

吸気流動計測用 簡易スワール・タンブルメータの開発

Development of a Simple Swirl and Tumble Meter for Measuring Intake Air Motion

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要 旨

燃焼室内でスワールやタンブルを利用して空気と燃料の混合を改善しているエンジンが自動車会社により開発されている。これは薄い混合燃料の燃焼を可能としたり、部分負荷時の排出ガスの再循環 (EGR) 量を増加可能とするために行われている。この技術を駆使することにより燃費が向上され、排気窒素酸化物 (NO_x) 排出が減少する。

本田技術研究所オハイオ研究所は燃費向上が達成でき、また、量産のシビック CX2 バルブ/シリンダ・エンジンと同様の馬力が維持できるようなエンジンの研究開発に取り組んでいる。このプロジェクトチームは燃費向上デバイスとして EGR を使用することを決定したが、そのためには EGR 量を更に増加することができるシステムが要求される。というのは、EGR 使用時に燃焼が不安定となり、ドライバビリティが悪化することから量産では可能な EGR 量が決まってしまうためである。この問題対策として、シリンダヘッドの吸気口を変更することにより EGR 量に与えるスワールとタンブルの影響を研究した。形の異なる吸気口でのスワールとタンブル比率の評価を行うため、プロジェクトチームは単純で低コストのスワール/タンブルメータを設計した。

この論文はプロジェクトチームがその目標である「馬力の損失なく燃費の向上を図る」を達成するため、どのようにこのスワール/タンブルメータを使用したのかを述べている。このスワール/タンブルメータにより実施された分析例によれば、燃焼不安定による運転性能問題が生じることなく EGR 量を増加することが可能である。また、馬力を維持することも可能である。

ABSTRACT

Automobile companies are developing engines with swirl and tumble motion of the air/fuel in the combustion chamber to increase the ability of burning a leaner fuel mixture and increase the amount of exhaust gas recirculation (EGR) at partial load. Using this technology, fuel economy can be improved and exhaust NO_x emissions reduced.

Honda Research and Development North America, Inc. Ohio Center was working on an engine development project to increase fuel economy and maintain the same power of a mass production Civic CX2 valve/cylinder engine. The project team decided to use EGR to improve fuel economy. This required an increase in the ability to add more EGR, because with the production engine only a limited amount of EGR could be added without driveability problems due to combustion instability. To countermeasure this, we studied the effect of both swirl and tumble on EGR by modifying the cylinder head intake port. The team designed a simple, low-cost swirl and tumble meter to evaluate the swirl and tumble flow rates of different shaped ports.

This paper demonstrates how the swirl and tumble meters were used to meet the project teams goals: improve fuel economy with no power loss. Examples of the analysis performed using the swirl and tumble meter show that it was possible to increase the EGR without driveability problems due to combustion instability and still maintain the same power.

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1. INTRODUCTION

1.1. Background

The motion of the air in the combustion chamber of a reciprocating engine can influence the engine's performance significantly. The swirl or tumble motion during combustion can be used to determine engine power, improve partial load fuel economy and reduce exhaust NOx emissions. By adjusting the intake air motion we can make improvements

that are less complex and costly when compared to other alternatives in engine design layout. Fig. 1 shows the swirl and tumble motion in the cylinder.

