Gasoline Engines

1 Introduction

Global vehicle sales fell heavily due to the global financial crisis that started in the U.S. in 2008, before starting to increase again in 2009 and overcoming the credit crisis in Europe in 2010. Sales in 2014 reached an all-time high, buoyed by robust growth in China and low-interest rates and low crude oil prices in the U.S. that created favorable market conditions.

At the same time, awareness of the environment and environmentally friendly technology is growing all around the world, leading to the introduction of more stringent fuel economy and emissions regulations in Japan, the U.S., and Europe. At the same time, while other regions have decided to adopt the emissions regulations drawn up by Europe or the U.S., more countries are introducing independent regulations, such as those in China and India. As a result of these trends, technologies to lower engine emissions or boost fuel efficiency are growing in sophistication, affecting for vehicles that automakers are launching on a global basis as well as vehicles for emerging markets.

This article introduces the main gasoline engines and new engine technologies that were developed and launched between January and December 2014. It also summarizes the trends in the research and development of gasoline engines.

2 Japan

2. 1. Summary

The Japanese vehicle market suffered a double blow, from the U.S. financial crisis in 2008 and the Great East Japan Earthquake in 2011. The market has since recovered from these substantial drops in sales and recorded a year-on-year increase in 2014, partly due to the last-minute demand that occurred before the consumption tax hike in April 1014. In particular, sales of mini-vehicles grew, reflecting the excellent fuel economy and low maintenance costs of these vehicles. Sales of hybrid vehicles were also robust.

Most of the new vehicles launched in 2014 were eligible under Japan's preferential tax scheme for environmentally friendly vehicles. The fierce competition in the mini-vehicle market for better fuel efficiency continued, and a number of vehicles launched in 2014 have already exceeded the fuel economy standards for 2020 by more than 20%. A number of new mini-vehicles and hybrid vehicles that use regenerative energy to provide motor assist on acceleration were launched. Other vehicles achieved better fuel economy by refining and combining existing technologies without the use of motors or other electrical devices, such as high compression ratios and improved combustion characteristics, higher engine thermal efficiency by reducing losses, lighter body frames, and coordinated control with the transmission, and the like. A number of vehicles installed with downsized turbocharged engines were also launched.

2. 2. Trends of each manufacturer

Table 1 shows a list of the main new types of gasoline engines that were sold by Japanese automakers in 2014. A summary of the new engines developed by each manufacturer is provided below.

2. 2. 1. Daihatsu

The Daihatsu Mira e:S is installed with the inline 3-cylinder 0.66-liter KF engine (Fig. 1). This engine improves fuel efficiency through a higher compression ratio than the previous engine (11.3 increased to 12.2), re-designed intake port geometry to intensify tumble, and high ignition performance spark plugs that expand the range of the flame in the initial stage of ignition. Knocking, which tends to occur at higher compression ratios was prevented by adopting the Atkinson cycle, dual injectors (Fig. 2), and cooled exhaust gas recirculation (EGR). The Atkinson cycle also reduces pumping loss and the dual injectors stabilize combustion by atomizing the injected fuel into extremely small droplets. Combining these

