

Development of a Four-stroke Engine with Turbocharger for Personal Watercraft

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ABSTRACT

Recently, there is a movement to apply emission control in marine engines in the United States. Environmental measures for marine engines have become severe. Honda has developed a three seat personal watercraft with a 4-stroke engine installed in consideration of environmental suitability and the future. Using the motorcycle CBR1100XX in-line 4-cylinder 4-stroke engine, with a displacement of 1,100 cm³ as the base engine, the specifications were modified for marine use to satisfy such areas as engine performance, function, and corrosion resistance, as a PWC engine. Moreover, the turbocharger was employed to obtain a power/weight ratio greater than that of PWCs with 2-stroke engines. Driveability and durability exceeding conventional PWCs with 2-stroke engine were achieved. Emission performance of the engine satisfied EPA2006 and CARB2004 regulations, while fuel economy also improved by 16 % compared to conventional 2-stroke engine models.

1. Introduction

Personal watercrafts (PWC) are widely used as marine leisure craft in Japan, the US and numerous other countries. However, increasing concern over environmental issues has led to emission regulations being applied to marine engines, including outboard motors and PWC, since 1994 in the US. Honda has given consideration to the future, and developed a 4-stroke engine for PWC, which satisfies the requirements of these emission regulations. The remainder of this section will discuss the current trend of emission regulations and the concept behind the new engine.

1.1. Trend of Emission Regulations

The US is a major market for large outboard motors. The comparatively large numbers of these engines and their high level of emissions against power make them the main targets of marine emission regulations. The number of PWC is low in comparison, but they show similarly high levels of emissions against power, and have therefore become the target of emission regulations.

1.1.1. U.S. Environmental Protection Agency (EPA) emission regulations

The U.S. EPA marine emission regulations, as Fig. 1 shows, stipulate a step-by-step reduction from 1998 levels,

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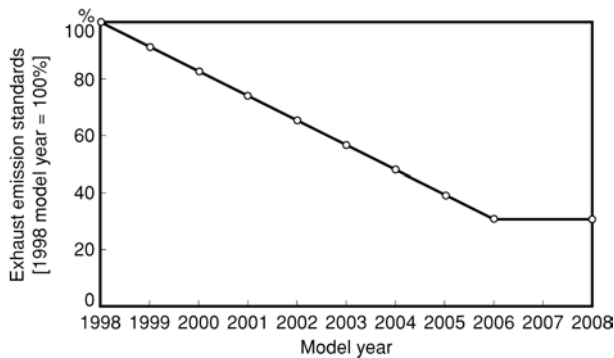


Fig. 1 EPA exhaust emission standards

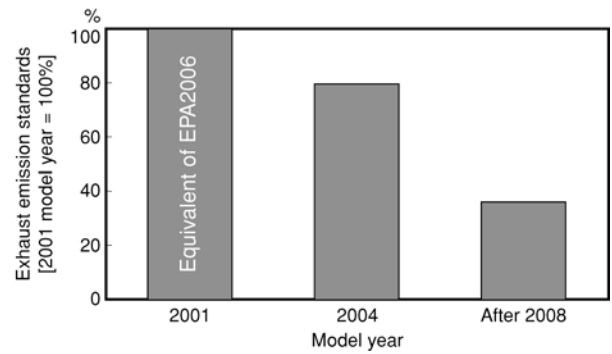


Fig. 2 CARB exhaust emission standards

considered as 100%, to 25% in 2006. Table 1 shows emission measurement modes and their weighting factors. There are five modes based on the power peaks established by the International Council of Marine Industry Associations (ICOMIA). The modes cover idling to full power with wide-open throttle, and almost exactly correspond to running resistance peaks during actual operation. The target for measurements is the combined value of HC and NO_x emissions; CO emissions fall outside the scope of these measurements. Five years or 350 hours of operation are required for a PWC to receive assurance for emission deterioration. The regulation values are extremely strict. One of the modes measures emissions with a wide-open throttle; in addition, it has proven to be very difficult to modify conventional 2-stroke engines which were designed as marine engines and do not utilize exhaust gas after-treatment technology to satisfy the regulations. Because of this, design changes such as the incorporation of direct injection have become necessary.

