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ABSTRACT

Measurement using a three-dimensional anemometric-tester was made for the gas flow inside the cylinder of a two-stroke engine while the shape of the transfer port was modified. The relationship between port shape and engine performance was investigated for various factors that characterize the flow in cylinder. In this paper, we focused mainly on two engine running conditions: the maximum output at 11750 rpm and the output at 10000 rpm. As a result, we found that the maximum output is most related to the tangential inclination angles of the main transfer port, and the inner vent radius of the main transfer duct.

INTRODUCTION

The two-stroke engine is relatively small and has high output. This characteristic is very important for the power source of transportation. Among many design elements, the shape of the transfer port is one of the most important factors contributing to engine performance. Although Jante[1] , Blair[2][3][4] , and other researchers[5][6] made the extensive studies on scavenging in the past, the relationship between port shape and engine performance has yet to be clearly confirmed. As a matter of fact engineering of the port has been based on experience.

In this study, we measured the gas flow inside the cylinder using the anemometric-tester for an engine with several port configurations. Then eleven factors for the port shape were selected for design of experiments to investigate the relationship between port shape and engine performance.

TEST DEVICE AND TEST SPECIFICATIONS

TEST DEVICE – The anemometric-tester used in this experiment was based upon the Jante's method and developed by Jaros[7][8]. The schematic representation of the anemometric-tester is shown in Fig. 1. A pressure probe is inserted into the cylinder through the groove of the cylinder head. Static and dynamic pressures are measured by the probe of the three-dimensional Pitot tube. Motors are attached to the measuring head and enable the probe to rotate or move vertically and horizontally. Thus, the three-dimensional flow vector in nearly entire area of the cylinder can be measured. A piston is fixed in an arbitrary position. The scavenging process is reproduced by applying pressure to the surge tank, which is placed under the cylinder and functions as a crankcase. The total flow amount is measured by the flowmeter of the venturi nozzle.

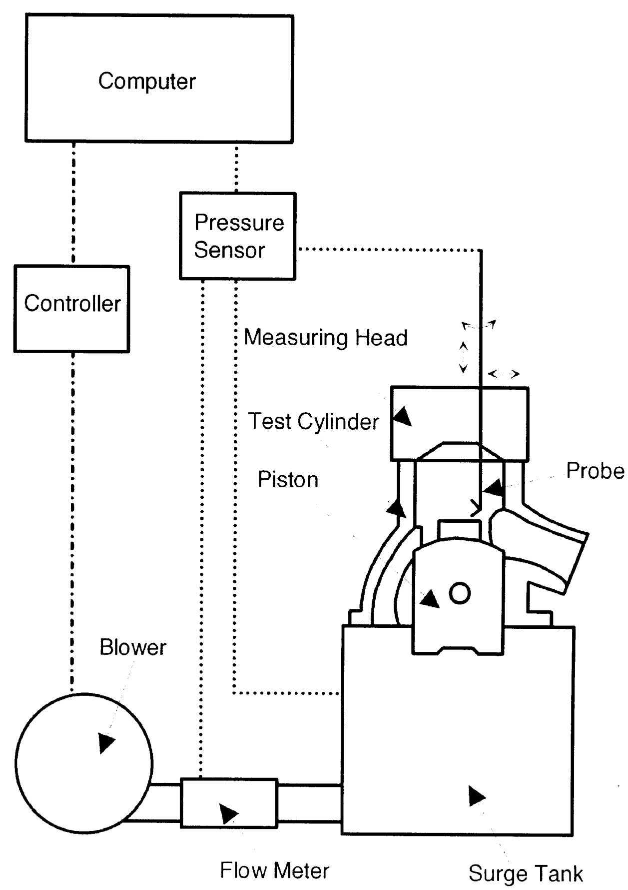


Figure 1. Anemometric-tester System

Fig. 2 is the photo of the measuring part of the anemometric-tester. In the flow test, the actual and laser molded cylinders were used. Fig.3 shows an example of laser-molded cylinder for this test.

From the result of the flow test, the velocity distribution on a measuring plane (Fig. 4) and the following physical quantities were given.

1. Vector of Flow Velocity
2. Reduced Flow Coefficient (RFC)
3. Trapping Efficiency (ETR)
4. Power Coefficient (PC)
5. Total Flow by Measuring Plane (TF)

These physical quantities are defined in the Appendix.

RFC is the division of the actual flow amount by the calculated flow amount that is derived from the cylinder sectional area and the differential pressure. RFC is dimensionless and free from the influence of the cylinder sectional area and the differential pressure.

TEST SPECIFICATIONS – Table 1 shows the specifications of the engine. Laser molding was applied to manufacture the cylinders from three-dimensional CAD data. These cylinders were independent on the errors that occur in casting or machining.

