GASOLINE ENGINES

1 Introduction

Passenger car fuel economy standards for 2030 were formulated in Japan in 2019. The standards set stricter regulation values to urge more improvement in energy consumption performance. They also complement the current tank-to-wheel (TtW) with that of well-to-wheel (WtW) in anticipation of an increase in electric vehicles[1].

Some countries and regions in Europe have announced they would ban the sale of internal combustion vehicles within the next years or decades. The new engine models have been released over the last few years to meet the CO_2 reduction target of 37.5% from 2021 levels by 2030, and to comply with the Corporate Average Fuel Efficiency (CAFE) CO_2 emissions regulation of 95 g/km[2] that will be introduced in 2021.

In the U.S., the Zero Emission Vehicle (ZEV) regulation that promotes electric vehicles is under review, and its status remains unclear. China has been enforcing its New Energy Vehicle (NEV) regulation resulting in faster sales of electric vehicles (EVs), plug-in hybrid electric vehicles (PHEVs) and fuel cell vehicles (FCVs).

Despite the advancing pace of vehicle electrification, conventional or hybrid vehicles with gasoline engines are still expected to account for the majority of vehicles in 2030[3]. Hence, the disuse of all internal combustion engine vehicles is unlikely. Vehicle gasoline engines must complement their ongoing advances in higher efficiency and lower emissions with technological innovation.

This article introduces the new technologies used in the main gasoline engines launched or announced in 2019, and presents the research and development trends for such engines.

2 Japan

2. 1. Overview

Sales of new vehicles in Japan in 2019 reached 5.2 million vehicles, a decrease of 1.5% compared to 2018, for registered and mini-vehicles combined. Mini-vehicles accounted for 36.8% of all new vehicle sales[3].

Many examples of thermal efficiency improvement have been reported. Announcements made by various manufacturers include spark controlled compression ignition and the mass production of resin ports inserted into cylinder head intake ports for passenger vehicles. Three cylinder engines for mini-vehicles have, in combination with hybrid systems, eliminated the balance shafts, introduced multi-spark plug mass production, and been equipped with dual injectors.

2. 2. Trends of Each Manufacturer

Table 1 lists the new gasoline engines launched or announced by manufacturers in Japan in 2019, which are summarized below.

(1) Toyota

Toyota announced the mounting of its newly developed M15A-FKS/FXE 1.5-liter L3 naturally aspirated engines (Fig. 1) in the Yaris. These new modular engines developed based on the Toyota New Global Architecture (TNGA) concept share the combustion characteristics of the M20A-FKS/FXE 2.0-liter L4 naturally aspirated engine series announced in 2018.

The engines have a bore diameter of ϕ80.5 mm and a stroke length of 97.6 mm, which are identical to those of the M20A engines. Thus, they carry over the same fast burn performance concept as the M20A. Balance shafts were used only in the M15K-FKS engine for gasoline vehicles to address the low-engine speed range vibrations typical of three-cylinder engines. The M15K-FKS engine for gasoline vehicles use a direct injection (DI) system, while the M15K-FXE engine use a port fuel injection (PFI) system. The same laser-clad valve seat as in the M20A engines is used, enhancing air intake efficiency.

Toyota also developed a new dedicated G16E-GTS engine for the GR Yaris WRC homologation model. This is a 1.6-liter L3 turbocharged engine with a maximum output of 200 kW and maximum torque of 370 Nm that