1.1.2 California air resources board (CARB) marine emission regulations

California is an extremely important market for marine products, prompting the CARB to announce emission regulation values stricter than those of the EPA. Figure 2 shows CARB emissions values, with EPA 2006 values shown as 100% of CARB 2001 values. The CARB regulations stipulate reduction to 80% of EPA 2006 values by 2004, and 35% of EPA 2006 values by 2008. The 2008 emission values can be cleared by current 4-stroke outboard motors with a specific power of 50 kW/L, but has proven to be difficult for

conventional 2-stroke engines. The California Department of Water Resources has also commenced a program of water analysis to determine the effect of marine engines on water quality, focusing in particular on pollution by unburned oil from the mixed lubrication utilized in 2-stroke engines.

1.2. Engine Development Concept

Various engine types were studied to provide a new PWC engine, including 2-stroke direct injection and stratified scavenging and 4-stroke engines. However, the increasing stringency of the environmental regulations applied to marine engines prioritized considerations of environmental friendliness and adaptability to future regulations. For this reason it was decided to develop a 4-stroke engine for PWC use. The selection of a 4-stroke engine enables the EPA 2006 emission level to be met, and prevents water pollution caused by the combustion of mixed oils. The following design concepts were established to develop a 4-stroke engine which could compete with 2-stroke engines mainly used in PWC:

- (1) A high level of environmental friendliness combined with sportiness and ease of handling;
- (2) Superior specific power and power-weight ratio to a 2-stroke engine to achieve class-topping power performance;
- (3) Use of a mass-production engine as the base engine, to enable existing facilities to be used for production; this would control cost increases occasioned by a new engine design, and allow the product to be offered to purchasers at a reasonable price;
- (4) Superior durability and reliability in marine use to that of a 2-stroke engine.

2. Engine Technologies

Table 1 Test procedure specified in ICOMIA

Mode number	Engine speed as a percentage of engine rated speed	Engine torque as a percentage of maximum torque at rated speed	Mode weighting factor
1	100	100	0.06
2	80	71.6	0.14
3	60	46.5	0.15
4	40	25.3	0.25
5	IDLE	0	0.40

2.1. Selection of Engine Configuration

Motorcycle, automobile and outboard motor engines were examined to provide the base engine. The CBR1100XX motorcycle engine was finally selected due to weight considerations, compactness and specific power capable of competing with the 2-stroke engines already on the market. The stroke of the engine was extended 5 mm, and the displacement increased to 1,235 cm³. Figures 3 and 4 show cutaway views of the base engine and the newly developed PWC engine respectively. Table 2 shows the main specifications of both engines. Despite their numerous advantages, 4-stroke engines are generally inferior to 2-strokes in specific power. Increasing engine speed,



Fig. 3 Based motorcycle model

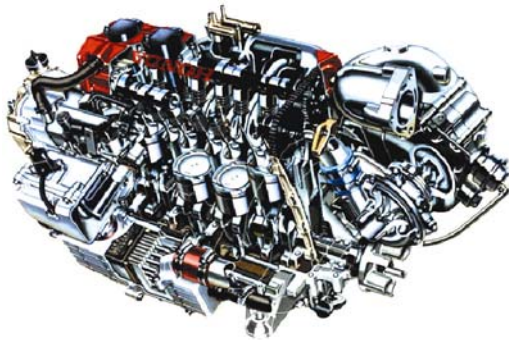


Fig. 4 Developed turbocharged model

supercharging, and increasing displacement were examined as methods of increasing power in the new engine. Increasing the cruising engine speed would cause cavitation to occur in the water jet pump, reducing its efficiency. Engine speed reduction was studied as a method of preventing the engine from exceeding the impeller application limit revolutions, but this caused a feeling of over revving and was rejected to maintain the inherent quietness of the 4-stroke engine. A large increase in displacement would increase weight, affecting the power-weight ratio. These considerations led to the development of an engine fitted with an exhaust turbocharger to meet target performance requirements.

2.2. Configuring the Motorcycle Engine for Marine Use

The configuration of PWC engines is simple, without water pumps, transmissions, etc. However, certain other features are indispensable to a marine engine; configuration changes necessary to convert a motorcycle engine to marine use are discussed below.

2.2.1. Lubrication system

In PWC engines, the jet pump and crankshaft are generally directly connected by a damper. The engine layout locates the crank center in the lowest possible position, bringing the jet pump as close to the bottom of the craft, as possible, thereby increasing pump efficiency. The new engine has been provided with a dry sump lubrication system, with a thin oil pan located at the bottom of the crankcase. The crank center has therefore been lowered 93 mm from the bottom of the engine in comparison to the base model. The oil tank has been re-positioned to the front end of the front cover, and is integrated with the engine. The oil pump is built in and is directly driven from the ACG flywheel boss by means of a semi-Oldham's coupling. This has simplified the structure, dispensing with the need for chains and drive gears.

