Development of Horizontally Opposed 2.0-liter Natural Aspiration Gasoline Engine for Subaru BRZ

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Summary

The all-new FA20 engine was developed exclusively to be fitted in the Subaru BRZ. The basic construction comes from FB20, a former unit developed as the Subaru's third generation 4-cylinder horizontally opposed 2-liter natural aspiration engine. To achieve both high horsepower and environmental friendliness, which is highly demanded for the new generation sports car, the engine adopted technical changes such as Toyota's D-4S system and main components changes for higher engine revolution speed to produce higher output. Also the height of the intake and exhaust parts was restrained to meet the BRZ packaging. This report shows the overview of this newly designed FA20 unit.

*D-4S：Direct injection 4-stroke gasoline engine Superior version

1 Introduction

This new engine aims to have higher output of 100PS/L suitable for the sport car “BRZ and GT86 (FR-S)” based on the FB20 engine. The bore x stroke was completely re-designed to Ø86 mm x 86 mm, which was determined by considering the required volume of air intake. The combination of Toyota’s D-4S direct injection technology and Subaru’s engine development technology generates high engine speed exceeding 7000 rpm while producing high output of 147 kW (200PS) and high torque of 205 Nm. In addition, the class leading Europe fuel efficiency of CO_2 159 g/km is accomplished while the emission regulation EURO5 requirements are met. This means that the new engine overcame the conflicting factors: higher engine output and environmental friendliness. (Fig. 1, Fig. 2)

Originally, by its nature, the horizontally opposed engine is characterized as a lightweight and compact engine with the low center of gravity. The layout of the air intake and exhaust systems was totally modified for BRZ. The overall height was reduced by approximately 84 mm and the mounting position and angle were also specially designed. To maximize the benefits of the horizontally opposed engine, its mounting position was lowered to the limit, which contributed to the improvement of vehicle driving performance (Fig. 3).

	BRZ	IMPREZA('12MY)
E/G Model	FA20 D-4S	FB20
Max Power	147kW(200PS)/7000rpm	110kW(150PS)/6200rpm
Max Torque	205Nm/6400～6600rpm	196Nm/4200rpm
Max Engine Speed	7400rpm	6600rpm
Fuel	Premium	Regular
Displacement	1998cc	1995cc
Bore × Stroke	φ86mm×86mm	φ84mm×90mm
Compression Ratio	12.5	10.5
Valve system mechanism	DOHC(Roller rocker arm)	DOHC(Roller rocker arm)
	Chain driven	Chain driven
EGI System	D-4S(DI+MPI)	MPI
Exhaust layout	4-2-1	4-1
TGV	-	O
EGR	-	O