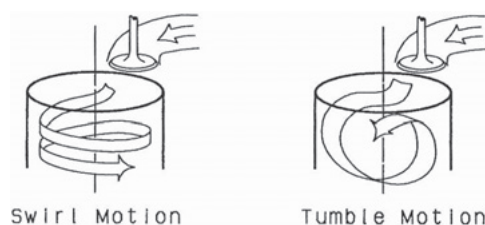


Fig. 1 Swirl and tumble motion in the cylinder

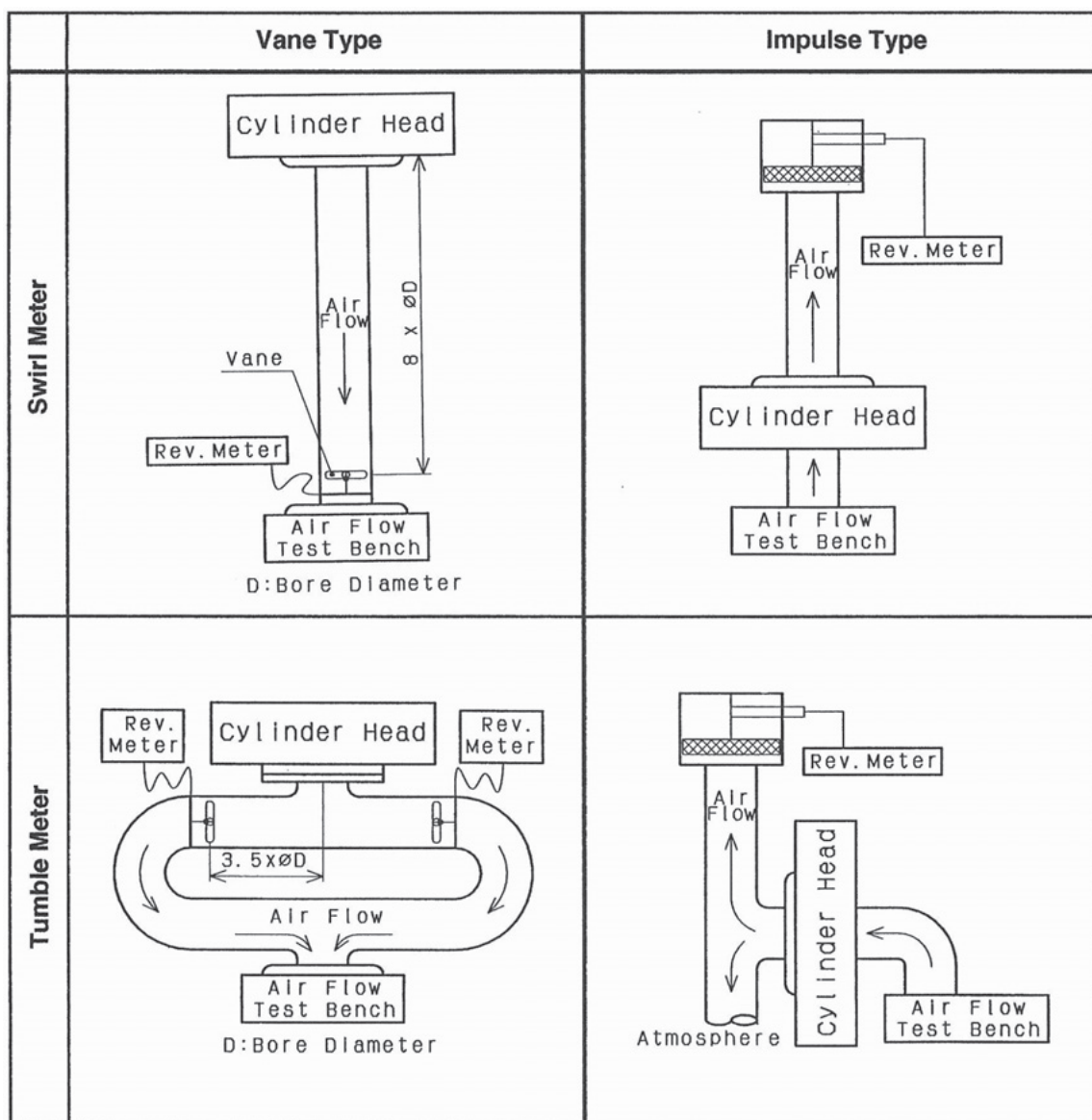


Fig. 2 Vane and impulse swirl/tumble meter layout

1.2. Swirl and Tumble Meter Background

To evaluate the swirl and tumble flow rates between different shaped ports, a measuring device was needed. The swirl meter used for this project is similar to early versions, using a vane located in a tube below the combustion chamber. The tumble meter was a unique design utilizing two vanes perpendicular to the cylinder head, which could be rotated 360 degrees to determine the highest degree of tumble. These methods were used to measure swirl and tumble ratio at Honda Research and Development North America, Inc. Ohio Center (HRA-O). Fig. 2 shows the vane and impulse style swirl and tumble meters.

