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Development Trends in the Technologies of Automobile Internal Combustion Engines

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Abstract: This study compares the advantages offered by new energy vehicles and those offered by internal combustion engines (ICEs) to achieve low carbon emissions and zero pollution. ICEs are predicted to remain as the primary driving force of automobiles for a long time. High-efficiency, energy-saving, and clean new technologies for automobile ICEs are summarized herein, including advanced combustion, turbocharging, miniaturization technologies, multisystem and multivariable control technologies, waste heat recovery, intelligent cylinder deactivation, and water injection technology. New ICE technologies of great potential have continuously emerged to resolve issues like environmental pollution, global warming, and the energy crisis. The ICE industry in China must continue to develop because it is crucial for the advancement of China's automobile industry towards making China a major automobile power.

Keywords: Internal combustion engine; technical advantages; development potential; new technologies; highly efficient and clean

1 Developments and innovations in the automobile industry

Innovations have historically determined the direction of developments in the automobile industry. A study by the Boston Consulting Group reported that in 2016, one out of four companies among the top 20 most innovative companies in the world were car manufacturers [1]. During the first half of 2015, the number of car manufacturing companies listed in the top 20 companies of the world was more than the number of technology companies. According to the statistics provided by the Alliance of Automobile Manufacturers, the amount of money being spent by car manufacturers on research and development (R&D) has exceeded US$ 100 billion per annum, with U.S. companies alone accounting for US$ 18 billion of the annual R&D spending. In a report by Booz & Co, the R&D spending of car manufacturers has increased from US$ 7.5 billion in 2013 to US$ 102 billion, which is four times the amount spent on aerospace and defense R&D globally (US$ 25.5 billion per annum). Investments made in the automobile industry therefore account for a very large portion of the total investments made in science and technology in each country. In particular, improvements to powertrain efficiency, the realization of the potential of automotive power systems, and the development of electronic modules are important targets for innovations in the automotive industry. The internal combustion engine (ICE) is considered the heart of an automobile, and its performance has a direct influence on the power, cost effectiveness, emissions, and maneuverability of automobiles. ICE-powered vehicles are unlikely to be replaced in the near future. Automobile manufacturing companies will have to focus on the development and innovation of ICE technologies to gain a competitive edge in the market.

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2 ICE will continue to dominate the automobile industry for a long time

2.1 Advantages of ICE technology in automobile applications

The ICE has undergone extensive development over the course of a century, and it is still the foremost technology among all competing technologies in terms of energy density, thermal efficiency, fuel flexibility, market share, and processing techniques [2].

(1) ICEs have very high energy densities. In passenger cars, the highest power-per-liter achieved thus far is 150 kW/L.

(2) ICEs have high levels of thermal efficiency. The thermal efficiency of a petrol engine can reach 45%, which is comparable to the efficiency of ultra-supercritical coal-fired plants and integrated gasification-combined cycle (IGCC) power plants. Diesel engines on the other hand have thermal efficiencies that approach 50% [3].

(3) ICEs can run on various types of fuels, including fossilized fuels, natural gas, biofuels, and renewable energy sources such as ethanol.

As of the end of March 2017, automobile ownership in China exceeded 300 million, with cars accounting for 200 million. Domestic car brands of China now occupy the primary positions in the automobile market. The processing techniques of ICEs are relatively mature, and hence, they are straightforward to use and maintain.

2.2 ICEs still possess tremendous potential for development

From the perspective of ICE technologies, ICEs still have significant potential for improvement in terms of controlling CO_2 and pollutant emissions.

(1) Higher ICE thermal efficiencies. Thermal efficiency is the primary focus of many major ICE research centers worldwide. The short-term goal of these research centers is achieving an effective thermal efficiency of 60% [4], whereas in the long term, they hope to achieve a thermal efficiency of 85%.

(2) ICE electrification. Electronic control and informatization are rapidly being introduced into ICEs; this has led to the development of technologies such as electronic water pumps, electronically controlled unit injectors, electric turbochargers, and exhaust gas recycling (EGR). These developments will further refine the control of ICEs and significantly increase their efficiency.

