

Development of 2.0 L Engine for New Accord Hybrid

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ABSTRACT

A 2.0 L gasoline engine for which the development target was the realization of thermal efficiency of 40% or higher (a first for Honda) has been developed for the new Accord hybrid. As in the case of the previous model, the developed engine employs the Atkinson cycle and the cooled EGR system. In order to further increase theoretical thermal efficiency, knocking has been reduced through the application of mirror finishing to the intake valves and the use of sodium-filled exhaust valves, and the higher compression ratio than the previous model. To reduce heat loss, high-speed combustion has been realized by increasing EGR amount and employing high-tumble-flow ports. Technologies for the reduction of mechanical loss, including low-friction plateau honing and a low-friction balance shaft, have been employed in the other engine framework, helping to enable the realization of a minimum fuel consumption rate of 208.1 g/kWh (thermal efficiency: 40.6%) in the engine unit in isolation.

The verification results of the fuel efficiency performance achieved in an actual vehicle through the use of the newly-developed engine demonstrated a reduction of 1.96 mpg in fuel consumption in the US Combined Mode as an effect of the engine unit in isolation.

1. Introduction

Today, automakers are introducing new powertrains in an effort to increase fuel efficiency in order to reduce automotive CO₂ emissions. At the end of 2012, Honda marketed an Accord plug-in hybrid provided with a two-motor hybrid system⁽¹⁾⁻⁽³⁾. In 2016, Honda added an exhaust heat recovery system to the hybrid system. In order to make it possible to supply hybrid systems to an even greater number of customers, at the beginning of 2018 Honda announced an Accord hybrid provided with a hybrid system designed to promote a more widespread use of the vehicles. The two-motor hybrid (SPORT HYBRID i-MMD) system offers three patterns as driving modes. Pattern 1 is EV Drive Mode. In this mode, the motor is driven using electrical energy stored in the battery. Pattern 2 is Hybrid Drive Mode. In this mode, the motor is driven using electrical energy generated by the engine, via battery assist or charging. Pattern 3 is Engine Drive Mode. In this mode, the vehicle is directly driven using engine power (Fig. 1). The aim in the development of the SPORT HYBRID i-MMD system was to realize a hybrid system offering a

class-topping level of efficiency. A specialized gasoline engine has been developed in the system in order to further increase fuel efficiency.

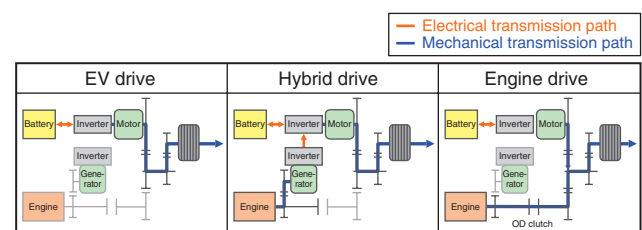


Fig. 1 SPORT HYBRID i-MMD system operations

2. Development Aims

The gasoline engine specialized for hybrid vehicle use was developed in order to satisfy the following targets:

- (1) In relation to reduced fuel consumption, realization of increased fuel efficiency in the Hybrid Drive Mode use range (thermal efficiency: 40% or higher)

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- (2) Realization of increased fuel efficiency performance in an actual vehicle by means of optimization of the engine operating line.

3. Technologies for Increased Fuel Efficiency Performance

Table 1 compares the specifications of the developed engine and a mass-production 2.0 L full hybrid electric vehicle (FHEV) engine achieving a thermal efficiency of 39.1% (the previous model).

3.1. Technologies for Increased Unit Fuel Efficiency Performance

Based on an analysis of loss in the previous model, the achievement of increased theoretical thermal efficiency, reduced heat loss, and reduced mechanical loss in order to increase indicated thermal efficiency were set as the three focal points for the realization of increased fuel efficiency.

3.1.1. Increased theoretical thermal efficiency

Increasing the compression ratio is effective in increasing theoretical thermal efficiency, but it also results in increased knocking. In order to address this issue, the introduction amount of exhaust gas recirculation (EGR) gas was increased, mirror finishing was applied to the intake valves, and sodium-filled exhaust valves were employed. These measures made it possible to increase the compression ratio from 13.0 to 13.5 with no increase in knocking (Fig. 2).