TGV: Tumble Generating Valve
EGR: Exhaust Gas Recirculation

Fig. 1: Engine specification

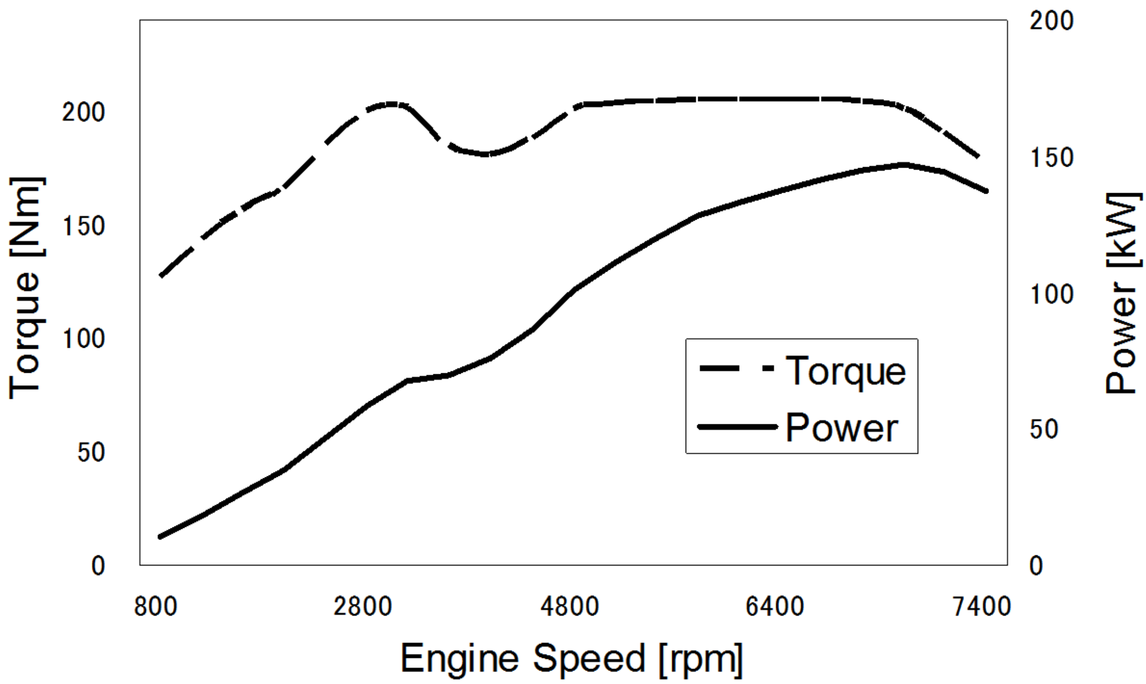

Fig. 2: Engine performance

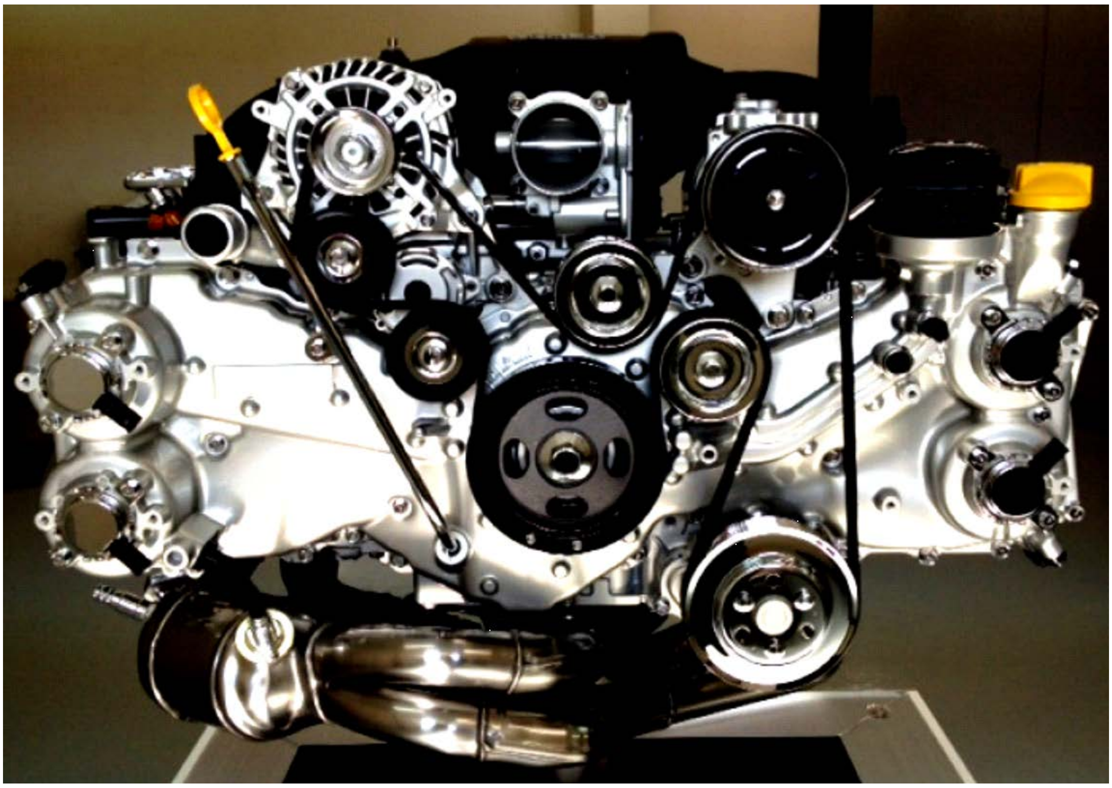

Fig. 3: Engine overview

2 Approach to high engine speed and high output

The specifications had to be totoally reviewed to achieve both 100PS/L and over 7,000 rpm reliability based on the FB engine(1) ,which was designed for better fuel efficiency.

2.1 High output

2.1.1 Cylinder head / combustion chamber, and compression ratio

Various types of cylinder heads and combustion chamber shapes, including those of past models, had been repeatedly simulated and carried out steady-flow analysis to determine combustion chamber specifications required to achieve 100 PS/L (Fig. 4 & Fig. 5).

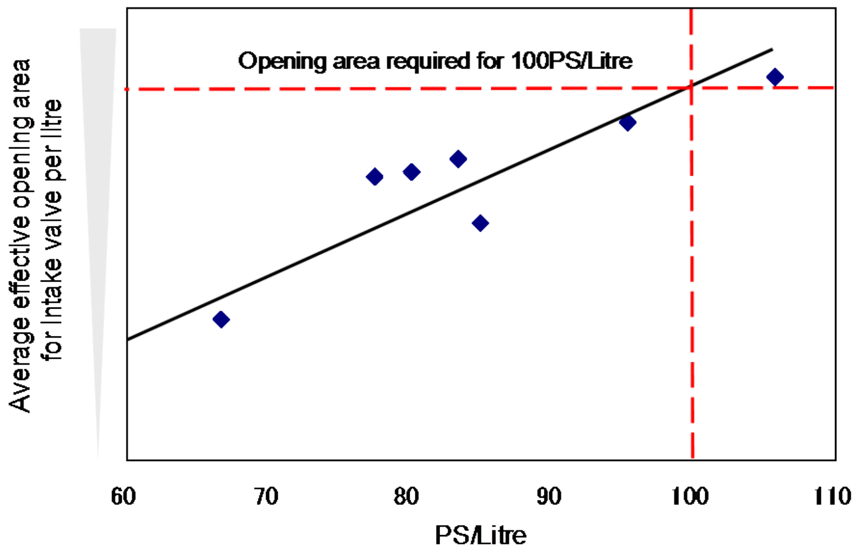

Fig. 4: Intake air flow rate for horsepower per liter

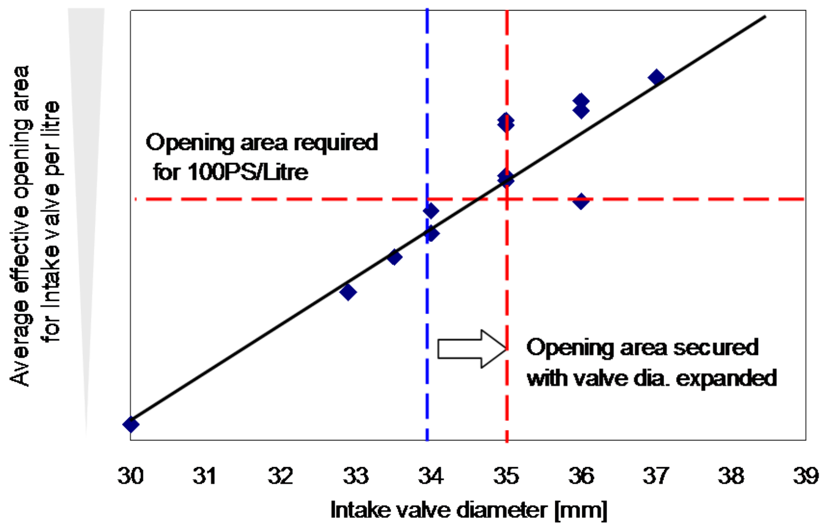

Fig. 5: Intake valve diameter for horsepower per liter

As shown in Fig. 4 and Fig. 5, the valve diameter (Intake: Ø34 mm, Exhaust: Ø28 mm) of the FB20 engine was not sufficient for providing necessary air for required engine output. For this purpose, the valve diameter was expanded. To keep the small number of S/V ratio(2), which stands for combustion chamber surface / combustion chamber volume, the valve diameter expansion had to be minimized (Intake: Ø35 mm, Exhaust: Ø29 mm). The bore size was also changed from Ø84 mm to Ø86 mm to accommodate the expanded valves while the stroke was changed from 90 mm to 86 mm.

To maximize the effects of the expanded valve diameter, the combustion chamber shape around the air intake valve was designed to generate less biased flow and pressure loss in the intake air. The area surrounding the exhaust valve was intended to induce the bell mouth effect with a bulge added around the exhaust valve compared to the intake side. In designing this combustion chamber shape, higher output was set as a first priority for this powerunit without sacrificing environmental performance.

And also, the compression ratio was increased from 10.5 to 12.5 to achieve good thermal efficiency.

2.1.2 Intake manifold and air intake port

The branch length was reduced from 370 mm to 300 mm and the branch pipe equivalent diameter was also continuously varied from Ø60 mm to Ø52 mm. With this smooth intake line, the increased air flow speed was maintained at the cylinder head port. In the middle of the air intake port, a straight line was created to accelerate the air intake speed. This design allowed the pulsation tuning point to be optimized for higher engine revolution and the effect of air intake inertia to be maximized.

The pressure loss was reduced as much as possible by designing details of intake line. For example, the bend shape of the branch was optimized and the gap between components was minimized (Fig. 6).

The TGV, tumble generating valve, used in the FB20 was taken away to get rid of obstacles for smoother air flow.

