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CO_2 Reduction Request and Future High-Efficiency Zero-Emission Argon Power Cycle Engine

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Abstract

To meet the requirements of strict fuel consumption and emission limits, continuously increasing the thermal efficiency of an internal combustion engine and decreasing its exhaust emissions are the main challenges to its sustainable development within the automotive industry. Considering the competition with other zero-emission powertrain systems, such as vehicle batteries and fuel cells, the development of the internal combustion engine needs to focus on producing higher efficiency and zero emissions to meet the request of CO_2 reduction. This paper introduces two novel concepts for an internal combustion engine featuring high efficiency and zero emissions. Referred to as the argon power cycle engine fueled with either hydrogen or natural gas within an oxygen–argon mixture, its fundamentals and characteristics are expounded. This includes a method necessary to absorb carbon dioxide when natural gas is used as fuel instead of hydrogen.

Keywords CO_2 Reduction · Argon power cycle · Internal combustion engine · High efficiency · Zero emission

Abbreviations

BMEP	Brake mean effective pressure
CVVL	Continuously variable valve lift
DCP	Dual cam phasing
DEA	Diethanol amine
DOHC	Dual overhead cam
DVVL	Discrete variable valve lift
EGR	Exhaust gas recirculation
GDI	Gasoline direct injection
ICP	Intake cam phasing
ICE	Internal combustion engine
MEA	Monoethanolamine
MDEA	Methyldiethanolamine
PFI	Port fuel injection
SOHC	Single overhead cam
VVL	Variable valve lift
CR	Compression ratio
ICE	Internal combustion engine

List of Symbols

η_{Brake}	Effective thermal efficiency
$\eta_{\mathrm{Combustion}}$	Combustion efficiency
$\eta_{\mathrm{Thermodynamic}}$	Thermal efficiency
$\eta_{\mathrm{GasExchange}}$	Gas exchange efficiency
$\eta_{\mathrm{Mechanical}}$	Mechanical efficiency
γ	Specific heat ratio

1 Introduction

At present, most of the energy used by the global community is extracted from natural fuels to be burnt into available heat energy and converted into power. In the foreseeable future, internal combustion will continue to be an important technical mode of fuel-energy conversion and utilization. In the next few decades, the internal combustion engine (ICE) is seen to remain the main source of power for mobile power plants. China's production of engines was maintained at a steady growth in 2016 with the annual output reaching 2260 gigawatts [1]. Therefore, the study of high-efficiency and low-pollution combustion and the ICE is still of great significance. The frontier of the relevant basic research includes: efficient clean combustion theory of traditional fuel power plants, new combustion methods and combustion theory, alternative fuel combustion theory and efficient clean com-

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bustion theory of its power devices, and fuel chemistry mechanisms and reaction kinetics. In addition, the reduction of CO_2 emissions is an important issue confronting fuel combustion. A study has found that for every 1% increase in the manufacturing industry sector, the average increase in carbon emissions is 56 million tons (MT) [2]. To promote less energy-intensive technologies is at the core in reducing carbon emissions. With a decline of 1% in energy demand, carbon emissions will be reduced by an average of 33 MT [2]. At present, China's total CO_2 emissions have exceeded that of the United States, ranking first in the world. In this context, the Chinese government promised that CO_2 emissions per GDP unit in 2020 will decline by 40–45% based on 2005 levels. Therefore, exploring China's low-carbon development path has become important scientific and social issues that requires urgent resolution within our country. Under the current target, power trains of vehicles are to be developed for near-zero emissions and ultimately zero emissions in the coming future.

2 Energy Supply Status and Environmental Issues

2.1 Energy Demand and Challenge of CO_2 Emissions

Energy consumption is one of many human activities that have impacted the planet. The common sources of energy are oil, natural gas, coal, nuclear energy, biomass and hydropower. The energy consumption for the USA between 1776 and 2040 (Fig. 1) [3] highlights that, as societies develop, energy consumption increases year by year. Since the late 19th century, fossil fuel has been dominant in all forms of energy consumption. And the petroleum will still play key role for the transportation energy till 2040. This shows that production and social activities of humans impose huge demands for energy, minerals, and other natural resources. The consumption of fossil fuels has resulted in massive emissions of CO_2-based greenhouse gases. In the contribution of greenhouse gases to global warming, carbon dioxide accounted for about 65%, methane for about 17%, nitrous oxide for 6%, and other greenhouse gases for about 12%. The average concentration of atmospheric carbon dioxide, methane, and nitrous oxide in 2014 increased by 43, 154, and 21% over the pre-industrial revolution year of 1750. The World Meteorological Organization reported the fluctuations of global average annual temperature in 1850–2015 [4]. The global average temperature in 2015 was about 0.76 °C higher than that of 1961–1990, which clearly makes 2015 the hottest year in the historical records. The continued increase in the global average temperature has led to the rise of sea levels, glacier retreats, and frequent occurrences of extreme weather events. As one of the important reactions to climate change, the rise of sea level has drawn international attention and is studied around the world. From the global average of sea level changes in 1993–2010 (Fig. 2) [5], sea levels have been continually rising. According to the research report, IPCC 2001, CO_2 emissions have a long-term impact on the global CO_2 concentration, global temperature, and sea level rise. After the global CO_2 emissions peaks, it takes 100–300 years for the global CO_2 concentrations to reach equilibrium, several centuries for the global temperature, and thousands of years for sea levels because of glacier ablation.