1.3. Impulse meter vs. HRA-O's vane meter background

There are many methods used to measure swirl and tumble. Here only two are compared, the Vane and the Impulse swirl/tumble meter.

The vane swirl meter uses a small rectangular paddle wheel with a maximum clearance of 3 mm from the cylinder wall. The vane is mounted on a low friction encoder at a distance of $(8.0) \times$ (bore diameter) below the combustion chamber. The air is drawn from the bottom of the meter at three steady flow settings: 300 mmHg, 400 mmHg and 500 mmHg pressure.

This design has been superseded by the impulse swirl meter that consists of a honeycombed matrix that arrest all swirl so that the torque reaction is measured as a total angular momentum flux ¹⁾. The air is pushed through the intake port at one constant steady flow rate. This is considered to be a more accurate method of measurement than the vane swirl meter ¹⁾.

HRA-O's design for the tumble meter was somewhat unique in that it utilized 2 small rectangular paddle wheels located on opposite sides and perpendicular to the combustion chamber. These were mounted $(3.5) \times$ (bore diameter) from the center line of the combustion chamber. The

cylinder head was able to rotate 360 degrees in order to find the maximum tumble rate. The air is drawn from the bottom of the meter at three steady flow settings of 300 mmHg, 400 mmHg and 500 mmHg pressure.

The impulse type tumble meter design is similar to the vane, but only uses one impulse meter mounted on the side of the tube rather than the top. The air is pushed through the intake port at one constant steady flow rate as with the swirl meter design.

The main merits of the HRA-O meters are the simple design, low cost and its ability to determine relative differences in swirl and tumble. These meters can be used during initial development of an engine to optimize macro swirl and tumble characteristics.

2. OBJECTIVE

The following objectives were defined at the beginning of this project: develop an original HRA-O swirl/tumble air flow test rig and test method.

2.1. Swirl Meter

HRA-O developed its own vane type swirl meter. The body of the meter is constructed with clear polyvinyl chloride (PVC) tubing and plate. The vane is located $(8.0) \times$ (bore diameter) below the combustion chamber with a maximum blade clearance of 3 mm from the cylinder wall. The PVC tube is the same diameter as the combustion chamber. The HRA-O meter utilized an airflow test bench that pulled air from the bottom of the meter through the intake port. Fig. 3 shows how the distance of $(8.0) \times$ (bore diameter) was chosen to avoid vane speed fluctuations and to limit the maximum vane speed. The test conditions involved changing the location of the vane then taking steady flow measurements at intervals of 300 mmHg, 400 mmHg and 500 mmHg pressure with the intake

valve lift openings set in 1 mm increments ranging up to 10 mm.

2.2. Tumble Meter

HRA-O developed its own tumble meter constructed of PVC tubing using 2 vane swirl meters located perpendicular to the cylinder head and $(3.5) \times$ (bore diameter) from the center line of the combustion chamber. The cylinder head can be rotated 360 degrees with relation to the paddle wheels so that the highest tumble rate can be measured. The effect of the head rotation on the tumble ratio is shown in Fig. 4. It can be seen that after rotating 180 degrees the same tendencies are repeated from 180 degrees to 360 degrees. The HRA-O meter utilized a flow bench that pulled air from the intake port through the bottom of the meter. Steady flow measurements were taken at intervals of 300 mmHg, 400 mmHg and 500 mmHg