Table 1. Test Engine Specifications

Type	Two-Stroke, Single Cylinder, Water Cooled	
Scavenge	Loop-Scavenge	
Bore	54.0	(mm)
Stroke	54.5	(mm)
Displacement	124.8	(cm^3)
Exhaust Port Opening	83	(°A,BTDC)
Transfer Port Opening	115	(°A,BTDC)
Number of Transfer Port	5	

The first in the test process was to investigate the correlation between physical quantities obtained by the flow test and engine performance. Several kinds of casting cylinders were prepared and tested by both the anemometric-tester and the dynamometer. The second was to make cylinders with modified port shapes and to investigate the relationship between port shape and the physical quantities selected in the first test. The result of these leads to the relationship between port shape and engine performance.

TEST RESULTS

CORRELATION TEST – The first we investigated the correlation between the physical quantities and engine performance. When the maximum output is particularly emphasized in two-stroke engine, the output curve generally has a tendency to have a trough at the vicinity of the maximum output. This affects the drive-ability of the vehicle. Ideally, the output curve should shift upwards. So we investigated the above correlation at the two different revolutions: 11,750 rpm (Point A) at which the maximum output is obtained and 10,000 rpm (Point B). (Fig. 5)

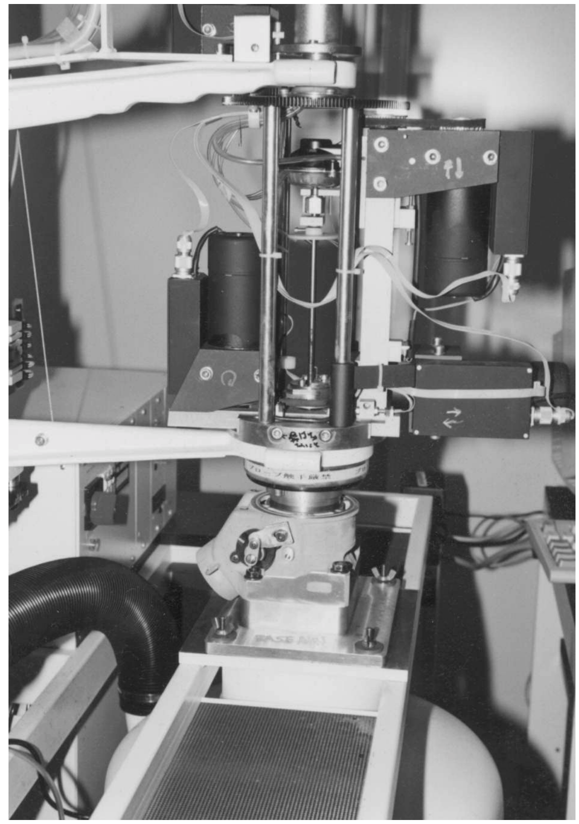


Figure 2. Anemometric-tester Device

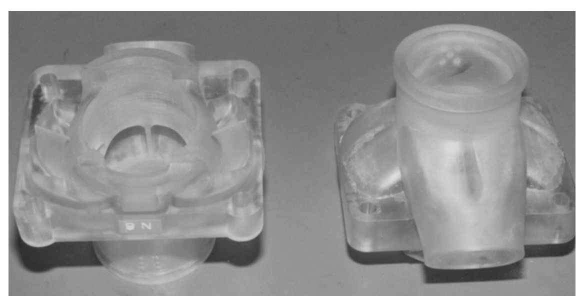


Figure 3. Test Cylinder (laser molding)

