

Development of Deviceless Tumble Enhancement Method for Small Motorcycles

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ABSTRACT

Using the CFD and targeting at small motorcycles, we have pursued a technology that can enhance the tumble flow in the cylinder only in a low load range of the engine without the need to use any intake path switching mechanisms. In a throttle body with a butterfly valve, a reverse flow occurs after the intake air has passed the throttle valve when the throttle valve opening is small. We have confirmed that installing a flow separator behind the throttle valve that vertically divides the intake port flow can successfully capture the reverse flow into one of the two flow paths. Furthermore, we confirmed that optimizing the separator position can capture most of the intake air into one path, thereby gaining the required amount of flow that can generate tumble in the combustion chamber. Through the analysis of combustion pressure of an actual engine, we have confirmed that the combustion period in the low load range is shorter in the new design than in the conventional port design, which proves that the target tumble effect has been achieved. With the new design applied, the emission norms of EURO5 and India's BS-VI are satisfied as well as improving the fuel economy of the motorcycle by 1.7% in the WMTC mode. For mass production, the separator is created as an integral part of the inlet pipe casting by incorporating a slit in the port core. This enables application of the new tumble port design without adding extra parts or modifying existing production equipment.

1. Introduction

In recent years, as a means to prevent global warming, reducing CO₂ is increasingly required across most industrial sectors. For the mobility sector, achieving better fuel economy is something that is now urgently needed. Therefore, in order to enhance combustion under the condition of a high exhaust-gas recirculation level or in the use of lean air-fuel ratios, such techniques that can enhance the circulation of intake air in the cylinder are being widely studied. With this, the generation of tumble in the cylinder is effective, as a method to enhance circulation of the intake air. Thus far, a tumble enhancement by optimizing the intake port configuration has been widely studied and practically implemented^{(1), (2)}. Akimoto et al. and Nakayama et al. have developed a technique to enhance tumble by implementing a partition inside the intake port and adding a flow path switching mechanism, which has in turn been applied to practical use on passenger vehicles^{(3), (4)}.

However, to use such a method on a small and

inexpensive motorcycle, the addition of exclusive parts for the flow path switching system and associated control system would lead to the issue of implementation and also have a cost impact. To solve these issues, Shirasuna et al. invented a method to enhance tumble by offsetting the inlet valve in the perimeter direction of the cylinder bore⁽⁵⁾. With this method, when the inlet valve lift is low, a part of the opening is masked by the cylinder wall. As this increases the flow towards the exhaust port, it can enhance tumbling.

However, as this method enhances tumble not only in a low load operating condition for practical use of an engine but also in high load conditions, applying it to a small motorcycle leads to the issue of increased noise due to the resulting rapid combustion. As the engine is exposed on most small motorcycles, such noise is easily transmitted to the motorcycle rider. Furthermore, the use of ball bearings to support the crankshaft is a negative factor in terms of noise generation. As such, there are certain limits in increasing the level of tumble.

In this study, we aimed to establish a technology that

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would be useful for small motorcycles to enhance tumble only within a low load range of an engine without using any intake path switching mechanisms. We used computational fluid dynamics (CFD) to analyze the flow around the throttle valve and we discovered that a reverse flow occurs in the port when the throttle opening is low. Also, we found that installing a flow separator in the port can effectively capture part of the reverse flow into one of the divided flow paths. By making use of this phenomenon in the actual intake port of an engine, we established a technology that can enhance tumble only within a low load range of the engine without using any intake path switching mechanisms.

Furthermore, in an attempt to apply the new design to the mass production, the design of core molding die splitting has been modified to create a slit, which serves as a separator, in the intake port core. Accordingly established is the technique that creates the separator as an integral part of the intake port casting without adding extra parts or modifying the existing production equipment.

2. Target Setting

Before conducting this study, we established target values to be achieved based on experimental and CFD analysis results.

2.1. Test Engine and Designation of Tumble Reinforcement Zone

We used an engine of a small scooter for this experiment. Table 1 shows the major specifications of the test engine. Figure 1 shows the cross section of the intake path of said test engine. The butterfly type throttle valve opens clockwise as can be seen in this figure. The fuel injector is placed at the outer periphery portion of the U-shaped inlet pipe.

In order to determine the engine speed and the throttle opening range that would be effective for improving fuel economy, we used a specific WMTC mode to investigate the frequency distribution of engine speed and throttle opening. Figure 2 shows the frequency distribution map. Besides the idling state, the engine is generally operated with a throttle opening of 30% or less. In particular, we can see that an engine speed of around 4,000 rpm and a throttle opening of 15% to 30% are most frequently used. From the above results, we determined that tumble should be enhanced for the throttle opening range of 15% to 30%.

2.2. Setting of Target Tumble Ratio

To set the target tumble ratio, we conducted a number of experiments using a tumble control valve (TCV) system, which can arbitrarily adjust the tumble ratio according to the throttle opening. The tumble ratio characteristics at various throttle openings was assessed by conducting steady flow tests. The definition of tumble ratio and the steady flow test method are as per the reference literature by Shirasuna et al.⁽⁵⁾.

Table 1 Vehicle and engine specifications

Engine type	Forced air cooled, 4-stroke, single-cylinder, gasoline engine
Bore × Stroke [mm]	50.0 × 63.1
Displacement [cm ³]	124.9
Compression ratio	10
Valve diameter [mm × number]	Intake: $\Phi 25.5 \times 1$ Exhaust: $\Phi 21 \times 1$
Valve lift [mm]	Intake: 6.3; Exhaust: 6.2
Ignition system	Full transistorized
Fuel system	Fuel injection
Throttle bore diameter [mm]	$\Phi 22$
Maximum power [kW/rpm]	6.1/6500
Maximum torque [Nm/rpm]	10.3/5000
Transmission	CVT
Vehicle dry weight [kg]	107
WMTC mode	Class 1

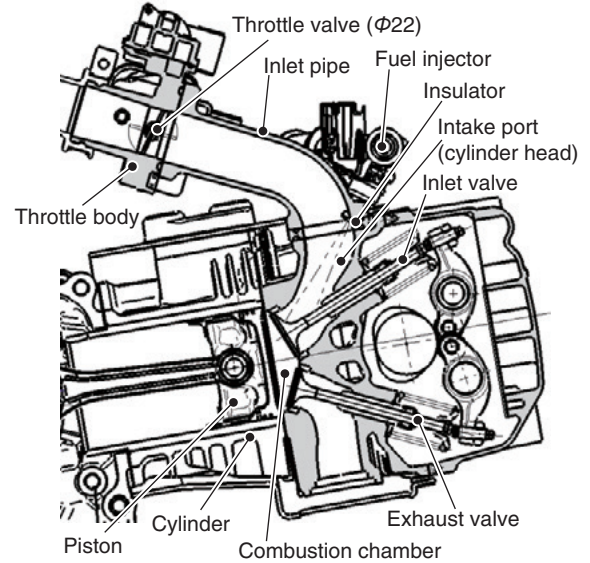


Fig. 1 Section of test engine (conventional port)

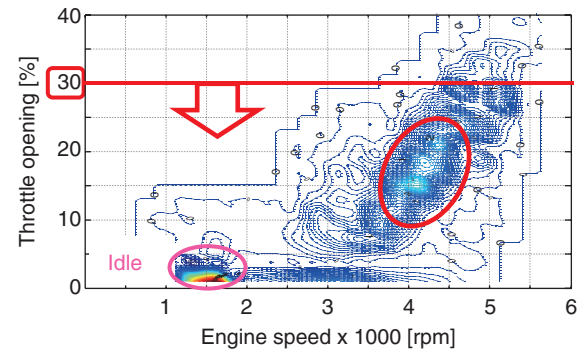


Fig. 2 Distribution of throttle opening and engine speed in WMTC mode

Figure 3 shows a cross section of the tumble port with TCV when the engine is low loaded. We then placed a separator wall for the port downstream of the inlet pipe to divide it into two ports, i.e., a partially open throttle (POT) port for low loading and a wide-open throttle (WOT) port for high loading of the engine. The cross-sectional area of both ports at the port entrance is the same.