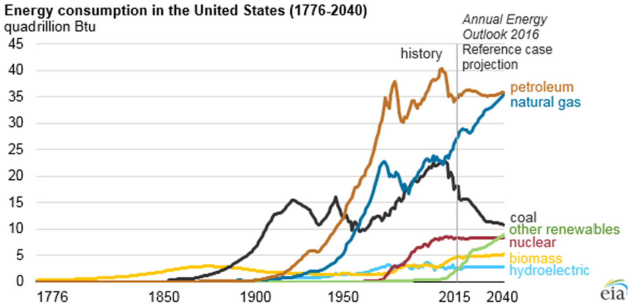


Fig. 1 Energy consumption in the USA between 1776 and 2040 [3]

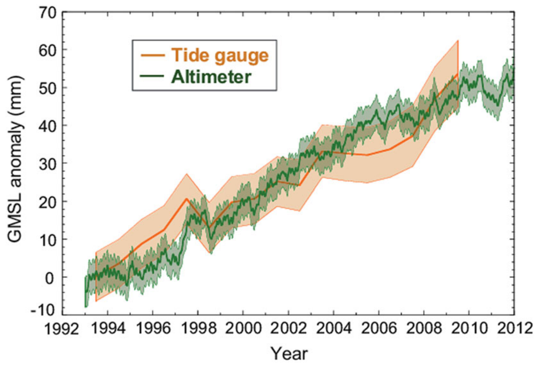


Fig. 2 Global average sea level change in 1993–2010 [5]

As the world's second largest economy, China's annual increase in CO_2 emissions has kept pace with its rapid economic growth. Its CO_2 emissions in 2016 had exceeded that of the USA (Fig. 3) and will continue to increase based on the study of Chen at Beijing University in 2009 [6]. It will reach 7000 MT in 2020 and close to 10,000 MT in 2030. Based on the China Climate Bulletin 2015, with the exception of 2001 and 2013, China's average temperature since the start of the 21st century is higher than the annual average temperature of 1981–2010. The glacial areas of China in the past 50 years provide a perspective of the impact of the increase in average temperature on China's environment. The annual rate of change in these glacial areas between 1960 and 2009 (Fig. 4) [7] reflects the general trend in glacial recession in China. With slight growths in precipitation in China's glacial area, the change in temperature is the main factor affecting the changes in glacial areas in China.

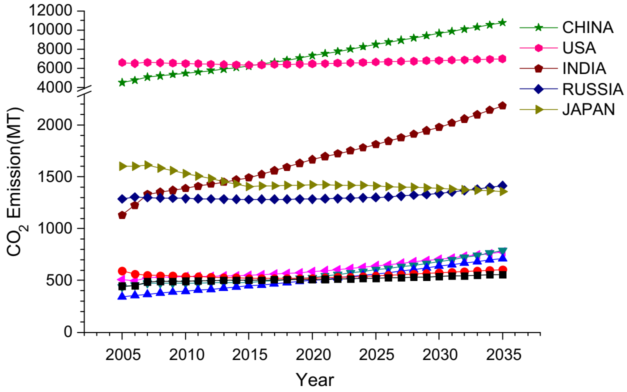


Fig. 3 Amount of CO_2 emissions in the main countries [6]

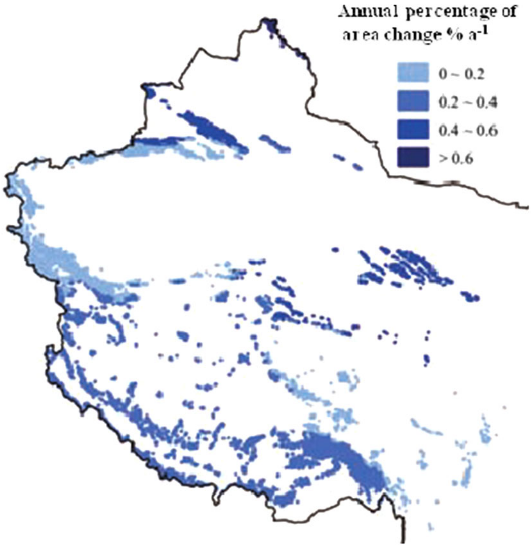


Fig. 4 Annual retreat rate of glacier area in China between 1960 and 2009 [7]

2.2 Energy Supply-Current and Future

Of the world's total energy consumption in 2012, natural gas ranked second and accounted for 15.2% of the total consumption, with oil accounting for 40.7%, and coal for 10.1%, based on the EIA2014. By 2050, the world's main primary energy will still be dominated by fossil fuels, which mainly include coal, oil, and natural gas. After 2045, however, energy consumption growth will stagnate and the world's primary energy consumption growth will slow down gradually [8]. Under the influence of an accelerated economic restructuring and through policy controls of the total energy consumption, China's energy consumption will reach a peak around 2035 [8], which will have a profound impact on global carbon reduction and climate change. In the next 35 years, energy efficiency will play a key role in energy development and the intensity of global energy consumption will gradually decline. Therefore, the development of clean and efficient technology is an important means to improve energy efficiency. In the next 30 years, economic growth will be faster than energy consumption growth; that it will be faster than CO_2 emissions growth will be a main policy feature of China and the world in the future. Hence, to improve energy efficiency has great import in developing the economy and reducing the levels of CO_2 emissions. According to China's economic development practice, the improvement of energy efficiency means that the ratio between economic growth and carbon emissions is decreasing.