Table 1 Main new gasoline engines in Japan

Manufacturers	Engine model	Cylinder arrangement	Bore × stroke (mm)	Displacement (L)	Compression ratio	Valve train	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main installation vehicles	Characteristics
Daihatsu	KF	Inline 3	63.0×70.4	0.658	12.2	DOHC 4 V	36/6 800	57/5 200	Mira e:S	Variable intake valve timing, spark plugs with high ignition performance, Atkinson cycle, dual injectors, cooled EGR
Fuji Heavy Industries	FB16DIT	Flat 4 turbocharged	78.8×82.0	1.599	11.0	DOHC 4 V	125/4 800–5 600	250/1 800–4 800	Levorg	Direct injection, variable intake/exhaust valve timing, cooled EGR, tumble generating valves, water jacket spacer
	FB25	Flat 4	94.0×90	2.498	10.3	DOHC 4 V	129/5 800	235/4 000	Legacy, Outback	Variable intake/exhaust valve timing
Mazda	P3-VPS	Inline 4	71.0×82.0	1.298	12.0	DOHC 4 V	68/6 000	121/4 000	Demio	Direct injection, variable intake valve timing, Miller cycle
Nissan	MR16DDT	Inline 4 turbocharged	79.7×81.1	1.618	10.5	DOHC 4 V	140/5 600	240/1 600–5 200	Juke	Direct injection, variable intake/exhaust valve timing with mid-position lock, Miller cycle, low-pressure cooled EGR, polished bore thermal spray cylinder block, electronic wastegate, variable capacity oil pump
Suzuki	R06A	Inline 3	64.0×68.2	0.658	11.5	DOHC 4 V	38/6 500	63/4 000	Alto	Variable intake/exhaust valve timing, EGR, cylinder head integrated with the exhaust manifold
	R06A	Inline 3	64.0×68.2	0.658	11.2	DOHC 4 V	38/6 000	63/4 000	Wagon R	Variable intake/exhaust valve timing
Toyota	1KR-FE	Inline 3	71.0×83.9	0.996	11.5	DOHC 4 V	51/6 000	92/4 400	Passo, Vitz	Atkinson cycle, cooled EGR, variable intake valve timing, cylinder head integrated with the exhaust manifold, water jacket spacer
	1NR-FKE	Inline 4	72.5×80.5	1.329	13.5	DOHC 4 V	73/6 000	121/4 400	Vitz, Ractis	Atkinson cycle, cooled EGR, variable intake/exhaust valve timing (intake side: electronic), water jacket spacer, 4-2-1 exhaust manifold
	8AR-FTS	Inline 4 turbocharged	86.0×86.0	1.998	10.0	DOHC 4 V	175/4 800–5 600	350/1 650–4 000	NX200 t	Atkinson cycle, direct injection + intake port injection, twin-scroll turbocharger, water-cooled intercooler, cylinder head with integrated 4 into 2 exhaust manifold, variable valve timing with mid-position lock, sodium-filled exhaust valves

measures with lower running resistance and greater regeneration of deceleration energy through an enhanced power generation control enables this vehicle to achieve a fuel consumption of 35.2 km/l in the JC08 test cycle.

2. 2. 2. Fuji Heavy Industries

The new Subaru Levorg is installed with the horizontally opposed 4-cylinder ("flat 4") 1.6-liter FB16 direct injection turbo (DIT) engine (Fig. 3). Combining direct injection with a turbocharger gives this engine equal or higher power than a 2.5-liter naturally aspirated engine. Compared to the previous unit, this engine features improved cylinder head internal cooling performance, multi-stage fuel injection, improved combustion characteristics through a high-tumble combustion chamber, and a larger EGR cooler. As a result of these measures, this engine achieves a compression ratio of 11.0 with regular gasoline and fuel consumption of 17.4 km/l in the JC08 test cycle.

The new Legacy features the flat 4 2.5-liter FB25 en-

Fig. 1 Daihatsu 0.66-liter KF engine [4]

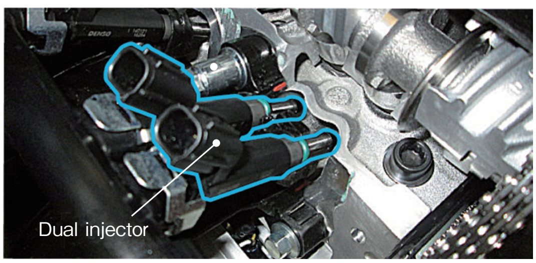

Fig. 2 Daihatsu dual injectors [4]

Fig. 3 Fuji Heavy Industries 1.6-liter FB16 DIT engine [4]