Here, we set the throttle valve to open in the counterclockwise direction in the figure to help prevent TCV from interfering with the separator wall when the throttle valve is wide open. The air flow that has passed the throttle valve opening on the WOT port side is forced to change direction by TCV and enter the POT port. As a result, the flow ratio of the POT port increases with respect to the total flow out of the throttle valve. The POT port exit is suitably shaped to increase the directivity of the flow into the exhaust valve side, and also to ease its separation from the wall (refer to circled area in the enlarged view in Fig. 3).

2.2.1. Setting of upper/lower limits of tumble ratio

Figure 4 shows the relationship between the tumble ratio at the throttle opening of 25% and the improvement ratio of brake specific fuel consumption (BSFC) at brake mean effective pressure (BMEP) of 250 kPa. Here, we used an engine speed of 4,000 rpm and a stoichiometric air-to-fuel ratio of 14.7 as measurement conditions. We determined the ignition timing according to the minimum spark advance for best torque (MBT) condition. As the tumble ratio increases, the combustion speed increases and thus the degree of constant volume increases to improve BSFC. As can be seen, when the tumble ratio becomes 1.5 or more, the improvement ratio of BSFC is saturated. From the results, we selected 1.5 as the target value for the lower limit tumble ratio.

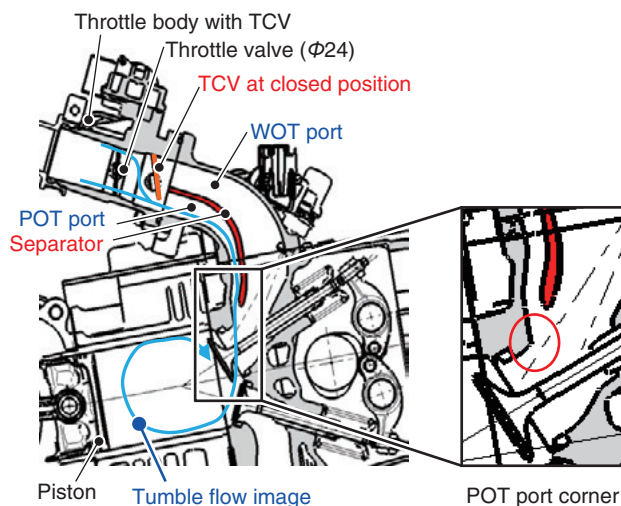


Fig. 3 Tumble port with TCV and detail of POT port exit

Then, we evaluated the effect of the tumble ratio on engine noise through sensory evaluation by experts. In doing this, we used a throttle opening of 25%. As the tumble ratio increases, combustion speed increases, while the rate of pressure increase ($dP/d\theta$) in the cylinder also increases. Accordingly, engine noise due to clearance at the crankshaft bearings increases. It can be seen that a tumble ratio of 2.0 or less is acceptable in terms of engine noise generation. From the results, we selected 2.0 to be the target value of the upper limit tumble ratio.

Figure 5 shows the tumble ratio characteristics when a conventional intake port is used. We can see that the tumble ratio is less than 1.5 for a throttle opening of up to 30% and that it is nearly constant between 1.6 and 1.7 when the throttle opening is 30% or wider.

The red box in the figure shows the target range of the tumble ratio and the throttle opening, as determined from test results previously mentioned.

2.2.2. Target flow ratio of POT port

We used CFD to analyze the air flow in the tumble port with TCV. For this CFD analysis, we modeled the port

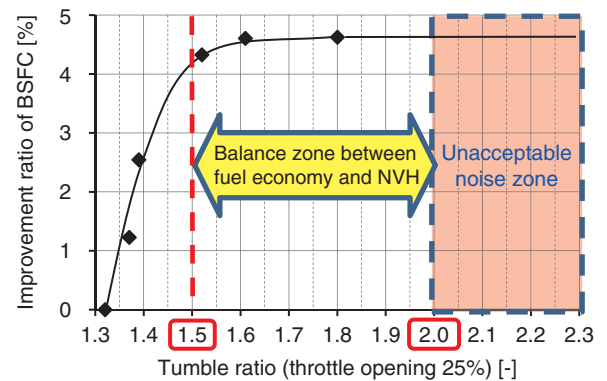


Fig. 4 Relationship between improvement ratio of BSFC, evaluation of engine noise, and tumble ratio

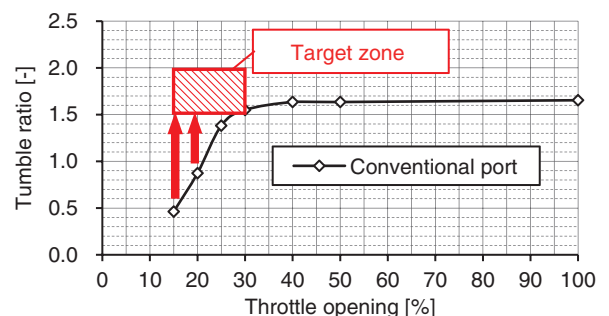


Fig. 5 Tumble ratio characteristics and target zone

configuration based on the method of Ricardo plc. Figure 6 shows the CFD analysis model and the analysis conditions. The details of analysis are as per the reference literature of Shirasuna et al⁽⁵⁾. We used a throttle valve opening of 15%, at which the tumble ratio needs to be improved the most.

We investigated the flow ratio RQ_{POT} of the POT port that can achieve the desired lower limit tumble ratio of 1.5. The flow ratio RQ_{POT} is defined by:

$$RQ_{POT} = \frac{Q_{POT}}{Q_{ALL}} \times 100$$

RQ_{POT} : Flow ratio of POT port [%]

Q_{POT} : Volumetric flow into POT port [m³/s]

Q_{ALL} : Total volumetric flow into cylinder [m³/s]

Figure 7 shows the relationship between the flow ratio of the POT port RQ_{POT} and the resulting tumble ratio when the TCV opening is varied with the throttle valve opening fixed at 15%. From the analysis results, we found that the flow ratio of the POT port RQ_{POT} needs to be 83% or higher in order to obtain the targeted minimum tumble ratio of 1.5.

2.2.3. Target of effective port opening at full load

In order to achieve the same power as that of the

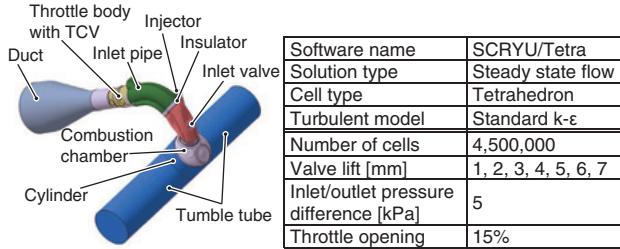


Fig. 6 Model of tumble port with TCV and analysis condition

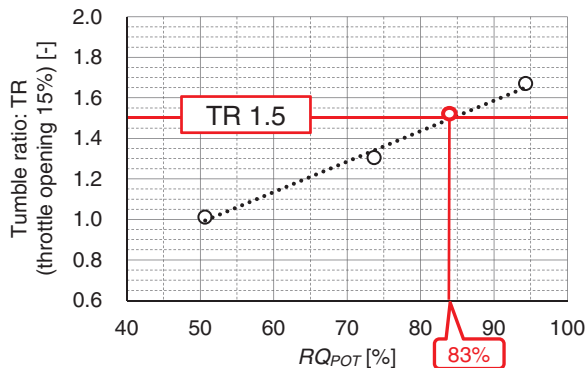


Fig. 7 Relationship between RQ_{POT} and tumble ratio

conventional engine, we used a Z curve (effective port opening area vs. inlet valve lifts) with a target value equivalent to that of the conventional port.

Based on the experimental results for the tumble port with TCV, we determined the target parameters for the tumble port system without TCV to be as follows:

- (1) In the CFD analysis, a POT port flow ratio RQ_{POT} of 83% or higher is to be achieved at a throttle opening of 15%;
- (2) In an actual steady flow test, a tumble ratio of 1.5 to 2.0 is to be achieved for the throttle opening range of 15% to 30%; and
- (3) In a full throttle steady flow test of the port, an effective opening area equivalent to that of the conventional engine is to be achieved.

