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ABSTRACT

The "RA168E", a turbo-charged V-6 1.5-liter engine, was developed by Honda Motor Co., Ltd. for the 1988 Formula One Championship Race events.

Despite boost restrictions (2.5bar), the engine boasts a maximum power of 504 kw (685 ps), which is equivalent to 336 kw/ℓ (457 ps/ℓ). The development of improvements on the fuel consumption of this engine allowed the achievement of a minimum brake specific fuel consumption of 272 g/kwh (200 g/Psh).

This paper introduces major specifications, along with power output and fuel consumption characteristics of the RA168E racing engine. In addition, the effects of intake air temperature, boost, air-fuel ratio, fuel temperature and fuel ingredients on fuel efficiency and power output are presented.

SINCE 1983, HONDA has been supplying leading Formula One racing teams with dual turbo-charged V-6 1.5-liter engine. Although the engines were all identical in overall configuration, they were modified each year as the regulations were revised; therefore, respective engine code names were used for each modification, as shown in Table 1.

Honda engines have won 40 Grand Prixs in the last five years. As a result of these victories, Honda has been awarded the Constructor's Championship for the last three consecutive years. In accordance with the new regulations, beginning in 1989 only naturally-aspirated 3.5-liter engines will be allowed, and turbo-charged 1.5-liter engines are eliminated from participating in the Grand Prix races.

Stricter fuel restrictions have been gradually adopted, as shown in Table 1. In 1988, the restriction became particularly noticeable, with the boost limit being lowered to 2.5 bar and the maximum fuel capacity being restricted to 150 liters for the turbo-charged cars. Fuel restrictions lead to a reduction in total energy available during a race; therefore, indirectly limiting the maximum power of the engines. This description characterizes the 1988 Grand Prix racing season.

Honda's 1988 engine, the RA168E, was developed to simultaneously realize higher power and better fuel efficiency. The highest possible achievement of these two conflicting objectives resulted in an unprecedented 15 victories in 16 events in the 1988 World Championship races.

Few research papers have mentioned high-speed, high-boost engines(1-3)*; and there has been no research reported concerning the fuel efficiency of those engines. This paper introduces the major specifications and power characteristics, and presents study results relating to the fuel efficiency of the RA168E.

RA168E ENGINE SPECIFICATIONS

A highly rigid and compact cylinder block and bearing caps are cast from strong and stiff ductile cast iron. For reducing its weight, cylinder block thicknesses range between 2-3.5 mm, which also satisfies stiffness requirements. Aluminum alloy (Al-Si6Cu4) was adopted as the material for the cylinder head, while almost all remaining parts being cast from magnesium alloy (e.g., oil-sump and head cover). All this resulted in a compact, light-weight engine; only 146 kg fully-dressed with all equipment. This light-weight coupled with excellent power characteristics and reliability, made the RA168E

Table 1 Restrictions on turbo-charged cars and respective engine code names

Year	1985	1986	1987	1988
Boost pressure(bar. abs)	–	–	4.0	2.5
Fuel Capacity(ℓ)	220	195	195	150
Engine code name	RA165E	RA166E	RA167E	RA168E

*Numbers in parentheses designate references at end of paper.

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a highly competitive engine. The major engine specifications are given in Table 2, Figures 1 and 2 show the cross section and the external appearance of the RA168E, respectively.

The RA168E features a stroke of 50.8 mm and bore of 79 mm, (a stroke-bore ratio of 0.643), providing it with somewhat of a longer stroke when compared with ordinary racing engines. The valve angle is relatively narrow (32°), with the heads of the pistons set almost flat. This configuration allows a compact combustion chamber and a fairly high compression ratio of 9.4 to realize high power output and good fuel efficiency.

The camshafts are driven by the crankshaft via two idler gears. The valve operating mechanism, using rocker arms, allows high-load valve springs in the limited space between the valves. Through using this type of configuration, the reduction in the equivalent inertia weight of the mechanism has improved the revolution limit to an engine speed of more than 13,500 rpm.

Table 2 RA168E engine specifications

Engine Code name	168E
Layout	80°V6
Bore (mm)	79
Stroke (mm)	50.8
Displacement (cc)	1494
Compression Ratio	9.4
Weight (kg)	146
Fuel System	HONDA PGM FI
Ignition System	HONDA PGM IG(CDI)
Super Charger	Ceramic Turbo