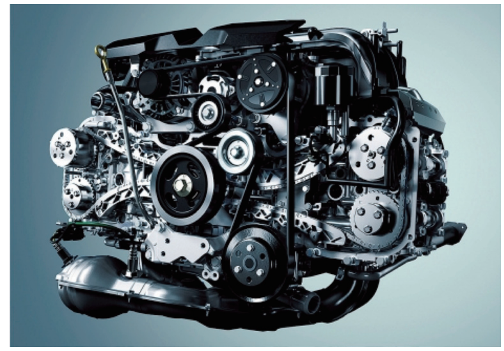

Fig. 4 Fuji Heavy Industries 2.5-liter FB25 DIT engine [4]

Fig. 5 Mazda 1.3-liter P3-VPS engine [4]

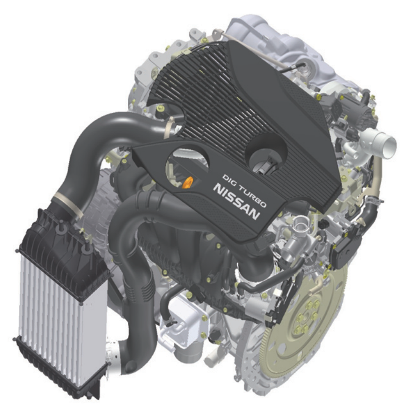

Fig. 6 Nissan 1.6-liter MR16DDT engine [4]

gine (Fig. 4). In addition to substantial enhancements to the intake, exhaust, and combustion systems, this engine improves fuel efficiency by creating more intense intake tumble and adopting a higher compression ratio.

2. 2. 3. Mazda

The new Mazda Demio is installed with the inline 4-cylinder 1.3-liter PS-VPS engine (Fig. 5). This engine features a different compression ratio to the previous SKYACTIV-G family engines, enabling higher torque in all engine speed regions, as well as better acceleration and fuel efficiency.

2. 2. 4. Nissan

The Nissan Juke is installed with the inline 4-cylinder 1.6-liter turbocharged MR16DDT engine (Fig. 6). This engine features innovations such as a higher compression ratio (increased from 9.5 to 10.5) than the previous engine, a polished bore thermal spray cylinder block, redesigned intake port and piston top surface geometry, a turbocharger with a lower rotor moment of inertia, and an exhaust manifold integrated with the turbine housing.

These enhancements have the effect of improving both acceleration and fuel efficiency. In addition, low-pressure cooled EGR is introduced upstream of the turbocharger compressor after the exhaust gas from the catalyst is cooled, thereby improving fuel efficiency in the turbocharger operation range by reducing knocking and the exhaust gas temperature.

2. 2. 5. Suzuki Motor Corporation

The new Suzuki Alto is installed with the inline 3-cylinder 0.66-liter R06A engine (Fig. 7). This engine improves fuel efficiency by increasing the compression ratio (from 10.5 to 11.5), adopting variable valve timing on the exhaust side as well as the intake side, installing an EGR system, and redesigning the intake and exhaust port geometry. In addition, the size and weight of the engine were reduced by adopting a cylinder head integrated with the exhaust manifold and a simpler catalyst case structure. Combined with a lighter body, high-efficiency continuously variable transmission (CVT), and lower running resistance, this engine achieves a fuel consumption of 37.0 km/l in the JC08 test cycle.

The Wagon R is also installed with the inline 3-cylinder 0.66-liter R06A engine. The engine in this vehicle features refinements to increase thermal efficiency such as a higher compression ratio, improved combustion characteristics, and lower friction loss. It combines these with a generator with a motor function (ISG), which is powered by regenerated deceleration energy to assist acceleration, thereby achieving fuel consumption of 32.4 km/l in the JC08 test cycle. The belt-driven ISG starter function also reduces noise on engine re-start when the idling stop system is operating.