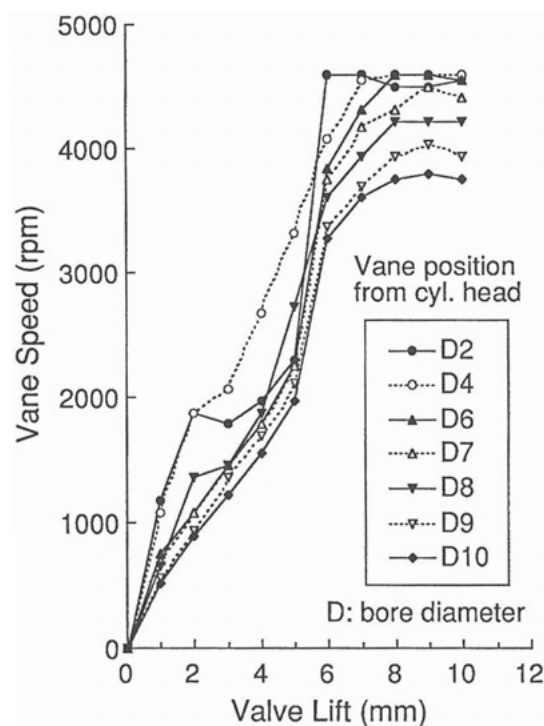


Fig. 3 Characteristics of vane height on impeller speed

pressure. The intake valve lift openings were set in 1 mm increments ranging up to 10 mm. The layout of the vane tumble meter can be seen in Fig. 2.

After designing the swirl and tumble meter, it was necessary to develop a testing method. To simulate an actual reciprocating engine as closely as possible, it was decided to measure the swirl and tumble at different valve lifts and different air flow rates. An airflow test bench was used to measure the pressure differential from the intake port past the valve at 300 mmHg, 400 mmHg and 500 mmHg pressure. The efficiency ratio was calculated to

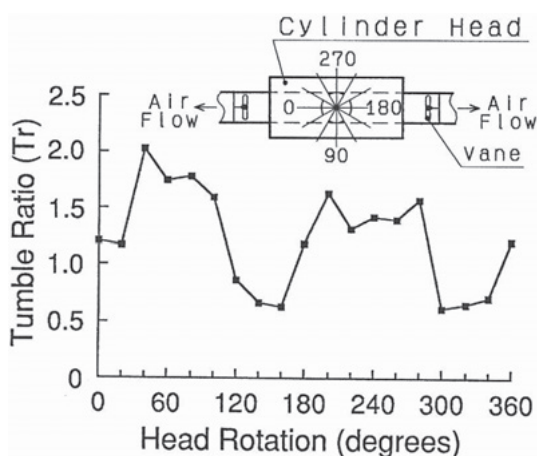


Fig. 4 Characteristics of head rotation vs. Pressure differential

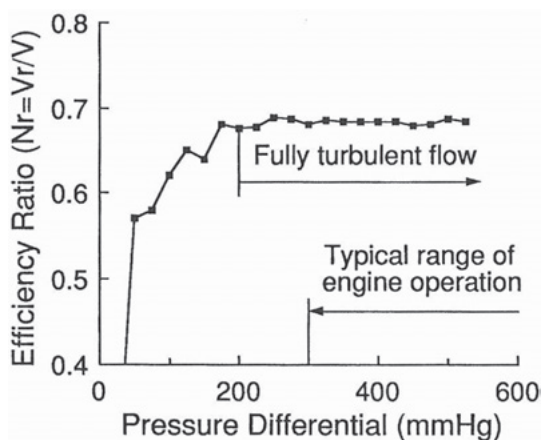


Fig. 5 Characteristics of swirl efficiency vs. pressure differential

determine fully turbulent flow and was found above 200 mmHg pressure which can be seen in Fig. 5. These conditions are considered to be a typical range of engine operation and are also used during port flow testing¹⁾. At each 1 mm increment of valve lift swirl and tumble measurements were taken. Then these values were used to acquire our swirl and tumble coefficient. After calculating these coefficients for each valve lift and each flow rate, the average was taken and input into an integration program. The area under the curve of the swirl/tumble ratio vs. valve lift was calculated based on crank angle.