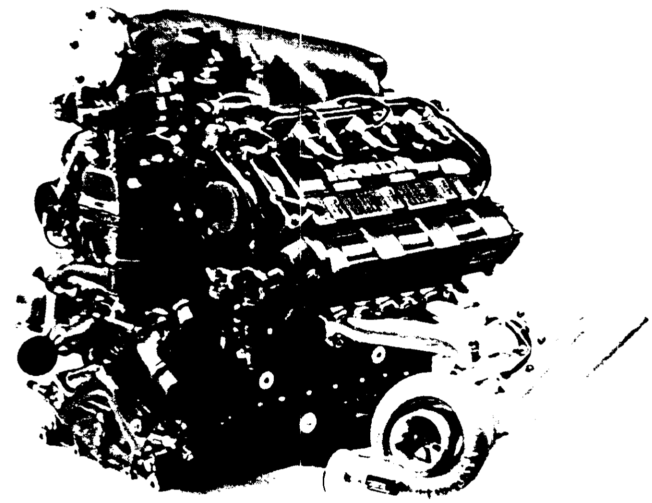

Fig. 2 RA168E external appearance

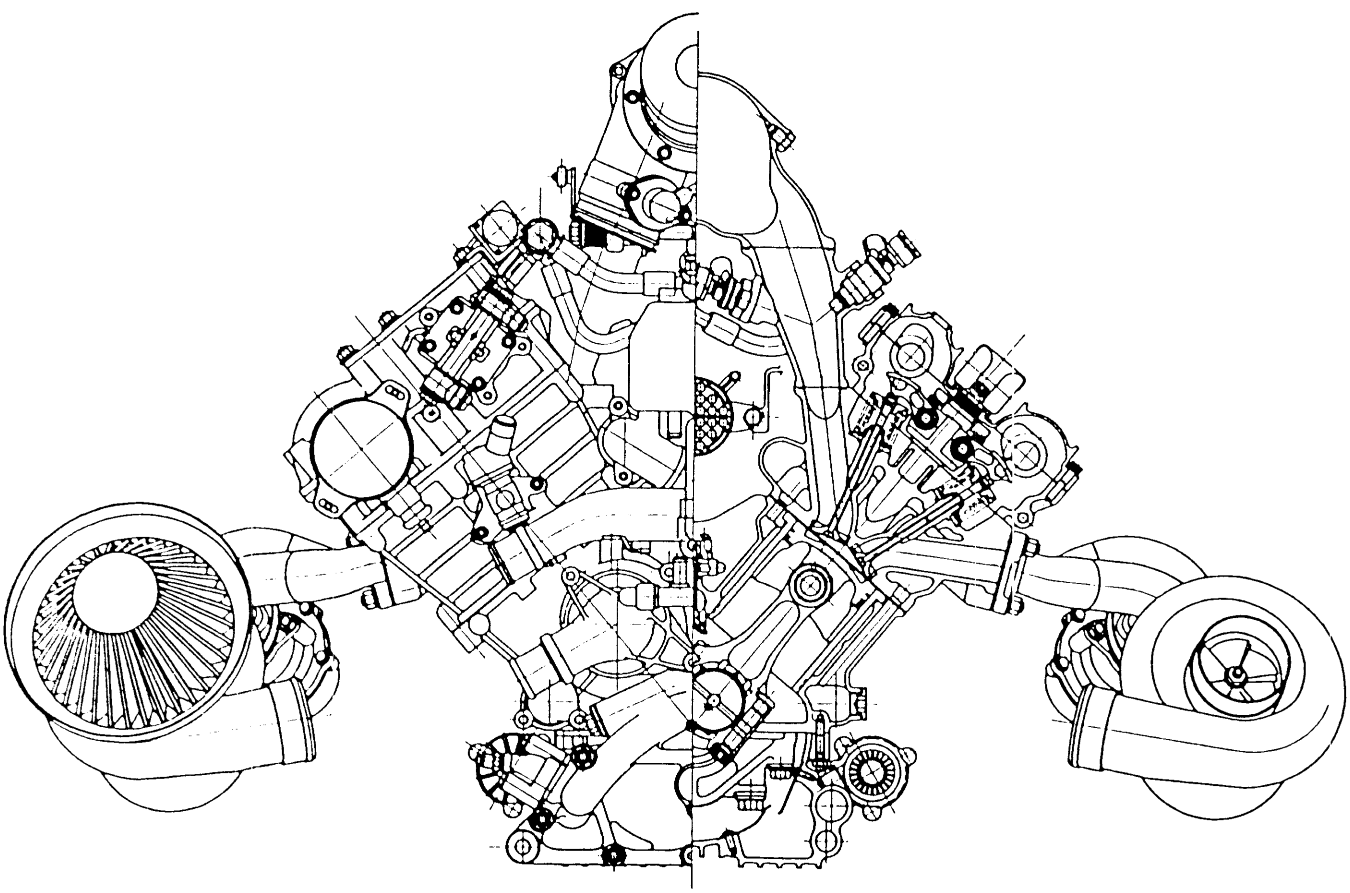

Fig. 1 RA168E cross section

A dry-sump lubrication system was adopted for the RA168E. Four independent scavenging pumps draw the lubricant through strainers at the corners of the oil-sump, and then feed it into an oil tank. With this layout, the scavenging pumps effectively circulate the lubricant, which tends to gather in the oil-sump due to longitudinal and lateral G-forces during acceleration, deceleration and cornering respectively.

Application of an appropriate cooling system is as important as that of the lubrication system for a racing engine. The RA168E has two water pumps which supply water from each side of the cylinder block. Water galleries are located on the outer walls of the cylinder block and the inner walls of the cylinder heads. Water travels from the cylinder block galleries, passing by the cylinder liners and through the cylinder heads, and flows into the cylinder head galleries. The lateral flow of water through the engine allows uniform thermal conditions throughout all cylinders.

We adopted a PGM-FI (Programmed Fuel Injection System), produced in-house, which sequencially injects fuel into six cylinders. Each cylinder is equipped with two injectors. Whether single- or double-injection is used depends on the amount of fuel required. In addition, the fuel line between the fuel pump and the injectors has a heat exchanger for pre-heating fuel by using water from the cooling system.