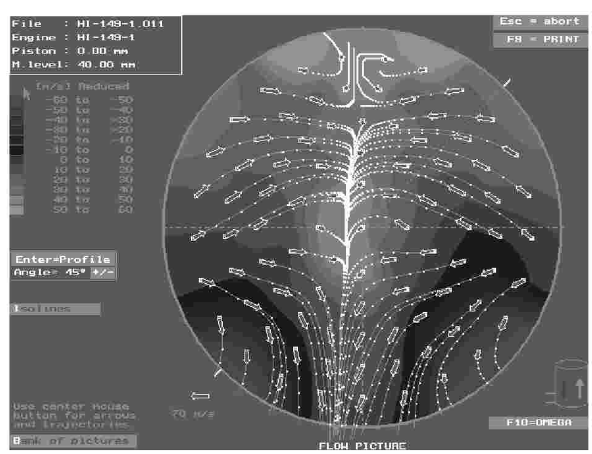


Figure 4. Flow Picture

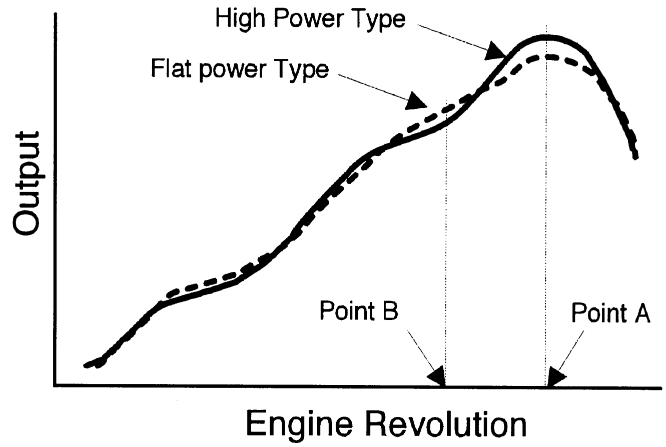


Figure 5. Power curve for the Two-Stroke Engine

Correlation at Point A – The correlation between the physical quantities and the output at point A is shown in Fig. 6. We converted the maximum output into the percentage. The average of the maximum output was 100 percent.

There was a visible correlation between RFC and the maximum output. There was a small correlation with PC. TF(40) is the amount of the gas flow that passes up through a horizontal measuring plane 40 mm below from the surface of the cylinder. This position is 1.5 mm higher from the upper edge of the transfer port. TF(40) means the up-flow amount which subtracted a direct short-circuit amount to exhaust port from total flow amount. TF(40) and ETR did not affect to the output at point A. On conclusion, RFC was thought to be the most appropriate physical quantity to correlate to the maximum output among the several ones given by the flow test at point A.

Just as the Fig. 6, the maximum output increases as RFC increases. However, it does not continue to increase indefinitely and reaches to its maximum when RFC is approximately 0.325. We conjecture that high RFC cylinders don't match with the intake and exhaust systems properly. If the intake and exhaust systems are matched to high RFC cylinders, we should see a still greater improvement in output.

Correlation at Point B – The correlation between physical quantities of the anemometric-tester and the output at Point B is shown in Fig. 7. The RFC did not show distinct correlation with the output at point B such as seen at point A. We investigated the correlation between the other physical quantities and the output at Point B.

There was a visible correlation between TF(16) and output. TF(16) is the amount of the gas flow that passes up through a horizontal measuring plane 16 mm. TF(16) was thought to be the most appropriate physical quantity to correlate to the output among the several ones given by the flow test at point B.