Clean energy will be one of the themes concerning global energy use in the next 30 years. From its low carbon emissions, natural gas has gradually become a major source of energy for an increasing number of countries, especially in developing countries. Global demand for natural gas will continue to grow, and the golden age of natural gas will continue. For developing countries, natural gas will by 2035 serve as the third largest source of primary energy, ranking after coal and oil, based on the report of BP Energy outlook 2014. The Asia Pacific area will become the largest natural gas consumption region. China's primary energy consumption structure will witness huge changes, showing the beneficial characteristics of clean energy. China's future peak production of natural gas will reach 420 billion cubic meters. Natural-gas supply will exceed that of oil in 2040, accounting for nearly 20% of the total energy application, while coal will drop to 40% [8]. Over the next 30 years in China, the attributes of clean energy in terminal energy consumption will also be evident. In the transport sector, the proportion of natural gas will still be greater than that of electric energy. China will approach the current level of the USA in future gas consumption and become the largest importer [8].

Both electric energy used in vehicles and gasoline/diesel used in vehicles are secondary energy sources. In the study of its energy consumption and emissions, the international approach is the life-cycle assessment, which is the core content of the circular economy of the automotive industry. Many scholars both home and abroad have assessed the different vehicle energy paths from the perspective of their whole life cycle [9–11]. At present, the models used to analyze different alternative fuels and carbon emissions are mainly the life-cycle emission models and the model for greenhouse gas, regulated emissions, and energy use in transportation (GREET) [12–14]. Researchers at Tsinghua University have developed the Tsinghua life-cycle analysis model based on the domestic situation. Using the whole life-cycle theory, Ou. et al. believe that greenhouse gas emissions of vehicles using CNG as fuel will decrease by 10–20% compared with that of gasoline vehicles [15].

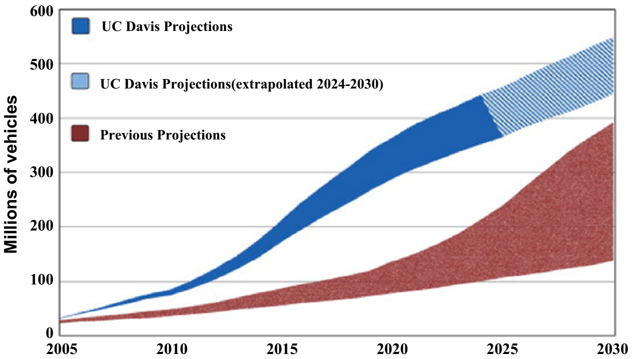


Fig. 5 Prediction of the vehicle population in China [16]

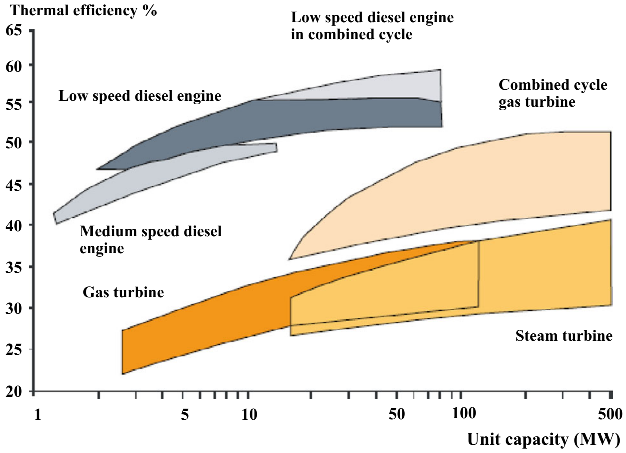


Fig. 6 Comparison of the efficiencies of various types of internal combustion engines [17]

3 Requirements and Challenges for Future Development of an Automotive PowerTrain System

With the rapid development of China's economy, the domestic-annul vehicle production in 2016 has reached 28.119 million. Figure 5 is a predicted curve of China's vehicle population [16]. The blue band is the predicted vehicle population growth for China using models based on Japan and Korean; the red band presents predictions using the models of seven countries: USA, Japan, Germany, Italy, Korea, Spain, and Brazil. The blue model is closer to China's actual situation and suggests the vehicle population will reach 280–350 million in 2020, and 450–550 million in 2030.

Global energy consumption in transportation in the foreseeable future features a certain degree of diversity; however, fossil fuels will remain dominant. Nevertheless, low carbon emissions will become the greatest challenge to automotive technology development in the coming decades. By 2020, the automotive carbon-emission limit for Europe will be 95 g/km, whereas for China this limit will be 130 g/km. It raises higher requirements on the powertrain system of automobiles. A comparison of the efficiencies of various types of ICEs at the present time (Fig. 6) shows that among the various contemporary internal combustion power machines, diesel engines have the highest efficiency. With unit capacities in the range of 2–100 MW, the efficiency of low-speed diesel engines is around 55%, with their thermal efficiency approaching 60% if a combined cycle is adopted; moreover, the thermal efficiency of medium-speed diesel engines is also higher than that of turbomachinery. The power efficiency of a reciprocating piston engine is the highest among contemporary high-efficiency power machines. Therefore, in the general context of energy conservation and emission reduction, the great import of research on the reciprocating piston engine is clear, along with endeavors to improve its thermal efficiency. At the present time, thermal efficiency limits have not been reached. The emergence of various new materials and new technologies will enable improvements to be attained.