3.1.2. High-flow-rate EGR system

The introduction amount of EGR gas was increased in order to reduce heat loss. This had an effect in controlling knocking, and was also effective in allowing the realization of an increased compression ratio.

Having set the target of increasing the introduction amount of EGR gas from 17% in the previous model to 23%, the potential for realizing a high flow rate in the EGR system was examined. The value of the flow rate was calculated in relation to a thermal efficiency of 40%.

In order to realize a high flow rate, a new EGR valve was developed. This valve has a larger diameter and balances the amount of gas leakage from the valve seat and the valve responsiveness. A poppet valve shape was employed, and the valve diameter was increased (Table 2). A linear solenoid was employed in the drive section. The coils and the magnetic circuits were redesigned to help ensure the drive power necessitated by the increased valve diameter.

Pressure loss in the EGR passages was reduced in order to boost the effect of the increased valve diameter. The EGR gas introduced downstream from the catalyst passes through the EGR pipe, the EGR cooler, and the EGR gas passage in the water outlet before entering the EGR valve. Following this, the EGR gas once again passes through the

Table 1 Engine specifications

	Developed	Previous
Cylinder configuration	Inline 4	
Bore × Stroke [mm]	81 × 96.7	
Displacement [cm ³]	1993	
Valvetrain (intake)	VTEC and E-VTC	
Valvetrain (exhaust)	Finger rocker arm (with HLA)	
Number of valves	4	
Valve diameter [mm] intake/exhaust	33 (Mirror-surface) /26 (Na-filled)	33/26
Cylinder offset [mm]	6	
Crank journal diameter [mm]	50	
Crankshaft counterweight	Semi-8 (without dent)	4 (with dent)
Compression ratio	13.5	13.0
EGR system	Cooled	
EGR valve flow rate [L/min]	450	230
Water pump	Electric	
Thermostat open valve temperature [°C]	82	78
Fuel injection type	Port injection	
Fuel	Regular	
Maximum power [kW]	107	
Maximum torque [Nm]	175	
Emission regulation	SULEV30	

Table 2 EGR valve specifications

	Developed	Previous
Valve type	Poppet	
Valve seat diameter [mm]	12.5	8.3
Flow at 6.7 kPa [L/min]	450	230
Valve leak [L/min]	< 3	
Response time [msec] from closed state to fully open	≤ 80	

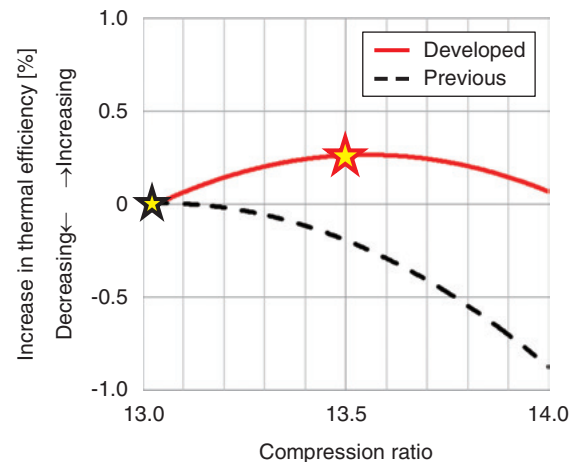


Fig. 2 Increase in thermal efficiency against previous model

gas passage in the water outlet and the cylinder head, and is then reintroduced to the intake manifold.

Figure 3 shows a comparison of the shapes of the EGR passage in the vicinity of the EGR valve, which has a significant effect on pressure loss, for the high-flow EGR system and the previous EGR system.