This result gives the final swirl or tumble ratio for a given port shape

3. INSTRUMENTATION AND METHODS

3.1. Swirl Coefficient (Cs) Equation

$$Cs = W_p \cdot B / V_o$$

W_p : angular velocity
of swirl meter vane
 B : cylinder bore diameter
 V_o : velocity of inlet air

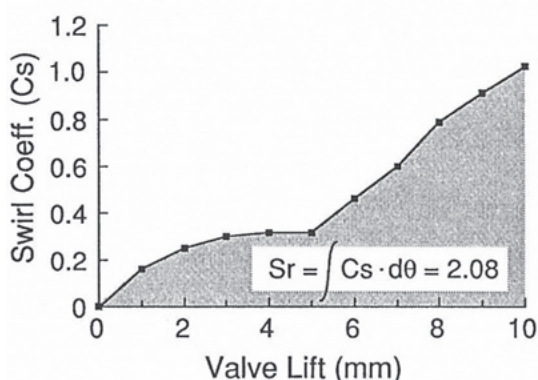
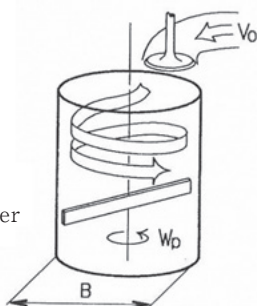


Fig. 6 Base swirl coefficient showing the area under the curve

Example:

Valve lift = 5 mm

Valve diameter = 29 mm

Cylinder bore diameter(B) = 75 mm

P atm = 300 mmHg

Steady flow(Q) = 22.2 (l/s)

Impeller speed(Np) = 31.5 rev/sec

$W_p = 2\pi \cdot N_p(\text{rad/sec}) = 198 \text{ rad/sec}$

$V_o = Q(1000)/(\text{valve dia})\pi(\text{valve lift})$

$= (22.2 \text{ l/s})(1000 \text{ cm}^3/\text{liter})/(2.9 \text{ cm})\pi(.5 \text{ cm})$

$= 4873 \text{ cm/sec}$

$Cs = W_p \cdot B / V_o = 0.304 \text{ at } 300 \text{ mmHg}$

0.313 at 400 mmHg

+0.328 at 500 mmHg

total/3 = 0.315 average swirl
coefficient

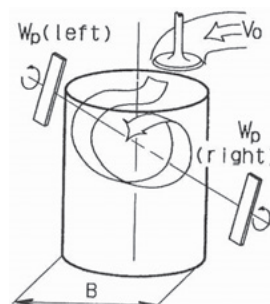
Swirl Ratio(Sr) Equation

$Sr = \int Cs \cdot d\theta$ = the area under the curve of Cs vs. valve lift based on crank angle. Fig. 6 shows this calculated area under the curve.

3.2. Tumble Coefficient (Ct) Equation

$$Ct = W_p \cdot B / V_o$$

W_p : angular velocity
of tumble meter
vanes
 B : cylinder bore
diameter
 V_o : velocity of inlet
air



Example

Valve lift = 5 mm

Valve diameter = 29 mm

Cylinder bore diameter(B) = 75 mm

P atm = 300 mmHg

Steady flow(Q) = 23.3 l/s

Right impeller speed(Np) = 41.4 rev/sec

$$\begin{aligned}
 \text{Left impeller speed}(N_p) &= 16.4 \text{ rev/sec} \\
 W_p &= 27 \pi \cdot N_p(\text{rad/sec})(\text{left}) + 2 \pi \cdot N_p(\text{rad/sec})(\text{right}) \\
 &= 363.2 \text{ rad/sec} \\
 V_o &= Q(1000)/(\text{valve dia}) \pi (\text{valve lift}) \\
 &= (23.3 \text{ l/s})(1000 \text{ cm}^3/\text{liter})/(2.9 \text{ cm}) \pi (.5 \text{ cm}) \\
 &= 5114.9 \text{ cm/sec} \\
 C_t &= W_p \cdot B/V_o = 0.533 \text{ at } 300 \text{ mmHg} \\
 &\quad 0.525 \text{ at } 400 \text{ mmHg} \\
 &\quad +0.537 \text{ at } 500 \text{ mmHg} \\
 &\quad \text{total}/3 = 0.531 \text{ average swirl} \\
 &\quad \text{coefficient}
 \end{aligned}$$

Tumble Ratio(Tr) Equation

$$\text{Tr} = \int C_t \cdot d\theta = \text{the area under the curve of } C_t \text{ vs. valve lift based on crank angle. Fig. 7 shows this calculated area under the curve.}$$