For conventional fuel engines, improving the thermal efficiency while reducing CO_2 emissions equates to cutting down fuel consumption. The National Research Council assessed various low-fuel consumption technologies suitable for light-duty vehicles [18]. The assessment indicated that for gasoline engines fuel consumption can be reduced by 3.5–4.9% by adopting low-friction + thermal management technology; 2.6% by DOHC-ICP technology, 5% by DOHC-DCP technology, 3.5% by SOHC technology; 3.6% by DOHC + DVVL technology, 4.6% by DOHC + CVVL technology, and 3.6% by SOHC + DVVL technology. For SOHC and DOHC engines, if cylinder deactivation technology is used on top of DCP and VVL technologies, fuel consumption will be reduced further by 0.7%. For a PFI I4 engine with fixed valve timing and lift, which employs pressure boosting and engine miniaturization technology, fuel consumption can be reduced by 11.1–14.9% when BMEP is 1.8 MPa, 14.4–20.1% when 2.4 MPa, and 17.6–24.6% when 2.7 MPa (however, with EGR & inter-cooling technology as well) [18].

Carbon-emission reduction from fuel is an important aspect of automotive powertrain systems. Figure 7 illustrates the course of development of fuels, including mainly coal, petroleum, gaseous fuel, and future hydrogen energy. In the low-carbon-emission era, gaseous fuel, especially natural gas, as an alternative fuel, will play a significant role [19]. Its outstanding advantages lie in its high-octane number and the smaller carbon-to-hydrogen ratio of the fuel. They provide conditions required for increasing the compression ratio of natural-gas engines, improving thermal efficiency, and lowering CO_2 emissions. Lean-burn natural-gas engines have lower maximum in-cylinder combustion temperatures [20] and hence higher thermal efficiency and lower hazardous

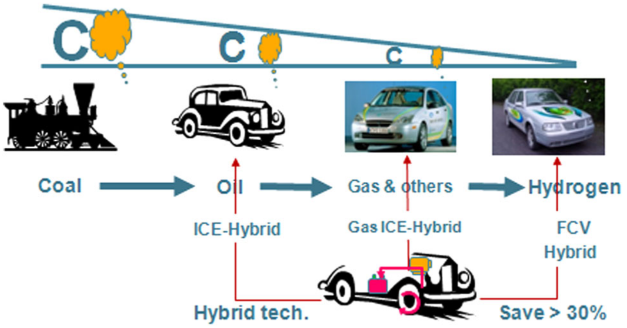


Fig. 7 Roadmap of fuels for power trains

emissions [21]. For the same thermal efficiency and air-fuel ratio, lean-burn natural-gas engines emit less CO_2 than diesel engines do; and the CO_2 emissions of natural-gas engines are 20% lower than those of gasoline engines of the same power [22]. Moreover, lean-burn natural-gas engines have lower NO_x emissions under heavy load [23]. The statistical results by Khan et al. [24] indicate that CO_2 and other hazardous emissions can be reduced markedly when natural gas is employed as an alternative fuel, compared with diesel and gasoline. However, realizing "zero carbon emissions" requires the wide application of hydrogen energy.

To analyze the efficiency of a powertrain system in a comprehensive way, an efficiency assessment should be performed from the perspective of its full life cycle. Well-to-wheel (WTW) efficiency refers to the overall efficiency of automobiles from crude oil extraction to drive wheels, including energy conversion, conveyance, and transmission efficiencies of each stage. The energy-conversion process can be divided into two steps: "well-to-tank" (WTT) and "tank-to-wheel" (TTW). WTW is an important indicator for assessing the feasibility of developing new energy automobiles. The efficiency analysis for ICE vehicles burning oil can be divided into extraction, dispensing from refinery to gasoline station, ICE and transmission shaft. The efficiency analysis for electric vehicle can be divided into refining (from crude oil to fuel oil), power generation, transmission and distribution, battery charger, battery charging/discharging, power converter, motor, and transmission shaft. Based on WTW evaluations, the full life-cycle simulation software GREET developed by Dr. Michael Wang of Argonne National Laboratory (USA) was used to calculate and compare the WTW efficiency of ICEs and electric automobiles (see Table 1). When the TTW of ICEs are 21.9%, the difference in final efficiencies of the two is a mere 1%. With an efficiency for gasoline engines produced in 2015 of 38%, and that in 2016 of 40%, the WTW of gasoline engines is close to or above the WTW of electric vehicles powered by batteries.

Table 1 Comparison of the efficiencies of ICE and electric automobiles based on WTW

	ICE automobile	Electric automobile
WTT efficiency (%)	79.5	38.0
TTW efficiency (%)	21.9	48.5
WTW efficiency (%)	17.41	18.43

4 Future Competition and Development of Zero-Emission Vehicle Power Systems

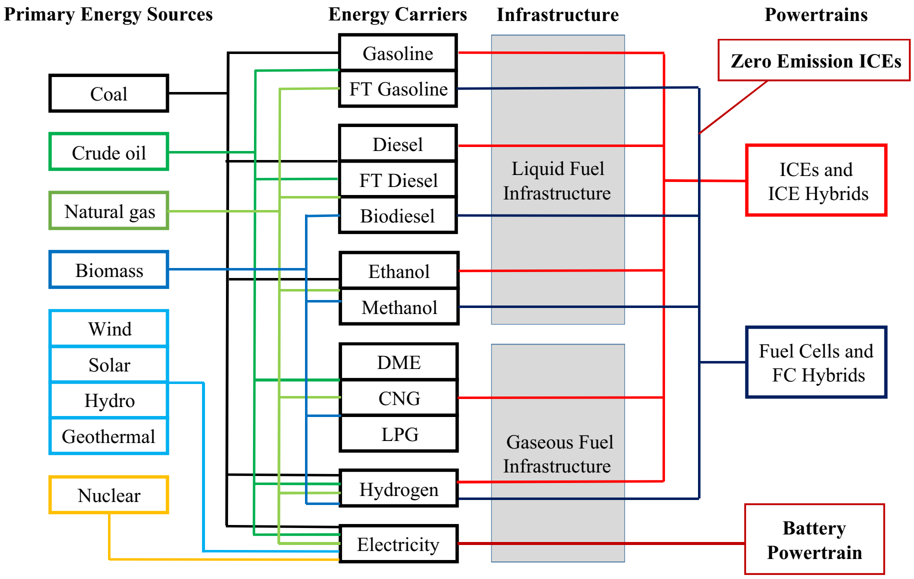
In the future, power systems for vehicles will include ICE/hybrid power systems with near-zero emission, fuel cell power systems, pure-electric power systems and new ICE power systems with zero emissions (Fig. 8) [25]. In a mutually competitive environment, such power systems will coexistence, among which the new zero-emission ICE power systems have the following four characteristics: emissions without harmful gas, carbon-free emissions, near 100% work efficiency, and intelligent operations(smart engine).