The throttle diameter was expanded from Ø60 mm to Ø65 mm and intake is from the front of the vehicle since the engine has been placed lower and nearer the vehicle center for better road performance. The air intake pressure loss was also significantly reduced compared to the FB20 engine.

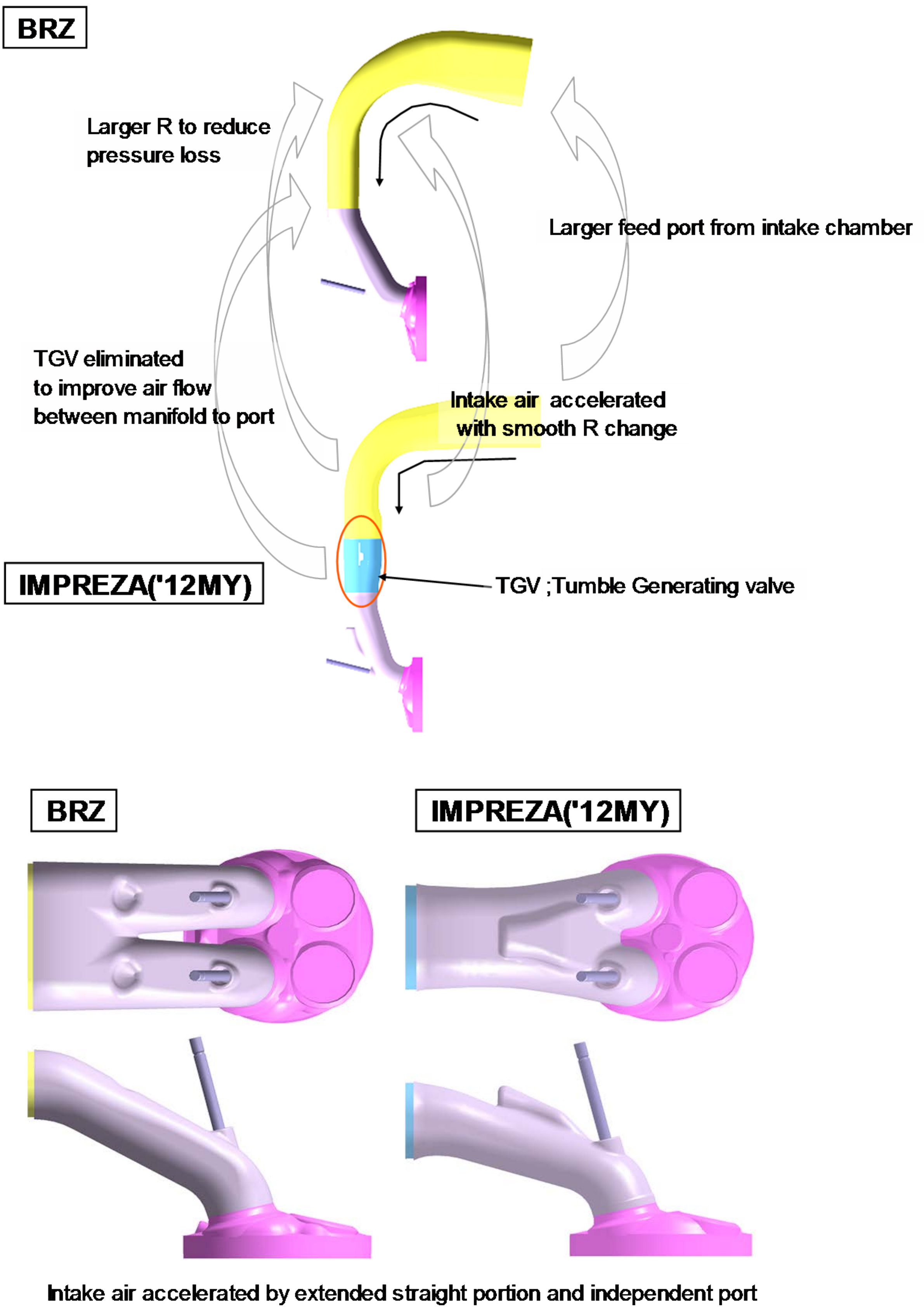

Fig. 6: Intake manifold and port profile

2.1.3 Intake & exhaust cam

The effective angle of intake cam was widened from 120°CA of FB20 engine to 128°CA for the new engine, and the exhaust cam from 112°CA to 126°CA. The valve lift amount was also lifted up to 11 mm for both intake and exhaust, which provided substantial increase in flow rate compared to the FB20 engine.

2.1.4 Exhaust port

For the exhaust port, the venturi shape was tuned to suppress the shrinking flow caused by the exhaust gas separation around the valve seat which is generated especially at the high flow rate. This exhaust port design further lowered exhaust pressure than that for the FB20 engine (Fig. 7).