(3) The increasingly stringent regulations on energy consumption and emissions. Many countries worldwide have formulated regulations to significantly reduce fuel consumption and CO_2 emissions. In addition, real driving emission tests are currently being prepared for implementation in light vehicles. These measures are highly conducive to the reduction of pollutant emissions from ICEs.

(4) The continuous development of emission control technologies for vehicles. Currently, the emission of harmful substances from ICEs is already approaching zero, and the emission of major pollutants has been reduced by approximately 90%.

Furthermore, owing to the exacerbation of energy and environmental problems on a global scale, there is the urgent need to reduce the energy consumption of ICEs and the CO_2 emissions by ICEs for the automotive industry. The CO_2 emission reduction schedules for some of the major countries and regions worldwide are shown in Fig. 1. In China, the automobile industry has to reduce CO_2 emissions from passenger cars by 5% annually.

2.3 New energy vehicles (NEVs) cannot replace ICE vehicles in the short term

New energy vehicles (NEVs) hold numerous advantages over ICE vehicles in terms of CO_2 emissions and zero pollution control. However, a development schedule has yet to be defined for new energy sources such as solar energy, wind energy, and renewable biomass energy. Currently, the battery technologies required for NEVs have yet to fully mature, and the processes involved in the manufacture of battery materials are associated with a number of environmental problems. Therefore, a number of social and technical barriers must be overcome before NEVs can be widely used. Based on optimistic estimates in the *2017 Strategy & Digital Auto Report*, 73 million electric cars are expected in China by 2030, which should account for 10% of the total number of cars in circulation at that time [5]. Therefore, ICE vehicles will continue to dominate the automobile industry and market at least in the near future.

3 Highly efficient and clean ICE technologies

3.1 Endless emergence of next-generation combustion technologies

During the 1990s, people had thought that a lower bound ex-

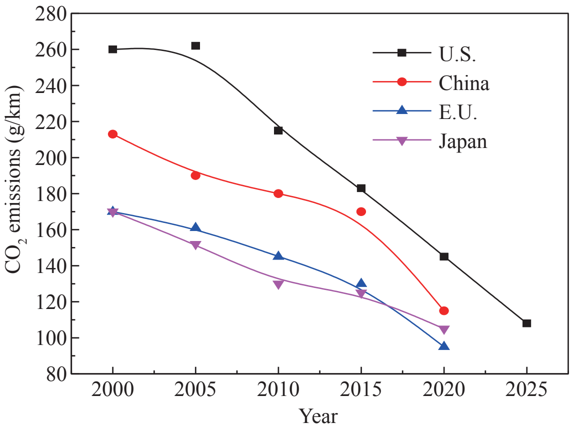

Fig. 1. Schedule for CO_2 emissions reduction in major countries and regions worldwide.

ists for the emission of harmful substances such as NOx and soot from conventional diesel engines; for example, the minimum limit for NOx emission was thought to be 2.5 g/kW·h. However, in the last 20 years, tremendous developments have been made to increase the thermal efficiency of and reduce emissions from ICEs worldwide (including China), and the 2.5 g/kW·h limit has long been surpassed. Some of the most advanced ICE combustion technologies are gasoline compression ignition, reactivity controlled compression ignition (RCCI), highly premixed charge combustion [8,9], homogeneous charge compression ignition (HCCI) [3], and gasoline direct compression ignition [10]. All of these technologies exhibit extremely high levels of thermal efficiency.

According to recent reports, the Oak Ridge National Laboratory of the U.S. has already achieved thermal efficiencies of above 55% for certain multicylinder engines. The Toyota 8NR-FTS-Turbo GDI engine only consumes 5.15 L per 100 km, which is 10% better than the efficiency regulations stipulated by the Japanese government. The Mazda SKYACTIV-G gasoline engine, which uses HCCI combustion, can achieve a thermal efficiency of 40% and produce high torque at low speeds. Furthermore, this engine has a fuel consumption that is 35%–45% lower than a Mazda engine produced in 2008 with the same displacement. Owing to this achievement, Mazda has postponed its adoption of hybrid engine technology.