2. 2. 6. Toyota

The inline 3-cylinder 1.0-liter 1KR-FE engine (Fig. 8) installed in vehicles such as the Toyota Passo and Toyota Vitz adopts the Atkinson cycle and cooled EGR previously adopted in hybrid vehicle engines to reduce pumping loss. This engine also uses a water jacket spacer to optimize the cylinder wall temperature and reduce mechanical loss. Due to a combination of other refinements, such as redesigned intake port and combustion chamber geometry to intensify tumble and achieve high-speed combustion, as well as a higher compression ratio, this engine achieves a maximum thermal efficiency of 37%. As a result, the Passo achieves fuel consumption of 27.6 km/l in the JC08 test cycle.

Fig. 7 Suzuki 0.66-liter R06A engine [4]

Fig. 8 Toyota 1.0-liter 1KR-FE engine [4]

Fig. 9 Toyota 1.3-liter 1NR-FKE engine [4]

The inline 4-cylinder 1.3-liter 1NR-FKE engine (Fig. 9) installed in the Vitz, Ractis, and the like also adopts the Atkinson cycle and high compression ratio (13.5) from hybrid vehicle engines. It also features electronic continuously variable valve timing on the exhaust side to improve cold start capability and fuel efficiency in low load engine operation regions. Combining these measures with cooled EGR and high-tumble intake ports, the resulting high-speed combustion expands both the EGR and knocking limits. Finally, resin-coated bearings and other technologies to reduce friction loss give this engine a maximum thermal efficiency of 38%.

The new Lexus NX200t is installed with the inline 4-cylinder 2.0-liter turbocharged 8AR-FTS engine (Fig. 10). This engine combines a cylinder head with an integrated 4 into 2 exhaust manifold with a twin-scroll turbocharger to improve low end torque and optimize the exhaust temperature. In addition, the combination of direct injection, injection into the intake ports, and high-tumble, enable high-speed combustion. The engine also features better response through a water-cooled intercooler that is attached directly to the engine, better fuel efficiency in low engine load operation regions and cold start performance through the use of continuously variable valve timing with a mid-position lock system, and various technologies to reduce friction loss such as a variable capacity oil pump and the adoption of surface treatment on the piston skirts. The result is improvements in both power and fuel efficiency.

Fig. 10 Lexus 2.0-liter 8AR-FTS engine [4]

3 U.S.

3. 1. Summary

The U.S. economy was robust in 2014, spurring a continuing increase in vehicle sales due to low interest rates and falling gasoline prices. The market essentially recovered to pre-financial crisis levels. Sales of small and medium sized vehicles were particularly strong.

As the U.S. phases in more stringent fuel economy regulations over the next few years, 2014 saw various innovations to improve fuel efficiency, such as downsized turbocharged direct injection engines and cylinder deactivation in larger displacement engines.

3. 2. Trends of each manufacturer

Table 2 shows a list of the main new types of gasoline engines that were sold by U.S.-based automakers in 2014. A summary of the new engines developed by each manufacturer is provided below.

3. 2. 1. Chrysler

The high-performance V8 6.2-liter Hemi engine (Fig. 11) installed in the Dodge Challenger and Charger features various technologies to improve fuel efficiency, such as a supercharger, water-cooled intercooler, sodium-filled exhaust valves, and variable capacity electric water pump. The engine has a maximum power of 527 kW and a maximum torque of 881 Nm.

Table 2 Main new gasoline engines in the U.S.