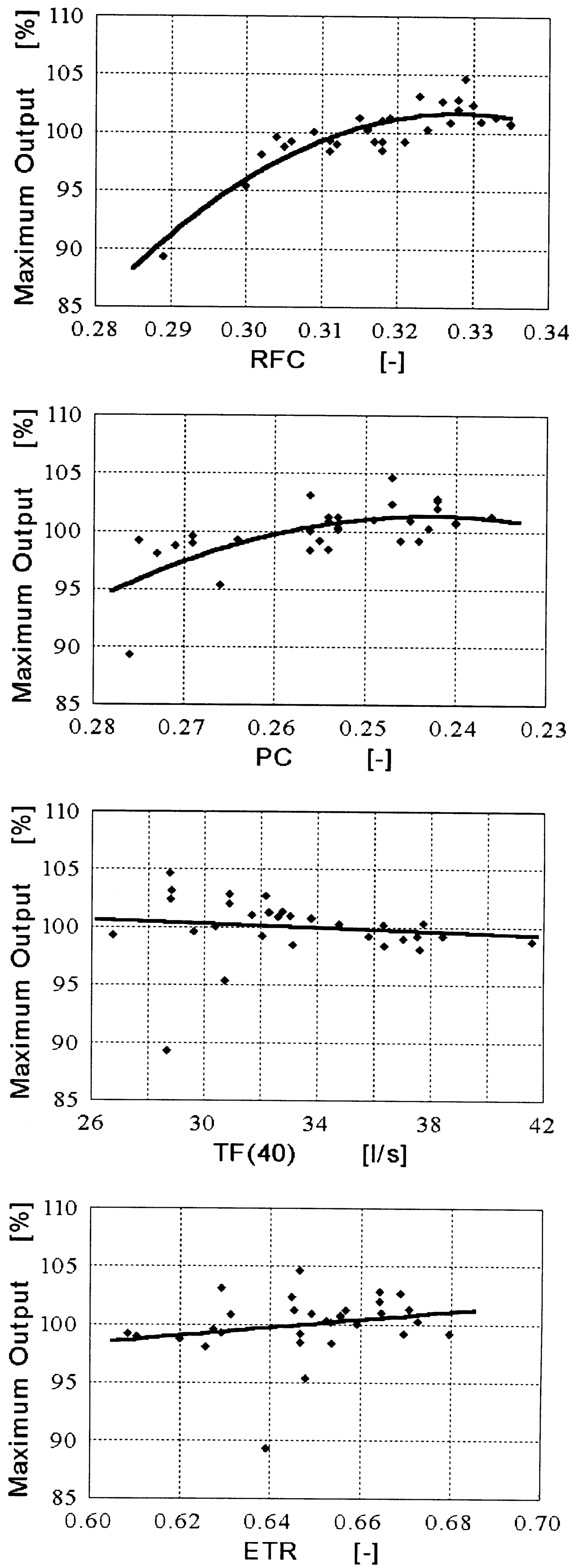


Figure 6. Correlation at Point A

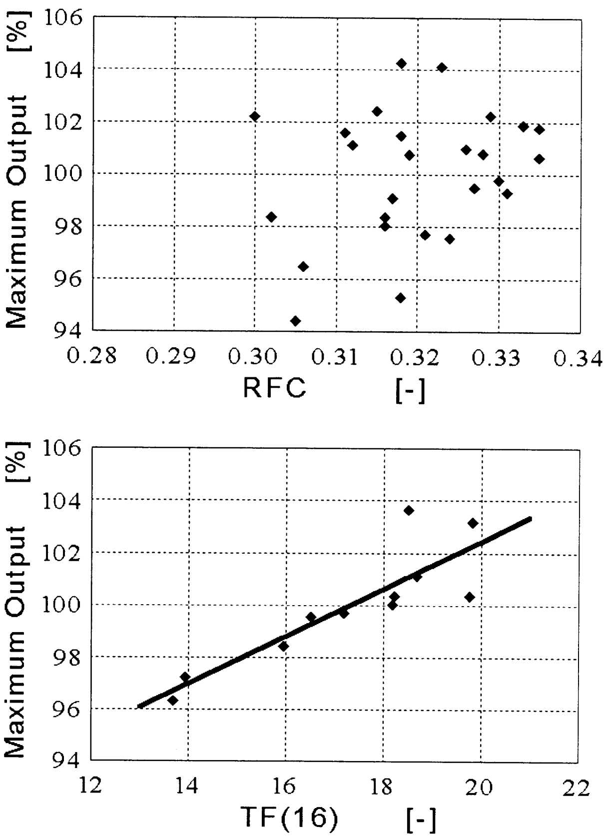


Figure 7. Correlation at Point B

However, as seen in Fig. 8, we got the result that there was a trade-off between RFC and TF(16). This result explains the general idea based on experiments that the effort to increase the maximum output is followed by the creation of the trough of the output curve.

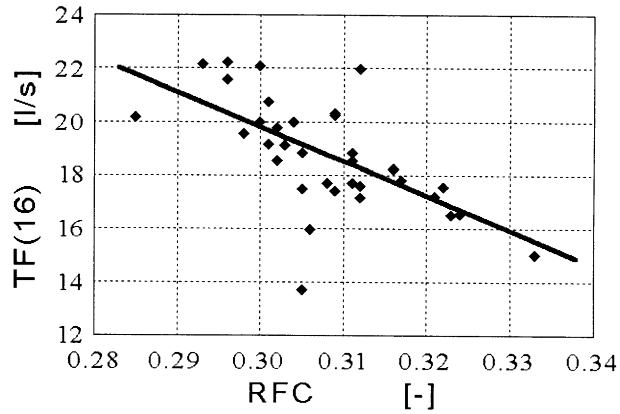


Figure 8. Relationship RFC and TF(16)

PORT SHAPE MODIFICATION TEST – To understand the effect of port shape, we adopted design of experiment, which consisted of seven factors and two levels (Latin square 8 test: $L_8(2^7)$). We selected these factors which we thought to have influence on RFC or TF(16) from factors forming the port shape. Particularly, we put emphasis on the main transfer port factors. There were eleven factors in total: eight for the main transfer port, one for the auxiliary transfer port, and two for the exhaust port. Table 2 shows the different combinations of eleven factors with two levels for design of experiments and Fig. 9 explains each factor schematically. Levels of factors were given according to the relationship between output and each port shape configuration supposed from the experiments in the past. Throughout this test, the port opening area and timing were unchanged except F-7 and F-8. The rate of increase of the port opening area was 2.1 % by F-7 and 1.3 % by F-8. For this reason, we need to be carefully to analyze these data.