Dual turbo-chargers, code named "RX6D", are products of Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI). They feature ceramic turbine wheel and ball bearings; drastically upgrading the transient properties by reducing the inertia moment and friction of revolving parts.

ENGINE PERFORMANCE

POWER OUTPUT AND TORQUE - For comparative data, we first present the performance of our RA167E engine. The RA167E was redesigned and upgraded to the prerequisites of the 4 bar boost restriction. Its maximum power was 742 kw (1,010 ps) at 12,000 rpm with a maximum torque of 664 Nm (67.7 kg-m). Power characteristics are shown in Figure 3; which were recorded under the following operating conditions: (1) Boost was 4 bar. A portion of the exhaust gas is emitted from the waste gate of the exhaust manihold. Turbine speed is controlled by adjusting the opening of the waste gate, thus controlling the boost at 4 bar. (2) Intake air temperature was 40°C. Hot intake air compressed by the turbo-chargers is cooled with air-cooled intercoolers. A portion of the air flowing into the intercoolers is expelled via by-pass valves. A temperature of 40°C is maintained through controlling the valve opening. (3) Equivalence ratio was 1.23. (4) Ignition timing was set at MBT or retarded at the knock limit. (5) Fuel with a toluene content of 84% was used. As far as this report is concerned, this fuel was generally used during bench dynamometer tests and race events (see Table 3).

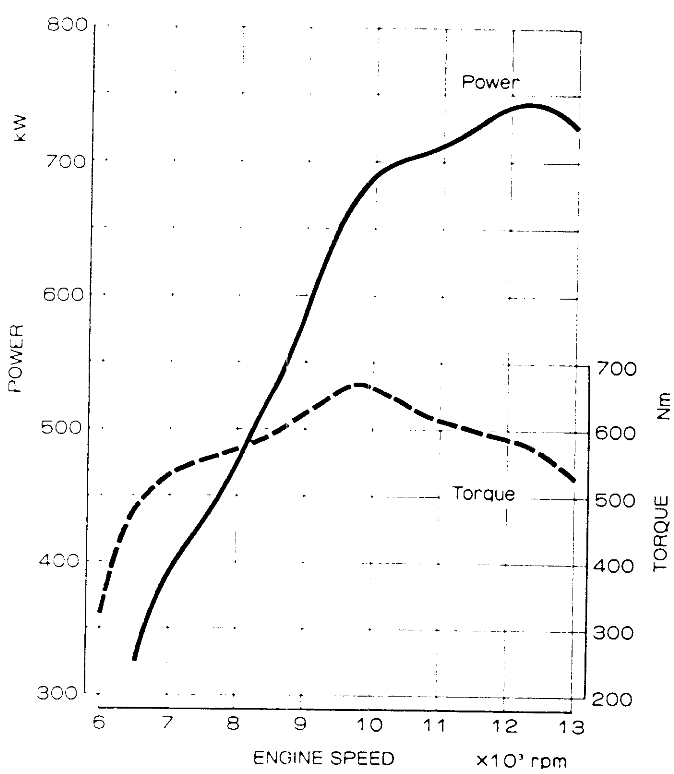

Fig. 3 RA167E power characteristics

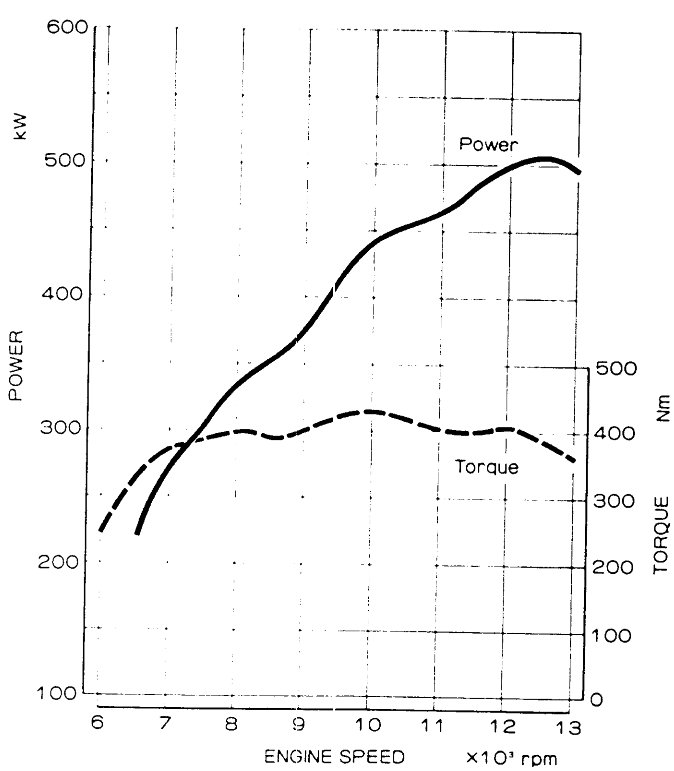

Fig. 4 RA168E power characteristics

Regulations were further revised in 1988 restricting the boost limit to 2.5 bar and fuel tank capacity to 150 liters. In order to generate higher power output, and improve fuel efficiency at the same time, the compression ratio of the RA168E was increased to 9.4, up from 7.4 of the RA167E. Figure 4 shows the power characteristics of the RA168E, which produces maximum power of 504 kw (685 ps) at 12,500 rpm and maximum toruque of 424 Nm (43.2 kg-m). Running conditions were set at;(1) boost of 2.5 bar, (2) intake air temperature of 40°C, (3) equivalence ratio of 1.15 and (4) ignition timing of MBT or spark retard at the knock limit. With a rich mixture of the equivalence ratio being 1.15 and a low intake air temperature of 40°C, the engine generates its maximum power. However, the fuel efficiency under these conditions was not satisfactory.

