and the other is a mechanical system[5].

The capability of adaptive valve timing control system and the physics in its application is investigated with the help of computer simulation. Simulation, or modeling, can make major contributions to engine engineering at different levels of generality or detail, corresponding to different stages of model development, by[1]:

1. Developing a more complete understanding of the process under study from the discipline of formulating the model;
2. Identifying key controlling variables to provide guidelines for more rational and therefore less costly experimental development efforts;
3. Predicting engine behavior over a wide range of design and operating variables to screen concepts prior to major hardware programs, to determine trends and tradeoffs, and, if the model is sufficiently accurate, to optimize design and control;
4. Providing a rational basis for design innovation.

This study aimed at investigating effect of valve opening and closing timing on the pressure pulsation in manifold, and on volumetric efficiency, power, and thermal efficiency of an engine system by computational simulation, or modeling.

MODELING

To simulate the effect of the existence of a throttle valve in an engine system, a model of engine was selected as shown in Fig. 1. It has four cylinders, intake and exhaust manifolds, a throttle plate which manipulate the amount of air flow into cylinder, a muffler, and intake and exhaust pipes. 4-cylinder, 2 liters engine was selected and its specifications are listed in Table 1.

Methodologies for predicting the gas flow rate in pipe system of engine have been developed by many scientists and can be classified into quasi-steady model and gas-dynamic model[1]. Gas dynamics model is superior to quasi-steady model, in that it accounts for the pressure pulsation in the pipes of engines.

Benson et al.[6] applied MOC(Method of characteristics), which can solve hyperbolic partial differential equation with first order accuracy, and boundary conditions to deal with the gas dynamics model in engine pipes system. Several scientists have developed FDM(Finite difference method) to simulate the pressure pulsating phenomenon in pipes of an engine system with higher accuracy.

In this study, Two-step Lax-Wendroff method was adopted to take the gas dynamics into consideration with second order accuracy, and FCT(Flux Corrected Transport) was used to eliminate the non-physical oscillation which can occur in the procedure of solving hyperbolic equation with central difference scheme.

The continuity, momentum and energy equation that were assumed to govern the one-dimensional nature of wave pulsation in engine pipe system can be represented as following:

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho \\ \rho u \\ \frac{1}{2}\rho u^2 + \frac{p}{k-1}\end{pmatrix} + \frac{\partial}{\partial x}\begin{pmatrix}\rho u \\ \rho u^2 + p \\ \frac{1}{2}\rho u^3 + \frac{k}{k-1}up\end{pmatrix} = \begin{pmatrix} -\frac{\rho u}{F}\frac{dF}{dx} \\ -(\frac{\rho u^2}{F}\frac{dF}{dx} + \frac{2\rho f}{D}u\,|\,u\,|) \\ \rho q - \frac{1}{F}\frac{dF}{dx}(\frac{1}{2}\rho u^3 + \frac{k}{k-1}up)\end{pmatrix} \quad (1)$$

where, ρ : density
u : velocity
p : pressure
F : area of pipe
D : diameter of pipe
k : specific heat ratio
q : heat transfer
f : friction coefficient

Basic boundary conditions, such as cylinders, multi-junctions, muffler, inflow from ambient, throttle valve and etc., were developed using the techniques which Benson, et al.[6,7], introduced.

BOUNDARY CONDITIONS

Two-step Lax-Wendroff method, which can handle the hyperbolic equations with second order accuracy, and boundary conditions by Benson et al. were adopted. Some representative boundary conditions are introduced hereafter.

Throttle plate

Throttle plate is the most important component in this study, for it produces most pumping work in engine system. The pressure loss coefficient f_c through throttle plate can be represented as

$$\frac{\Delta p}{\frac{1}{2}\rho u^2} = f_c \quad (2)$$

If f_c is given by experiments, the pressures at the inlet and exit of throttle can be determined by continuity and energy equations. f_c is a function of flow speed at downstream, area ratio between up- and down-stream, and throttle position. The greater the coefficient is, the smaller is the wave reflection and transmission. For the engine system with adaptive valve timing control system, load is controlled by advancing or delaying the valve opening, closing timing, while throttle boundary condition is not necessary.

Plenum chamber

Plenum chamber is modeled as a series of connection of Y(multi)-junction and three pipes. There are two kinds of model to simulate the multi-junction system. One is a constant pressure model, which assumes the same pressure at every node point which consists of a junction. The other is a pressure loss model, which takes the pressure loss among nodes into consideration. In this study, constant pressure model was used for the ease of application which does not involve experiments to get pressure loss coefficient among junction nodes.