3. Tumble Enhancement without Using TCV

To find a method that can enhance tumble without using TCV, we first analyzed the basic characteristics of the air flow that is generated downstream of the throttle valve.

3.1. Flow Analysis (CFD)

3.1.1. Straight pipe analysis model

Figure 8 shows a general view of the analysis model. In this straight pipe flow analysis, we used the same flow path configuration as that used in an actual throttle body. To model the downstream of the throttle body, we used a simple straight pipe with no bends, with a length equivalent to that measured from the inlet pipe to the intake port exit at the cylinder head of an actual unit. Figure 9 shows an enlarged view around the throttle valve. We used a butterfly type throttle valve with a throttle bore diameter of 22 mm. In the figure, the valve turns clockwise to open. In this clause, the throttle valve edge that opens towards the upstream is called “leading edge,” while the one that opens towards the downstream is called “trailing edge.”

3.1.2. Results of straight pipe analysis

Like the previous chapter, we assumed a throttle opening

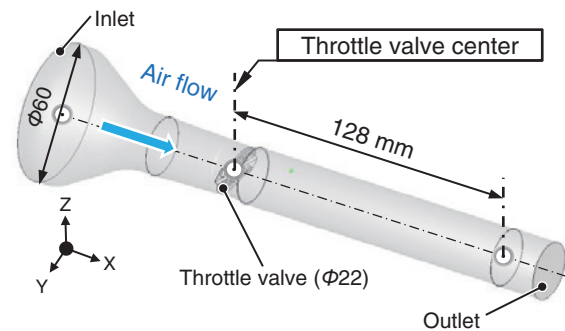


Fig. 8 CFD model for straight port

of 15%, with an inlet/outlet pressure difference of 5 kPa for the CFD analysis. Figure 10 shows the analysis results in the form of flow lines and flow velocity downstream of the throttle valve. The contour of the flow line in the analysis result indicates flow velocity. The white arrow mark shows mainstream flow.

The figures (a) to (c) in Fig. 10 that show the flow lines are from three view directions as described below:

- (a) Upper view along the Z-axis to show flow lines that have passed the throttle opening on the trailing edge side only
- (b) Side view of the flow path as seen from the Y-axis to show flow lines that have passed the throttle opening on both trailing edge and leading edge sides
- (c) Bottom view along the Z-axis to show flow lines that have passed the throttle opening on the leading edge side only

The specific characteristics of the flow, as observed in these figures, are summarized below.

As shown in (a), the central flow that has passed the trailing edge opening moves straight in the upper part of the pipe in Z direction. The edge flow (IIB) that passes both

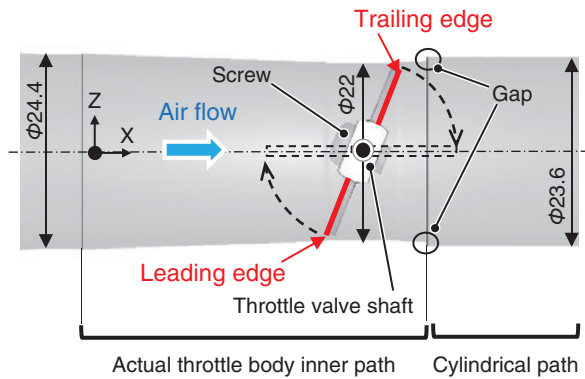


Fig. 9 Detail of throttle valve

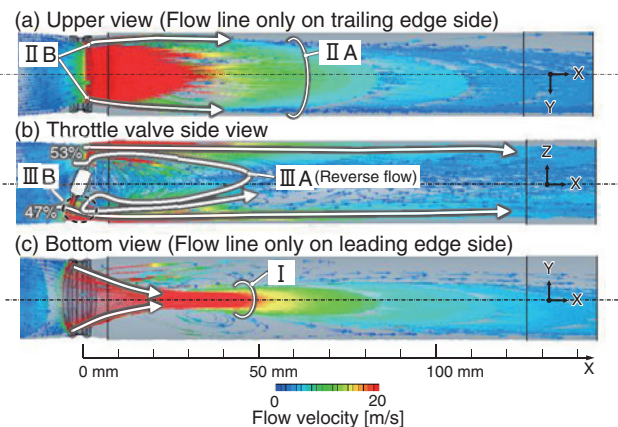


Fig. 10 Flow line for straight port on each side view

ends of the opening flows in the direction in that the flow diffuses in the Y-axis direction while moving toward the lower stream along the cylindrical surface (IIA). It can be seen that the end flow is slower than the central flow, and slower than the flow velocity of the flow that has converged on the leading edge side as (c) shows.

As shown in (b), it can be seen that the total flow into the leading edge and trailing edge openings is almost evenly divided into 47% and 53%, respectively. Also, part of the air from the trailing edge generates some reverse flow towards behind the throttle valve (IIIA).

As shown in (c), the flow on the leading edge side converges towards the center of the pipe (I). That is because the end flow that passes on both ends of the opening flows toward the lower end in Z direction along the cylindrical surface, and merges with the central flow although the central flow in the leading edge side moves straight.

3.1.3. Reverse flow on trailing edge side

The reasons of the reverse flow are discussed hereafter.

Figure 11 shows the pressure distribution on an X-Z section in Fig. 8 downstream of the throttle valve. From the pressure distribution, we can see some low-pressure area (1) behind the throttle valve. We can also see some local low-pressure areas (2) immediately behind both openings.

At first, the slow edge flow on the trailing edge side is pulled back by the low pressure (1), and generates a reverse flow (IIIA) as Fig. 10 shows. Then, the reverse flow (IIIA) is further pulled by the local low-pressure zone (2) on the leading edge side and is guided towards behind the throttle valve (Fig. 10 IIIB). After that, it merges with the converging flow that comes from the leading edge opening towards downstream (Fig. 10 IIIB). The finally merged flow is then separated from the tube surface and flows downstream towards the center of the pipe.

3.1.4. Analysis model of straight pipe with separator

In relation to the results in the previous clause, we focused our attention on the fact that the reverse flow generated on the trailing edge side merges with the mainstream flow on the leading edge side (Figs. 10 and

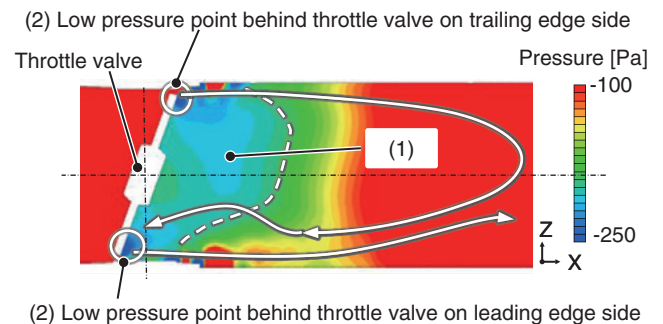


Fig. 11 Distribution of static pressure and aperture flow

11). We thought that installing a separator wall on the leading edge side to form a POT port might be able to capture the reverse flow on the trailing edge side, and would increase RQ_{POT} . Figure 12 shows the analysis model. Based on the straight pipe model discussed in the previous clause, we added a separator in the pipe to be parallel to the throttle valve shaft and the pipe centerline. For application to the test engine, we set the separator length at 120 mm, from 8 mm up to 128 mm downstream of the throttle valve. By means of the separator, we can form simulated POT and WOT ports. In order to evaluate any possible changes due only to the additional separator from the analysis results

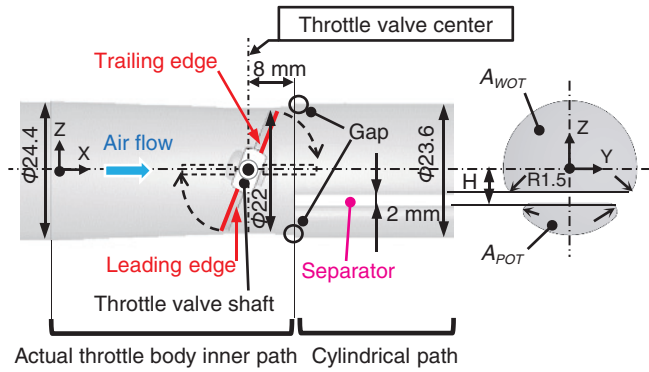


Fig. 12 Detail of throttle valve and separator plate

discussed in the previous clause, we used the same cylinder diameter as the one without a separator. Also, we had the model not change the cross-section areas of the POT and WOT ports along the downstream path before merging the ports near the exit. Considering application to mass production, we chose the thickness of the separator to be 2 mm, which is a typical value used in casting. Regarding the corners formed in installing the separator, we used a curve of 1.5 mm radius to connect the surfaces in order to help avoid adverse effects on the analysis.