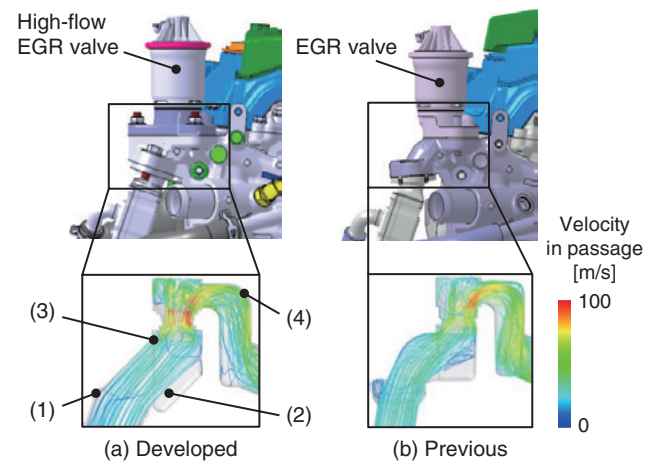
Against the passage shape in the previous system, the following modifications were applied.

- (1) Increase in passage opening to $\phi 21$
- (2) Reduction of unnecessary volume in passage
- (3) Straightening of EGR cooler cone
- (4) Change to R15 in EGR valve passage

These modifications have reduced pressure loss in the passage by 70%.

To respond to increased time loss due to a slowing of combustion with an increase in the introduction amount of EGR gas, a high-tumble-flow port was employed in order to realize rapid combustion even under high-flow EGR conditions.

Figure 4 shows the shape of the port employed in the system. In comparison to the port shape in the previous model, the lower section of the port area directly before the



- (1) Increase in passage opening to $\phi 21$
- (2) Reduction of unnecessary volume in passage
- (3) Straightening of EGR cooler cone
- (4) Change to R15 in EGR valve passage

Fig. 3 High-flow EGR passage

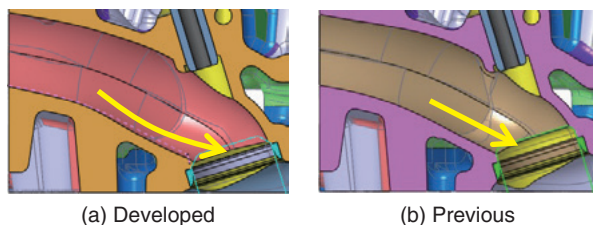


Fig. 4 High-tumble port shape

intake valve swells outwards, increasing the acuteness of the angle of incidence and strengthening the tumble flow. This has increased the tumble ratio at an operating point of engine speed: 2000 rpm and engine load: 120 Nm by 25%, and the turbulent kinetic energy (TKE), which correlates with combustion speed, by 3%. Figure 5 shows the effect in boosting the TKE of the flow.

As a result, the same combustion period as the previous model has been realized (Fig. 6), and it has been possible to reduce heat loss and knocking with no increase in time loss.