Table 2. Factor and Level of two L_8-tests

Factor			Test 1		Test 2	
No.	Port	Details	Level 1	Level 2	Level 1	Level 2
F-1	Main Transfer	Tangential Inclination at point-1 (ζ_1)	66 deg.	61 deg.	63 deg.	69 deg.
F-2	Main Transfer	Tangential Inclination at point-2 (ζ_2)	39.5 deg.	35 deg.		
F-3	Main Transfer	Axial Inclination (ε)	25 deg.	29 deg.	23 deg.	27 deg.
F-4	Main Transfer	Passage Inner Vent Radius (r_1)	13.5 R	6 R	11 R	15 R
F-5	Main Transfer	Passage Outer Vent Radius (r_2)			53.1 R	55 R
F-6	Main Transfer	Tangential Inclination at point-3 (ζ_3)			21.8 deg.	26.8 deg.
F-7	Main Transfer	Width of Main Transfer Port (Δw)			STD	+0.8 mm
F-8	Main Transfer	Corner Radius at point-3 (r_c)			4 R	3 R
F-9	Auxiliary Transfer	Auxiliary Transfer Type	Type 1	Type 2		
F-10	Exhaust	Maximum Width of Exhaust Duct (W_E)	56.5 mm	59.5 mm		
F-11	Exhaust	Shape of Lower Part	STD	Swell Type		

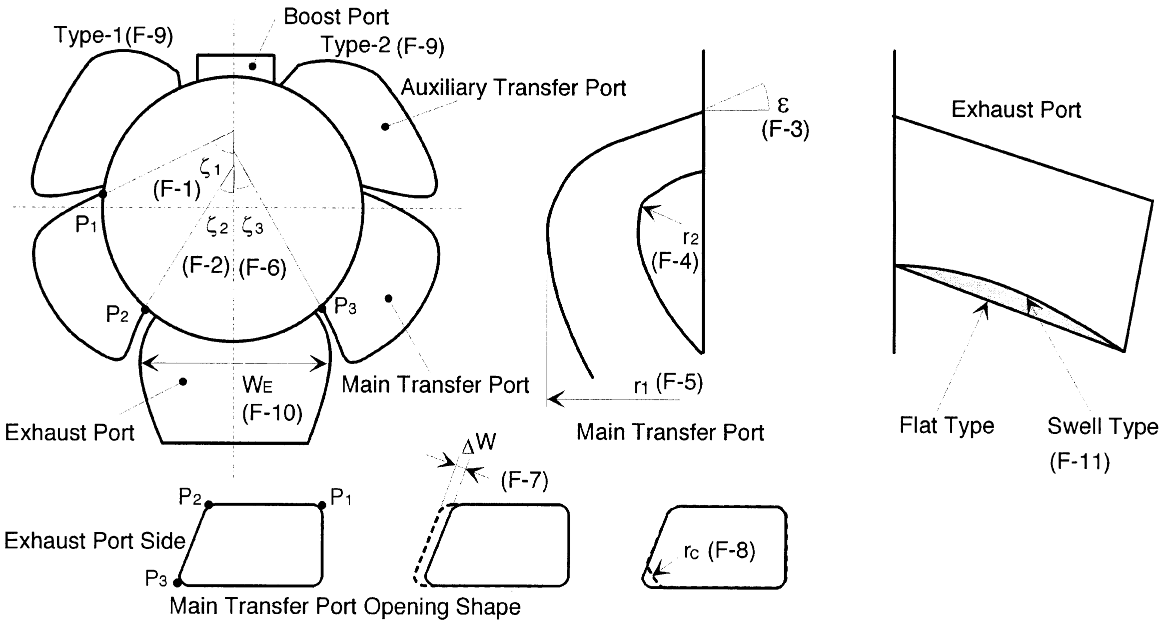


Figure 9. Explanation of Factors

L_8 test was conducted twice using the seven factors from the eleven factors. The factors used at test-1 were F-1, F-2, F-3, F-4, F-9, F-10 and F-11. The factors used at test-2 were F-1, F-3, F-4, F-5, F-6, F-7 and F-8. Three factors, F-1, F-3 and F-4, were used in both tests. However, levels of these factors were changed.

We designed and made eight cylinders per each L_8 test. They were all laser molded. Port shapes of eight cylinders per each L_8 test were given according to the orthogonal array. (Table 3)

Measured RFC and TF(16) of sixteen cylinders are shown in Table 4. The maximum value of RFC was 0.312 in the Cyl-14. However, this cylinder had minimum value of TF(16).