Under the conditions described above, it was sometimes obvious that it would be impossible to complete an entire race with such poor fuel efficiency. During a race specified running conditions were selected to improve fuel efficiency. Maximum power conditions were realized mainly in qualifying sessions, where sustained running was not necessary.

In terms of power per liter, the RA167E generated 495 kw/ℓ and the RA168E produces 336 kw/ℓ. As shown in Figure 5, taking boost pressure into consideration, comparison of the power characteristics shows that the RA168E is favorable, due to a higher compression ratio and lower friction.

CYLINDER PRESSURE DIAGRAM ANALYSIS - The RA168E generates 504 kw (685 ps) at 12,500 rpm. In the case of high-speed, high-boost engines, combustion often becomes unstable; in the worst case, leading to misfiring. This could pose a problem when attempting to manufacture engines which constantly generate high power. Concerning the RA168E, we increased the compression ratio, and modified the intake port configuration and the fuel injection system in order to stabilize combustion.

There have been few studies concerning cycle variations in a high-speed, high-boost engine. The cycle variation was analyzed by measuring cylinder pressure during maximum power generation.

A pressure transducer (product of Kistler) connected to a charge amplifier was used to measure the cylinder pressure. Samples were taken at each crank angle degree. A combustion analyzer (product of Ono Sokki) was adopted for the analysis.

Figure 6 is an averaged pressure diagram of 500 consecutive cylinder pressure measurements under the conditions of 12,500 rpm, boost of 2.5 bar, intake air temperature of 40°C, equivalence ratio of 1.15 and ignition timing of 35° B.T.D.C.

The maximum combustion pressure was 16.7 MPa, crank angle at which maximum pressure produced was 17° A.T.D.C., and indicated mean effective pressure (I.M.E.P.), was 3.8 MPa.

Figure 7 shows the frequency distribution of I.M.E.P. indicating that the standard deviation was 0.20 MPa against the average value of I.M.E.P. of 3.8 MPa, which revealed that fairly stable combustion was achieved.

FUEL EFFICIENCY

The main objectives when developing the RA168E to consume less fuel during a race were to improve fuel consumption characteristics and the development of high energy fuel (heavy specific weight fuel).

The throttle opening distribution during

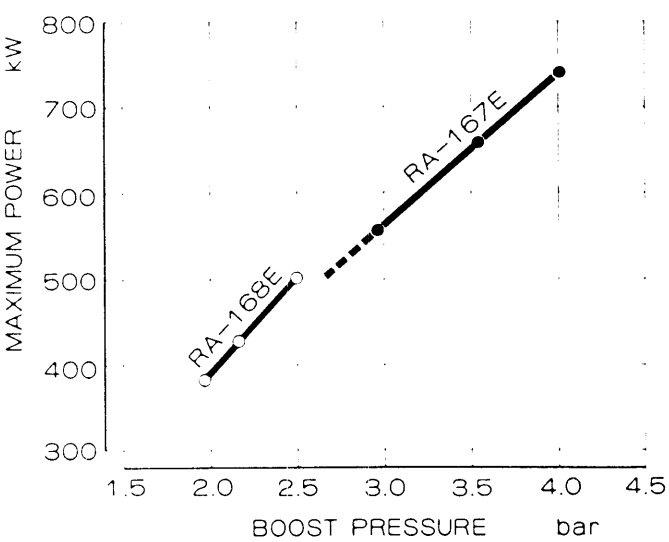

Fig. 5 Maximum power of RA168E and RA167E related to boost pressure

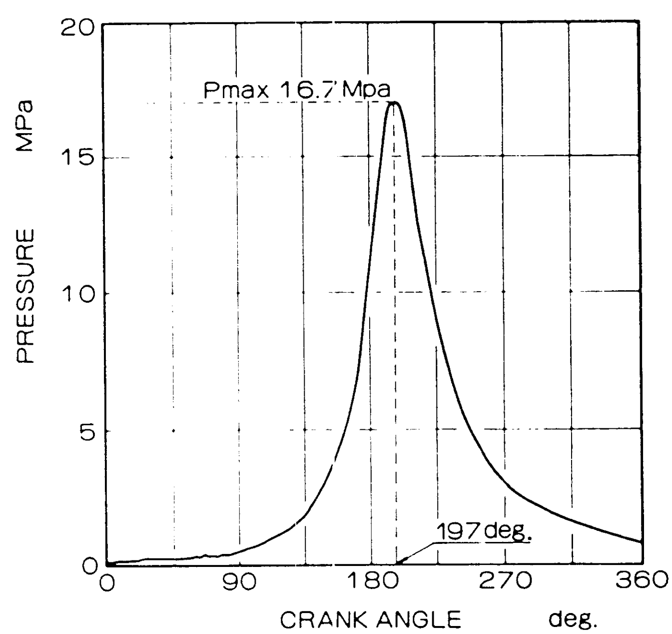

Fig. 6 Cylinder pressure diagram of RA168E under condition of maximum power generation

a race is shown in Figure 8 (1988 San Marino GP, with driver Alain Prost). Since it was revealed that full-throttle and closed-throttle dominate the throttle conditions during a race, we concentrated on improving the fuel consumption at full-throttle.