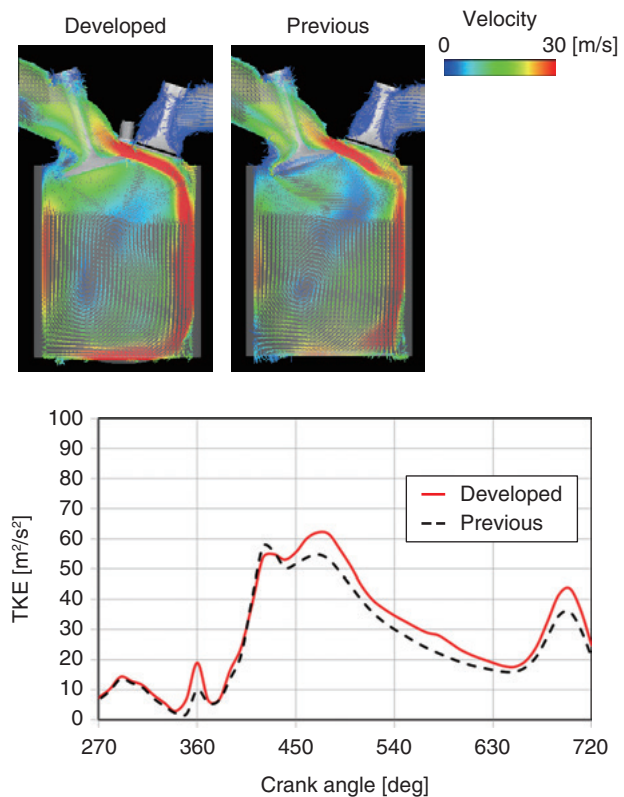


Fig. 5 Results of flow simulation

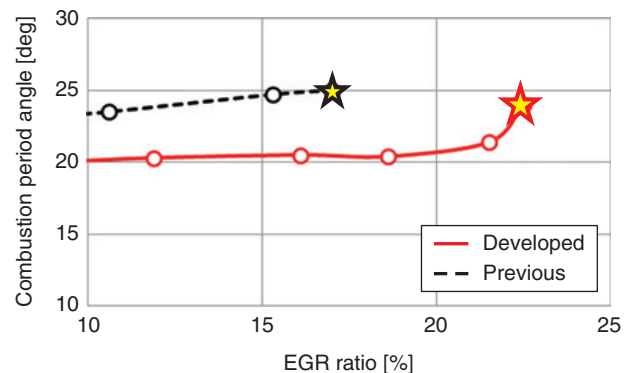


Fig. 6 EGR flow rate and combustion period

3.1.3. Reduction of knocking

The rear surfaces of the intake valve umbrellas were mirror finished and sodium-filled exhaust valves were employed in order to reduce knocking.

In the case of the intake valves, the aim was to reduce surface area and control heat transfer between gases in the surrounding area and the valves by increasing the smoothness of the valve umbrella rear surfaces, which are exposed to the interior of the combustion chamber. The reduction of heat transfer by this means has made it possible to reduce the heat of combustion gases escaping to the cylinder head via the valves, thus reducing heat loss. In addition, because the temperature of the valves themselves is also reduced, the temperature of the intake air is reduced, and this has an effect in reducing knocking [Fig. 7(a)].

In the case of the exhaust valves, valves in which hollow centers are filled with sodium have been employed [Fig. 7(b)]. The aim of this was to promote rapid heat transmission of the areas around the exhaust valves, which are prone to reaching high temperatures, to the stem parts by means of the up-down motion of the melted sodium inside the valves, and to dissipate the heat through the cylinder head water jacket, via the valve guide which makes contact with the valve stem.

The application of these technologies has had the effect of reducing knocking by 0.9 degrees at an operating point of engine speed: 2000 rpm and engine load: 120 Nm. The achieved level of reduction of knocking is shown in Table 3.

Table 3 Amount of mitigation of knocking

Amount of mitigation of knocking		
Valve cooling	Mirror-surface intake valve	+0.3 deg
	Na-filled exhaust valve	+0.6 deg

Table 4 Mechanical loss reduction technology

Part	Item
Cam shaft	Mirror-surface cam journal
Crank shaft	Mirror-surface crank journal
	Increased crank rigidity
Balance shaft	MoS ₂ shot to balance shaft metal
	Change in balance shaft weight and shape
Oil pump	Low-tension oil seal
Piston	MoS ₂ thick coat + Staggered coat
	Change in 2nd ring shape
	Change in land diameter
Chain	Cam chain (application R shape on back face and smoother surface roughness)
	Low-friction chain guide
Block	Low-friction plateau honing