Manufacturers	Engine model	Cylinder arrangement	Bore × stroke (mm)	Displacement (L)	Compression ratio	Valve train	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main installation vehicles	Characteristics
Chrysler	6.2 L HEMI	V8 supercharged	103.9×90.9	6.166	9.5	OHV 2 V	527/6 000	881/4 000	Challenger, Charger	Supercharger, water-cooled intercooler, sodium-filled exhaust valves, powder metal forged connecting rods, variable capacity electric water pump
Ford	2.3 L EcoBoost	Inline 4 turbocharged	87.5×94.0	2.260	9.5	DOHC 4 V	231/5 500	434/3 000	Mustang	Direct injection, twin-scroll turbocharger, variable intake/exhaust valve timing, cylinder head integrated with the exhaust manifold
	2.7 L EcoBoost	V6 twin turbocharger	83.0×83.0	2.699	10.0	DOHC 4 V	242/5 750	509/3 000	F150	Direct injection, twin-turbocharger, variable intake/exhaust valve timing, cylinder head integrated with the exhaust manifold
GM	LT1	V8	103.2×92.0	6.162	11.5	OHV 2 V	339/6 000	624/4 600	Corvette	Direct injection, OHV variable valve timing, single-bank cylinder deactivation, powder metal forged connecting rods

Fig. 11 Chrysler 6.2-liter Hemi engine [4]

Fig. 12 Ford 2.3-liter EcoBoost engine [4]

3. 2. 2. Ford

Ford added an inline 4-cylinder 2.3-liter engine (Fig. 12) to its global EcoBoost series. In the U.S., this engine is installed in the Ford Mustang. In the same way as the existing members of the EcoBoost series, this engine features basic specifications such as direct injection, continuously variable exhaust valve timing, and a cylinder head integrated with the exhaust manifold. In combination with a twin-scroll turbocharger, this engine achieves power performance at least equivalent to the V6 3.7-liter natural aspirated engine used in the same model of the Mustang, with excellent fuel efficiency.

The V6 2.7-liter EcoBoost engine shown in Fig. 13 was installed in the F-150 pick-up truck. In addition to direct injection, continuously variable exhaust valve timing, and a cylinder head integrated with the exhaust manifold, this engine also includes a plastic oil pan. While providing power at least equivalent to a V6 3.5-liter natural aspirated engine, fuel efficiency was also improved by the adoption of an idling stop system and a lightweight aluminum body.

3. 2. 3. GM

The Chevrolet Corvette is installed with the 6.2-liter

Fig. 13 Ford 2.7-liter EcoBoost engine [4]

LT1 engine (Fig. 14). While retaining the 90-degree V8 2-overhead valve (OHV) basic layout of its famous small block predecessor, this engine also features technologies to improve fuel efficiency such as direct injection, a high compression ratio, continuously variable valve timing, and single-bank cylinder deactivation. These measures have improved both power and fuel efficiency.

4 Europe

4. 1. Summary

The U.S. financial crisis in 2008 and European credit crisis in 2010 resulted in continued falls in vehicle sales in Europe. However, sales finally rose on a year-on-year basis in 2014 for the first time in seven years. Although the market recovery is gradual, sales of vehicles installed with downsized engines to improve fuel efficiency and reduce CO_2 continue to be robust and have risen substantially. A particular trend in 2014 was the launch of a number of 3-cylinder downsized turbocharged direct injection engines.

4. 2. Trends of each manufacturer

Table 3 shows a list of the main new types of gasoline engines that were sold by Europe-based automakers in 2014. A summary of the new engines developed by each manufacturer is provided below.

4. 2. 1. BMW

The BMW i8 plug-in hybrid is installed with the inline 3-cylinder 1.5-liter turbocharged B38A15 engine (Fig. 15). Tuned to different power levels, this engine is also installed in the 218i Active Tourer and Mini. Part of BMW's so-called TwinPower Turbo series of engines, it features direct injection, a continuously variable valve lift mechanism, continuously variable exhaust valve timing, and thermal spray bores. The aluminum turbo