Table 3. Orthogonal array

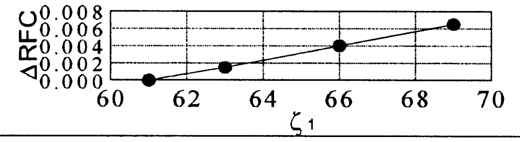
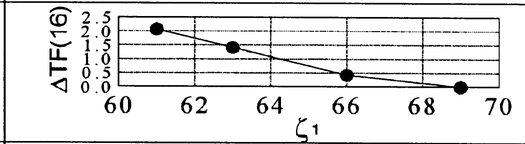
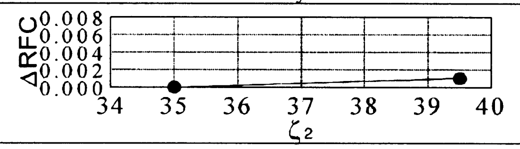
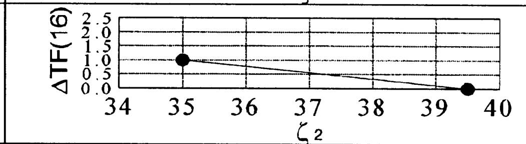
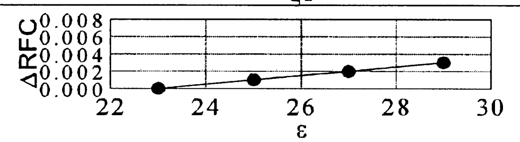
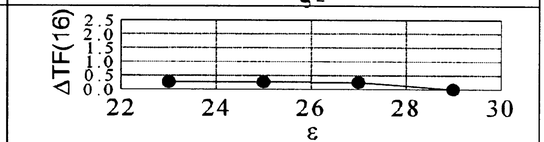
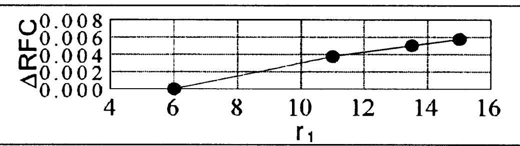
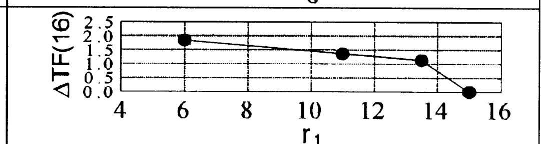
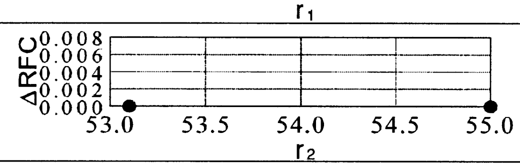
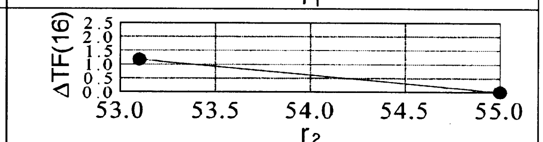
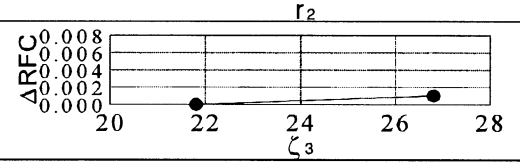
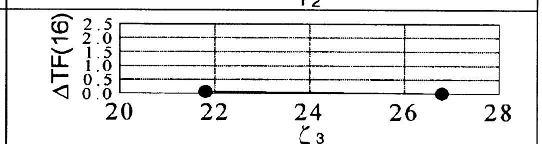
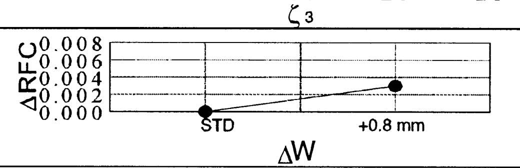
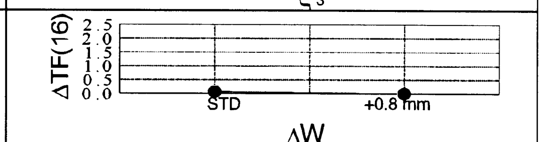
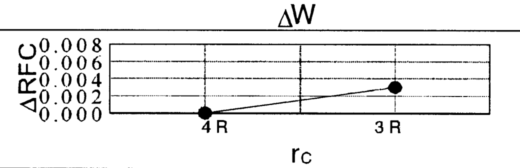
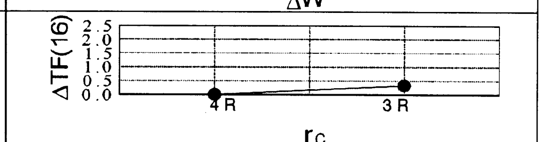
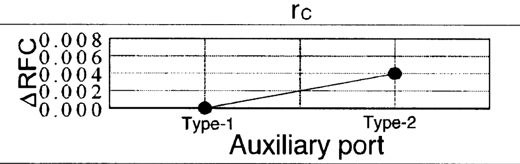
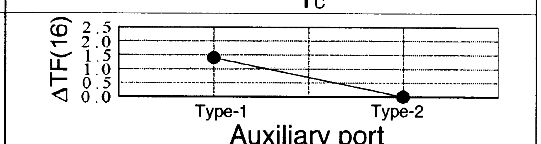
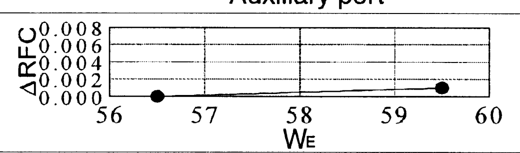
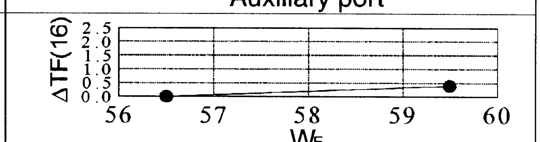
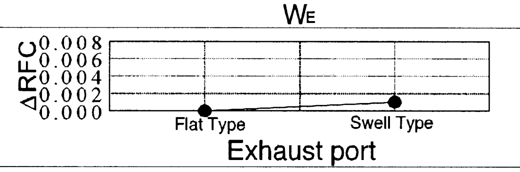
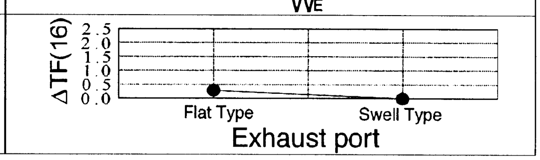
	Cylinder No.	Factor										
		F-1	F-2	F-3	F-4	F-5	F-6	F-7	F-8	F-9	F-10	F-11
TEST 1	Cyl-1	1	1	1	1					1	1	1
	Cyl-2	1	1	1	2					2	2	2
	Cyl-3	1	2	2	1					1	2	2
	Cyl-4	1	2	2	2					2	1	1
	Cyl-5	2	1	2	1					2	1	2
	Cyl-6	2	1	2	2					1	2	1
	Cyl-7	2	2	1	1					2	2	1
	Cyl-8	2	2	1	2					1	1	2
TEST 2	Cyl-9	1		1	1	1	1	1	1			
	Cyl-10	1		1	1	2	2	2	2			
	Cyl-11	1		2	2	1	1	2	2			
	Cyl-12	1		2	2	2	2	1	1			
	Cyl-13	2		1	2	1	2	1	2			
	Cyl-14	2		1	2	2	1	2	1			
	Cyl-15	2		2	1	1	2	2	1			
	Cyl-16	2		2	1	2	1	1	2			