Table 1 Main New Engines in Japan

Manufacturers	Engine model*1	Cylinder arrangement	Bore×stroke (mm)	Displacement (L)	Compression ratio	VVT valve train*2 specifications IN/EX	Intake system	Fuel injection system*3	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main installation vehicles	Characteristics
Toyota	M15 A-FKS (Not released)	L3	φ80.5×97.6	1.490	Undisclosed	DOHC 4-valve Roller rocker Hydraulic/hydraulic	NA	DI	88/5,500	145/4,800−5,200	Yaris	Common: Cylinder head with exhaust manifold, catalyst near exhaust manifold, long stroke, laser clad valve seat FKS: Gear-driven balance shaft FXS: High tumble intake port, low viscosity oil, small electric water pump, outer balance crank pulley, long intake duct
	M15 A-FXE (Not released)	L3	φ80.5×97.6	1.490	Undisclosed	DOHC 4-valve Roller rocker Hydraulic/hydraulic	NA	PFI	67/5,500	120/3,800−4,800	Yaris	
Nissan	BR06-DE	L3	φ62.7×71.2	0.659	12.0	DOHC 4-valve tappet Hydraulic/ —	NA	PFI (dual)	38/6,400	60/3,600	Dayz	High tumble intake port, high compression ratio, highly rigid frame, equal-length intake port, optimized web shape, piston cooling rib, DLC coating (top and oil piston rings, valve lifter), mirror finished crankshaft and camshaft journals DE: Low viscosity oil, EGR cooler
	BR06-DET	L3	φ62.7×71.2	0.659	9.2	DOHC 4-valve Direct tappet Hydraulic/ —	TC	PFI (dual)	47/5,600	100/2,400−4,000	Dayz	
	PR25 DD	L4	φ89×100	2.488	12.0	DOHC 4-valve Direct tappet Electric/hydraulic	NA	DI	140/6,000	244/3,600	Altima	Resin port, cylinder head with exhaust manifold, EGR cooler, variable intake system, mirror bore coating, variable capacity oil pump
Suzuki	R06 D	L3	φ61.5×73.8	0.657	12.0	DOHC 4-valve Direct tappet Hydraulic/hydraulic	NA	PFI (dual)	36/6,000	58/5,000	Hustler	EGR cooler, rapid combustion, high compression ratio
Mitsubishi	4 B40	L4	φ75×84.8	1.499	10.0	DOHC 4-valve Direct tappet Hydraulic/hydraulic	TC	DI+PFI	120/5,500	250/1,800−4,500	Eclipse Cross	Electric wastegate actuator (WGA), cylinder head with exhaust manifold, high tumble intake port, sodium-filled exhaust valve
Mazda	HF-VPH (SKYACTIV-X)	L4	φ83.5×91.2	1.997	15.0	DOHC 4-valve Roller rocker Electric/electric	SC	DI	132/6,000	224/3,000	Mazda 3	Spark controlled compression ignition (SPCCI) lean burn, EGR cooler, cylinder pressure sensor (CPS)
Daihatsu	KF-VE7	L3	φ63×70.4	0.658	11.5	DOHC 4-valve Direct tappet Hydraulic/ —	NA	PFI (dual)	38/6,900	60/3,600	Tanto	Common: Multi spark, high tumble straight intake port, atomizing injector, compact combustion chamber, cylinder head with exhaust manifold VE7: EGR cooler
	KF-VET2	L3	φ63×70.4	0.658	9.0	DOHC 4-valve Direct tappet Hydraulic/ —	TC	●PFI (dual)	47/6,400	100/3,600	Tanto	

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*2 : In this article, VVT and VVL are used as unified designations for camshaft position variable mechanisms and valve lift variable mechanisms, respectively.

boasts a high BMEP[4].

(2) Nissan

The BR06-DE/DET (Fig. 2) are 0.66-liter L3 naturally aspirated/turbocharged engines mounted in the Dayz. The engines were newly developed for mini-vehicles while inheriting the basic frame of registered vehicle engine series with a 1.0-liter upper limit. The engines feature enhanced dual injectors, a cooled exhaust gas recirculation (EGR) system to improve thermal efficiency. They also use a combination of a piston oil jet nozzle and cooling ribs acting as a heat sink structure on the back of the piston, and a highly thermally conductive top piston ring, to address knock resistance. A hydrogen-free diamond-like carbon (DLC) for the valve lifter and the top and oil piston rings, as well as mirror-finished sliding surfaces that suppress surface roughness on the column shaft and crankshaft, are used to reduce friction. The naturally aspirated engines use low-viscosity 0W-8 engine oil (0W-16 for the turbocharged engines), resulting in a 20% friction reduction. The use of cylinder heads that integrates dual injectors and an exhaust manifold in the exhaust system allows both the naturally aspirated and turbocharged engines to comply with the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) mode introduced in the 2018 regulations[5][6].