Table 3 Main new gasoline engines in Europe

Manufacturers	Engine model	Cylinder arrangement	Bore × stroke (mm)	Displacement (L)	Compression ratio	Valve train	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main installation vehicles	Characteristics
BMW	B38A15	Inline 3 turbocharged	82.0×94.6	1.499	11.0	DOHC 4 V	170/5 800	320/3 700	I8	Direct injection, variable intake/exhaust valve timing, variable valve lift
							100/4 400	220/1 250–4 300	218i Active Tourer, Mini	
	B48A20	Inline 4 turbocharged	82.0×94.6	1.998	10.2	DOHC 4 V	170/5 000	350/1 250	225i, Mini	Direct injection, variable intake/exhaust valve timing, variable valve lift
Daimler	M178	V8 twin turbocharger	83.0×92.0	3.982	10.5	DOHC 4 V	375/6 250	650/1 750–4 750	AMG-GT	Direct injection, water-cooled inter cooler, steel thermal spray cylinder core, dry sump lubrication, variable capacity oil pump
Opel	LE1	Inline 3 turbocharged	74.0×77.4	0.999	10.5	DOHC 4 V	85/5 200	170/1 800–4 500	Adam	Direct injection, variable intake/exhaust valve timing, cylinder head integrated with the exhaust manifold, variable capacity water pump, powder metal forged connecting rods, variable capacity oil pump
PSA	1.2 EB2	Inline 3 turbocharged	75.0×90.5	1.199	10.5	DOHC 4 V	96/5 500	230/1 750	308, C3	Direct injection, variable intake/exhaust valve timing, sodium-filled exhaust valves, variable capacity oil pump, timing belt drive
Volvo	Drive-E T6	Inline 4 supercharger + turbocharger	82.0×93.2	1.969	10.3	DOHC 4 V	225/5 700	400/2 100–4 800	S60, V60, XC60	Supercharger + turbocharger, direct injection, variable capacity oil pump, electric water pump

Fig. 14 GM 6.2-liter LT1 engine [4]

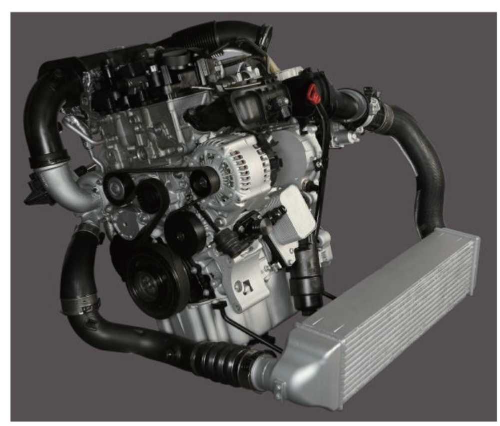

Fig. 15 BMW 1.5-liter B38A15 engine [4]

housing is water-cooled and integrated with the exhaust manifold, thereby improving fuel efficiency by reducing weight and promoting the warm-up process. The 4-cylinder 2.0-liter B48A20 engine (Fig. 16) uses a twin-scroll turbocharger that achieves higher efficiency by restricting exhaust interference. This engine is also used in the 2 Series Active Tourer and Mini.

4. 2. 2. Daimler

The Mercedes-AMG GT is installed with the V8 4-liter turbocharged M178 engine (Fig. 17). This engine features two turbochargers provided between the V banks (Fig. 18), direct injection with piezo injectors, a dry sump lubrication system, closed deck cylinder block, and the Nanoslide cylinder liner coating. The result is a compact lightweight engine with high power and low fuel consumption, which is capable of achieving 650 Nm or torque between 1,750 and 4,750 rpm.

4. 2. 3. Opel

Fig. 16 BMW 2.0-liter B48A20 engine [4]

Fig. 17 Daimler 4-liter M178 engine [4]

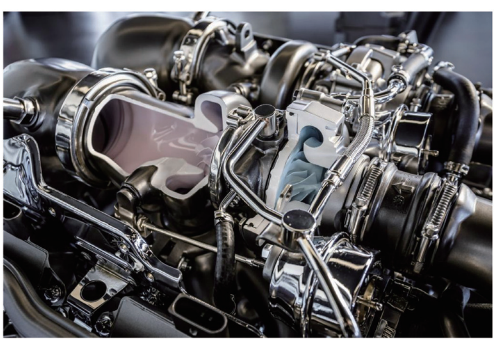

Fig. 18 Daimler M178 turbocharger [4]

The Opel Adam is installed with the inline 3-cylinder 1.0-liter turbocharged LE1 engine (Fig. 19). This is a new member of the Ecotec engine series developed by GM and Opel. It features direct injection, continuously variable intake and exhaust valve timings, a cylinder head with an integrated exhaust manifold, variable capacity oil pump, oil jets, and other technologies to improve fuel efficiency and power, while reducing noise.