Table 2 Specification of based motorcycle model and developed turbocharged model

Items	Based motorcycle model	Developed turbocharged model
Engine type	4 stroke inline 4 cylinder	4 stroke inline 4 cylinder
Valve train	DOHC 16 valve	DOHC 16 valve
Displacement (cm ³)	1 137	1 235
Bore × stroke (mm)	79 × 58	79 × 63
Compression ratio	11.0	8.5
Cooling system	Liquid cooled, closed loop	Water cooled, open loop
Lubricating system	Wet sump	Dry sump
Fuel supply system	Programmed fuel injection	Programmed fuel injection
Intake system	—	Turbocharger and intercooler
Balancer shaft	Applied	Applied
Max. power / ne (kW/rpm)	105.6 / 9 500	121.4 / 6 100
Max. torque / ne (N·m/rpm)	111.9 / 7 250	191.8 / 5 500

Ruffling of the engine oil level generated by extremely high acceleration such as when a PWC jumps or spins can cause air to mix with the oil. To prevent this, the oil tank in the new engine is positioned vertically so that the oil level is consequently high. The oil tank is separated into front and rear chambers by a metal gasket. The scavenging pump discharges into the rear chamber. The front defoaming chamber features four baffle plates to prevent ruffling of the oil level. By positioning the oil pump suction opening at the bottom of the tank, aeration has been prevented even during hard spins or when the craft hits the water after a jump, causing impact acceleration in excess of 400 m/s^2 .

The new engine is provided with oil pressure warning switches for both high and low pressures. When the oil pressure falls below the pressure required to maintain engine revolutions at normal craft speed, the switch issues a warning, controls engine speed, and signals the need for an oil check to the user. The low pressure switch shuts off the engine when there is no oil, or when it judges that the craft has overturned. These switches ensure that warnings are issued in advance of engine trouble caused by low oil due to the user having forgotten to check, etc.

Because a PWC can overturn while in operation, measures have to be taken to prevent outflow of oil. In a 4-stroke engine in particular, it is essential to prevent oil flow from the breather system when the engine is overturned. A vertical breather chamber was therefore built into the vertical oil tank, positioned at the side of the engine and the oil tank, as shown in Fig. 5. When the engine is overturned, the oil level is lower than the height of the separate line of the both breather chambers. This system ensures that even if the craft remains in an overturned position, oil will not flow into the breather hose. This is a simple structure with no special accessories, ensuring a high level of reliability.

2.2.2. Cooling system

PWC are not fitted with water pumps, and are generally provided with direct cooling systems using jet pump water pressure. The layout is the same in the new engine. A branched orifice is positioned behind the jet pump cooling water intake, providing water to the oil cooler, which cools the engine system, and the intercooler, which cools the exhaust system. Figure 6 shows the operation of these systems. Because jet pump water pressure reaches up to

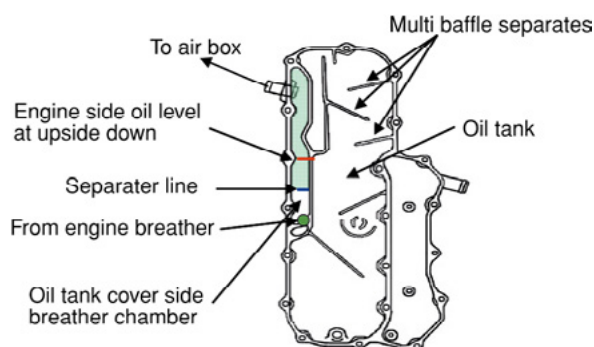


Fig. 5 Engine breather system

490 kPa at the craft's top speed, if a thermostat is positioned at the engine cooling water outlet, the cooling system reaches an almost equivalent pressure to the jet pump before the thermostat valve opens. For this reason, outboard motors are usually provided with a spring-operated relief mechanism. However, this causes the thermostat to stop functioning to control water temperature. In addition, when flushing the system with fresh water after use on the sea, it is difficult to ensure a sufficient volume of water if water pressure is low. Because jet pump water pressure in the new engine is proportional to engine speed, water volume has been adjusted by optimization of the diameter of the orifice without a thermostat. The temperature range was established for a target area spanning from low-speed planning to high-speed operation. Chromate treatment and resin top coating were adopted to increase corrosion resistance on the inner surfaces of the cooling system because of the proven record of this treatment in outboard motors.