In-cylinder phenomena

Combustion in cylinders is modeled as simple addition of heat as a function of mass burn fraction which is given by Wiebe function, to get rid of the complexity of applying two-zone modeling with chemical dynamics.

Valve lift

It is known that the representative switching time of adaptive valve timing system is 3 msec [2], which corresponds 18 °CA at 1000 RPM, 54 °CA at 3000 RPM, and 90 °CA at 5000 RPM. To open and close the valve needs double the crank angle presented above.

Duration to achieve 10 to 90% effective area opening is around 30 °CA with conventional valve. It can be concluded that the abrupt opening and closing of valve is not possible with present art of technology. It is assumed that just adjustment of valve opening and closing angle are possible with scaled valve schedule. Trapezoidal valve schedule which assumes 10 °CA of linear valve lift to open or close valves and constant valve open lift between them is also tested to preview the effect of further refinement of valve actuating components. Fig. 2 shows each profile of various valve systems.

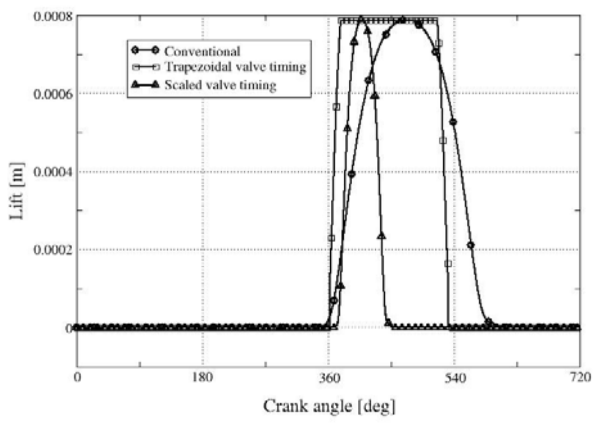


Figure 2. Intake valve profiles

RESULTS AND DISCUSSION

In this study, torque increase at low engine speed, reduction of pumping loss at part load conditions, and reduction of idle speed are investigated with various intake and exhaust valve opening and closing timings, and valve lift profiles (as shown in Fig. 2) as parameters.

Higher ‘low-end torque’

Torque can be increased by eliminating the period during which reverse flow occurs. Fig. 3 shows the mass flowrate change through the intake valve during a cycle. From the Reverse flow is apt to occur at the end of valve schedule at low RPM, and at the beginning of valve schedule at high RPM. Varying either valve opening or closing timing schedule, the flow pattern into cylinder is affected greatly by change of pressure waves traveling among cylinders, and it is laborious to find the valve timing for maximum volumetric efficiency or torque. Only intake valve timings were changed to find it, for the reduction of computation time. Each valve timing was found by trial and error method at which reverse flow was avoided.

The reverse flow at low RPM occurs inevitably to gain the advantage of ram effect at high RPM conditions. By advancing valve closing schedule, the volumetric efficiency or engine torque can be improved under low RPM conditions.

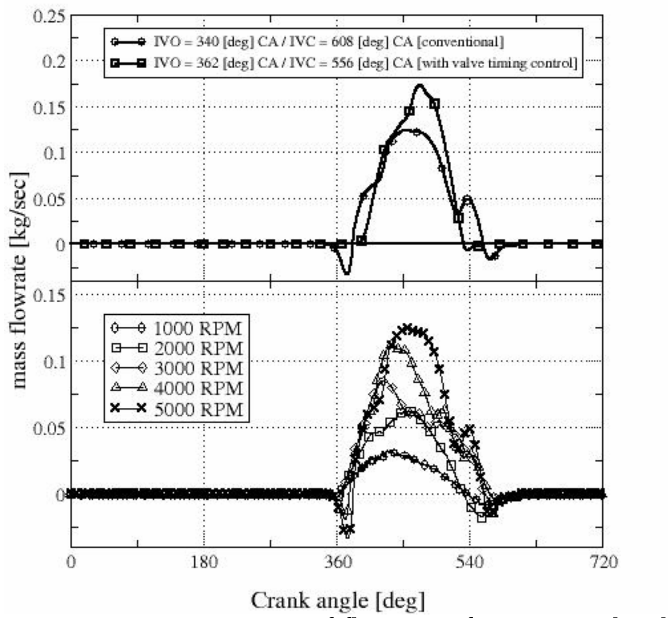


Figure 3. Top : comparison of flowrates of conventional and adaptive valve timing control system through the intake valve
Bottom : Flow through the intake valve of the given engine with conventional valve system at full load

The reverse flow at high RPM is caused by the insufficient time to push out the exhaust gas from cylinder into exhaust manifold. Delaying the intake valve opening timing, it is possible to eliminate this. Intake valve opening angle gets retarded at higher engine rotating speeds, and intake valve closing time gets retarded at lower engine speeds to prohibit the reverse flow.