Figure 9 shows the RA168E performance when the major factors were set to minimize fuel consumption, indicating that minimum brake specific fuel consumption (B.S.F.C.) is 272 g/kwh (200 g/psh) at 12,000 rpm, and maximum power is 456 kw (620 ps) at 12,500 rpm. The operating factors of this condition are a boost of 2.5 bar, intake air temperature of 70°C, equivalence ratio of 1.02 and fuel temperature of 80°C.

Concerning circuits used for GP racing, straight stretches, number and type of corners and overall racing distances are not always the same. Thus, even if the engine's operating conditions remain the same, fuel consumption (km/ℓ) differs.

When favorable fuel consumption was observed at some circuit richer mixture setting and reduction in intake air temperature were possible. Though these conditions worsen B.S.F.C. of the engine itself, they can be selected as operating factors to generate higher power.

EFFECT OF INTAKE AIR TEMPERATURE - The intercooler system makes it possible to cool the intake air down to a temperature which is only 15°C higher than that of ambient air. This is achieved by closing the by-pass valves and directing all the air through intercoolers. As the intake air temperature increases, B.S.F.C. becomes better (see Fig. 10). After the intake air temperature exceeds 70°C, B.S.F.C. improvement tends to become saturated. Despite relatively bad volatility of the fuel used, a rise in the intake air temperature promotes vaporization. This B.S.F.C. improvement might be attributed to the well vaporized fuel.

However, as the temperature increases, there is a tendency to generate knocking, and the ignition timing must be retarded to avoid it. When the timing is retarded further from M.B.T., the results have an undesirable effect on B.S.F.C.

EFFECT OF BOOST PRESSURE - Higher boost has good effects on both power and B.S.F.C., as shown in Fig. 11. One of the prominent reasons is that, in proportion to the rise in boost, charging efficiency increases and provides higher indicated horse power while the engine's mechanical loss remains almost the same, resulting in an improvement of brake thermal efficiency.

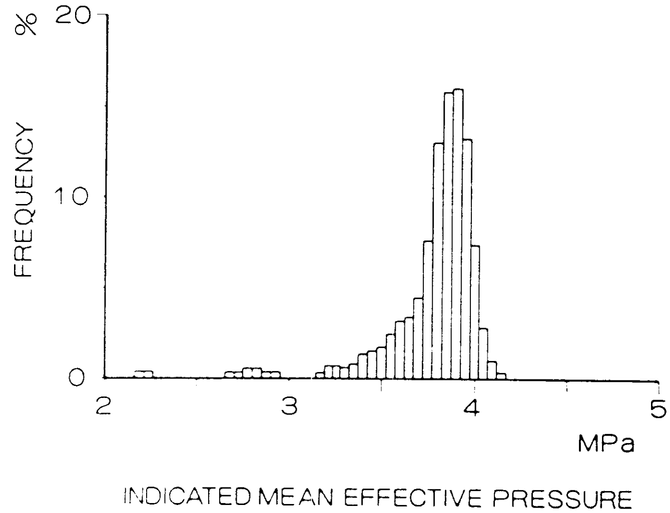

Fig. 7 I.M.E.P. frequency distribution

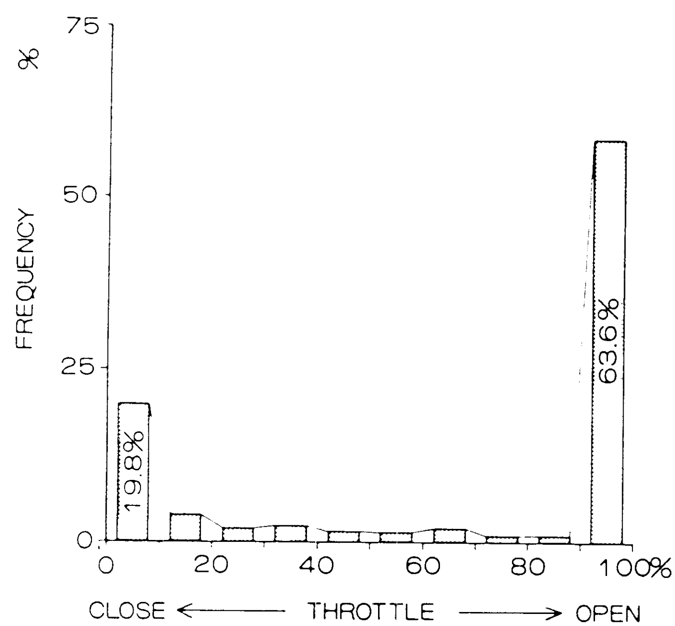

Fig. 8 Throttle opening distribution during a race event ('88 San Marino GP)