2.2.3. Exhaust system

Apart from the turbocharger, the exhaust system is constructed of aluminum with a water-cooled jacket, enabling cost reductions and weight savings. To prevent exhaust energy loss to the turbocharger as much as possible, the system has been provided with the shortest isometric collecting type exhaust manifold available. Because melting damage can easily occur if insufficient cooling water is supplied to the aluminum exhaust manifold, body temperature is monitored by a contact type thermo-switch. This system enables trouble to be prevented by issuing warnings before overheating occurs when the cooling system is blocked or is being flushed. The cooling system in most marine engines operates by injecting cooling water into the exhaust system. In PWC, this necessitates measures to control reverse flow. Measures to prevent reverse flow of

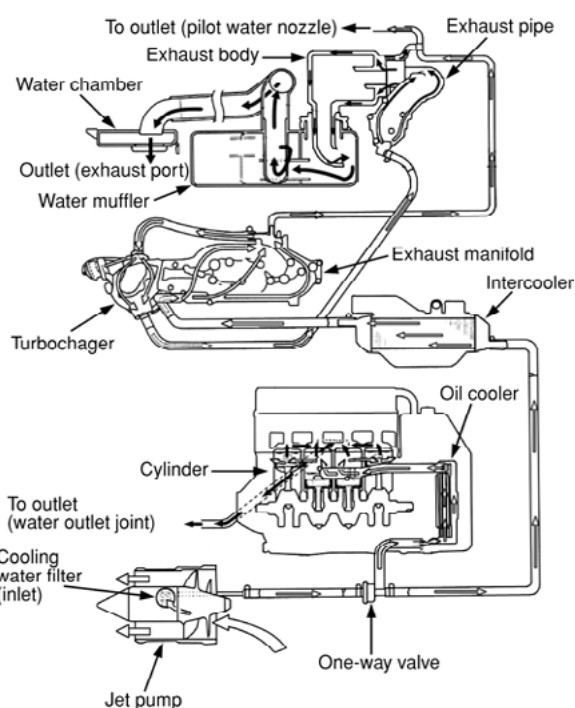


Fig. 6 Cooling system

cooling water when the new engine overturns are shown in Fig. 7. The water level inside the water muffler remains below the exhaust inlet even when the craft is upside-down. Even if a little water gets past this system, a water trap volume in the upper section of the exhaust body prevents reverse flow, therefore preventing inundation of the exhaust turbocharger and the engine itself.

2.3. Engine Performance

2.3.1. Power performance

One development concept behind the PWC to be fitted with the new engine was the achievement of natural turning performance with a lean angle similar to a motorcycle's. To achieve this, a deep-V hull was adopted for the bottom of the craft. Because this hull shape has a high running resistance, the power requirement for the craft was higher than the maximum power of conventional PWC with 2-stroke engines. This level of power was achieved by providing the engine with an exhaust turbocharger. Figure 8 shows the power performance of the newly developed PWC turbocharged engine, developed by changing the specifications of the CBR1100XX motorcycle engine. Figure 9 shows the indicated mean effective pressure for the engine speeds shown in Fig. 8. The new engine has a specific power of 98.3 kW/L, and a power-weight ratio of 0.78 kg/kW; this figure rises to 2.77 kg/kW in the completed craft, the top level for a three-person PWC. Engine speed at maximum power has been kept down to 6,100 rpm, and users will therefore have no concern about excessive engine speed when operating the craft continuously at maximum power with WOT, experiencing a smooth sense of acceleration due to the effectiveness of the turbo.

2.3.2. Turbocharger specifications

The exhaust turbocharger was specifically designed for the new engine, and is exclusively manufactured by Ishikawajima-Harima Heavy Industries Co., Ltd. It is the first direct-water-cooled turbocharger with a waste gate of this size in the world. The layout of the turbocharger is shown in Fig. 10. The turbine housing is constructed of niresist cast iron, a material with superior seawater corrosion resistance, and has a replaceable anode to prevent stray current