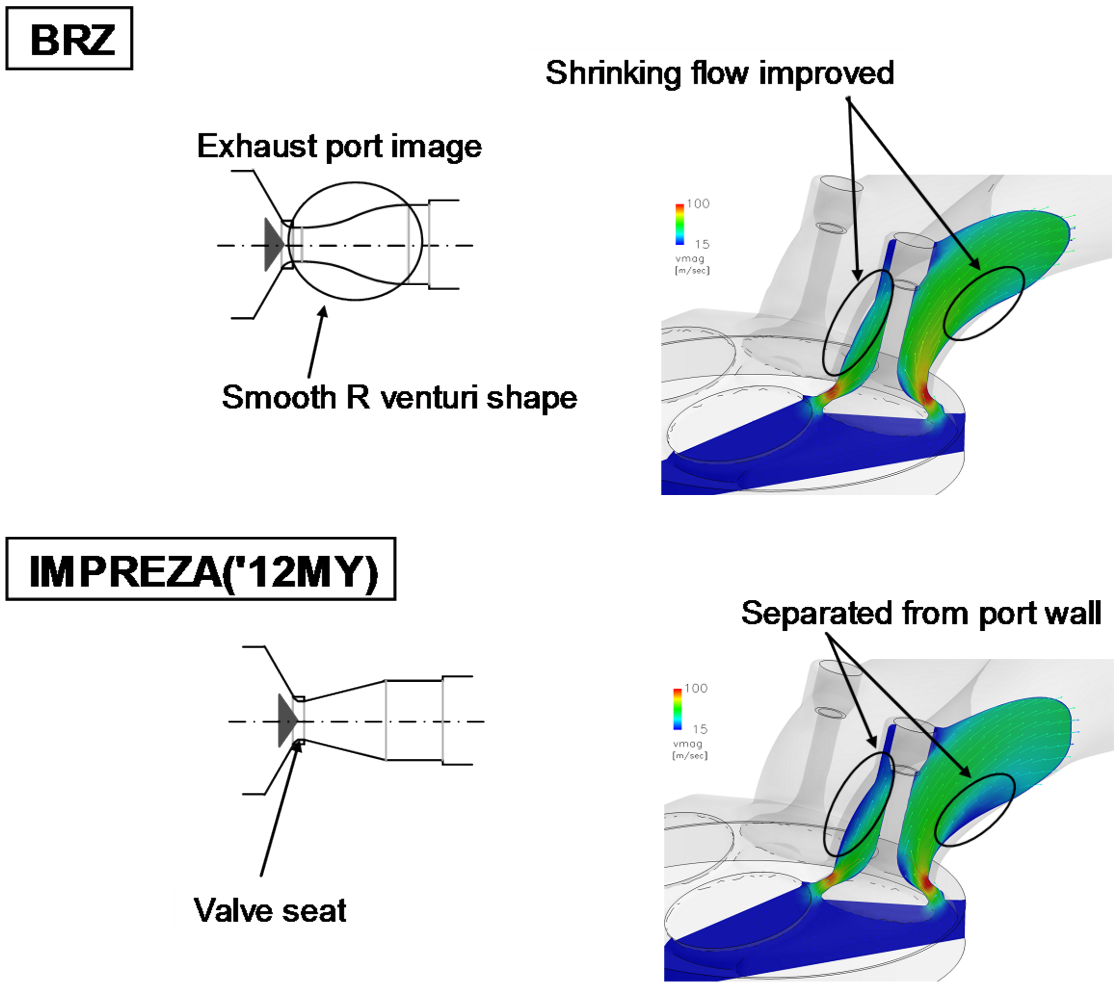

Fig. 7: Flow patterns in exhaust port

2.1.5 Fuel injection system

As a way to improve high compression ratio and volume efficiency, the Toyota's D-4S direct injection technology was employed.

For the direct injection pump, the cam shaft drive on the left-hand bank was adopted to secure high discharge rate. The fuel supplied at 400 kPa is raised up to the maximum fuel pressure of 20 MPa to secure the injection amount required for high speed and high power. The high pressure pump is equipped with a pulsation damper to reduce the fuel pressure pulsation and a relief mechanism to be used when abnormality happens in fuel pressure. This high pressure injection system is a significantly simplified design. In addition, the fuel volume capacity of the direct injection was designed to be as large as possible. While the fuel pulsation was further controlled, superb controllability of fuel injection was ensured with the use of a fuel pressure sensor (Fig. 8 & Fig. 9).

The fuel supply pipe for direct injection has return-less specification. With the simplified and parallel layout of the fuel supply pipe immediately after the feed pump outlet inside the fuel tank, the pulsation transfer from high-pressure direct injection fuel system to low-pressure port injection fuel system is reduced as much as possible.

The port injector was mounted on the intake manifold, increasing the chance of getting the manifold wall wet with sprayed fuel. To solve this, a long nozzle injector is used to get the injection point close to the combustion chamber. At the same time, to secure the performance of a vehicle crash safety, a shorter body injector was adopted.

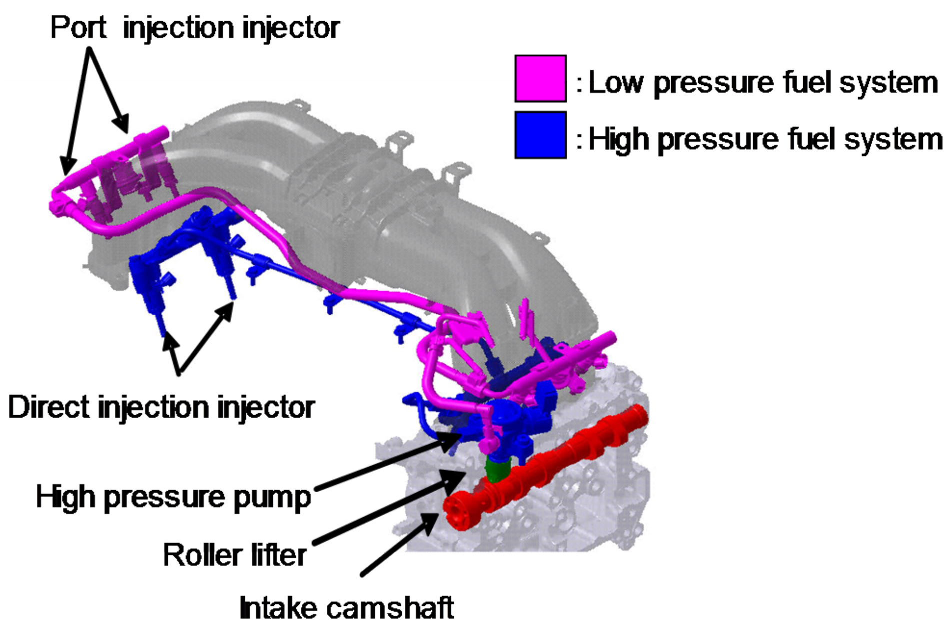

Fig. 8: D-4S fuel system

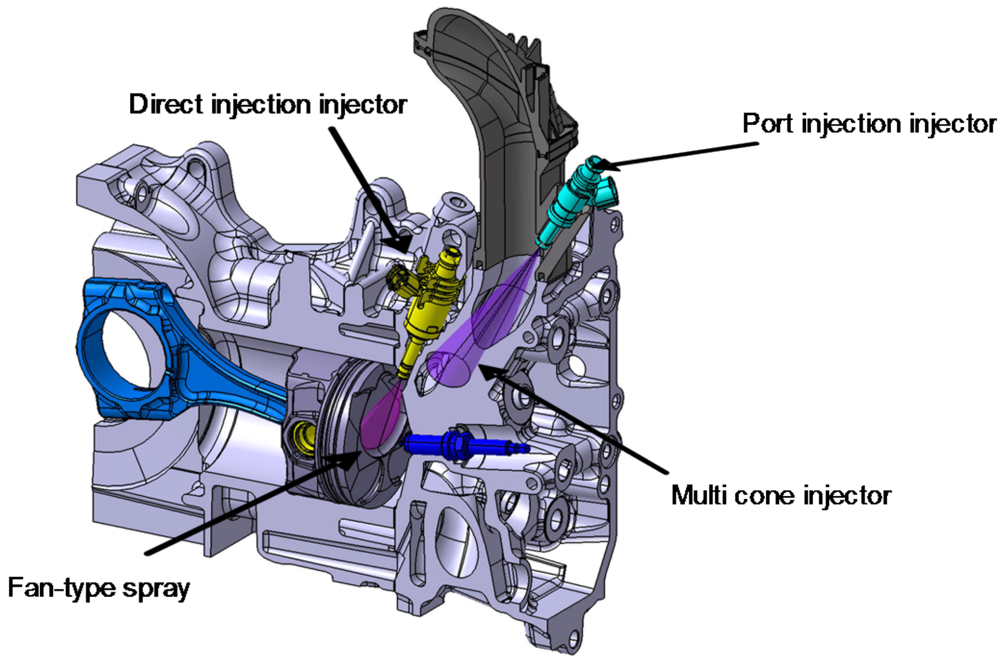

Fig. 9: Combustion chamber configuration

2.1.6 Exhaust pipe

The exhaust pipe has a 4-2-1 layout to achieve higher engine power. Pipe diameters have been increased to reduce exhaust pressure loss. As well as intake manifold, this exhaust pipe design is one of the most important efforts to overcome contradictory issues; high output as a naturally aspirated engine, environmental friendliness, and ultra low center of gravity packaging. (Fig.10)