The Su Group in Tianjin University conducted a detail study on the physical and chemical processes of an ICE engine in a variety of combustion states (e.g., different engine loads and rotation speeds). Consequently, they proposed mixing control, chemical-reaction time scales, and combustion pathways in the combustion processes of a diesel engine [11]. They subsequently proposed and implemented a new type of technology known as high mixing rate multipulse fuel injection. This ultimately led to the formulation of the high-density low-temperature combustion (HD-LTC) theory [12] and the theory of combustion pathway control [13]. These technologies allow diesel engines to achieve the phase VI pollutant emission standards and a thermal efficiency of 45.5%.

3.2 Turbochargers and miniaturization technologies

The miniaturization of turbochargers is currently a mainstream direction for the development of automobile ICEs. According to the University of Michigan Transportation Research Institute (UMTRI) in the U.S., 50% of all passenger cars will use turbochargers by 2025 [14]. Almost all new cars in China are already using miniaturized turbochargers.

Advanced high-pressure turbocharger technologies have developed at a fast pace in recent years; the most advanced turbochargers technologies currently are electrically driven compressors (eBooster), variable geometry turbochargers (VGTs), and regulated two-stage turbocharger (RTST) systems. The eBooster in particular can significantly improve the response characteristics of intake systems and increase the high-load efficiency of ICEs. However, eBoosters are expensive and its electronic devices do not tolerate high temperatures very well [15]. VGTs are a commonly used technology in high-specifications, small-displacement ICEs, e.g., ICEs in sedans. This turbocharger technology improves the torque characteristics at low and high speeds and significantly improves the power density of ICEs; furthermore, this technology also promotes the miniaturization of ICEs. RTST systems are available in two configurations: waste gas turbocharger (WGT) + fixed geometry turbo (FGT) systems, or VGT + FGT systems. These systems are typically used in large displacement ICEs; for example, the BMW 740MY2010 3.0 L ICE uses a VGT + FGT turbocharger system that reduces the fuel consumption of the engine by approximately 10% and allows the engine to match the performance of V8 and V10 engines.

The Liu Group in the Academy of Military Transportation has developed a VGT + FGT turbocharging system for a heavy-duty diesel engine meant for high-altitude operations [16], which uses a control strategy that adapts to its operational altitude [17]. A high-altitude simulation system for ICEs (see Fig. 2) was used to simulate the effects of different altitudes and operating conditions on the performance of this RTST diesel engine. The results demonstrate that the RTST system improved the maximum torque and rated power of the diesel engine by 11.0% and 11.8%, respectively, when the altitude was 5500 m above sea level. The turbocharger system also improved the average torque at low speeds by 31.1%, increased the adaptability coefficient by 19.2%, and decreased the minimum fuel consumption and low-speed fuel consumption by 4.8% and 15.3%, respectively. The combined operating curve of the low-pressure turbocharger and diesel engine remained in the high-efficiency regime of the compressor, regardless of the altitude.

3.3 Intelligent control technologies for multivariable, multisystem ICEs

The rapid development of multisystem, multiparameter/variable control techniques in recent years has accelerated the "smartization" of ICEs. The subsystems of an engine include numerous controllable parameters, e.g., the turbocharger system (size of the opening of the VGT blades and waste gate valve), fuel injection system (pre-injection, primary injection, fuel injection timing, and the amount of injected fuel), EGR system (size of the valve opening and the timing for closing the valve), and the throttle linkage [18] (valve lift and timing). The variable intelligent technologies used in ICEs include variable turbocharging, variable EGR, variable valve timing/lift, variable direct injection and dual injection, and variable compression ratio [19,20] technology.

A simplified schematic of the hybrid turbocharging (HyBoost)