The PR25DD 2.5-liter L4 naturally aspirated engine is mounted in the Altima in the U.S. It is the first engine is in the world to use resin ports inserted in the intake ports. The resin ports make it possible to reduce the intake temperature in the ports, improving knock resis-

Fig. 1 Toyota M15A-FXE

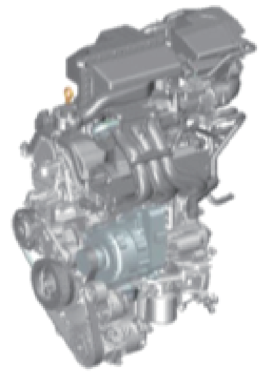

Fig. 2 Nissan BR06-DE

Fig. 3 Suzuki R06D

tance by the equivalent of 1.5 kW in output. Using cylinder heads integrated with the exhaust manifold shortens the length of the port up to the catalyst, achieving a high gas temperature of about 300 ℃ at the catalyst inlet. This margin of improvement in temperature rise makes it possible to shorten the ignition timing retard set to raise the temperature at the inlet of the catalyst during cold starts, generating greater negative pressure. The engine also uses a variable valve timing (VVT) mechanism with an intermediate lock mechanism on the exhaust side, a responsive electric motor VVT on the intake side, and a variable intake system for the intake manifold. Regarding noise, vibration, and harshness (NVH), improvements in transmission characteristics reduced the vibration level of mounting rubber by 3.5 dB at 4,000 rpm, while enhanced powertrain rigidity reduced the peak value vibration level by 1.5 dB. Radiated sound was reduced by 4 dB around the VVT cover, and by 10 dB around the crankshaft pulley[(5)(7)].

(3) Suzuki Motor Corporation

The R06D (Fig. 3) is a 0.66-liter L3 naturally aspirated engine mounted on the Hustler. The 1.07 bore and stroke ratio of the R06A was extended to 1.2 in the R06D. This long stroke and changes to the intake port shape achieve rapid combustion. This was the first time Suzuki used dual injectors in the fuel injection system of a mini-vehicle. The injectors allow fine-grained fuel injection and a uniform gas mixture. Suzuki also introduced a cooled EGR in its mini-vehicles for the first time to reduce combustion temperature and improve knock resistance[(8)].

(4) Mitsubishi

The 4B40 (Fig. 4) is a 1.5-liter L4 turbocharged engine mounted on the Eclipse Cross. The European Euro 6d-TEMP will impose much stricter requirements on emissions in the relatively high load operation ranges in the WLTP mode, as well as on robustness in the RDE test method. To address these requirements a gasoline particulate filter (GPF) is installed in the engine. In addition, the particle number (PN) in emissions and, using a soot model, deposit accumulation are estimated, and the temperature and oxygen concentration in the GPF is controlled and regeneration performed if these amounts exceed certain thresholds[(9)(10)].

(5) Mazda

The HF-VPH (SKYACTIV-X) (Fig. 5) is a 2.0-liter L4 turbocharged engine mounted on the Mazda 3. This engine uses the world's first spark controlled compression ignition (SPCCI), a proprietary Mazda technology. The engine represents the second step toward the Mazda goal of the ideal internal combustion engine. Mazda worked on improving the heat capacity ratio in the second step. More specifically, it directed its efforts at lean burn, introducing compression ignition for that purpose. Issues related to compression ignition such as noise and combustion stability are overcome with SPCCI. The engine achieves lean air and EGR over a broad operating range by adopting a high flow rate combustion chamber shape, a swirl control valve, a 70 MPa high fuel pressure injection system, a highly responsive air supply (roots-type blower supercharger system with electromagnetic clutch), and a cylinder inner pressure sensor. Moreover, heat management that includes oil control, friction reduction through surface treatments, and engine encapsulation have improved thermal efficiency. Applying combustion control, a noise insulation function, and transmission suppression provide NVH to that of current models[(11)(12)].