3.1.5. Relationship between cross-section area ratio and flow ratio of POT port

Firstly, we investigated the relationship between the cross-section area ratio and the flow ratio of the POT port. The cross-section area ratio of the POT port RA_{POT} is defined as follows:

$$RA_{POT} = \frac{A_{POT}}{A_{POT} + A_{WOT}} \times 100$$

RA_{POT} : Cross-section area ratio of POT port [%]

A_{POT} : Cross-section area of POT port [m²]

A_{WOT} : Cross-section area of WOT port [m²]

We modified RA_{POT} by changing the height H of the separator. We used a throttle valve opening of 15%.

Figure 13 shows the analysis results for different values

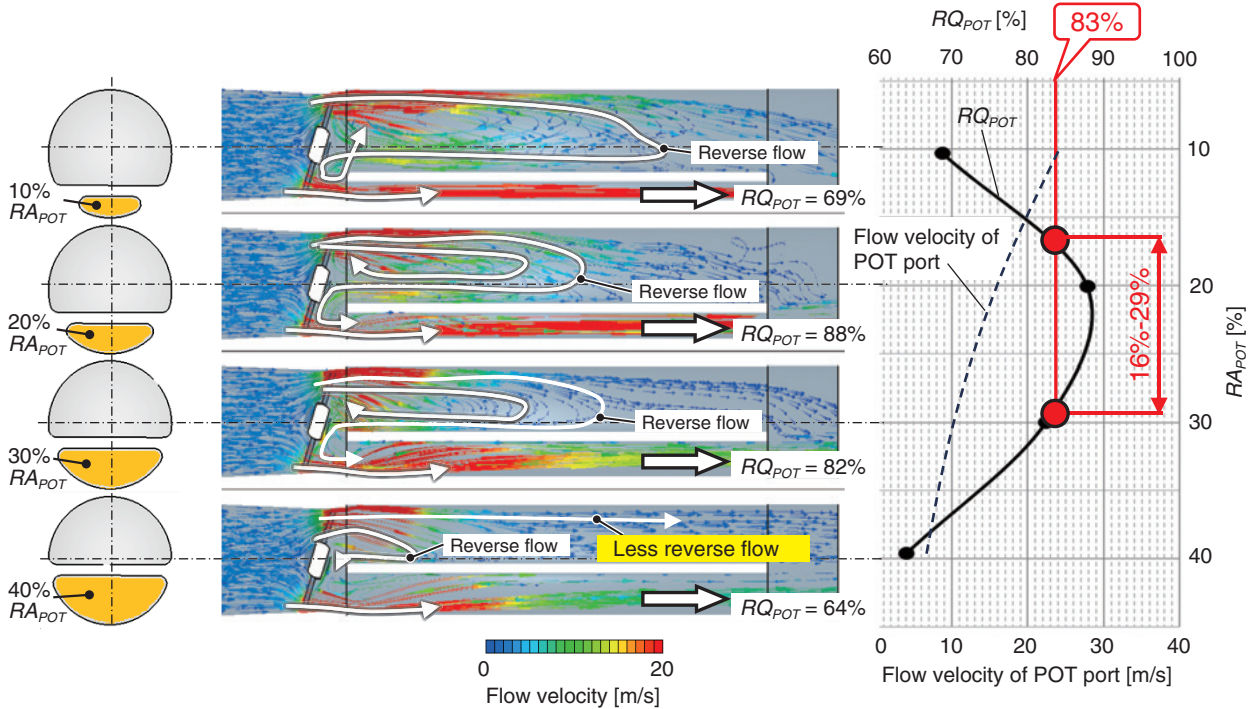


Fig. 13 Result of CFD analysis for straight pipe with each RA_{POT} (throttle opening: 15%)

of RA_{POT} . In the analysis results, the colored contour of the flow lines shows the flow velocity, while the large white arrows show mainstream flows. The graph on the right side shows the value of RQ_{POT} and average flow velocity at the POT port exit for various RA_{POT} values. Shown to the left of the analysis results are the cross-sectional shapes of the pipes.

From the analysis results, we found for every cross-section area ratio that:

1. The flow ratio of each opening to the total flow of the throttle valve was 47% for the leading edge opening and 53% for trailing edge opening. We observed no difference due to the existence of the separator.
2. The reverse flow generated on the trailing edge side is guided by the separator wall to be behind the throttle valve and then flows into the POT port.
3. For all RA_{POT} values, RQ_{POT} has increased from the flow ratio of 47% of the leading edge opening.

Next, we will explain the relationship between RA_{POT} and RQ_{POT} using the graph to the right of Fig. 13.

The RQ_{POT} value of 83% or more is achieved for the port area ratio RA_{POT} of 16% to 29%. RQ_{POT} peaks when RA_{POT} is 20%.

The targeted RQ_{POT} value is not reached when RA_{POT} is 10% and 40%. The reason for this is outlined below.

For RA_{POT} of 10%, RQ_{POT} is 69%. As the POT port opening area A_{POT} nears the opening area of the throttle valve, its ratio to the throttle valve opening area increases. Then, the amount of flow that can enter the POT port becomes limited compared to other cases (RA_{POT} of 20%, 30%, and 40%). In spite of a lot of reverse flow lines, they tend to merge with the trailing edge flow instead of merging with the POT port flow on the leading edge side.

When RA_{POT} is 40%, RQ_{POT} decreases to 64%. Due to the limited space to generate reverse flow on the WOT port side, the amount of reverse flow decreases. As a result, the downstream flow on the trailing edge side increases, while the reverse flow is suppressed.

From the above results, we found that it is important to have a POT port area that is sufficient for the merged flow to fully enter the port, and also to provide enough space to help ensure reverse flow generation.

Accordingly, we selected 20% for RA_{POT} to help ensure a sufficiently high POT port flow ratio RQ_{POT} and a high flow velocity in the POT port for the detailed flow analysis that is described in the next clause.

3.1.6. Effect of separator on capturing reverse flow into POT port

Figure 14 shows the flow analysis results for RA_{POT} of 20%. The large white arrow shows the mainstream flow. Figure 15 shows the pressure distribution analysis results on an X-Z section. From these analysis results, it can be seen as follows.

The converging flow (I) on the leading edge side and the

diffusing flow (IIA, IIB) on the trailing edge side as seen in Fig. 10 are similarly generated.

The diffusing flow on the trailing edge side generates some reverse flow due to the low-pressure region (1) in Fig. 15 (Fig. 14, IIIA). The reverse flow is guided by the separator wall to be behind the throttle valve.

Following that, the reverse flow is pulled by the local low-pressure zone (2) and divided into two flows (Fig. 14, IV).

The flow attracted by the negative pressure on the leading edge side enters the POT port (Fig. 14, V).

The flow IV described above merges with the converging flow that has passed the leading edge opening (Fig. 14, V).

As a result, RQ_{POT} reaches 88%.

From the above results, we can conclude that most of the intake flow can be collected in the POT port formed by the separator wall.

Next, we investigated the relationship between the POT port flow ratio and the throttle opening. With an RA_{POT} of 20%, we varied only the throttle opening to observe results.