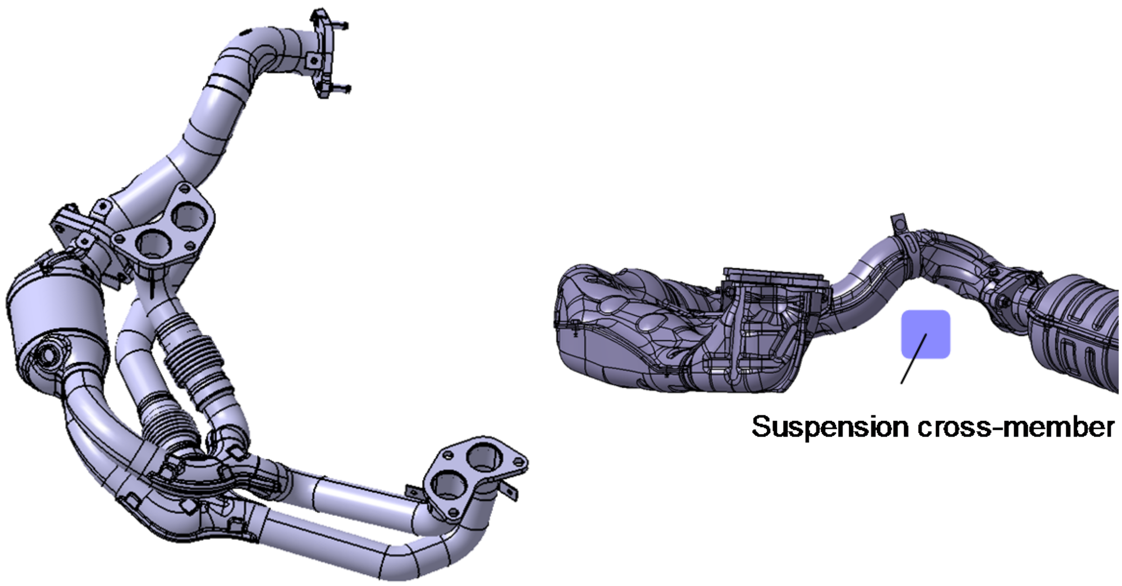

Fig. 10: Exhaust pipe

2.2 Higher engine rev speed

To provide higher engine speed exceeding 7000 rpm, the main moving parts in the FA20 were re-designed, based on the FB20. The crank shaft was newly designed with the pin diameter extended from Ø48 mm to Ø50 mm. Also the overlap area between the pin and the main journal was increased to secure sufficient crank strength and rigidity at higher speed. (Fig. 11)

Fig. 11: Crankshaft, Connecting rod, Piston

2.2.1 Development of connecting rod bearing metal

Based on the design concept of the FB20 engine, a diagonally flucture split type connecting rod was adopted, which has advantage in assembling the horizontally opposed engine. With this diagonally split connecting rod, there were two issues to realize higher engine speed and output.

(1) High surface pressure generated around connecting rod metal joint

(2) Reliability of tightening tension of connecting rod bolts.

These challenges were overcome through newly developed analysis technology and engineering innovation in the specifications of the connecting rod metal. By using this analysis, mass production feasibility and reliability were also established.

2.2.2 Measures for high surface pressure on connecting rod bearing

To clarify the mechanism of how the high surface pressure is generated around the connecting rod joint, an analysis on elastohydrodynamic lubrication (EHL) was used for the first time at Subaru (Fig. 12).

The established analysis method provides highly accurate repeatability of the phenomenon by confirming the correlation between the metal abrasion condition on actual engine and EHL analysis results. The high surface pressure mechanism was clarified through analysis on the bearing metal inner profile deformation. The deformation is correlated to the cylinder pressure, inertia force of reciprocating parts, and relative position between crank pin and bearing metal. Based on this, the inner profile of connecting rod metal was optimized and the connecting rod weight was reduced to suppress the inertia force of reciprocating parts (Fig. 13).