Table 4. Result of flow test

	Cylinder No.	RFC	TF(16)
TEST 1	Cyl-1	0.303	19.12
	Cyl-2	0.302	18.52
	Cyl-3	0.304	19.97
	Cyl-4	0.301	19.16
	Cyl-5	0.305	18.81
	Cyl-6	0.296	21.59
	Cyl-7	0.301	20.75
	Cyl-8	0.293	22.17
TEST 2	Cyl-9	0.300	19.98
	Cyl-10	0.308	17.70
	Cyl-11	0.309	20.30
	Cyl-12	0.305	17.49
	Cyl-13	0.311	17.71
	Cyl-14	0.312	17.14
	Cyl-15	0.309	17.40
	Cyl-16	0.312	17.60

The estimations of effects were calculated from the results of these flow tests. The influence of the port shape on performance can be gathered from Table 5, which combined the estimation of effects in the two tests. For example, by increasing ζ_1, tangential inclination at the main transfer port, from 61 degree to 69 degree, there is a gain of 0.0065 with respect to RFC, but conversely a drop of 2.1 for TF(16). As these results show, RFC and TF(16) are trade-off each other in most effective factors. The value of effect is small in effective factors, F-5, F-7, F-8 and F-10, at both physical quantities or at only one.

Table 5. Estimations of Effects

Factor	ΔRFC	ΔTF(16)
F-1		
F-2		
F-3		
F-4		
F-5		
F-6		
F-7		
F-8		
F-9		
F-10		
F-11		

Correlation of RFC – In the 11 factors, there were six factors that influenced the RFC: five main transfer port factors, and one auxiliary transfer port factor. Factor F-1, tangential Inclination at point-1, has the greatest effect. When angle ζ_1 is increased from 61 to 69, we can predict a rise in RFC of approximately 0.0065. This shape means the airflow from the main transfer port is directed toward the center of the bore, not toward the boost port. Factor F-4, passage inner vent radius, has the next greatest effect. When radius r_1 is increased from 6 to 15, we can predict a rise in RFC of approximately 0.0056. With respect to the other factors, the factor F-3, the main transfer port axial inclination, and the factor F-7 and F-8, port opening surface area enlargement, effectively improve RFC.

Correlation of TF(16) – There were five factors that influenced TF(16): four main transfer port factors, and one auxiliary transfer port factor. Factor F-1, tangential Inclination at point-1, has the greatest effect. When angle ζ_1 is reduction from 69 to 61, we can predict a rise in TF(16) of approximately 2.066. The factor F-4, the inner bent radius of main transfer duct, has the next largest effect. When radius r_1 is reduction from 15 to 6, we can predict a rise in TF(16) 1.837. With respect to the other factors, the factor F-2, the main transfer port tangential inclination at point-2, and the factor F-5, the main transfer port outer radius effectively improve TF(16).