Fig. 4 Mitsubishi 4B40

Fig. 5 Mazda HF-VPH

Fig. 6 Daihatsu KF-VE7

(6) Daihatsu

The KF-VE7/VET2 (Fig. 6) are 0.66-liter L3 naturally aspirated/turbocharged engines mounted in the Tanto. Following the Daihatsu New Global Architecture principle, they are built on the concepts of embodying the ultimate engine features, committing to good and affordable devices worthy of Daihatsu, and optimal low-speed-torque-oriented performance characteristics for mini-vehicle users. Even as they retain the existing basic frame, the engines use a high tumble straight intake port that improves the tumble ratio by 60% without reducing the flow coefficient. In addition, the combustion chamber was modified to decrease the S/V ratio. In the fuel injection system, fine-grained fuel injection achieved via swirl injection and the changing of the injector mounting position have reduced unburnt fuel loss. The first multi spark ignition system in Japan facilitates flame kernel development in ranges that require ignition strength due to high EGR. This approached improved the fuel economy of the new naturally aspirated engine by 5% (4% for the new turbocharged engine) compared to the existing engines. The exhaust system features a cylinder head integrated into the exhaust manifold to reduce the distance to the catalyst and the surface area. The naturally aspirated engine received the first five-star rating ever granted to a mini-vehicle engine[13][14].

3 U.S.

3. 1. Overview

Sales of new vehicles in the U.S. in 2019 reached 17.05 million vehicles, a decrease of 1.3% compared to 2018, but nevertheless marking the fifth straight year of exceeding the 17 million vehicle sales milestone[3]. The proportion of passenger car sales dropped, whereas that of pickup truck and sport utility vehicle (SUV) sales rose. In the U.S. high displacement V8 OHV engines used for pickup trucks were refined.

3. 2. Trends of Each Manufacturer

Table 2 shows the major new engines launched in the U.S. market in 2019, which are summarized below.

(1) Ford

The 99N (Fig. 7) is a 7.3-liter V8 naturally aspirated engine mounted on the F-Series Super Duty. The engine was developed to achieve maximum durability in the most severe environments, with consideration given to easy maintenance and total operation costs. The engine uses a variable capacity oil pump, a forged steel crankshaft and a large-diameter main bearing to improve durability, and a piston cooling jet useful for temperature control under high loads[15].

(2) GM

The LT2 (Fig. 8) is a 6.2-liter V8 naturally aspirated engine mounted on the Chevrolet Corvette. It was newly developed as part of the fifth generation of the GM small block architecture. Using a three-stage dry sump oil system reduces the engine installation position by 25 mm, decreasing the required oil by about 2 liters and ensuring oil supply under extreme cornering acceleration. The Active Fuel Management (AFM) control system improves fuel economy by stopping a half of the cylinders during light-load driving. In addition, sodium-filled exhaust valves are used to ensure cooling performance under high loads. The exhaust system uses equal-length exhaust pipes in a 4-1 layout for each bank to improve torque. Although not used for LT2, the Dynamic Fuel Management (DFM) system is used in the L87 engine launched in 2018[16]. It refines the AFM system and stops cylinders in various combinations.

Table 2 Main New Engines in the U.S.

Manu-facturers	Engine model*1	Cylinder ar-rangement	Bore×stroke (mm)	Displace-ment (L)	Compression ratio (−)	VVT valve train*2 specifications IN/EX	Intake system	Fuel injection system*3	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main installa-tion vehicles	Characteristics
Ford	99 N	V8	φ107 × 101	7.292	10.5	OHV 2-valve Rocker arm Hydraulic	NA	PFI	316/5,500	644/4,000	F-series Super Duty	Variable capacity oil pump
GM	LT2	V8	φ103.25 × 92	6.162	11.5	OHV 2-valve Roller rocker Hydraulic/hydraulic	NA	DI	369/6,450	637/5,150	Chevrolet Corvette	Sodium-filled exhaust valves, active fuel management (AFM), dry sump
	L8T (**Fig. 9**)	V8	φ103.25 × 98	6.564	10.8	OHV 2-valve Rocker arm Hydraulic	NA	DI	299/5,200	629/4,000	Chevrolet Silverado 2500 HD	

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Fig. 7 Ford 99N

Fig. 8 GM LT2

Fig. 9 GM L8T

4 Europe

4. 1. Overview

Sales of new vehicles in Europe in 2019 reached 15.76 million vehicles, an increase of 1.1% compared to 2018, representing a fifth straight year of growth and reaching their highest level since 2007. Electric vehicles accounted for 8.1% of total sales, an increase of 35% from 2018, while gasoline engine vehicles rose 5% from the previous year[3]. A GPF is used in the exhaust system of high performance models.