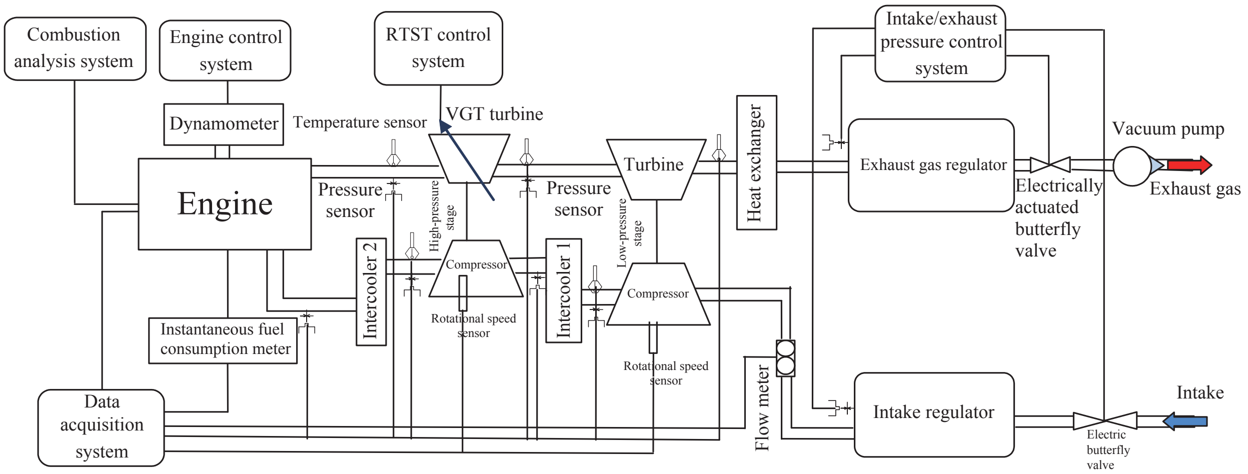

Fig. 2. Schematic of the experimental system for the simulation of high-altitude performance tests for a diesel engine equipped with an RTST system.

system designed by Ford for its 2.0 L naturally aspirated (NA) engine is shown in Fig. 3 [13]. This system represents a combination between electric superchargers and conventional exhaust gas turbochargers. The electric supercharger adaptively adjusts its turbine speeds according to the operating conditions of the engine to accurately control the intake charging process, and the HyBoost system simultaneously recycles some of the energy used by the engine at high loads. This significantly improves the low-speed torque and fuel consumption, and the cost effectiveness of this system is comparable to that of full hybrid engines.

Fig. 4 shows the multisystem, multiparameter intelligent control system developed by the Su group in Tianjin University for a Chinese diesel engine. The resulting diesel system included a variable two-stage turbocharger, variable EGR system, variable fuel injection system, and variable valve lift/timing technology. The parameters that are controlled by this system include the opening of the VGT blades, the compression ratio, the opening of the EGR valve, and the quantity of injected fuel. The intelligent control system can monitor the operating conditions and road conditions of the diesel engine. Based on factors such as transient processes, dynamic response characteristics, and peak PM values, the system subsequently implements the appropriate control strategy to control the subsystems and parameters of the diesel engine, in real time. This improves the thermal efficiency and fuel economy of the diesel engine and reduces its pollutant emissions.

The improvement in onboard computational capacity is a necessity for improving vehicle control technologies. This includes the solving of ICE control problems and computational problems, and more importantly, the enhancement of coupled control schemes for engine and vehicle systems. Based on a study by UMTRI on powertrain strategies in the 21st century, the proportion of ICE costs involving electronic products is expected to increase by 15% by 2025. Therefore, electrification and smartization are not the sole domains of electric cars, as electrification, informatization, and smartization are also important paths for the development of ICE vehicles.

3.4 Improving the efficiency of each operational stage of an ICE

Improvements in fuel consumption and thermal efficiency are determined by seven factors: compression ratio, specific heat ratio, combustion period, combustion timing, wall heat transfer,

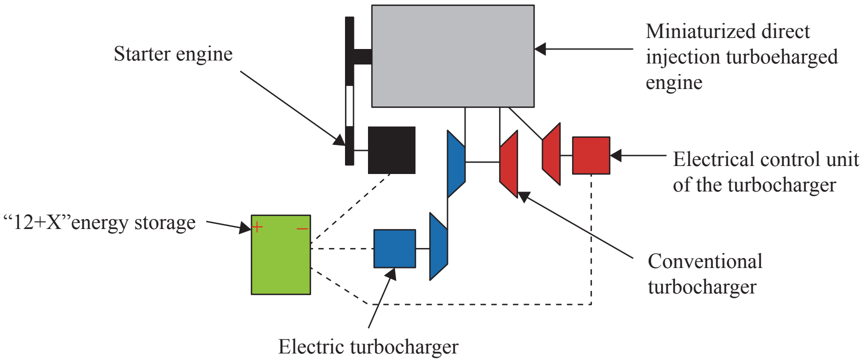

Fig. 3. HyBoost system for the Ford 2.0 L NA engine.