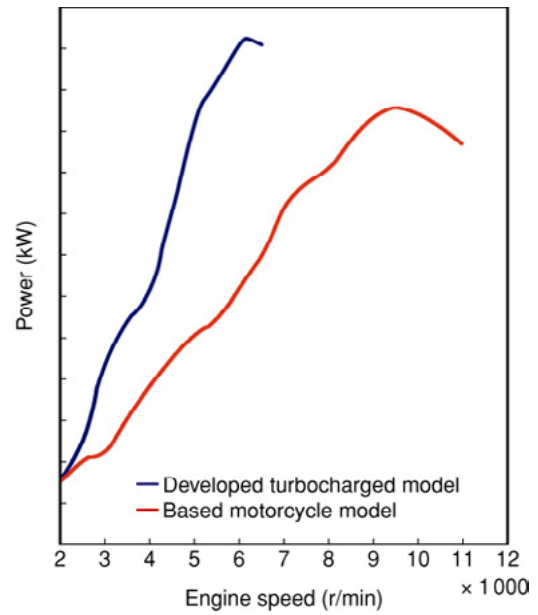


Fig. 8 Engine performance of based motorcycle model and developed model

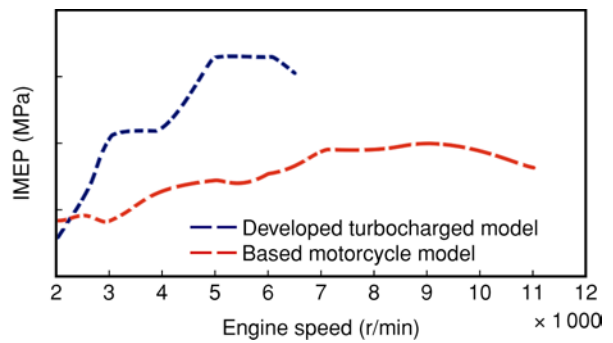


Fig. 9 IMEP of based motorcycle model and developed model

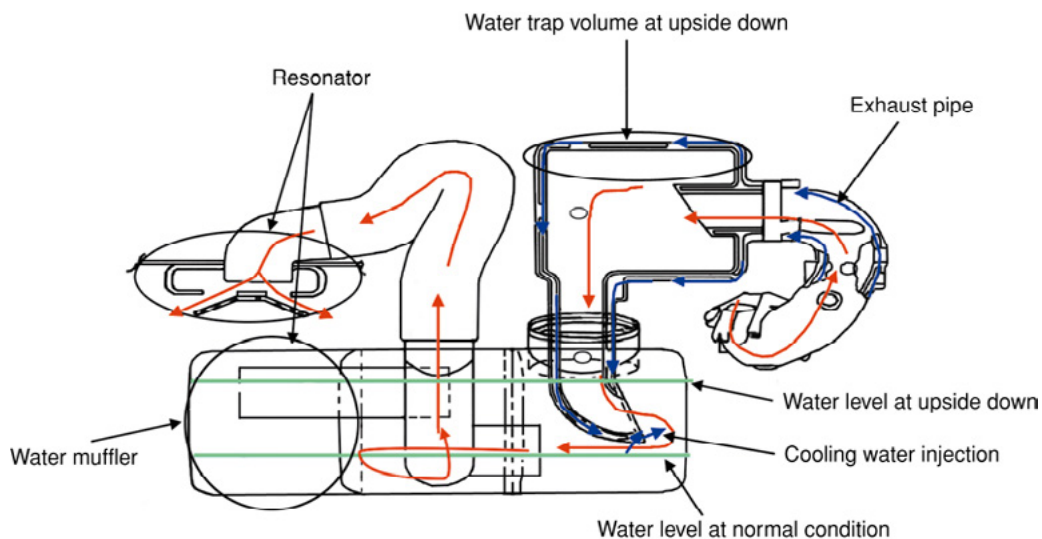


Fig. 7 Layout of exhaust system

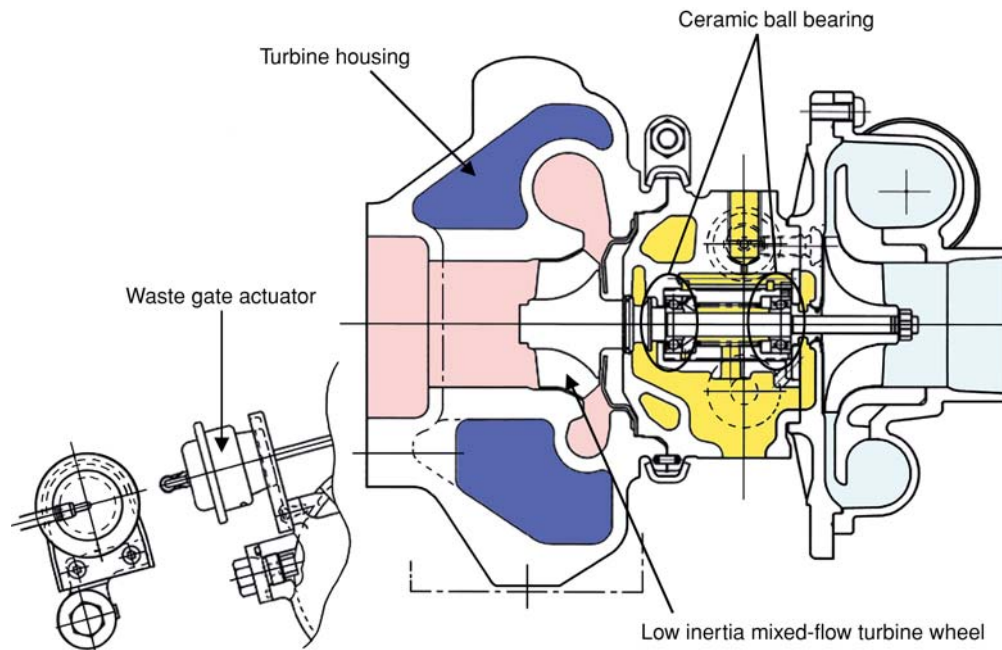


Fig. 10 Layout of the turbo charger

corrosion. The housing is exposed to high-temperature exhaust gas, but water cooling ensures that the surface temperature remains under 85 °C even at full power with WOT. To achieve the high level of throttle response required from PWC engines, a low-inertia mixed-flow turbine wheel has been adopted. As Fig. 11 shows, turbine weight has been reduced 22%, and acceleration performance has been increased 20%. In addition, turbo lag has been significantly reduced. Matching torque characteristics to this turbocharger has enabled the achievement of a unique feeling of acceleration. As Fig. 12 shows, the fineness of the exhaust pulse characteristic of turbos has reduced the acceleration noise level by 21% against a natural aspiration model, ensuring quiet and comfortable cruising.

The turbine speed of exhaust turbochargers normally increases when atmospheric pressure declines in high areas, to prevent over-run, the turbine speed at sea level was reduced. In the new turbocharger system, the craft's altitude is detected from the atmospheric pressure when the engine is started. Target supercharging pressures have been established

up to different altitudes; the pressure setting is lowered if it is judged that the craft is at an altitude where turbine over-run will occur. This system has enabled the engine to demonstrate the same power and maximum speed performance at 1,500 m as at sea level, leading to considerable speed differences between the new model and a craft with naturally aspirated engines in which power drops due to lower atmospheric pressure. It has therefore been possible to maintain performance levels with the adoption of a turbocharger.

2.3.3. Engine parts specifications for high power

The addition of a turbocharger to the new engine has increased IMEP by more than 40% against a naturally aspirated engine. To cope with this increase, various changes have been made to engine components. The pistons are cold-forged, and temperature is controlled by oil injection cooling to the backsides of the pistons to increase reliability at continuous high load use. High-rigidity fully rounded pistons have been utilized to prevent increased friction or