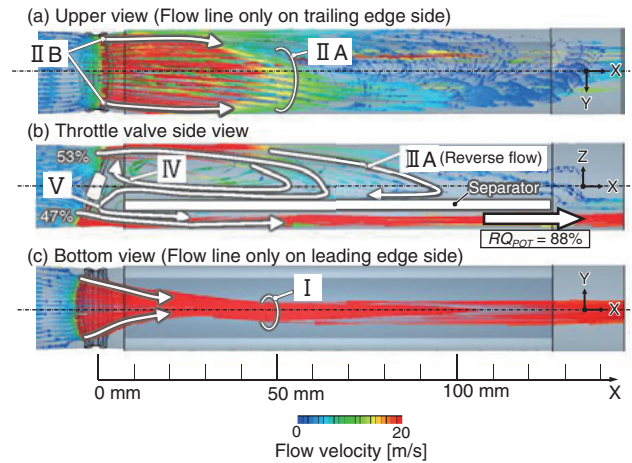


Fig. 14 Flow line for straight port with separator plate

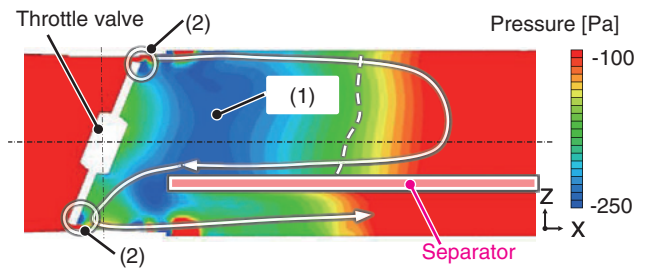


Fig. 15 Distribution of static pressure with separator plate

Figure 16 shows RQ_{POT} , total volumetric flow through the throttle valve (Q_{ALL}), volumetric flow on the leading edge side (Q_{LEAD}) and volumetric flow in the POT port (Q_{POT}) for different throttle opening values. As the throttle opening increases, Q_{ALL} increases quadratically, while Q_{POT} increases gradually compared to Q_{ALL} . As a result, RQ_{POT} becomes lower as the throttle opening increases.

From the above, we came up with the idea that increasing RQ_{POT} could enhance tumble at a throttle opening range up to 30%.

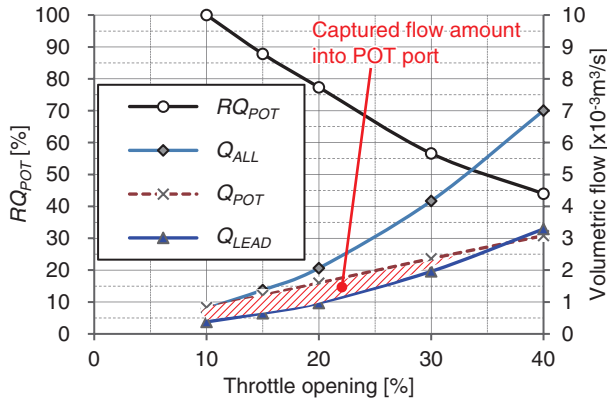


Fig. 16 RQ_{POT} , Q_{ALL} , Q_{POT} , and Q_{LEAD} vs. throttle opening

4. Effectiveness Verification in Actual Port Configuration

We checked whether the phenomenon of reverse flow capture in the POT port by installing a separator could be reproduced in an actual port configuration or not.

4.1. Analysis Model Having Actual Port Shape

Figure 17 shows a cross section of the tumble port without TCV. By setting RA_{POT} to 20%, in accordance with the straight pipe CFD analysis discussed earlier, we divided the inlet pipe into POT and WOT ports using a separator wall. The shape of the POT port exit is the same as that of the tumble port with TCV. The cross-section area of the POT port from entrance to exit at the cylinder head remains virtually unchanged. The diameter of the throttle valve is 22 mm, while the center position of the throttle valve shaft and the direction of valve rotation are the same as those of the original test engine.

4.2. Flow Analysis in Actual Port Shape

Figure 18 shows a flow analysis result of the tumble port without TCV. The flow out of the upper opening of

the throttle valve is shown in blue and the flow out of the lower opening is shown in red. Note that the flow shown in the figure is one when the inlet valve lift is 6 mm. From the analysis results, we can see that a merging of the reverse flow generated on the WOT port side with the leading edge flow is reproduced even with a curved port configuration downstream of the throttle valve. Furthermore, the flow ratio of the POT port RQ_{POT} is 91%, which is higher than

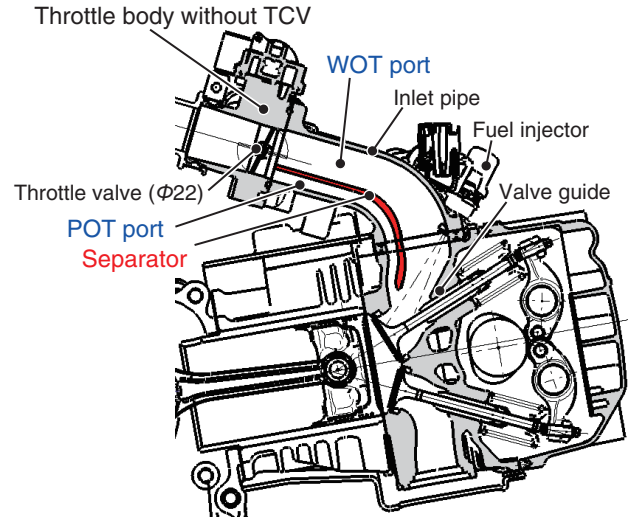


Fig. 17 Tumble port without TCV

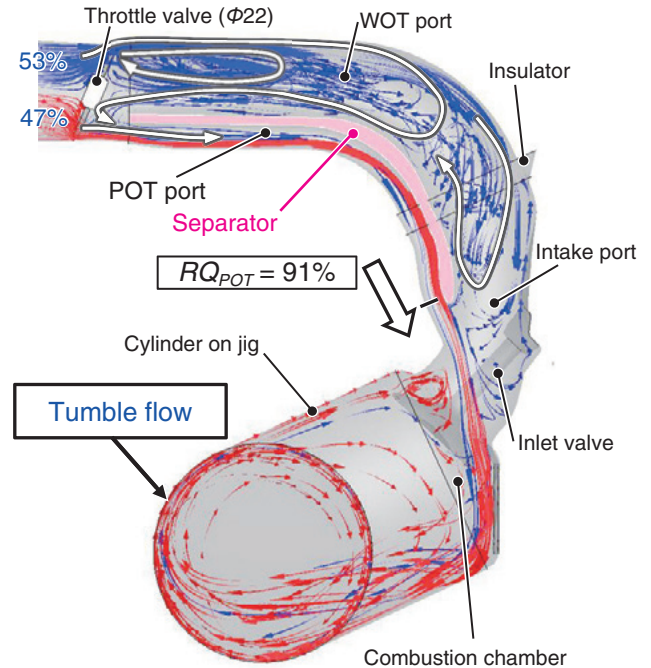


Fig. 18 Result of CFD analysis for flow of tumble port without TCV (throttle opening: 15%)

the 88% of the straight pipe, as shown in Fig. 14. This is considered due to the existence of the valve guide, which increases the ventilation resistance of the WOT port and increases the flow on the POT port side. Furthermore, we can see tumble generation by the intake air in the cylinder.

From the above results, we confirmed that the tumble port without TCV in an actual port configuration can also capture the reverse flow in the POT port to improve the POT port flow ratio RQ_{POT} .

As the RQ_{POT} value of 91% obtained without TCV exceeded the target value of 83% shown in Fig. 7, we felt that the targeted lower limit tumble ratio of 1.5 was achievable. However, as shown in Fig. 5, the tumble ratio of a conventional port increases as the throttle opening increases from 15% to 30%. Considering this effect, we surmised that the tumble ratio could exceed the upper limit of 2.0 with the tumble port without TCV in the above throttle opening range.

To reduce the RQ_{POT} value, we thought that moving the separator away from the throttle valve could reduce the amount of reverse flow capture. Therefore, we conducted a CFD analysis to determine the amount of shortening in the separator and found that a 10 mm contraction can reduce RQ_{POT} to 83%⁽⁶⁾.

Figure 19 shows a cross section of the tumble port without TCV when the separator is shortened along with the analysis results.