4. 2. Trends of Each Manufacturer

Table 3 shows the major new engines launched in the European market in 2019, which are summarized below.

(1) BMW

The S58B30T0 (Fig. 10) is a 3.0-liter L6 turbocharged engine mounted on the X3M and X4M. The engine is a high-performance version of the B58 engine launched in 2018 with a different bore and stroke ratio. Part of the cylinder head manufacturing process uses a core made with a 3D printer. For the cooling system, the cylinder block has a closed deck cooling configuration. The engines use the double VANOS variable valve timing system, and Valvetronic direct injection, a variable valve lift system. The engine has two mono-scroll turbochargers each having a highly responsive electric wastegate valve. The pressure of the fuel injection system was changed to 35 MPa from the previous 20 MPa to improve output and reduce emissions. A GPF is used in the exhaust system to enhance purification performance[17].

(2) Jaguar

The Land Rover P400 (Fig. 11) is a 3.0-liter L6 turbocharged engine used in the Range Rover. It is in the same family as the 2.0-liter L4 turbocharged Ingenium modular engine. The Range Rover has a 48 V mild hybrid electric vehicle (MHEV) system, and its electric supercharger uses a 48 V power supply to improve responsiveness and torque in the low-speed range. The engine also has a twin scroll turbocharger. Dividing the exhaust flow between sets of three cylinders extends the exhaust pulse interval, improving operability from low engine speed conditions. Continuously variable valve control is achieved by combining electrically and hydraulically controlled variable valve lifting with variable valve timing.

Table 3 Main New Engines in Europe

Manu-facturers	Engine model*1	Cylinder ar-rangement	Bore × stroke (mm)	Displace-ment (L)	Compression ratio (–)	VVT valve train*2 specifications IN/EX	Intake system	Fuel injection system*3	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main installa-tion vehicles	Characteristics
BMW	S58B30T0	L6	φ84.0 × 90.0	2.993	9.3	DOHC 4-valve Roller rocker Hydraulic/hydraulic	TC	DI	375/6,250	600/2,600–5,950	X4 M Competition	High pressure injection, Valvetronic, double VANOS, two monoscroll turbochargers
Jaguar Land Rover	P400	L6	φ83.0 × 92.29	2.996	10.5	DOHC 4-valve Roller rocker Hydraulic/hydraulic	TC	DI	294/5,500	550/2,000–5,000	Land Rover Defender	UniAir, electric supercharger, twin scroll turbocharger, variable coolant and oil pumps, roller bearing for camshaft journal, offset crankshaft, GPF
Daimler	M139	L4	φ83.0 × 92.0	1.991	9.0	DOHC 4-valve Roller rocker Hydraulic/hydraulic	TC	DI+PFI	310/6,750 (S-model) 285/6,500 (basic version)	500/5,000—5,250 (S-model) 480/4,750—5,000 (basic version)	Mercedes AMG A45S 4 MATIC+	Twin scroll turbocharger, Camtronic

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Fig. 10 BMW S58B30T0

Fig. 11 Jaguar Land Rover P400

Fig. 12 Mercedes-Benz M139

Furthermore, a variable coolant pump is used to improve thermal efficiency, and roller bearings are used in the camshafts to reduce friction. A GPF is used for the exhaust system to enhance purification performance[18].

(3) Daimler

The M139 (Fig. 12) is a 2.0-liter L4 turbocharged engine used in the Mercedes-AMG A45 S 4MATIC+. The roller bearing-equipped twin scroll turbocharger revolving at 169,000 rpm enables high supercharging. The turbocharger is used in combination with an electronic wastegate valve for flexible control. The fuel injection system uses both DI at 20 MPa and PFI at 670 kPa. The cylinder block relies on a closed deck structure to endure a maximum combustion pressure of 16 MPa. The cylinders were given a special base treatment, and twin wire arc spraying (TWAS) was applied to obtain mirrored coating films with a thickness of 0.1 to 0.15 mm. This low-friction cylinder coating technology is called Nanoslide. The cooling system uses an electric water pump to circulate fluid at 280 L/min as necessary. This pump allows accurate temperature control from the lowest to the highest temperature. A GPF is used for the exhaust system to enhance purification performance[19].