The valve system of this engine seems to be tuned at 3000 RPM condition, where the reverse flows at both ends are minimum. It was found that the volumetric efficiency at this operating condition is 0.9. The advantage of adaptive valve timing system would be the smallest at this point. The farther the operating RPM from the tuned condition is, the greater is the advantage.

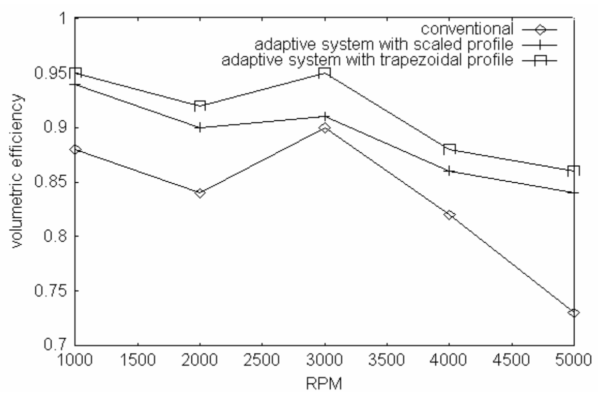


Figure 4. Comparison of torque improvement among valve control technique.

Fig. 4 shows the volumetric efficiency changes along engine speeds for various valve timing and profiles. From Fig. 4, 6 % of maximum volumetric efficiency improvement is achieved at 1000 RPM, and more than 10% of that is predicted at 5000 RPM. This means that the not only 'low-end' but also 'high-end' torque increase by adopting adaptive valve control system.

By applying trapezoidal valve lift to get more area for fluid passage, further improvement could be made. That means refinement of valve actuator can increase the torque of engines.

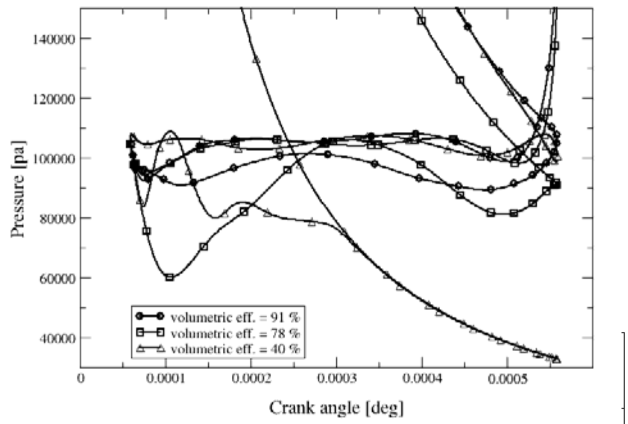
Reduction of pumping work

By controlling the valve opening and closing schedule, adaptive valve timing control system is possible to remove throttle plate which produce most of pumping loss in engine systems. Pumping work during intake stroke can be expressed as an integration of work($P_c dV_c$) between intake valve opening and closing. Without throttle plate, drastic pressure drop in intake manifold was not observed.

Fig. 5 shows P-V diagrams which shows the reduction of pumping work at 3000 RPM with adaptive valve control system. The volumetric efficiency was compared for adaptive valve timing control system with conventional system. The volumetric efficiency was 78 %. The pumping work of adaptive valve timing control system was reduced to around 50 % of that in conventional one.

Figure 5. Comparison of pressure between adaptive valve timing control system and conventional system of pressures where gas exchange occurs – 3000 RPM, 78% volumetric efficiency

Figure 6. Comparison of pressure traces of 1000, 3000, and 5000RPM with the same valve timing, IVO 8° ATDC, IVC 90° ATDC.