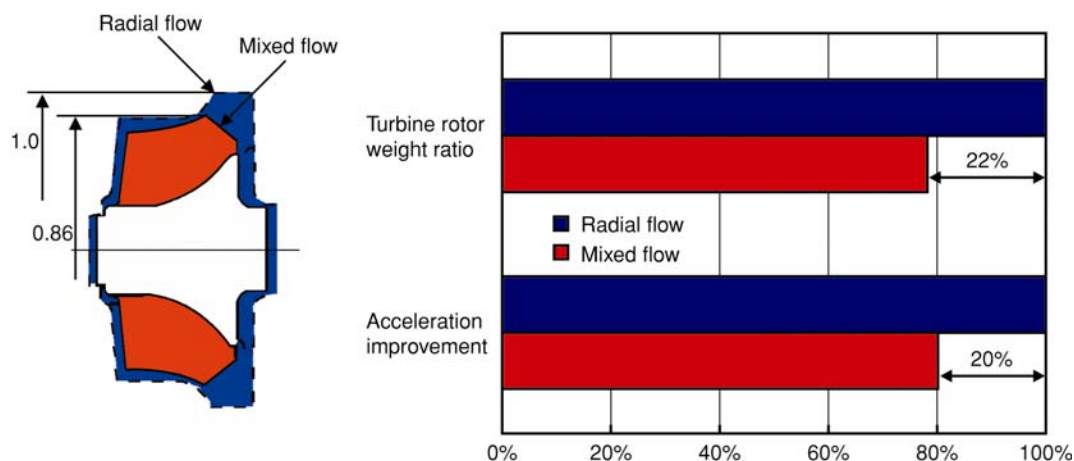


Fig. 11 Improvement of acceleration

temperature increases caused by deformation. Compression height has been increased as much as possible and sufficient land thickness ensured, enabling reduction of the ring groove temperature. The ring grooves receive hard alumite treatment. Figure 13 shows a comparison of the pistons in the newly developed model with the pistons in the base motorcycle model. Short, thick, high-strength connecting rods have been utilized; because the engine speed is low, the connecting rod lambda ratio has been reduced, consequently reducing the height of the engine and enabling the seat to be lowered. Figure 14 shows a comparison of the connecting rods used in the new model and the base motorcycle model. Surface treatment has been applied to the piston pins, and changes to the diameter and length of the pins have increased rigidity. This has increased durability and reliability under high loads, including that of the piston pin bosses.

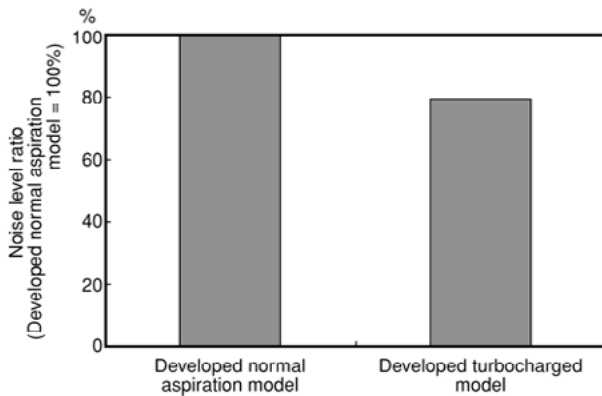


Fig. 12 Noise level of acceleration

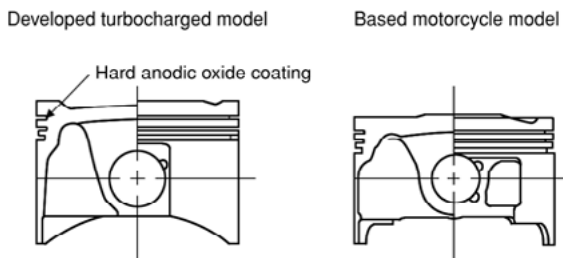


Fig. 13 Shapes of piston

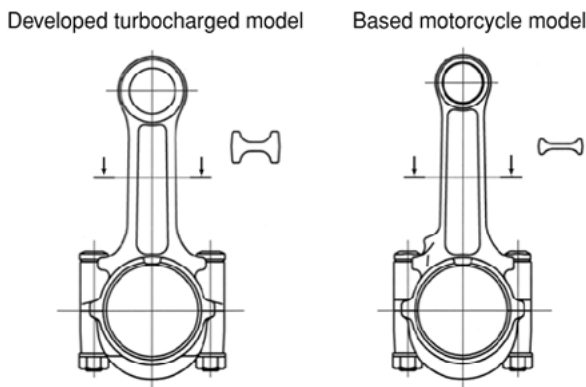


Fig. 14 Shapes of connecting rod

The new turbocharger-fitted engine has a volumetric efficiency of more than 180%, and the volume and temperature of exhaust gases place a severe load on the exhaust valves. To cope with this, SUH751 has been adopted as the material for the valves, to increase high-temperature oxidation resistance and prevent air leakage from the valve sheet. To reduce engine vibration and increase cruising comfort, a bi-axial secondary balancer has been fitted, necessitating increases to the durability and reliability of the turbocharger bearings.

3. Emission Performance

Figure 15 shows a comparison between CARB 2004 emission regulation values and family emission levels (FEL) calculated from power for the newly developed engine and a 2-stroke 3-cylinder 1,200 cc engine used for test purposes. Intensive study of valve timing and fuel injection timing have enabled the achievement of high power in the turbocharged engine while satisfying the CARB 2004 regulation values. Both the turbocharged and normal aspiration engines have received two star labels.