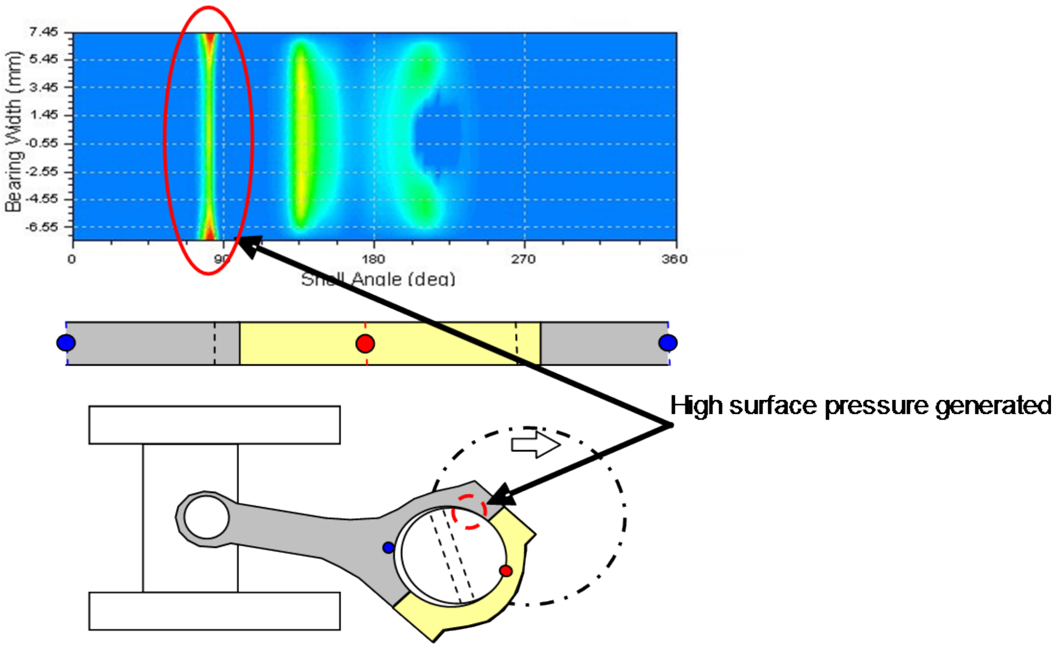

Fig. 12: Pressure distribution by EHL analysis

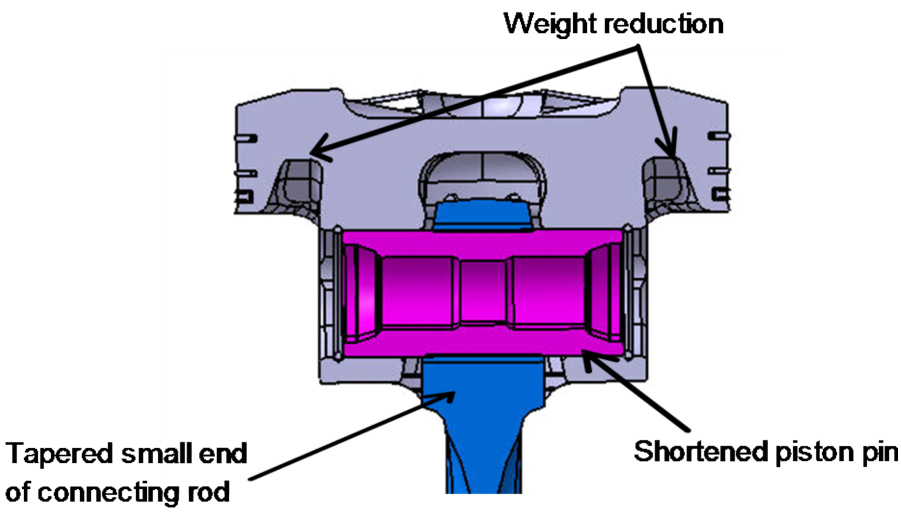

Fig. 13: Details of lightened area of piston and connecting rod

2.2.3 Reliability of tightening tension of connecting rod bolt

If reciprocating inertia force is applied to the connecting rod, uneven load is added to each of the two connecting rod bolts. More load is applied to the connecting rod bolt near the small end, which could eventually deform the circle shape at the larger end. Similarly, the deformation mode around the bearing metal contact surface could become complex especially on the smaller end side. A slight relative movement is generated between the back of the metal and inner side of connecting rod larger end, which could possibly cause fretting and sludge.

To solve this, the metal crush-height was increased as much as possible and the connecting rod bolt tightening was set so that the crush-height can be fully crushed and possible split between contacting surfaces of larger end joint can be prevented. For this purpose, the high strength bolt used for the FB engine was carried over but the screw size was extended (M8 to M9.5).

3 Balance between high output and environmental friendliness

3.1 Approach to low emission gas

The exhaust pipe length of 700 mm from the exhaust port to the catalyst increased the thermal capacity up to 1.22 times compared to that of the FB20 engine. And this deteriorated substantially the warming-up speed of the catalyst. In addition, tumble generating device was eliminated to achieve high output by decreasing pressure loss, which could lead to loss of strength of tumble flow and emission gas performance. This new engine FA20, however, soloved these issues by utilizing the Toyota’s D-4S system without using external EGR system.

The combination of fan-type fuel spray and wall-guide shape of piston crown can distribute fuel spray to the ignition plug stably only by the penetration inertia of injection spray, without support of cylinder inner gas turbulance. (Fig. 14). In combination with the port injection mixture, a stable stratified charge combustion and significant retard of spark ignition were achieved. Thus the catalyst warm-up performance was substantially improved [3][4].

With all above, Japanese new long term SULEV, Europe EURO5, North America Tier2 Bin5/LEV II LEV requirements were all met with minimum amount of precious metal in the catalyst.

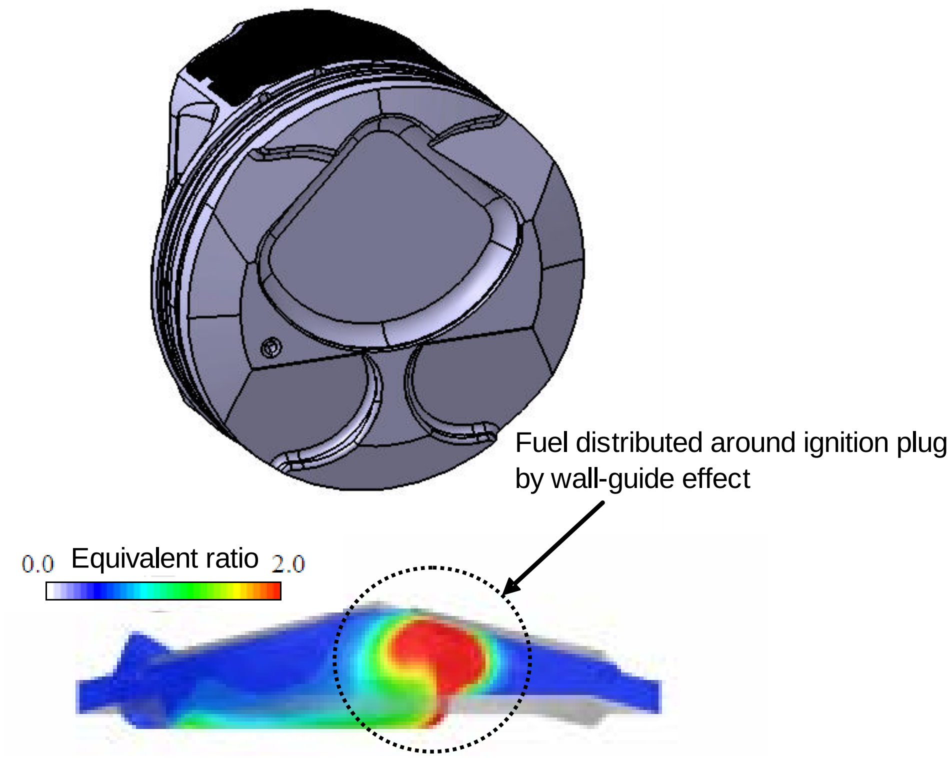

Fig. 14: Mixture distribution in combustion chamber

3.2 Fuel efficiency

The following items, taken for the FB20 engine, were carried over to the new engine FA20 D-4S to further improve fuel efficiency.

- Low friction roller rocker
- Optimization of water temperature distribution in cooling system
- Bottom bypass in cooling water circuit
- Cylinder bore processing with dummy cylinder head
- Adoption of cam carrier to improve coaxiality of cam shaft journal housing
- Mirror cycle effect using intake AVCS; Active Valve Control System, equipped with intermediate lock mechanism
- Inner EGR by retarding closing timing of exhaust valve

In addition to the items above, the following items were newly used to improve the combustion performance and vehicle fuel efficiency.

- Improvement of thermal efficiency by high compression ratio of 12.5
- Optimal air-fuel mixture formation with the simultaneous use of D-4S direct injection and port injection [3][4]
- Accelerated fuel atomization with high pressure direct injection (max. 20 MPa) [3][4]

With these new items added, Europe $CO_2$159 g/km, Japan fuel efficiency (JC08CH) 13.4 km/L, and North America fuel efficiency (Comb) 34.6 mpg were achieved without external devices for better fuel efficiency, including EGR, TGV.