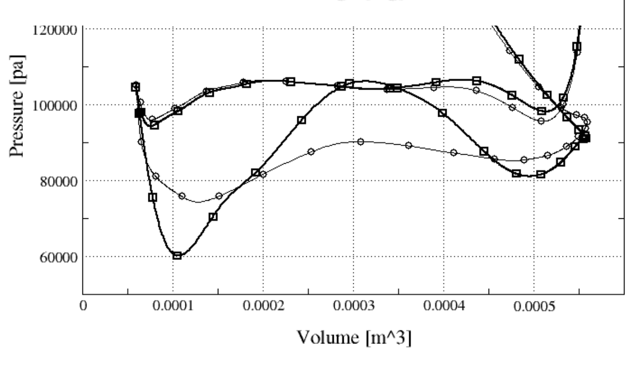
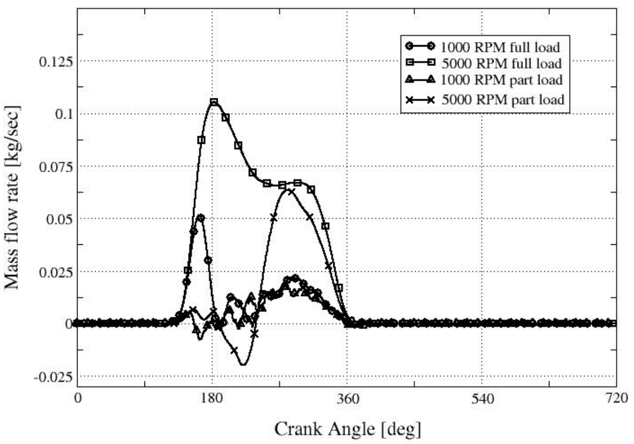


Fig. 6 shows the effect of RPM on the reduction of pumping work in an adaptive valve timing control system. PV diagram in Fig. 7 is plotted to show the effect of



the increase of intake pressure.

Idle speed reduction due to minimal residual gas fraction

As mentioned before, the increase of the amount of burned gas in intake manifold due to reverse flow at the moment of intake valve opening, may cause cycle to cycle, cylinder to cylinder variation. Fig. 8 shows the flowrates through exhaust valve during a cycle. It shows as load goes lower, the reverse flow from exhaust manifold into cylinder is apt to occur. The cylinder pressure at the end of expansion is reduced with decrease of load. Hence, the amount of discharge of exhaust gas during blow-down decreases, and further, the reverse flow occurs as shown in Fig. 8. Most part of exhaust gas is discharged by the stroke of piston.

The reverse flow is apt to occur at low RPM. In Fig. 8, the flowrate is drawn on the base of [kg/sec]. To compare 1000 RPM conditions with 5000 RPM conditions, 5.0 should be multiplied to 1000 RPM data.

Figure 8. Flowrate through exhaust valve vs. load condition : 1000, 3000 RPM

Residual gas fraction can be reduced by delaying EVO at idle condition to the point where no reverse flow occurs, and drivability can be enhanced. The engine idle speed can be reduced by delaying EVO, which reduces the residual gas fraction in cylinders and improves the combustion characteristics at idle condition.

CONCLUSIONS

The possibility of improvement of torque output at lower engine speed, reduction of pumping work at several throttle positions, and reduction of idle speed with the help of adaptive valve timing control systems were verified for an SI engine with an aid of one dimension computational simulation.

1. Engine torque could be increased by adjusting intake valve opening and closing time to stop the reverse flow from cylinder into intake manifold, by about 6 % at 1000 RPM and 10 % at 5000 RPM.

2. Additional improvement of maximum engine torque is expected with development of valve actuators.

3. Pressure fluctuation in intake manifold was affected by alteration of valve opening and closing timing, which changed the optimum points of valve opening and closing time.

4. Pumping loss reduction seemed to be significant with the increase of RPM and decrease of load.

5. Idle speed and combustion characteristics can be enhanced by adopting EVO delay to reduce residual gas fraction in cylinders.

6. Reverse flow is apt to occur under low load, low RPM conditions.

NOMENCLATURE

IVO : Intake Valve Opening crank angle
IVC : Intake Valve Closing crank angle
EVO : Exhaust Valve Opening crank angle
EVC : Exhaust Valve Closing crank angle
CA : Crank Angle
TC : Top Dead Center
BC : Bottom Dead Center
FCT : Flux Corrected Transport
MOC : Method of Characteristics
ρ : density
u : velocity
p : pressure
F : area of pipe
D : diameter of pipe
k : specific heat ratio
q : heat transfer
f : friction coefficient
f_c : pressure loss coefficient

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