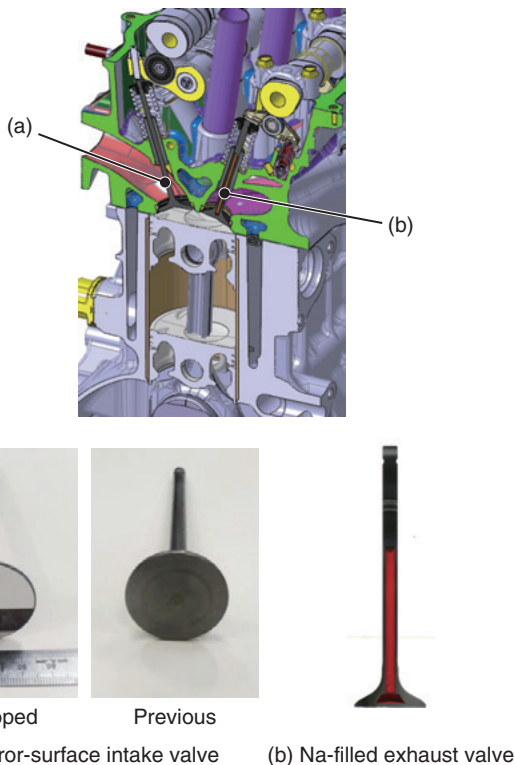


Fig. 7 Valve system

3.1.4. Reduction of mechanical loss

The main focuses for reduction of mechanical loss were the main moving system, including the crankshaft and the pistons, and the valve system, including the camshaft and the drive chain (Table 4).

In the cylinder block, the specifications of the grindstone and the processing conditions employed in plateau honing were modified in order to increase the smoothness of the sleeve surfaces in which the pistons slide at high speed by reducing the maximum height of the roughness of the surfaces, while also increasing the pitch of the grooves, thus reducing mechanical loss (Fig. 8). In addition, because the engine layout positions the balance shaft inside the oil pan, mechanical loss occurs due to the scooping-up of the oil in

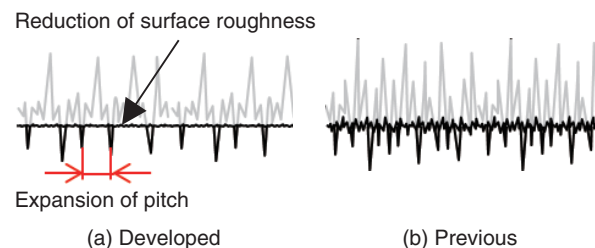


Fig. 8 Low-friction plateau honing

the oil pan when the engine is in operation. As shown in Figure 9, mechanical loss was reduced by creating a flow of oil over the surface of the balance weight by modifying its shape.

By increasing the temperature of the cooling water in order to reduce the viscosity of the lubricating oil, thus reducing mechanical loss and increasing fuel efficiency, the thermostat valve opening temperature has been increased by 4°C, from 78°C to 82°C. This was made possible by the reduction in knocking discussed in Section 3.1.3. This change in the valve opening temperature maintains the water temperature at a higher level from low-load to medium-load operation (Fig. 10), reducing mechanical loss.

As a result, mechanical loss has been reduced by 6.4% against the previous model at an operating point of engine speed: 2000 rpm and engine load: 120 Nm.

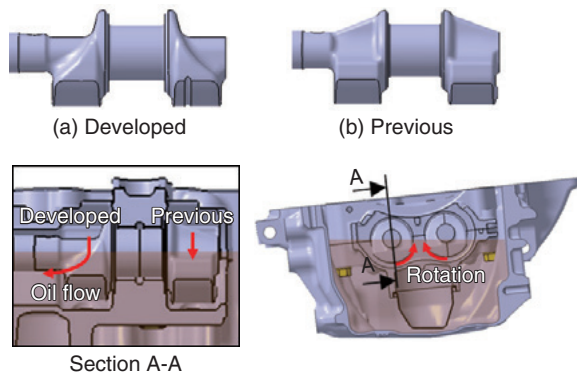


Fig. 9 Change in balance weight shape

3.2. Vibration Responses for Modification of the Engine Operating Line

In the operating domain in which rapid combustion reduced time loss and realized good brake specific fuel consumption (BSFC), the rate of pressure increase was increased, which made the engine vibration also increase. In the previous model, the engine operating line was set so as to balance the reduction of the rumbling sound produced by engine vibration in the complete vehicle with fuel efficiency, and as a result, the engine operating line did not employ the domain in which BSFC was at its lowest, as shown in Fig. 11. In the newly-developed engine, the reduction of vibration by means of modification of the engine framework was studied in order to increase fuel efficiency by making it possible for the engine operating