5 Trends in Research and Development

5.1. Government-Industry-Academia Collaboration

(1) Innovative Combustion Technology in the Strategic Innovation Promotion Program (SIP)

This five-year program, which sought to achieve a vehicle engine thermal efficiency of 50% through industry-academia collaboration, concluded at the end of March 2019. A thermal efficiency of 51.5% was achieved for gas-

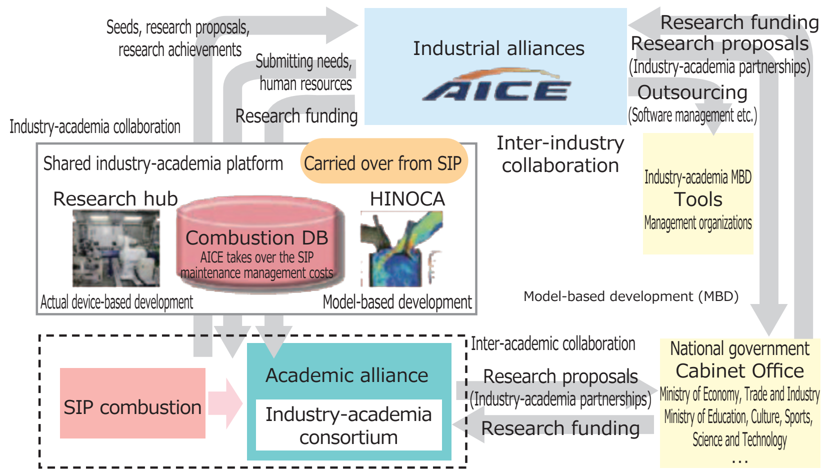

Fig. 13 Building a Sustainable Industry-Academia Collaboration System

oline engines. Specifically, this achievement was made through lean burn and low friction. Lean burn was implemented through an ignition system that enables ignition in super lean, high flow rate conditions, the optimization of tumble flow to promote flame propagation, the reduction of cooling loss by elucidating the wall surface heat transmission mechanism, and the creation of a knock control concept based on chemical reaction principles. Low friction was the result of making the turbocharging system highly efficient, improving thermoelectric generation efficiency and range using exhaust heat, as well as the evaluation of friction loss in both the piston and cylinder and crankshaft and bearing systems combined with the development of technology to reduce that loss. In terms of software, an advanced combustion control system was built by developing high-speed 3D calculation core software, the ignition, combustion, and exhaust submodel groups required for modeling as a whole, as well as a highly robust control protocol and tool that optimizes control model constants, which are necessary for controller design.

These and other outcomes were taken over by the Research Association of Automotive Internal Combustion Engines (AICE) in 2019 (Fig. 13)[20].

(2) The Research Association of Automotive Internal Combustion Engines (AICE)

Founded in April 2014, AICE started the second phase of its activities in FY 2019. Under the slogan of "environmentally friendly combustion engines for ultimate thermal efficiency and zero emissions", AICE studies themes in various fields. The combustion field covers cooling loss reduction, fuel, ignition, and flame propagation. The friction, reliability and NVH field addresses the modeling of corrosion resulting from condensate water and deposit accumulation, low friction, prediction of the high frequency components in combustion force, oil consumption modeling, and high frequency NV prediction. The heat management field involves establishing a methodology to search for highly efficient thermoelectric materials and modeling nucleate boiling heat transfer. The exhaust field deals with GPF with low pressure drop and high filtration efficiency, and light-off and degradation of precious metal catalyst. The system and control field covers cycle fluctuation prediction using HINOCA, time degradation of parts due to combustion variation, and modeling using AI[21].

5. 2. Research Papers

This section briefly describes the 2019 JSAE Awards-winning papers that are closely related to this article.