At present, zero-emission ICEs mainly include the internal combustion Rankine cycle (ICRC) engines and argon power cycle (APC) ICEs.

The concept of ICRC engines in vehicles was proposed by professor Bilger [26] based on CRC which was developed as the new zero-emission power station belonging to the Department of Energy (DOE) of the USA. The power station generates power through the combustion of fossil fuel with pure oxygen. The Clean Energy Systems (CES) Company in the USA undertook the Combustor Development Project of the DOE and developed a new combustor technology with financial support of DOE. With a gas generator developed by CES as its core, the combustor has a structure similar to a rocket propeller. The gas generator can withstand extremely high temperatures and support a direct reaction between oxygen and the fuel with a mix proportion around the equivalence ratio. To make full use of the thermal energy produced through the combustion, this system injects a large amount of water into the combustion chamber during the burning process to propel a high-temperature high-pressure vapor as exhaust from the combustor to turn turbines that generate the power. The system produces vapor with temperatures of up to 1649 °C and pressures of up to 10 MPa. This gas generator has a thermal efficiency of 65% or above, far better than that of a boiler with oxy-fuel combustion technology. Because combustion involves pure oxygen, only carbon dioxide and vapor are produced; the carbon dioxide in the flue gas is completely recycled through condensing separation. In this way, zero-emission recycling of fossil fuel can be realized.

Based on gas generator technology and supported by advanced techniques such as high-temperature turbines, CES

Fig. 8 Prediction for the 2030 power trains of vehicles [25]. Note: Zero-emission ICEs and Battery Powertrain added by authors



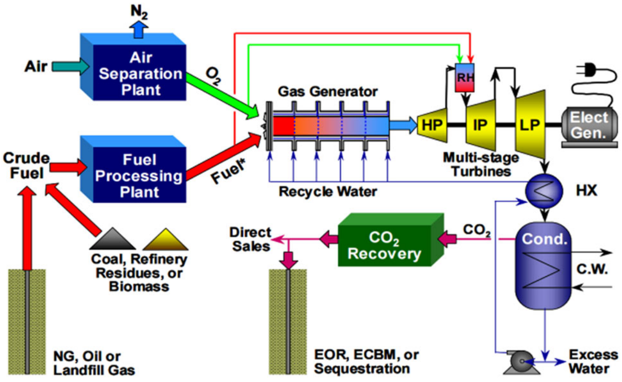


Fig. 9 Schematic of the CES power generation system [29]

has made great progress in oxygen-enriched combustion with cooperation from Siemens and GE [27]. The basics of the CES power system (Fig. 9) involves separating oxygen and nitrogen in a separation plant using deep cooling or an ion-transmission membrane (ITM). The separated oxygen is combined with the fuel and sent into the gas generator for combustion. Recycled water is injected into the gas generator and turned into a high-temperature high-pressure vapor using the thermal energy produced by combustion. This circulation still features vapor power cycling similarly use in the Rankine cycle, but is called an internal combustion Rankine cycle (ICRC) as fuel, oxygen, and water are injected into the combustion chamber together. The high-temperature gas flow generated during circulation contains 90% vapor and 10% CO_2. While the high-temperature high-pressure vapor drives multistage turbines that make electricity, it cools down gradually and finally goes to the heat exchanger to heat recycled water with waste heat. Water and CO_2 in the exhaust gas flow out of the heat exchanger and are separated in a condenser. The condensed water is recycled, whereas CO_2 is compressed and stored.

In March 2015, CES prototyped a 5-MW demonstration power plant in Kimberlina, California, the first zero-emission power plant in the world. A commercial 50-MW power plant in Norway has also started to use this oxy-fuel circulation system for power generation [28].

Since 2007, Wu and co-workers at School of Automotive Studies of Tongji University have conducted research on ICRC-based engines (Fig. 10) [30–32]. Their system is equipped with a liquid oxygen tank, which exchanges heat with recycled CO_2 from the heat exchanger. During liquid oxygen gasification, CO_2 turns into gas or liquid following a drop in temperature. Recycled water passes through the engine's cooling water and is heated by waste heat to a high-temperature high-pressure state for injection into the cylinder. The gas cloud, which consists of oxygen and fuel at its stoichiometric ratio, is ignited at the top dead center. High-temperature water is ejected into the cylinder in the last phase of combustion to generate expanded vapor to work the piston. This completes the ICRC. This ICRC engine has the following characteristics: 1. pure-oxygen combustion coupled with exhaust gas recirculation (EGR); 2. high-temperature high-pressure water ejection inside the combustion chamber ($P > 35$ MPa, $T > 120\,°C$); 3. carbon dioxide recycling; and 4. a power system for ICEs with near-zero emission, based on fossil fuel. To date, a second generation of ICRC engines has been developed in Tongji University. A prototype of this engine (Fig. 11) has a high compression ratio and large displacement with an efficiency of almost 42% (originally 33%) and a near-zero emission of combustion products.