From the above results, we conclude that the target tumble ratio characteristics are achievable in the tumble port without the TCV.

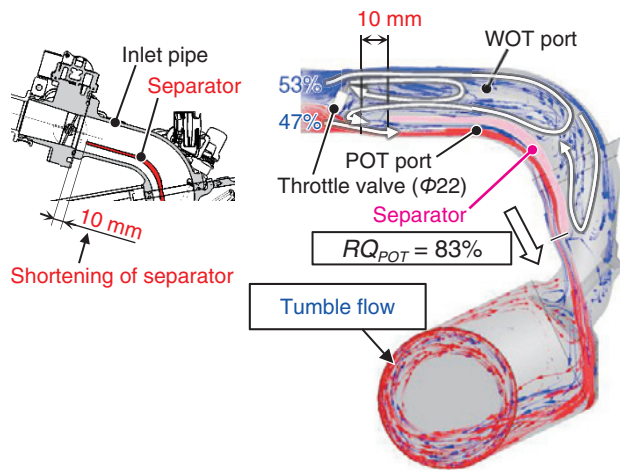


Fig. 19 Result of CFD analysis for flow of tumble port without TCV using short separator (throttle opening: 15%)

5. Verification Tests with Actual Unit

Described hereafter are the results of tests using actual engine.

5.1. Tumble Ratio Measurement

Figure 20 shows the tumble ratio measurement results. In the tumble port without the TCV, the measured tumble ratio at a throttle opening of 15% meets the targeted minimum value of 1.5. Also, at a throttle opening of 20% and 25%, the measured tumble ratio of 1.8 and 1.9, respectively, do not exceed the targeted upper limit value of 2.0. From these results, it was confirmed that a tumble port without TCV can achieve the targeted tumble ratio.

5.2. Verification of Improved Fuel Consumption at Lower Limit Tumble Ratio of 1.5

Figure 21 shows BSFC measurements of an engine unit made at BMEP of 250 kPa (equivalent to a throttle opening of about 15%) using a conventional intake port, a tumble port with TCV, and a tumble port without TCV. For the tumble port with TCV, we adjusted the TCV opening to set the tumble ratio to the lower-limit target of 1.5. For measurement conditions, we used an engine speed of

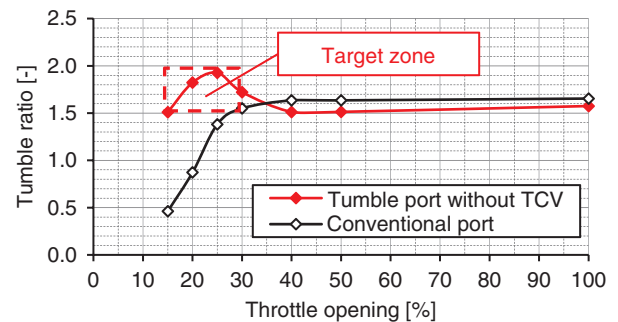


Fig. 20 Characteristic of tumble ratio

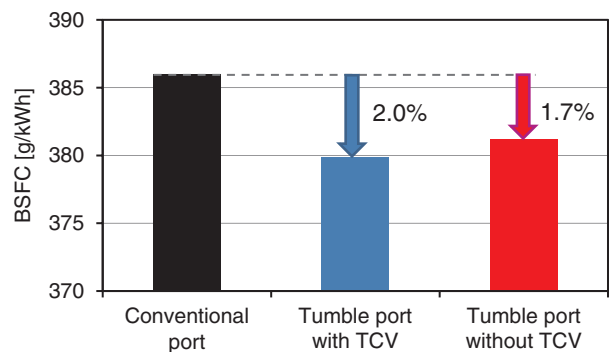


Fig. 21 BSFC results at BMEP of 250 kPa

4,000 rpm, a stoichiometric air-to-fuel ratio of 14.7, and an ignition timing of MBT for all types of port. The BSFC values of the tumble port with TCV and tumble port without TCV were improved by 2.0% and 1.7% from that of a conventional port, respectively. From the above results, we confirmed that increasing the tumble ratio to 1.5 or higher can effectively improve fuel consumption.

5.3. Verification of Engine Noise at Upper-limit Tumble Ratio of 2.0

Figure 22 shows the results of sensory evaluation for engine noise. Although both tumble ports are rated lower than a conventional port with a throttle opening of up to 30%, it is still within an acceptable range. At the fully loaded (WOT) condition, it is rated “very good” for all three ports. This is considered because the tumble ratio in a fully loaded condition is about the same as that of the conventional port as Fig. 20 shows.

From the above results, we conclude that the targeted maximum tumble ratio of 2.0 in low load range satisfies our in-house noise assessment criteria.

5.4. Verification of Effective Port Opening Area

Figure 23 shows the Z characteristics obtained from steady flow measurements at various inlet valve lifts. We

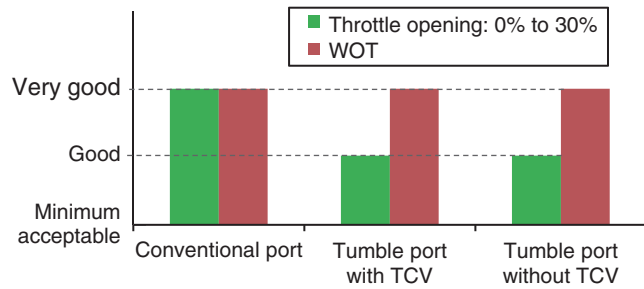


Fig. 22 Crank-noise evaluation (in-house standards)

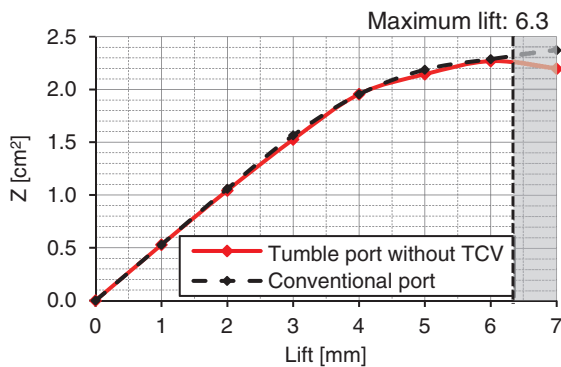


Fig. 23 Characteristics of effective opening area

found that the effective opening area Z of the tumble port without TCV is equivalent to that of a conventional port for the valve lift range of 1 mm to 6 mm. We also noted that the effective opening area Z starts to decrease after the lift exceeds 6 mm. The reason we supposed was that the flow out of the POT port collided with the flow from the WOT port, generated some vortex, causing a reduction in the effective opening area at the valve seat. The maximum lift of the inlet valve of the engine tested is 6.3 mm. Therefore, in terms of practical use, the Z characteristics of this port are equivalent to that of a conventional port.

5.5. Verification by Combustion Pressure Measurement

We verified the degree of constant volume, the initial combustion period (IG-MFB 10%), and the main combustion period (MFB 10%-90%) at various loads in the tumble port without TCV and in the conventional port. Figures 24-26 show the results at an engine speed of 4,000 rpm, A/F of 14.7 and the ignition timing at MBT.