4. Fuel Consumption in Actual Running

Table 3 shows specific fuel consumption at each load level in the EPA marine emission measurement modes measured during bench tests. The newly developed model represents a significant improvement over the 2-stroke, 3-cylinder 1,200 cm³ model used in tests. However, fuel consumption during actual running changes depending on the running resistance of the craft. The hull of the PWC in which the newly developed engine is fitted has a high level of drag. Increasing power to counteract this has meant that the improvements in fuel consumption during actual running cannot match the specific fuel consumption improvements measured in tests, and when running the craft at full speed with WOT, there is only a small fuel consumption improvement against existing 2-stroke models. On the other hand, Fig. 16 shows that the newly developed engine demonstrates a 16% improvement in fuel economy over approximately a month of idling, towing and ordinary running, and the same results can be expected in ordinary use.

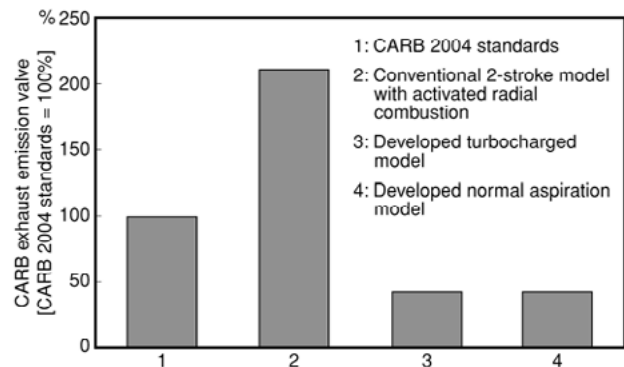


Fig. 15 CARB exhaust emission values

(g/kW h)

ICOMIA Mode Number	Conventional 2-stroke model with activated radical combustion	Developed turbocharged model	Developed normal aspiration model
1	389	310	286
2	343	307	305
3	330	329	341
4	350	418	421
5	(No load)	(No load)	(No load)

Table 3 Specific fuel consumption of emission test mode

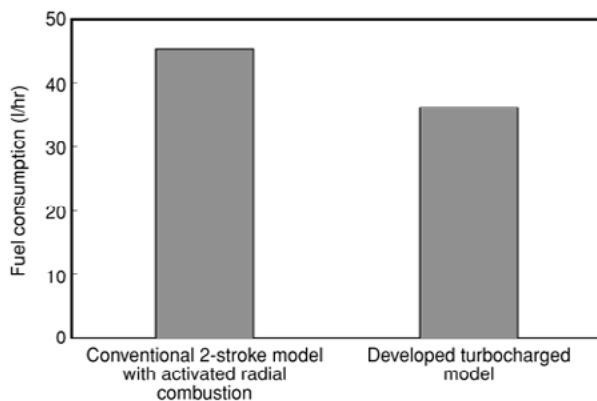


Fig. 16 Fuel consumption of actual riding

- (4) Restricting the exhaust pulse with the turbocharger and controlling engine speed at maximum power has reduced exhaust noise, and enabled a balance of quietness and speed. Lowering engine speed at maximum power has improved the feeling of acceleration, and increased the potential of the craft to provide enjoyable marine leisure to users.

6. Acknowledgments

The team at Ishikawajima-Harima Heavy Industries Co. Ltd. accepted the challenge of achieving a world first, and together with the Honda development team overcame difficult design issues in developing an exhaust turbocharger for exclusive use with the PWC discussed in this paper. The authors would like to take this opportunity to offer their sincere thanks to everyone concerned.

References

- (1) Shogase, H., et al.: Honda's New Personal Watercraft – The AquaTrax F12/F12X, Honda R&D Technical Review, Vol. 14, No. 1, pp. 1-10 (2002)

5. Conclusion

To develop the engine discussed in this paper, various changes were made to a base motorcycle engine to adapt it to marine use. These changes, and the addition of a turbocharger, have increased performance to a level higher than that of conventional 2-stroke models. This has enabled the development of a 4-stroke PWC which is both sporty and easy to handle, and which demonstrates a superior level of performance.

- (1) A motorcycle engine was adapted to PWC engine requirements such as ability to be overturned and direct seawater cooling. These adaptations enabled the development of a marine 4-stroke engine.
- (2) The new engine has cleared both the EPA 2006 and the CARB 2004 emission regulations. It does not cause water pollution due to unburned oils like 2-stroke models, and improvements to fuel consumption during actual running have contributed to reducing environmental impacts.
- (3) The fitting of an exhaust turbocharger has enabled the achievement of specific power and power-weight ratios equivalent to those of 2-stroke engines. In addition, control of turbocharger pressure has ensured optimal power characteristics with little change due to the altitude at which the craft is used.

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