For future zero-emission ICEs, a new concept referred to as the argon power cycle (APC) was proposed by Robert Dibble [33]. An APC engine uses hydrogen or methane as fuel,

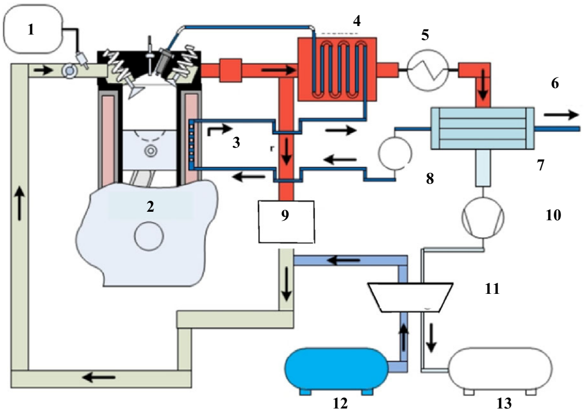


Fig. 10 Work principle of the ICRC engine [32]. 1—fuel; 2—ICRC engine; 3—1st water heater; 4—2nd water heater; 5—process heater; 6—H_2O emission; 7—condenser; 8—water pump; 9—EGR valve; 10—CO_2 compress pump; 11—heat exchanger; 12—liquid CO_2; 13—solid CO_2

Fig. 11 Test bench of the ICRC engine

oxygen as oxidant, and argon as the working fluid. The specific heat ratio of argon, a monatomic molecule, is higher than that of air with its characteristics of a wide range of inert gas sources. This new method of realizing high-efficiency and zero-emission combustion has attracted many researchers in the field around the world [33–35]. For a hydrogen-fueled APC system (Fig. 12), the engine uses a mixture of argon and oxygen as the charge, with direct-hydrogen injection. Spark-plug ignition is used to ignite the mixture, releasing a great amount of heat to convert to work. In theory, the exhaust gases consist of argon and steam (the steam is water as vapor droplets at the boiling temperature), which can be separated using a high-efficiency condenser. The argon can then be recycled as recycled working gas.

The effective thermal efficiency of the engine is given by

$$\eta_{\text{Brake}} = \eta_{\text{Combustion}} \times \eta_{\text{Thermodynamic}} \times \eta_{\text{GasExchange}} \times \eta_{\text{Mechanical}} \tag{1}$$

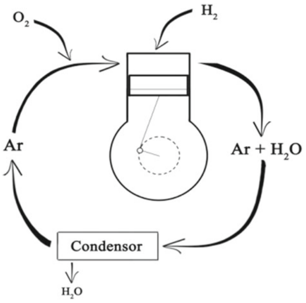


Fig. 12 Work principle of a hydrogen-fueled argon power cycle engine [17]

where $\eta_{\text{Combustion}}$, $\eta_{\text{Thermodynamic}}$, $\eta_{\text{GasExchange}}$ and $\eta_{\text{Mechanical}}$ refer to the combustion efficiency, thermal efficiency, gas exchange efficiency, and mechanical efficiency, respectively. Their values are usually higher than 90%. The thermal efficiency of the engine given by is the lowest of all the terms and has a limit of about 50–60%. Improving the thermal efficiency significantly would provide enormous gains for the effective thermal efficiency of the engine.

The expression for the indicated thermal efficiency of ICE is

$$\eta_{\text{Thermal}} = 1 - \frac{1}{CR^{\gamma-1}} \tag{2}$$

where CR and γ refer to the compression ratio and specific heat ratio, respectively. Increasing the compression ratio would be the best effective and significant measure for improving thermal efficiency. In the last decade, the compression ratio for gasoline engines has increased from 6–9 to 10–14, limited by the phenomenon of knocking. With a smaller compression ratio and bigger expansion ratio, the Atkinson cycle may improve the efficiency of the engine and has been widely researched in the field of hybrid engines. The development of GDI technology provides an effective way to solve the knocking problem and to increase the compression ratio. The GDI technology suppresses the tendency to knock through heat absorption because of gasoline latent of vaporization, which reduces the temperature of the mixture. However, for the same compression ratio, the thermal efficiency of an APC engine is bigger than a traditional engine, which uses air as working gas, because argon's specific ratio is higher.

Regarding the influence of the compression ratio and specific heat ratio on the thermal efficiency of engines (Fig. 13), the theoretical limit for traditional engines, such as gasoline and diesel engines, is about 50–60%, whereas for an APC engine it would be more than 80% when the CR is over 11, yielding more than 1.5-fold increase in the conversion of heat into power. From the effect of argon on the indicated work over a working cycle and the maximum in-cylinder tempera-

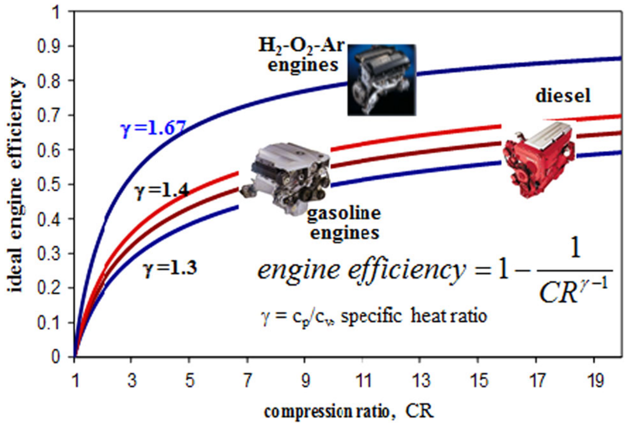


Fig. 13 Effect of compression ratio and specific heat ratio on the thermal efficiency [33]