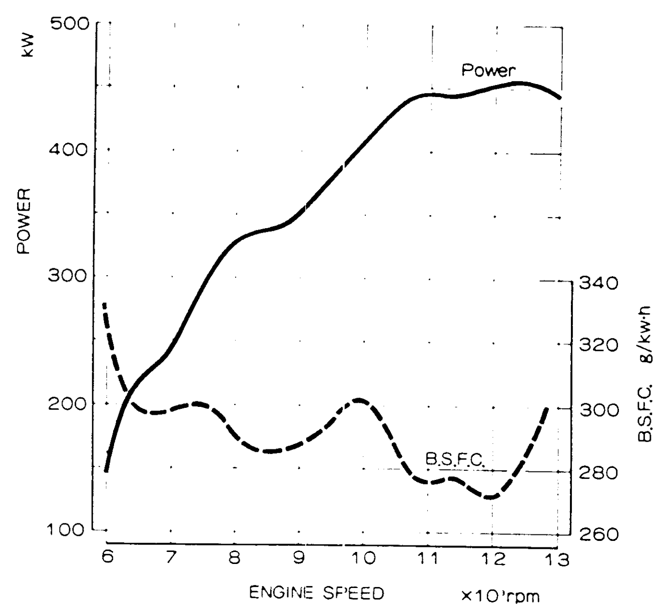

Fig. 9 RA168E performance at minimum fuel consumption

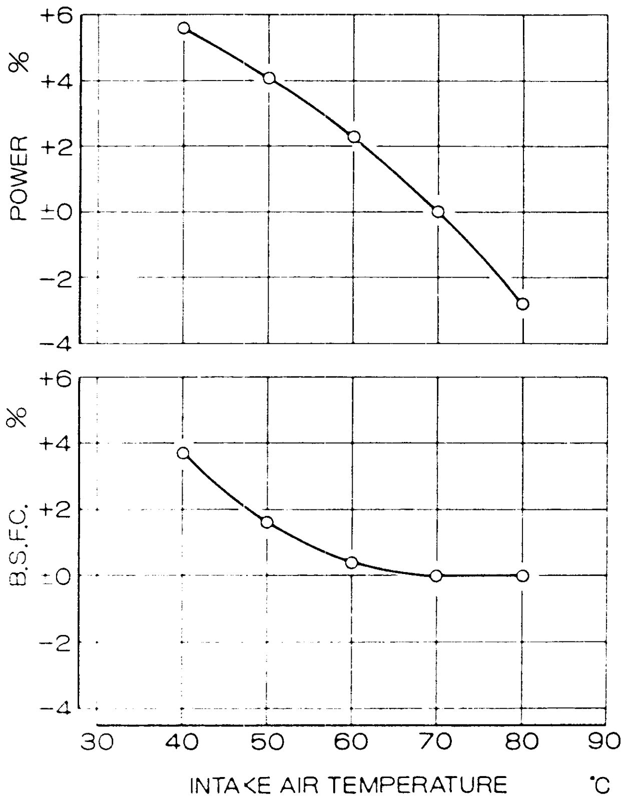

Fig. 10 Effect of intake air temperature on power and B.S.F.C.

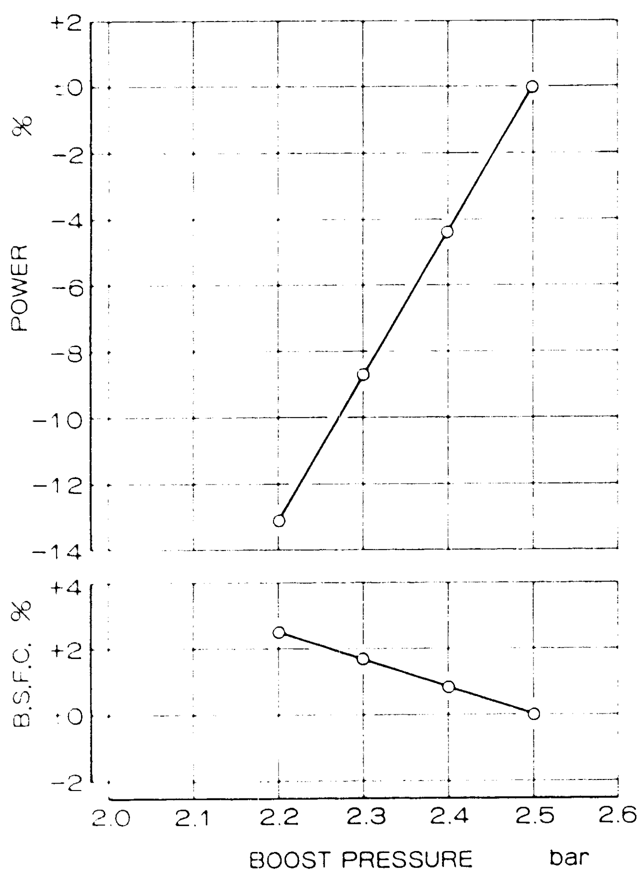

Fig. 11 Effect of boost pressure on power and B.S.F.C.

EFFECT OF AIR FUEL RATIO - Regarding air-fuel ratio, peak power is reached at an equivalence ratio of 1.15, and power gradually decreases as the ratio falls below this figure. The leaner the mixture becomes, the better the B.S.F.C., as shown in Fig. 12. However, with a ratio lower than 1.02, unsatisfactory transient response may appear, thus making the engine become insufficient for racing performance.