4 Contribution to vehicle dynamics

4.1 Low center of gravity and vehicle weight optimal balance

The intake manifold was designed much lower than Impreza('12MY) engine by 65 mm and exhaust pipe height was shortened by 19 mm. That is overall height of the engine is shorter by around 84 mm. Intake air is led from the front of the vehicle since the engine is placed lower and nearer to the vehicle center. This intake layout is the first to use in a Subaru vehicle. (Fig. 15)

And also, the engine itself was mounted further back by 240 mm toward a driver and much lower by 120 mm compared to the current Impreza.

The center of crankshaft was lowered by 60 mm, which also contibutes to low center of gravity of the car. As a result, the ultra low center of gravity allowed low engine hood design, giving the BRZ a sleek sports car styling with good front visibility and most importantly contributes to the product concept "Pure Handling Delight". (Fig. 16)

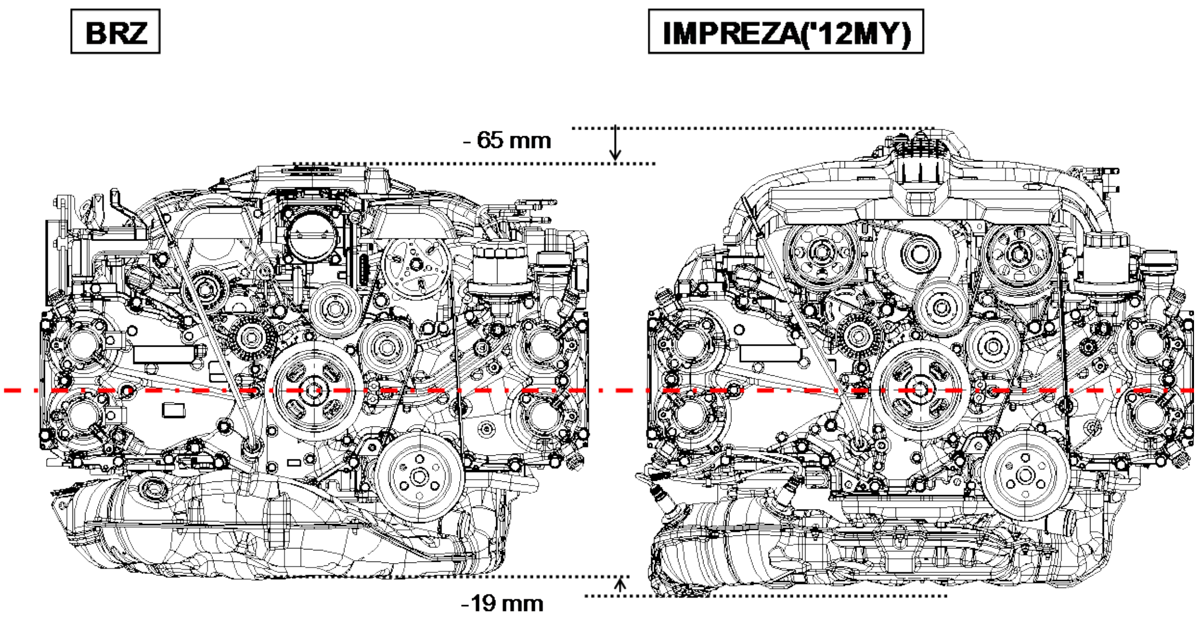

Fig. 15: Engine height

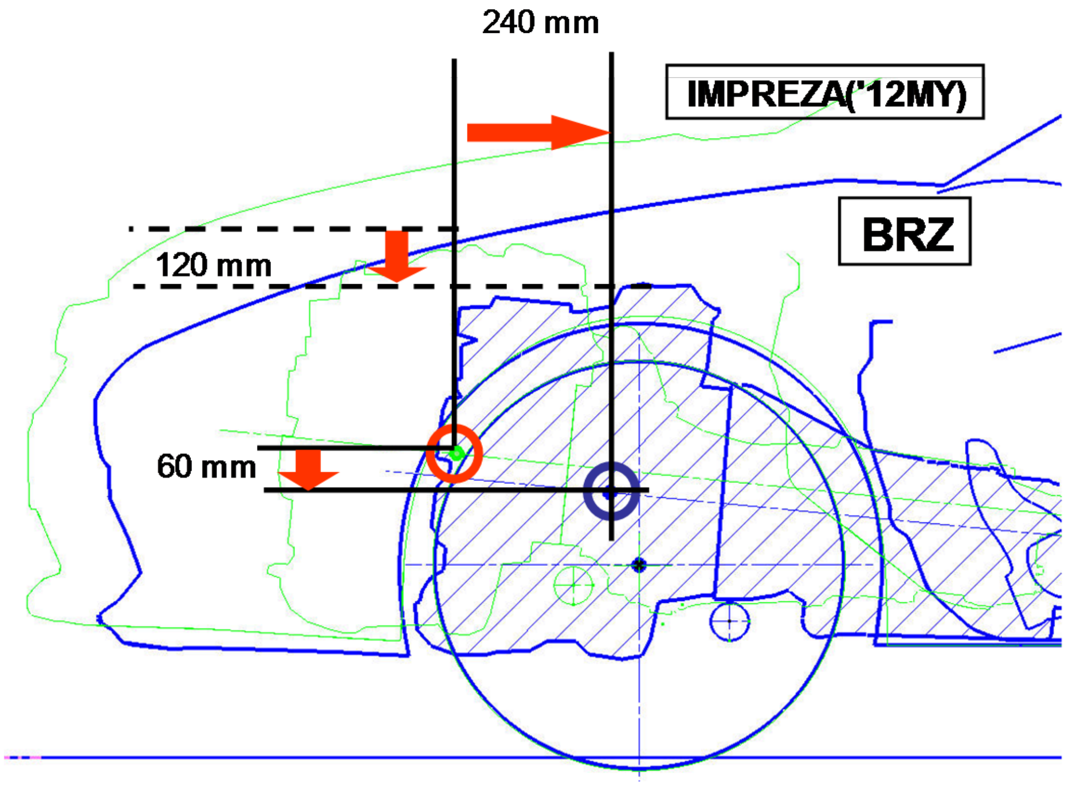

Fig. 16: Totally new engine packaging

4.2 Lubricating system under high lateral acceleration

A lubricating system was designed to steadily supply engine oil to every sliding part even when cornering under extremely high lateral acceleration.

Since the horizontally opposed engine is characterized by its width when longitudinally mounted in the vehicle, engine oil tends to be pushed to one side under high lateral acceleration. If the amount of the useless oil increases too much, the oil pump cannot suction oil properly, failing to supply necessary oil to engine components. To avoid this, the dry sump is considered as a counter measure. The dry sump, however, requires the use of oil tank and scavenge pump, which increases the system cost and weight substantially.