(1) Modelling on Spark Shorting under High-velocity Flow Conditions

Masuda et al. reported the building of a new model for shorting in the discharge path between the SI engine spark plug electrodes, as well as blow-out and re-discharging. In combination with a discharge path model and an electric circuit model, the new model links the discharge path extension, shorting, blow-out, re-discharge, and discharge waveform to enable the prediction of processes from discharge through ignition. Shorting at a discharge path is mostly caused by a potential difference between two adjacent points in the path, and blow-out is mostly caused by discharge-maintaining current. Accordingly, they are defined as different physical phenomena. The calculations under high-velocity flow and

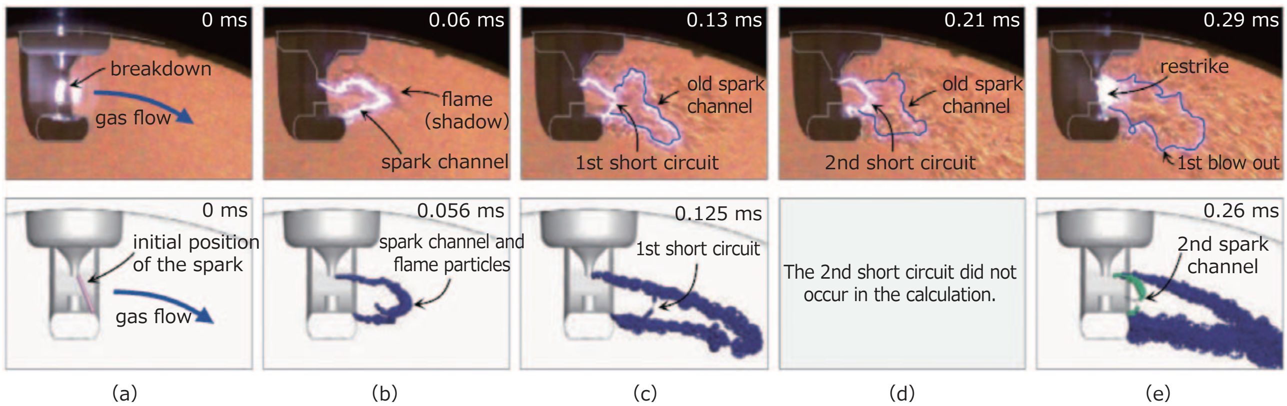

Fig. 14 Spark Plug Discharge Behavior in Swirl Chamber for Ignition Measurement

lean conditions were verified using a swirl chamber for ignition measurement. The results demonstrated a good reproduction of the discharge behavior in which shorting phenomena are dominant during the first half of discharging while blow-out and re-discharge are dominant in the latter half of discharging (Fig. 14). Verifying the calculation using a swirl chamber for ignition measurement to estimate lean burn limits showed that the behavior in which the initial combustion period increases as the EGR rate rises was reproduced with a a margin of error of about 2 points[22] [23].

(2) Development of World's First Mass Production Variable Compression Ratio Engine

Moteki et al. developed the KR20DDET, the world's first mass-produced variable compression ratio (VCR) engine. It features a unique multilink mechanism that controls the rotation position of a control shaft with an eccentric shaft using an electric motor via a harmonic drive system. The structure of the engine results in a distinctive piston process, and suppresses piston side thrust friction. The compression ratio of the engine can be varied between 8:1 to 14:1, allowing the 2.0-liter engine with a turbocharger to produce higher torque than V6 3.5-liter engines[24].

(3) Prediction of Cylinder Deformation Considering Shear Slipping Behavior of Cylinder Head Gasket

Kawaguchi et al. created a cylinder head gasket model used to predict the cylinder deformation that occurs during assembly. According to their findings, when the material characteristic of the rubber coating and metal plates is represented by a single material, the rubber coating characteristics are the dominant shear characteristics used in the gasket model, and compression characteristics need to be considered as they are affected by the cross-sectional shape of the cylinder head gasket at each bead portion. They also proposed a new model that takes the respective characteristics of rubber coating and metal plates into account and improves prediction accuracy. Although the difference in the cylinder head gasket contact state presented by the proposed model offers only a minimal improvement in cylinder deformation prediction, the model is useful to precisely reproduce the shear behavior of the cylinder head gasket and is expected to be applied to studying the design of cylinder head gaskets[25][26].

References

・European Commission website, https://ec.europa.eu/