4. 2. 4. PSA Peugeot Citroen

The Peugeot 308 and Citroen C3 are installed with the inline 3-cylinder 1.2-liter turbocharged EB2 engine (Fig. 20). This is the latest addition to the Pure Tech engine series consisting of 1.0-liter and 1.2-liter naturally aspi-

Fig. 19 Opel 1.0-liter LE1 engine [4]

Fig. 20 PSA 1.3-liter EB2 engine [4]

rated engines with intake port injection. The EB2 features direct injection, a high-speed turbo (270,000 rpm), cylinder head with an integrated exhaust manifold, and sodium-filled exhaust valves to increase output and fuel efficiency.

4. 2. 5. Volvo

The Volvo S60, V60, and XC60 are installed with the inline 4-cylinder 2.0-liter turbocharged T6 engine (Fig. 21), a member of the Drive-E engine series. The T6 shares the same bore and stroke for both gasoline and diesel variants, achieving different power levels through combination with supercharging. The maximum power of the T6 is 225 kW, which it achieves by combining direct injection with both a turbocharger and a supercharger.

5 Trends in Research and Development

5. 1. Research system establishment

In Japan, the Research Association of Automotive Internal Combustion Engines was established in 2014.

Fig. 21 Volvo 2-liter Drive-E T6 engine

This is a framework for cooperative research between industry, academia, and the government to examine subjects related to internal combustion engine (ICE) combustion technologies and emissions treatment systems. Its establishment reinforces ICE research and should help to promote the development of engine technology.

5. 2. Downsized turbocharged engines

Centered on Europe, downsized turbocharged engines are becoming more widespread as a means of improving fuel economy through higher mechanical efficiency. Research into these engines is looking for an explanation for the sudden pre-ignition phenomenon that occurs at low engine speed high-load regions, which is one issue preventing improvements in torque. A large number of reports were published in 2014 examining the root causes of this phenomenon through visualization and analysis.

5. 3. Homogenous charge combustion ignition (HCCI) technology

HCCI is regarded as a promising means of reducing NOx and achieving highly efficient combustion by reducing the combustion temperature. For this reason, it has been the subject of long-term research efforts. Currently, research is examining issues related to practical adoption such as expanding the actual usage regions and ensuring the robustness of ignition and combustion. Some research and development is proceeding with a targeted adoption schedule a few years in the future.

5. 4. Thermal efficiency improvement

The latest report into improving thermal efficiency includes achieving a thermal efficiency of more than 45% by combining a high compression ratio and massive EGR and optimizing the bore/stroke ratio (5). It is hoped that this research will move toward practical adoption. Research is also continuing to examine exhaust heat recovery by high-response heat shielding or thermoelectric elements with the aim of simultaneously reducing cooling loss and knocking. One particular focus is the divergence between expected efficiency gains and actual results. At the same time, advances in instrumentation technology are not limited to the visualization of single-cylinder engines. Reports have also described a method of directly observing the combustion chamber of an actual engine, which should help to speed up research and development.

References

(1) Proceedings of the Spring and Autumn Congresses of the Society of Automotive Engineers of Japan

(2) Society of Automotive Engineers of Japan, New Engine Developments Symposium (symposium No. 15-14)

(3) 23rd Aachen Colloquium Automobile and Engine Technology, 2014

(4) Websites, PR materials, and technical reports of each company

(5) Tagishi et al, Proceedings of the Society of Automotive Engineers of Japan No. 121-14, pp. 1-4, 20145712