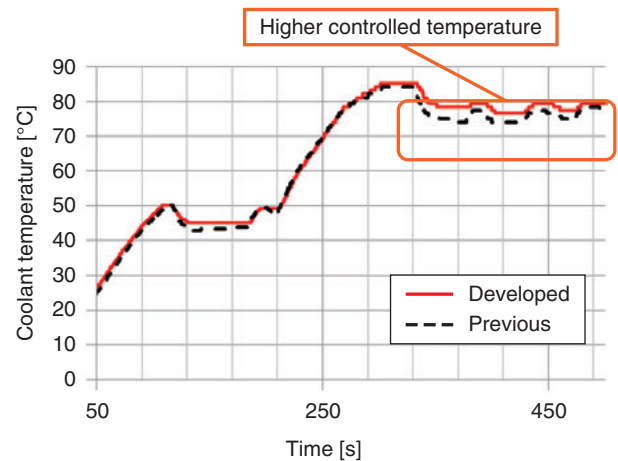


Fig. 10 Change in coolant temperature at cold start

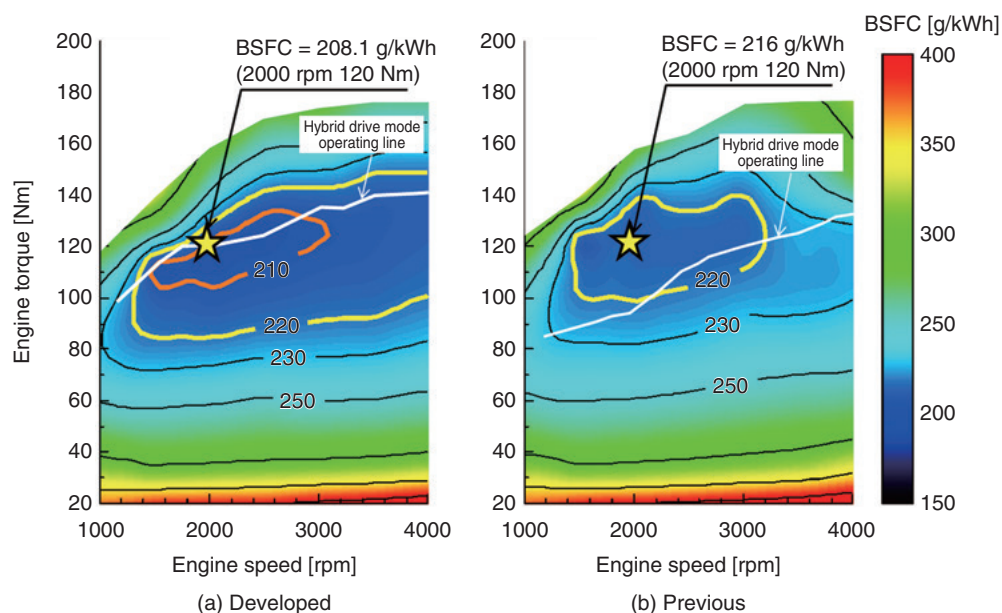


Fig. 11 Fuel consumption performance

line to use the low-BSFC domain and to help prevent increased vibration due to reduced BSFC.

The shape of the crankshaft was modified in order to reduce vibration. Figure 12 shows the shape of the modified crankshaft. In the previous model, the thickness of the shoulder section was reduced in order to lighten the crankshaft⁽²⁾. This approach has been done away with in the developed model, and in addition a web has been employed to increase thickness. Ultimately, the level of vibration of the engine mount attachment points in the 200 to 770 Hz range which affects the feeling of rumble in the complete vehicle has been reduced by 5 dB against the previous model. This is shown in Fig. 13. The studies discussed above made it possible to reduce BSFC while also reducing the level of vibration against the previous model.