4. RESULTS

4.1. Meter Sensitivity

Although the HRA-O vane swirl meter is a simple design, we were interested in the sensitivity and accuracy of the meter when the port angle and location were adjusted. The meter sensitivity was tested using a straight port capable of adjusting the angle and port location as shown in Fig. 8. The results showed that a small angle and a location closest to the cylinder wall gave the highest swirl reading. By moving the port to the middle and

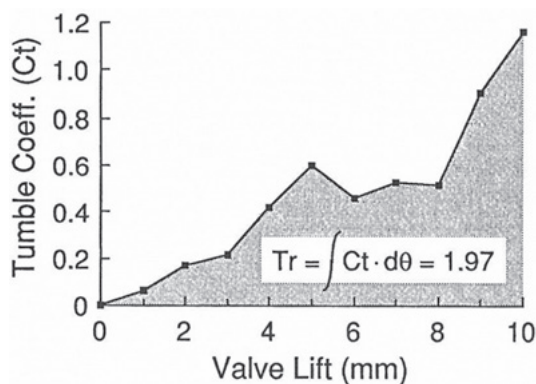


Fig. 7 Base tumble coefficient showing the area under the curve

increasing the angle to 90 degrees it showed a significant drop in swirl rate. The meter can detect a small change in port angle and location. This indicates the meter has some degree of sensitivity. Fig. 9 indicates that port location has a relatively greater effect on swirl ratio than does port angle. Also, it is clear that a port location close to the cylinder wall having a small angle has the best swirl potential.

To check the amount of fluctuation in the range of our testing we used a meter with a straight port directed at the vane impeller. This test rig can be seen in Fig. 10. Beginning at a low velocity airflow and increasing to a high velocity, an acceptable level of vane fluctuation was found above 900 cm/sec. Fig. 11 is the change in efficiency ratio with increasing air velocity. The testing conducted at

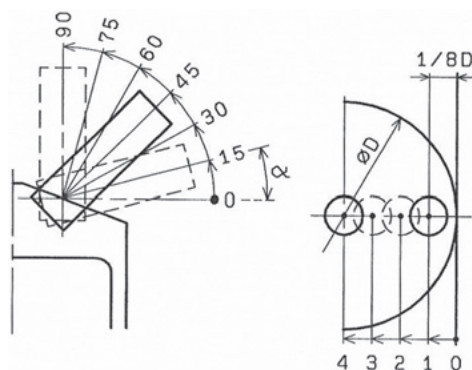


Fig. 8 Straight port with adjustable angle and location

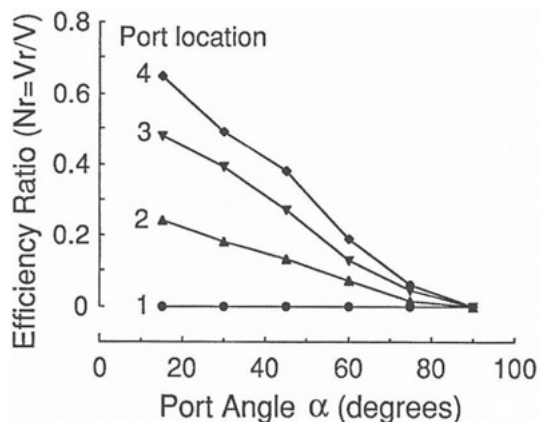


Fig. 9 Swirl meter efficiency by changing the port angle and the location

Table 1 Swirl/tumble ratio results with best ISFC/EGR%

	Port Type	Swirl Ratio	Tumble Ratio	Best ISFC/EGR%
Base	Civic CX (P09)	1.77	1.73	123.1 g/kWh/4%
No. 1	High swirl/High tumble	2.00	2.11	121.9/6%
No. 2	Low swirl/High tumble	1.43	1.95	122.2/7%
No. 3	High swirl/Low tumble	1.88	1.69	120.2/8%

HRA-O used an air flow above 900 cm/sec. So from this test we can assume no impeller fluctuation in the air flow range of our testing.