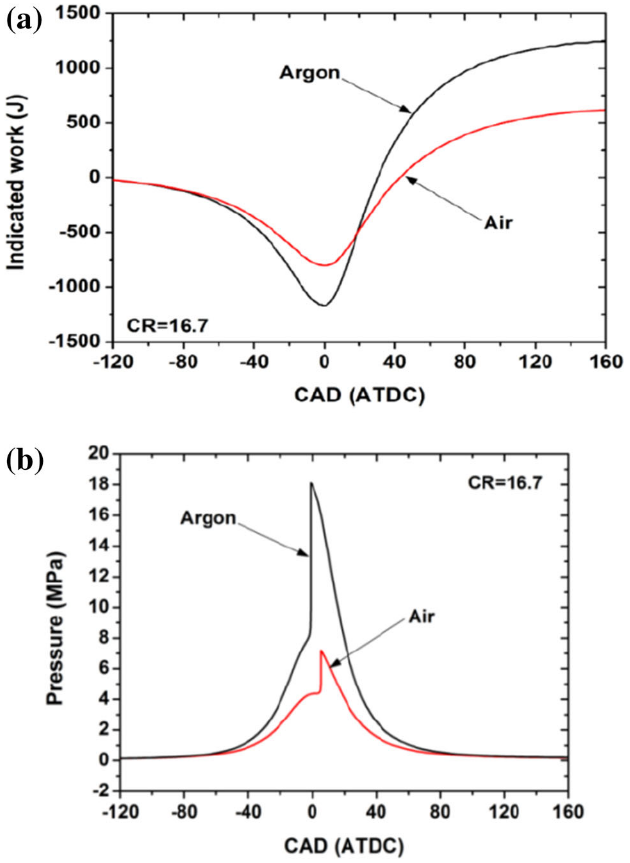


Fig. 14 Effect of argon on the indicated work, in-cylinder pressure, and temperature versus crank angle degrees (CAD) after top dead center (ATDC)

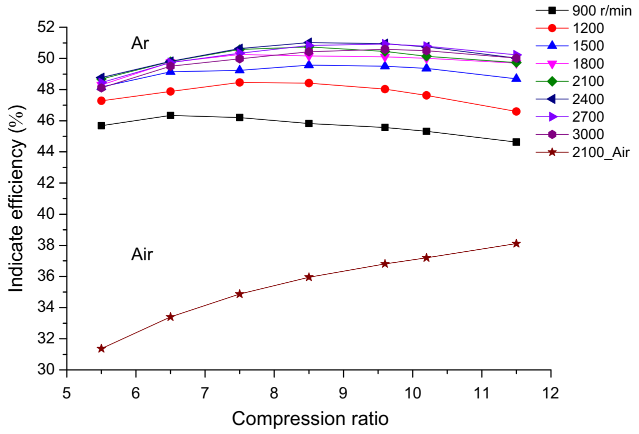


Fig. 15 Indicated thermal efficiency of argon engine based on GT-power

ture and pressure based on simulations for reference (Fig. 14), replacing nitrogen with argon increases both indicated work and pressure so that more power is outputted during the same period.

From the theoretical thermal efficiency of a spark ignition engine under argon+oxygen mode and air atmosphere (Fig. 15) simulated based on GT-Power, the indicated thermal efficiency is obviously higher for the APC engine than the air-based engine. The efficiency is maximum with a compression ratio between 7.5 and 9. The effect of CO_2 and H_2O on the indicated thermal efficiency of the APC engine (Fig. 16) shows that for the same compression ratio the indicated thermal efficiency decreases with increasing CO_2 fraction. The efficiency decreases by 5–6% when the fraction of CO_2 is 10%. To study the effect of H_2O on the indicated thermal efficiency of the APC engine, six different H_2O fractions were introduced. In particular, the efficiency decreases by 2.5% when the fraction of H_2O is 10%. This phenomenon indicates that added CO_2 and H_2O decreases the specific heat ratio of the mixture in the cylinder, and reduces the efficiency. Therefore, to maintain the APC engine at high efficiency, an effective CO_2 absorber and an efficient condenser are required to purify the argon from the exhaust pipe.

To realize a zero-emission ICE would be easy using an APC engine with hydrogen as fuel. Nevertheless, before the arrival of hydrogen energy, turning the APC concept into a practical product is more significant. A novel concept for a natural-gas APC engine is proposed here, in which natural gas is used as fuel instead of hydrogen and an additional CO_2 capture is performed in the after-treatment system. In 2016, a patent for this system was issued [36]. The CH_4-fueled APC engine system (Fig. 17) uses a mixture of argon and oxygen as charge, but with direct CH_4 injection. Similarly, spark ignition is used to ignite the mixture releasing then heat to be converted into work. The main components of the exhaust gases are argon, steam, and CO_2. With a high-efficiency condenser and CO_2 absorber to separate the argon, steam, and CO_2, argon can be recycled as working gas.