However, in either case, the results were different from those for the RFC. From Table 5 the three factors, F-1, F-4 and F-9, in common can give large influence on both RFC and TF(16). What is important here is that RFC and TF(16) are influenced to the opposite directions.

Table 6. Factors and Levels of Best RFC

Cyl-A (Test-1)							
Factor	F-1	F-2	F-3	F-4	F-9	F-10	F-11
Level	1	1	2	1	2	1	2
Cyl-B (Test-2)							
Factor	F-1	F-3	F-4	F-5	F-6	F-7	F-8
Level	2	2	2	2	2	2	2

Table 7. RFC of Verification Test

Cylinder	Estimation	Measured
Cyl-A	0.309	0.309
Cyl-B	0.313	0.312

VERIFICATION TEST – Two cylinders, which should have the highest RFC, were selected and made by laser molding. One was selected based on the L_8 test 1 and the other on the L_8 test 2. The first cylinder, Cyl-A, has the following specifications: factor F-1, F-2, F-3, F-4, F-9, F-10, and F-11 have the level of 1, 1, 2, 1, 2, 1 and 2. The second cylinder, Cyl-B, has the following specifications: factor F-1, F-3, F-4, f-5, F-6, f-7 and F-8 have the level of 2, 2, 2, 2, 2, 2 and 2. (Table 6)

The measured RFC of the first was 0.309, which was identical to the estimation. The RFC of the second cylinder was 0.312, which was nearly identical 0.313 to the estimation. From this, we were able to confirm that the factors were nearly independent and the effects predicted were achieved. (Table 7)

CONCLUSION

Using a three dimensional anemometric-tester, we analyzed the relation between the transfer port shape and the gas flow inside the cylinder and engine performance in a two-stroke engine. The following conclusions were drawn:

1. The maximum output is high when the airflow amount in the steady state flow tester is high.
2. To improve the airflow amount in the steady state, it is beneficial that the airflow from the main transfer port is directed toward the center of the bore and that the inner bent radius of the main transfer duct is large.
3. To solve the trough of output at the engine revolution lower than that at the maximum output, it is beneficial that the up-flow amount directing to the head cylinder is increased. However, there is a trade-off between the up-flow amount and the air flow amount.
4. We are able to add the estimation of the effect for the steady state airflow amount of each factor.

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APPENDIX

RFC Reduced coefficient of flow (-)

$$Q_{teo} = \frac{\pi D^2}{4} \times \sqrt{\frac{2\Delta p}{\rho}}$$

where
Q_{mer} - measured air flow through cylinder (m^3/s)
Q_{teo} - theoretical air flow through cylinder (m^3/s)
ρ - specific mass of air in cylinder (kg/m^3)
Δp - pressure gradient at cylinder (Pa)
D - cylinder bore (m)

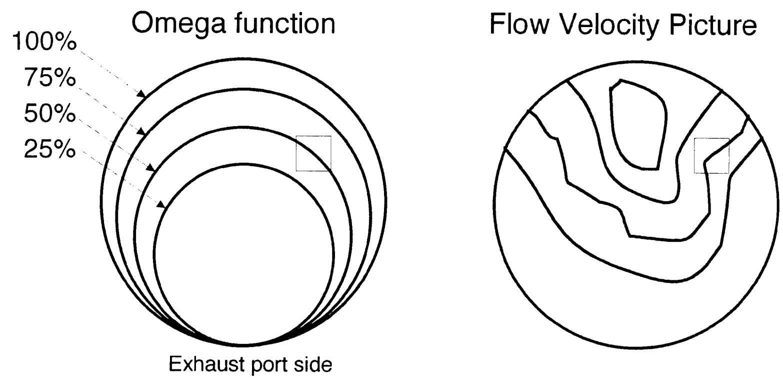

Figure 10. Calculation Principle for Trapping Efficiency

ETR The calculated value of trapping efficiency (%)

Fig. 10 shows:

- the trapping efficiency value depends exclusively upon the velocity field
- the trapping efficiency achieves its flow maximum in the vicinity of the cylinder wall
- the trapping efficiency does not express the possible loss under the measuring level.

$$ETR = \left(\sum^{n} \Delta S v_a \omega \Big/ \sum^{n} \Delta S v_a \right) \times 100$$

Where
ω - value of transport factor (omega function) (-)
v_a - axial component of velocity vector in filling stream (m/s)
ΔS - elemental surface in filling stream (m^2)

PC Coefficient of power (-)

$$PC = ETR \times RFC$$

TF(x) Air flow in measuring plane towards cylinder head (l/s)
x: measuring plane from the upper edge of the cylinder (mm)
example:
- TF(16): when the measuring plane was a horizontal plane 16 mm from the upper edge of the cylinder