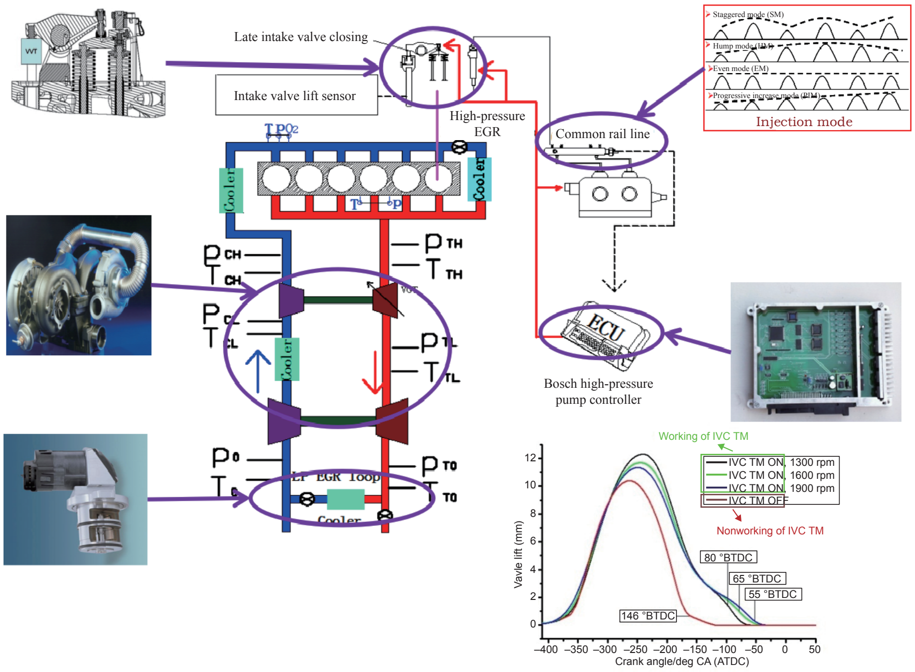

Fig. 4. Multisystem, multiparameter control system for a V6 diesel engine.

pressure differences in the suction stroke, and mechanical friction. The losses of an engine during operation include discrete/ignition losses, exhaust gas losses, cooling losses, pumping losses, and friction losses (see Fig. 5). Turbocharging, compression ratio optimization and waste heat utilization minimize ignition losses and exhaust gas losses, while low heat dissipation technologies will reduce cooling losses. Variable frequency pumps will reduce pumping losses, and friction losses can be reduced using lubrication technologies. However, the control of the total cost still remains a problem [21].

3.5 Other advanced ICE technologies

The technologies that could be used to further improve the thermal efficiency, fuel consumption, and emission performance of ICEs (in addition to the aforementioned technologies) include intelligent cylinder deactivation technology, split cycle technology, water injection technology, and increases to the octane number of gasoline engines.

3.5.1 Intelligent cylinder deactivation technology

Intelligent cylinder deactivation technology is important for reducing the emissions by and energy consumption of ICEs [22]. Intelligent cylinder deactivation technology is already being employed by the high-end cars produced by Robert Bosch GmbH and Bavarian Motor Works (BMW). Tianjin University has implemented intelligent cylinder deactivation technology in a natural gas engine. This engine was found to consume 45% less natural gas than an imported spark ignition natural gas engine, over a 100 km course on the same road. Furthermore, adaptive