3.3. Hybrid Mode Performance

The technological responses discussed above made it possible to realize a BSFC of 208.1 g/kWh (thermal efficiency: 40.6%) at an operating point with an engine speed of 2000 rpm and an engine load of 120 Nm. This represents a reduction of 8 g/kWh in BSFC against the previous model. Figure 11 shows the distribution of BSFC. The white lines in the graphs represent the operating lines in Hybrid Drive Mode, the yellow lines represent the range

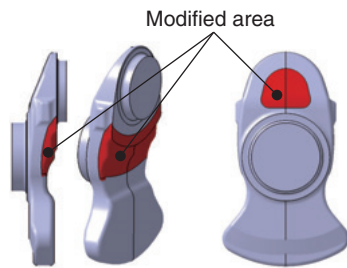


Fig. 12 Shape of modified crankshaft

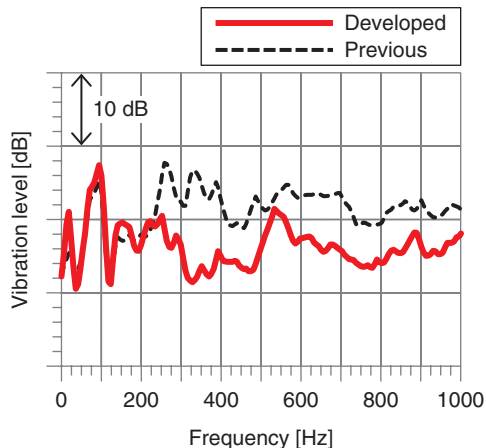
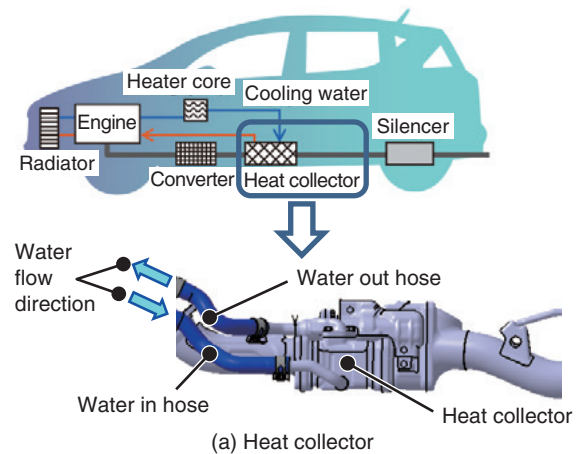


Fig. 13 Engine vibration level

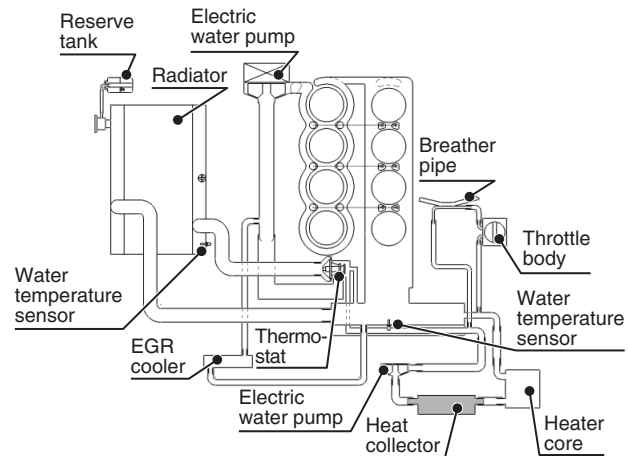
for a BSFC of 220 g/kWh, and the orange line represents the range for a BSFC of 210 g/kWh.

3.4. Actual Vehicle Fuel Efficiency Performance

An exhaust heat recovery system (Fig. 14) has been employed in the cooling circuit to boost the speed of the cooling water temperature increase at cold start, in order to speed up the timing of commencement of EV Drive Mode (Fig. 1). In US Combined Mode, the engine in isolation has the effect of reducing fuel consumption by 1.06 mpg, while the modification of the operating line contributes a reduction of 0.90 mpg, for a combined reduction of 1.96 mpg.



(a) Heat collector



(b) Cooling circuit diagram

Fig. 14 Cooling system

4. Conclusion

The technologies discussed above have been employed in the development of a competitive engine for use in a hybrid system possessing the potential to achieve widespread use. The results of the development can be summarized as follows:

- (1) The application of a high-compression ratio, a high-tumble-flow port, and a high-flow EGR system has made it possible to realize a BSFC of 208.1 g/kWh (thermal efficiency: 40.6%).
- (2) Modification of the engine operating line boosted fuel efficiency performance in the actual vehicle.

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