To solve this challenge with the existing lubricating system, oil flow was analized to reduce the internal space, which could be engine oil capacity in the engine.

To reduce the oil capacity, the shape of cam carrier and rocker cover were modified to downsize spaces in the right and left cylinder heads and valve rocker.

With the cam carrier and rocker cover modified, the system capacity was reduced by around 180 cc. In addition, a spacer was added inside the valve rocker cover to reduce the space by around 160 cc (Fig. 17)

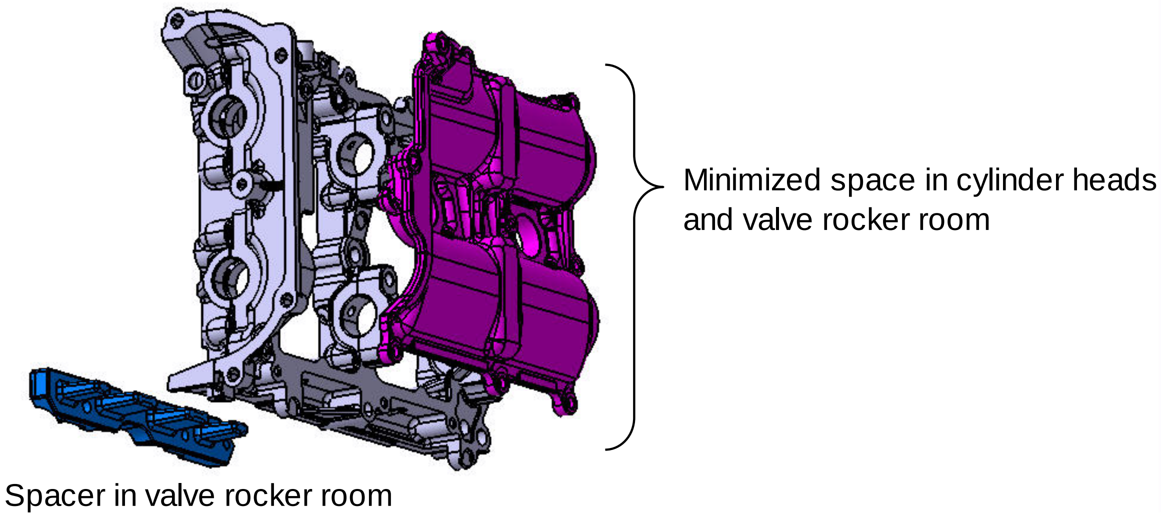

Fig. 17: Minimizing space for useless engine oil

For better oil recirculation, oil transportation ribs were added at appropriate place inside the chain cover so that engine oil can properly return to the oil pan even when driving under high lateral acceleration. With these ribs added, the amount of engine oil accumulated in the cylinder head / valve rocker volume and chain room was significantly reduced. As a result, sufficient oil can be secured in the oil pan to be steadily supplied by the oil pump (Fig. 18).

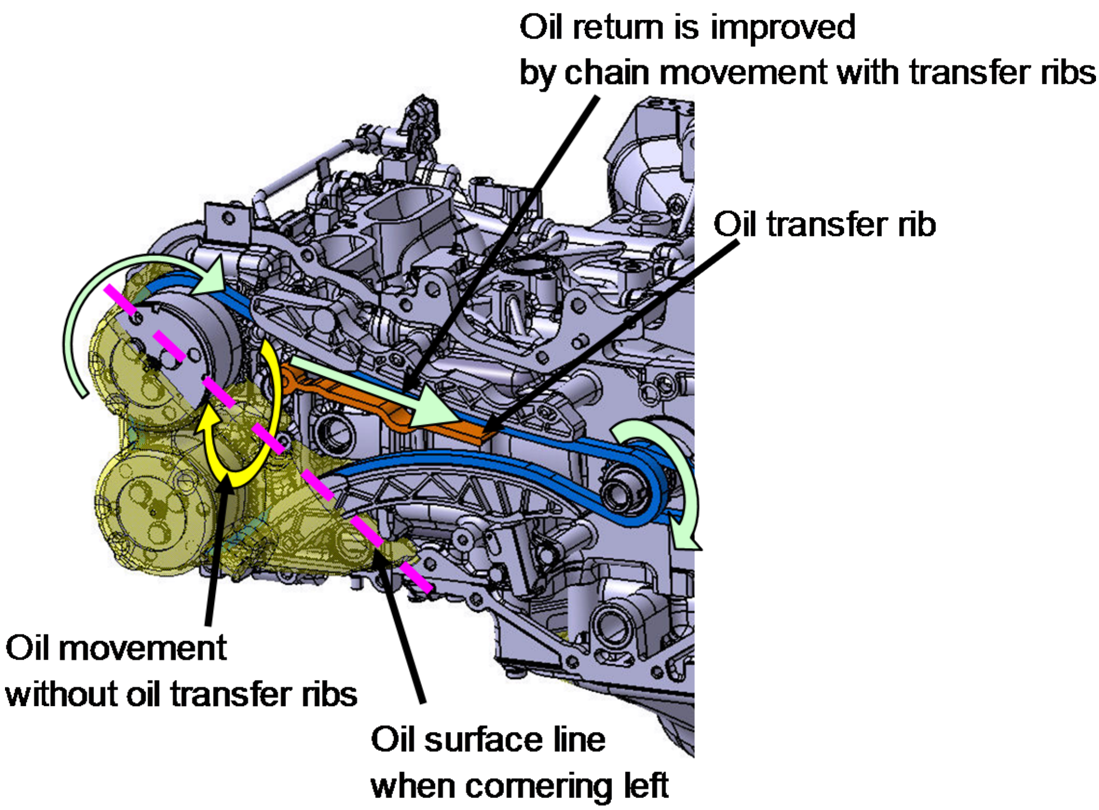

Fig. 18: Engine oil transportation

5 Summary

The new engine was developed for the Subaru BRZ/Toyota GT86 with the advantages of the horizontally opposed engine.

Aiming at high output and compact in size, the newly developed engine achieved 147 kW (200PS) with the overall height reduced 85 mm, yet meeting the fuel economy requirements of Europe $CO_2$159 g/km, Japan fuel efficiency (JC08CH) 13.4 km/L, and North America fuel efficiency (Comb) 34.6 mpg, and also the low emission standards of Japanese new long term SULEV, Europe EURO5, and North America Tier2 Bin 5/LEV II LEV.

Based on the “FB20” engine, which was developed focusing on environmental friendliness, a high potentiality of the Subaru horizontally opposed engine was demonstrated in two aspects “FA20 D-4S“ and the “FA20 DIT”, which was launched around the same time as a Subaru’s originally developed direct injection turbo engine.

Finally, we would like to express our deepest appreciation to Toyota Motor Co. for the D-4S technology and all others who have offered their cooperation to develop this engine.

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