The test results indicate that in the tumble port without TCV, the combustion period is shorter in the low loads, and about the same level in the high loads when compared to

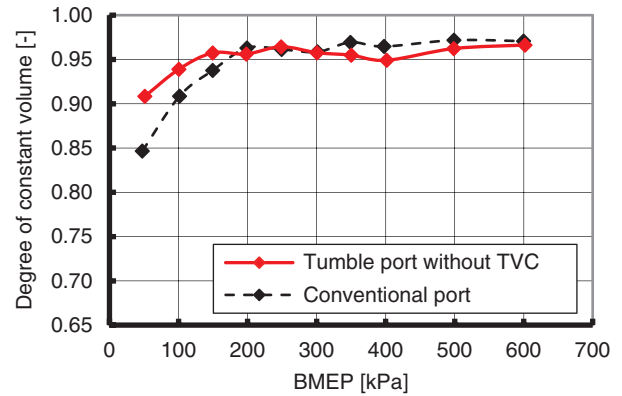


Fig. 24 Characteristics of degree of constant volume

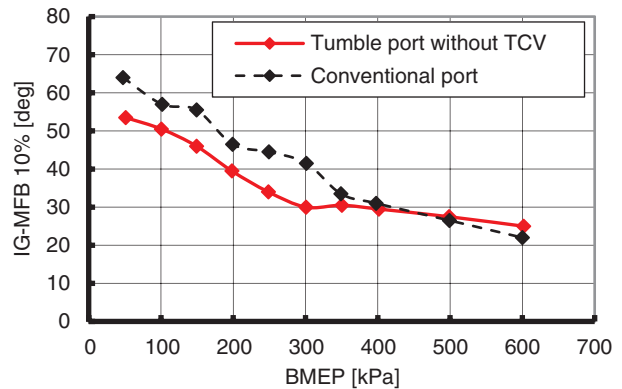


Fig. 25 Relationship between IG-MFB 10% and BMEP

Table 2 Improvement rate of fuel economy compared to conventional port

WMTC Class 1	Idle-stop on	Idle-stop off
Tumble port without TCV	+1.7%	+1.8%
Ref. Tumble port with TCV	+2.0%	+1.7%

Table 3 Results of emission measurements

EURO5/India's BS-VI WMTC Class 1	CO [mg/km]	THC [mg/km]	NOx [mg/km]
Emission regulations	1000	100	60
Tumble port without TCV	293	34	11
Conventional port	274	54	12
Ref. Tumble port with TCV	268	34	16

the conventional port, which proves that the target tumble effect has been achieved.

5.6. Verification in Complete Motorcycle

The fuel consumption in the WMTC mode and the exhaust emissions were measured from the complete motorcycle. Tables 2 and 3 show the results respectively. In the WMTC mode, a reduction of fuel consumption by 1.7% when using the idle stop system, and 1.8% when not are seen. The exhaust emissions are also compatible with the EURO5 and India's BS-VI, which is comparable to the conventional port.

From the above results, we have confirmed that the tumble is enhanced only in the low load range, contributing to a reduction of fuel consumption by 1.7% in the WMTC mode while meeting the EURO5 and India's BS-VI norms. The effective port opening area and the engine noise area are at the same level as in the conventional engine.

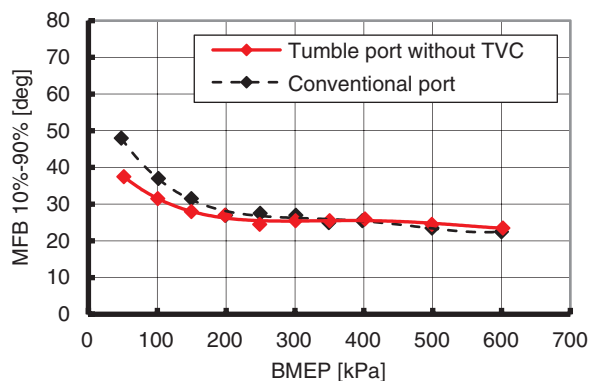


Fig. 26 Relationship between MFB 10%-90% and BMEP

6. Manufacturing of Tumble Port with Separator

Examples of practical applications of the tumble port with a separator wall to the mass production are seen in the fields of automobiles such as the one having a separate flat plate inserted in the port and another one having a flat plate cast together⁽³⁾. However, such methods are inapplicable to small motorcycles due to the restrictions from the curvature of the intake port as well as from the standpoint of cost. In addition, there is an issue in the use of existing production equipment. We have therefore set a target at establishment of a casting method that allows casting of the separator wall as an integral part of the inlet port without modifying the existing production equipment.

6.1. Construction of Port Core Molding Die

An option for integral casting of the separator is to separately mold cores for WOT and POT ports, and bond them together. In that case, two sets of dies are required for core molding. An increase of man hours for bonding of cores and lowering of dimension preciseness from misalignment are conceivable issues.

Our solution is to change the core molding die construction from the conventional horizontal split to the vertical split so that the WOT and POT ports can be created in a single molding operation. The separator wall is formed as a slit in the core. Figure 27 shows the conventional port and the tumble port with a separator. The dotted lines in the picture indicate the parting line of the core molding die. The arrow mark shows the direction of die split.

In the port core, there is a depression in the proximity of the valve guide as in Fig. 28. Such a depression does

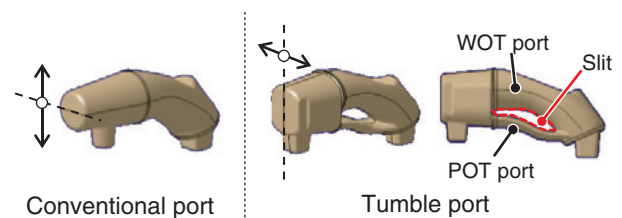


Fig. 27 Core shape of conventional port and tumble port



Fig. 28 Place of depression in valve guide

not allow vertical splitting of the die. To deal with this issue, the slide core has been added to form the valve guide depression. Figure 29 shows image pictures of the core molding.

The pictures indicate cross sections when die is closed, when the core sand is filled, and when die is opened. The construction is such that the angular pin held in the fixed die serves as a guide when the movable die opens and closes to move the sliding core up and down. The direction of sliding core movement is vertical while the movable die travels horizontally.

6.2. Verification of Manufacturability

We analyzed moldability of the tumble port core and castability of the cylinder head under the general processing conditions. The sand core is made of the resin-coated sand (RCS) in which the sand grains are coated with the phenolic resin as a binder at a rate of 1.4 wt.%.

Figure 30 shows the specifications of RCS and the molded tumble port core.

It has been confirmed that there is no detriment in the POT port of the core.

Figure 31 shows the cut separator wall in the cylinder head after undergoing a dye penetrant test.

It has been confirmed that there is no issue in the fillability of aluminum, and the cast product is free of internal casting detriment.

6.3. Removal of Sand Core

An incomplete removal of the sand core in the casting process may cause an increase of inspection in the latter

process, causing an increase of cost. General decoring methods are the hammering, which breaks the core by applying vibrations or the baking which heats the sand core in a heat treatment furnace⁽⁷⁾. Although the baking is an effective way of decoring, there are issues such as heat deformation of the cast product, the need of extra equipment, time, and energy⁽⁷⁾. It is therefore necessary to completely remove sand in the decoring process. Figure 32 shows the production processes. The decoring comes after the casting, and then the cast product is transferred to the heat treatment.

As there is a small-diameter POT port in the tumble port system unlike in the conventional port, we checked if there was any issue in the decoring of tumble port core. The decoring was verified using the existing hammering machine.

6.3.1. Sand removal by hammering

Figure 33 shows an overview of the hammering machine. It can be observed that the core sand in the port is taken out by the vibrating impacts from the hammer.

The following tests were conducted to determine optimum hammering conditions. The oscillation acceleration and the sand removal rate at various air

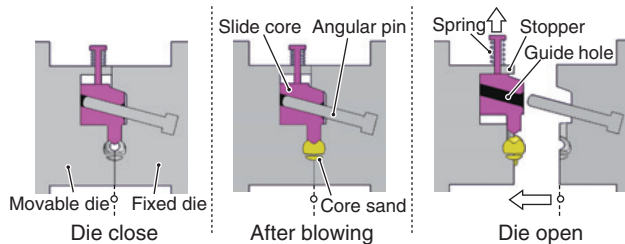


Fig. 29 Schematic diagram of tumble port core mold

Resin [wt.%]	1.4
Bending strength	405
Melting point [°C]	102
Grain size [AFS]	69

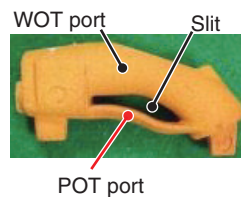


Fig. 30 Specification of RCS and appearance of tumble port core

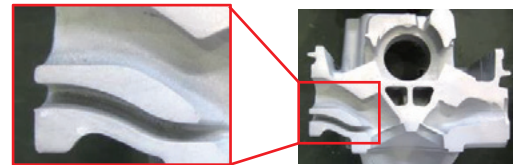


Fig. 31 Fillability and internal quality (dye penetrant test)