EFFECT OF PRE-HEATING FUEL - B.S.F.C. is improved through promotion of vaporization with higher intake air temperature. The same effect can be achieved using pre-heated fuel (i.e., fuel heated before injection). As the distillation characteristics shown in Table 3 reveal, the racing fuel for the RA168E is not easily vaporized at the ambient temperature because it does not contain low boiling-point ingredients. For this reason, the RA168E was equipped with a heat exchanger capable of pre-heating fuel using the water from the cooling system. After being fed by the fuel pump and then heated, it is distributed to the injectors. It is possible to heat the fuel to a temperature 15°C below that of the water.

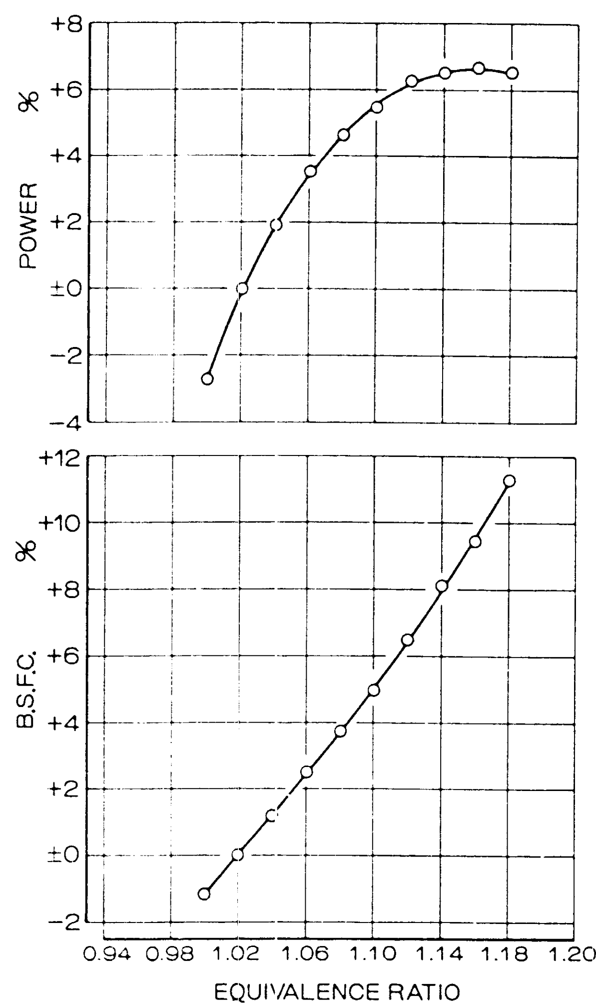

Fig. 12 Effect of equivalence ratio on power and B.S.F.C.

The amount of water which flows into the exchanger is controlled by a solenoid valve which maintains the desired fuel temperature.

Figure 13 shows the effect of fuel temperatures on the fuel efficiency. It is acknowledged that, although the effect is not significant, the fuel consumption is reduced as the fuel temperature rises.

A combination of operating factors to achieve the best B.S.F.C., while maintaining satisfactory performance, is an intake air temperature of 70°C, a boost of 2.5 bar, an equivalence ratio of 1.02 and fuel temperature of 80°C. With this combination, B.S.F.C. is 272 g/kwh (200 g/psh) at 12,000 rpm.

EFFECT OF TOLUENE CONTENT - The octane number of fuel for Formula One racing is limited to a maximum of RON 102. Adopting a higher compression ratio is expected to improve both power and B.S.F.C. However, at the same time, the possibility of knocking becomes higher. Therefore, the knocking properties of fuels determine maximum compression ratio. It sometimes appears that differences in fuel ingredients effect knocking properties, even though the RON of the fuels is the same. The development of a fuel with good knocking properties under high speed and boost conditions is essential for adopting a high compression ratio.

The tank capacity regulation limits fuel amount to 150 liters, and refueling during a race event is forbidden. In order to obtain a higher level of fuel energy for a race, a fuel largely calorific in capacity is needed (i.e., a dense fuel). Comparative evaluation of various fuels revealed that a fuel with high toluene content is most favorable to meet the requirements. Knocking properties and effects on B.S.F.C. of the test fuels (see Table 3) are shown in Figure 14.

Toluene content ratios were 30%, 60% and 84% for each test fuel. Appropriate amounts of normal heptane and isooctane were respectively mixed with toluene to achieve a RON of 102. As toluene has a heavier density when compared to paraffine fuels, a fuel containing much toluene has a larger calorific value in capacity (Cal/cc). Whether knocking occurred or not was observed through analyzing the output signal of a charge amplifier connected to a piezo-electric pressure transducer fixed in the place of the spark plug washer. Observations were conducted under the engine operating conditions of ; 12,000 rpm, 2.5 bar, intake air temperature of 70°C and an equivalence ratio of 1.15. The knock-limit ignition timing advances as the ratio of toluene increases in the fuel ingredients, resulting in better B.S.F.C. In addition, since the test fuels differ in density, "brake specific volumetric fuel consumption (B.S.V.F.C.)" (cc/kwh) was considered, and studies revealed that a fuel containing a higher ratio of toluene in the fuel ingredients proved most effective.