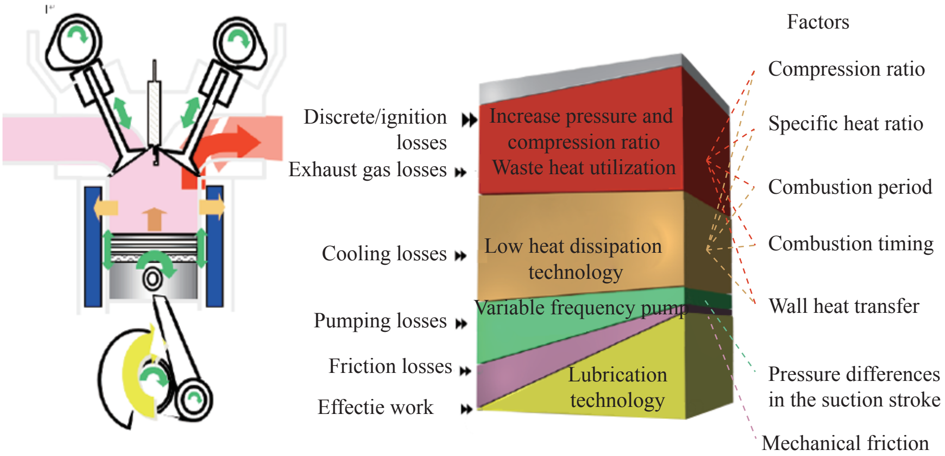

Fig. 5. Operational losses of an engine and the factors influencing these losses.3.5.3 Water injection technology

cylinder control (based on the operational mode of the engine) eliminates vibrational noise and balances the heat loads of the engine.

3.5.2 Split cycle technology

In a split cycle ICE, compressed air is transferred between multiple cylinders through a crossover passage. The transfer of compressed air allows the strokes of each ICE cycle to be divided between multiple cylinders. As the compression and power strokes are performed by different cylinders, the heat stress on the compression cylinder is relieved, which subsequently increases the compression ratio. Furthermore, the volume of the cylinders may be tuned such that the expansion ratio exceeds the compression ratio, thus allowing for a full expansion cycle. Although Scuderi, META, and General Motors (GM) have investigated this technology to different extents, this technology has yet to be implemented on an industrial scale [23–25].

Water injection technology reduces engine knocking and increases the torque of gasoline engines, up to the level of diesel engines that have the same quantity of emissions. Furthermore, the integration of the transmission box significantly reduces the overall fuel consumption of the vehicle. The knocking properties of twin-turbo and direct injection spark ignition gasoline engines are also significantly improved by the use of water injection technology. In a recent development, the use of a water-to-fuel ratio of 35% in an experimental engine developed by Bosch was found to reduce fuel consumption by approximately 13% [26,27].

3.5.4 Increasing the octane number of gasoline engines

Increasing the octane number of gasoline engines is important for increasing the thermal efficiency of ICEs. For example, the thermal efficiency of an ICE may be increased by 5% by raising its octane number to 95–100 [28]. Tatur et al. [29] noted that the governments of Europe and the industrial world have reached an understanding concerning the need to increase the octane number of gasoline engines. The highest octane number currently is RON 102, and this is beneficial for new technologies aiming to optimize the performance of gasoline engines. The State Key Laboratory of Engines (Tianjin University) has developed a new technology called the reformed-molecule homogeneous-charge compression ignition (RM-HCCI) [30,31] that improves fuel consumption at high loads and can achieve a thermal efficiency of 52%.

4 Conclusions

The ICE will continue to be crucial in powering automobiles for a long time period. Many clean, highly efficient, and energy saving ICE technologies have emerged owing to the pressures of environmental pollution, global warming, and the impending energy crisis. China must strongly prioritize clean and efficient ICE technologies in the formulation of its automobile development plans. Furthermore, China should also closely follow the global development trends in automobile technology investments and in its establishment of standards for the development of ICE technologies.

(1) The reduction of ICE energy consumption and emissions is an important long-term task; in the future, this will become an important battleground for the energy and environmental security of China. Owing to the importance of this task, it is of utmost importance to accelerate the development of ICE technologies as they will drive the development of China's automobile industry and the overall development of China.

(2) New ICE technologies are being developed at a fast pace worldwide to improve energy efficiency and lower emissions. These technologies include advanced combustion technologies, turbocharger technologies, multisystem multivariable control technologies, waste heat recycling technologies, intelligent cylinder deactivation technologies, and water injection technologies.

(3) The gap between China and other advanced nations in the development of ICE technologies is rapidly decreasing owing to the progress made by Chinese automobile manufacturers, who have achieved outstanding results on a global level. Owing to the rapid emergence of advanced ICE technologies, the ICE industry of China must not diminish. It is therefore important to encourage innovations in the ICE industry, support efforts to lead ICE technologies, and actively promote the advancement and industrialization of China's ICE technologies. The independent development of efficient and clean ICEs is important for China to become a major automobile power.

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