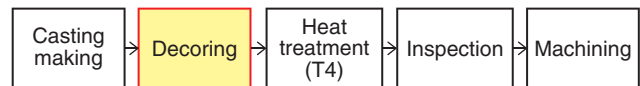


Fig. 32 Process chart

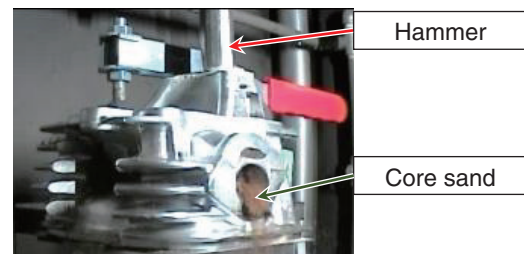


Fig. 33 State of decoring

pressures which is applied to hammer were measured. Note that the sand removal rate is defined by the percentage of the weight of the removed core sand against the weight of the intake port core. Figure 34 shows the test results. It has been confirmed that when the air pressure is above 0.3 MPa, the oscillation acceleration becomes more than 44 g, where the sand removal rate becomes 100%.

6.3.2. Collapsibility of sand core by heat treatment

Presuming a rare case of sand core remaining in the POT port after the chipping, we checked collapsibility of the sand core by heat treatment. The sand core is made of the RCS in which the sand grains are coated with the phenolic resin as a binder at a rate of 1.4 wt.% as Fig. 30 shows. The heat accelerates oxidative decomposition of the phenolic resin, and turns the resin to gases. In an attempt to clarify the temperature that causes the oxidative decomposition to occur, we conducted Thermogravimetry/Differential Thermal Analysis (TG-DTA) for the RCS⁽⁸⁾. Figure 35 shows the results. The DTA curve shows exothermic peak indicating oxidation at 428°C. The oxidative decomposition finishes at 500°C, which is the solution treatment temperature of the cast product. As a result, the phenolic resin serving as a binder disappears completely, which is an

indication of collapse of the sand core as Fig. 36 shows.

It is presumable that if the end of POT port on the combustion chamber side is closed by burr, the POT port sand core is exposed to the atmosphere only on the inlet pipe side, causing the oxidative decomposition of the phenolic resin not advancing far inside of the core. We have therefore tested collapsibility of the sand core by heating using the test piece in which the closed POT port is simulated in a simplified manner. Figure 37 shows the image picture of the test piece. The cross-sectional area of the opening that is exposed to the atmosphere is adjusted equal to that of the POT port. Figure 38 shows the relationship between the heating time and the collapse

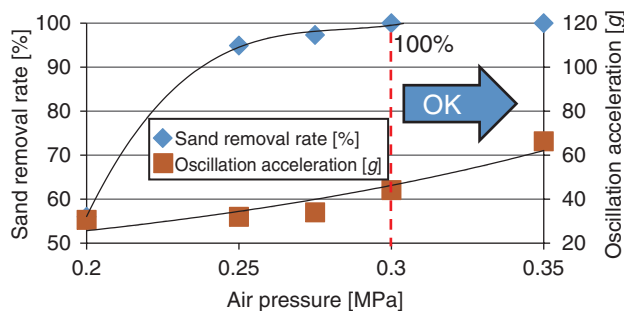


Fig. 34 Sand removal rate of intake port (after decorating for 30 seconds)

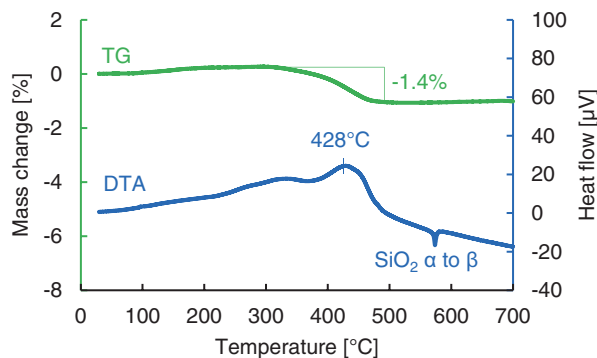


Fig. 35 TG-DTA curves at heating rate of 10°C/min

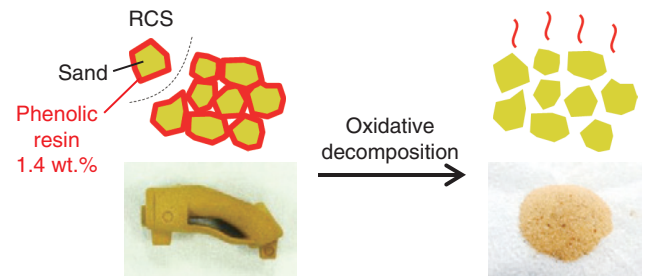


Fig. 36 Sand core collapse

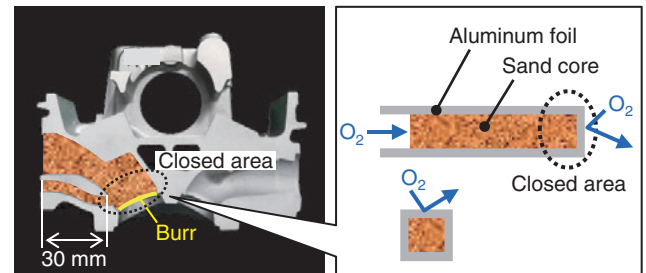


Fig. 37 Schematic diagram of test piece

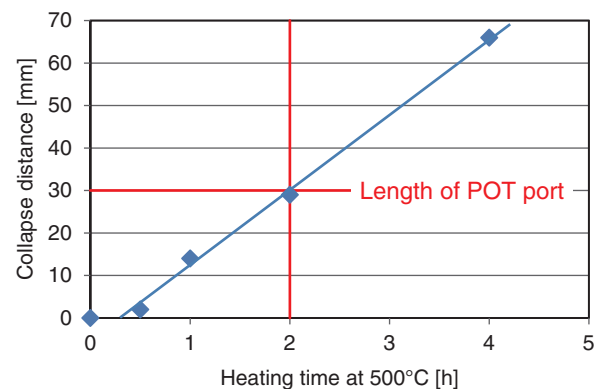


Fig. 38 Effect of heating on sand core collapsing

distance of sand core. The collapse advances proportionally to the heating time. After 2 hours of heating, the length corresponding to the 30 mm-long POT port has collapsed. Accordingly, we conclude that adequate collapse within the heat treatment time is prospective.

We have thus established the manufacturing method for integral casting of the separator in the intake port, allowing practical applications of the newly designed tumble port without modifying existing casting equipment.

7. Conclusion

We have established an inexpensive technology that can enhance tumble in a cylinder only when the engine is low loaded without using any flow path switching mechanisms.

The technology is based on the following findings:

- (1) In the intake port downstream of the throttle valve, the trailing edge side of the throttle valve produces a slow diffusing flow, while the leading edge side produces a fast converging flow.
- (2) The slow diffused flow on the trailing edge side is pulled by a low-pressure zone generated behind the throttle valve to produce some reverse flow.
- (3) By installing a separator in the port on the leading edge side of the throttle valve shaft, the reverse flow is guided along the separator wall to the low-pressure zone behind the throttle valve. It then merges with the converging flow on the leading edge side. As a result, more than 80% of the total flow is captured in the POT port⁽⁹⁾.
- (4) It has been confirmed from the combustion pressure analysis of actual engine that the combustion period is shorter in the low load range than in the conventional port, proving that the target tumble effects are achieved.
- (5) The emission norms of EURO5 and India's BS-VI are satisfied as well as improving the fuel economy of the motorcycle by 1.7% in the WMTC mode.
- (6) Using the vertical split construction for the intake port core molding die, the slit is made in the core to create the separator wall. This core enables the integral casting of the separator wall in the intake port.

By using this technology, we can improve fuel consumption performance at a practical operating range of an engine without sacrificing quietness or power performance. This technology also allows practical applications without adding extra parts or modifying existing production equipment.

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