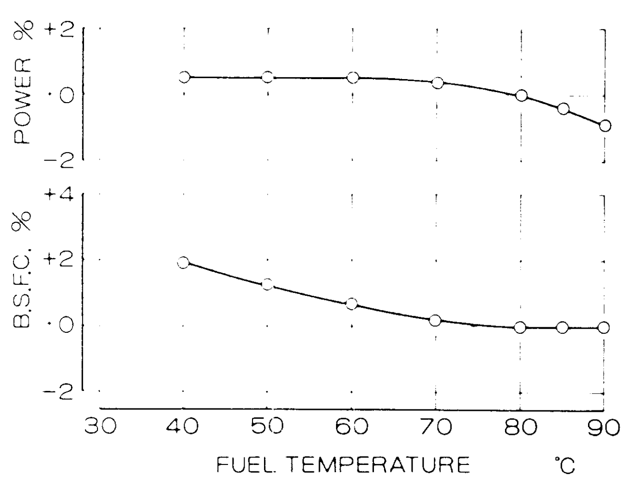

Fig. 13 Effect of fuel temperature on power and B.S.F.C.

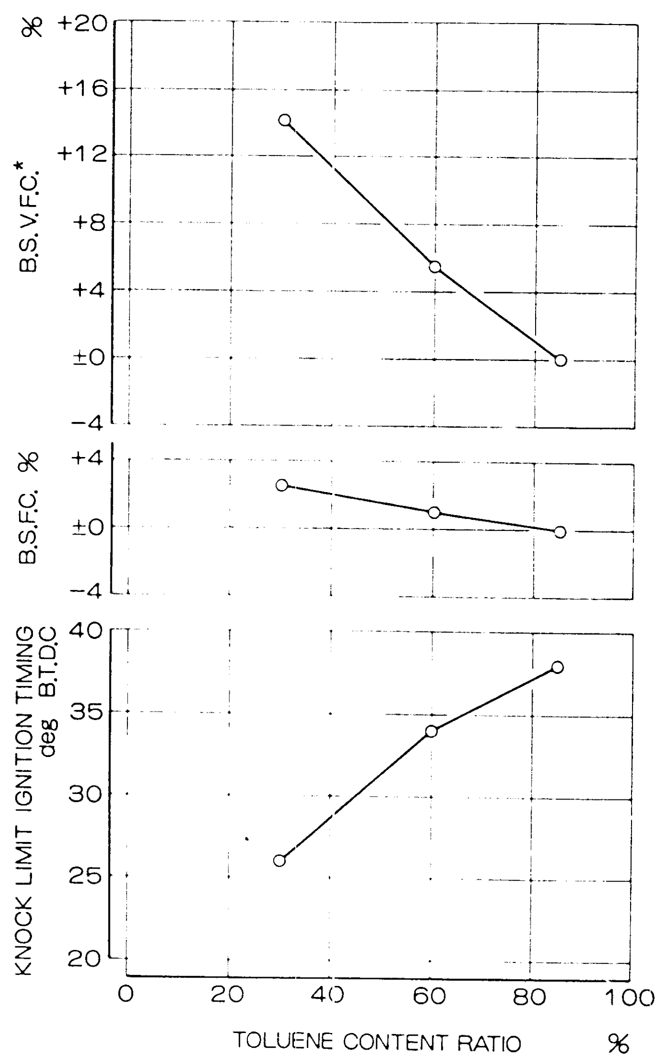

Fig. 14 Effect of toluene content ratio on knock limit ignition timing and fuel consumption

* B.S.V.F.C "brake specific volumetric fuel consumption" (cc/kwh)

Table 3 Test fuel specifications

		A	B	RACING FUEL *
Fuel ingredient	Toluene (%)	30	60	84
	n-Heptane (%)	4	9.5	16
	Isooctane (%)	66	30.5	0
Research Octane Number		101.6	101.9	101.8
Motor Octane Number		94.2	91.2	90.0
Density (at 15°C)		0.747	0.799	0.840
Net Calorific Value (Kcal/Kg)		10300	10015	9817
Stoichiometric Ratio		14.5	14.0	13.7
Reid Vapor Pressure (Kg/cm²)		0.154	0.141	0.120
Initial Boiling Point (°C)		96.0	98.5	100.0
10%	(°C)	97.5	100.5	105.0
50%	(°C)	98.5	102.0	106.0
90%	(°C)	100.0	105.0	108.0
End Point	(°C)	123.5	108.0	116.0

*This fuel is jointly developed by ELF FRANCE and HONDA for the special racing purpose.

SUMMARY

Honda has developed a Formula One turbo-charged V-6 1.5-liter engine, which was very successful in the 1988 Grand Prix racing season. Through the research and development on this engine, the results can be summarized as follows:

(1) Optimizing operating factors to produce the best results possible under the 2.5 bar restriction, the engine successfully produced a maximum power output of 504 kw (685 ps), which is equivalent to 336 kw/ℓ (457 ps/ℓ).

(2) A combination of operating factors was studied to minimize fuel consumption and the minimum brake specific fuel consumption was found to be 272 g/kwh (200 g/Psh) when the engine generated 456 kw (620 Ps).

(3) A high toluene content in fuel had a good effect on knocking properties and allowed advanced ignition timing, which resulted in improvement of brake specific fuel consumption. Toluene also had a good effect on improvement of brake volumetric specific fuel consumption because of the heaviness of its density.

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