4.2. Engine Development Using HRA-O Designed Meters

Using these meters a mass production Civic CX 2 valve/cylinder engine was modified. The project team used the base head port and removed metal, then modified the shape by using clay. Once a promising port shape with good swirl and tumble characteristics was developed, a silicone model was cast. This silicone model was then measured and translated into 3D data points so that a plastic port

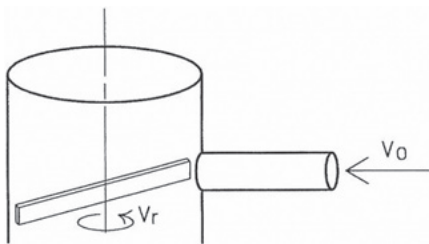


Fig. 10 Straight port testing

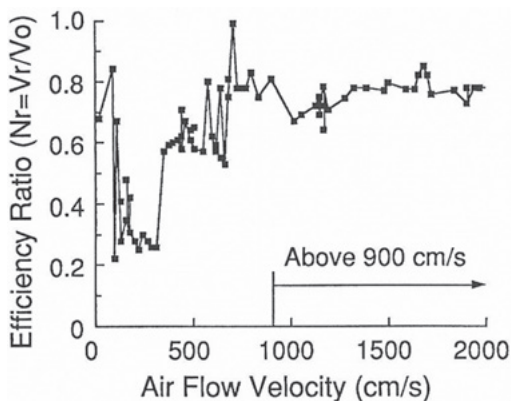


Fig. 11 Efficiency ratio vs. air flow velocity

Table 2 Power/fuel economy result

	base	Final Results
Ps max kW/rpm	51/5000	51/5000
T max N · m/rpm	124/2000	123/2000
FE* City/Hwy mpg	42/48	44/52

FE* test condition : FTP mode

model could be fabricated. The plastic port model was then retested to confirm the shape and then a prototype head was cast. This prototype head was then tested on the dynamometer to confirm EGR could be increased as well as indicated specific fuel consumption (ISFC), power, etc. Below are listed 3 types of port shapes that were tested and compared with the base port shape. Table 1 shows No.3 high swirl/low tumble port was capable of increased EGR amounts without driveability problems due to combustion instability, and fuel economy results were good.

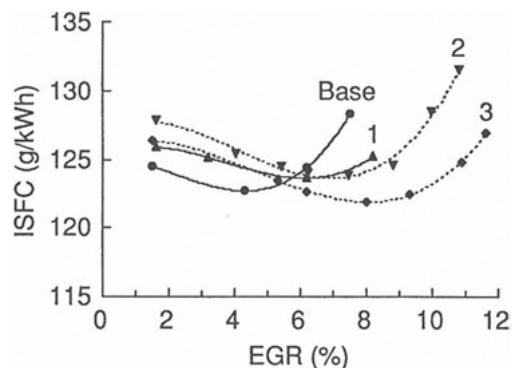


Fig. 12 Specific fuel consumption vs. EGR rate (%)

By using this development method we were able to create a port shape with a high swirl ratio and a low tumble ratio. **Table 2** and **Fig. 12** show the combination of high swirl/low tumble for this particular engine layout which was able to handle increased EGR amounts improve fuel economy while maintaining the original power characteristics.

5. CONCLUSION

HRA-O's swirl and tumble measurement method may be applicable to early development where simple testing equipment can be used to determine the gross airflow characteristics of a particular port design. Further research is necessary to determine if small differences in swirl/tumble can be detected using this test equipment.

ACKNOWLEDGMENTS

The authors would like to recognize the efforts of the following individuals from HRA-O: Mr. Dennis Graham was responsible for all the dynamometer engine testing; Mr. Chris Cox was responsible for port modeling and vehicle Exhaust Emission testing; Mr. Ken Lantz was responsible for the 3D CATIA modeling of the port and the illustrations; Mr. Tim Harris was responsible for measuring the silicone model.

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- 1) "Swirl and Tumble Test on a Honda Cylinder Head"; South West Research Institute Proposal No. EVR-1263, Engine. 1993.

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