In recent years, the research on resolving the CO_2 absorption issue has developed rapidly, mainly following three lines: (1) using ammonia solution as absorption solution; (2) applying highly efficient mixed amines as absorption

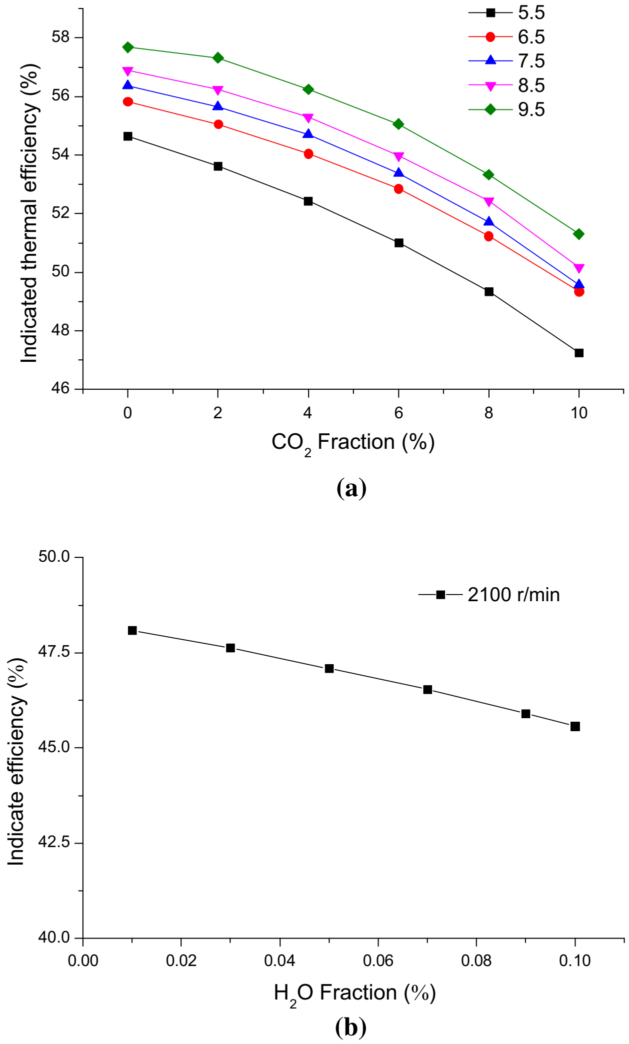


Fig. 16 Effect of CO_2 and H_2O fractions on the thermal efficiency of APC engine **a** CO_2 **b** H_2O

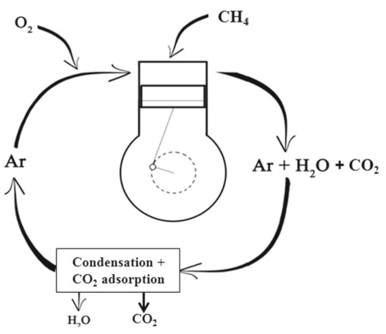


Fig. 17 Work principle of a natural-gas argon power cycle engine [36]

solution; and (3) using novel ionic liquids to absorb CO_2. The research [37,38] demonstrates that it is feasible to remove CO_2 from the flue gas using ammonia as absorption solution. The ammonia solution brings benefits of low cost absorption, high removal efficiency, and low energy consumption in regeneration. However, before any industrial application can be made, some problems remain to be solved, such as providing means to avoid leakage of the ammonia and explosion-proof running, as well as controlling its high volatility in regeneration. Currently, the research on highly efficient mixed absorption liquids is also actively pursued. Contradictions related to conventional single absorption liquids that are widely applied exist between high absorption efficiency and difficult regeneration (e.g., MEA, DEA), as well as low energy consumption in regeneration and low absorption efficiency (e.g., MDEA) [39,40]. Therefore, mixed absorption liquids with the advantages from the above two kinds of alcamines have been proposed from theory. Composed of positively charged ions and negatively charged ions, the ionic liquid represents a new type of absorption liquid. Different from typical organic solvents, ionic liquids are stable, non-volatile, and recyclable.

In addition, CO_2 can be selectively deoxidized by using highly efficient biomimetic photoelectrocatalysis. Zhao and co-workers at the School of Chemical Science and Engineering of Tongji University have made important progress in the research on the selective reduction of CO_2 using highly efficient biomimetic photoelectrocatalysis [41]. Their focus has been on the biomimetic photosynthesis of CO_2. Previously, cobalt oxide Co_3O_4 with high-index facets was found to perform well in the photoelectric catalytic reduction of CO_2 and have good conversion efficiency. Subsequently, the photoelectric catalyst Co_3O_4 and a biomimetic enzyme with a ruthenium complex of a specific structure were cleverly assembled onto the surface of carbon aerogels made from porous material with a high specific surface area. A biomimetic reaction interface was thereby constructed for the artificial photosynthesis of CO_2. The synergy of carbon aerogels and ruthenium-based enzyme enhances the concentration of CO_2 on the surface. This catalyst effectively absorbs sunlight, the illumination generating electrons that are then rapidly transported towards the CO_2 under the influence of the electric field. After CO_2 capture, a reduction of two electrons occurs, followed by a selective reduction to the target product, formic acid. This study is an important step towards the recyclable utilization of CO_2 with low energy consumption. CO_2 capture technology may be an efficient way to solve the issue of CO_2 emissions from fossil fuel applications in the future. If it will success in the future, neutral CO_2 recycle in energy application will be realized.

5 Conclusion

In the next 30 years, the main energy source of vehicle power system will still be dominated by fossil fuels. Hence to decrease CO_2 emissions, energy conservation and emission reduction of ICE play an important role and have to be solved. Zero emission will be the theme in the development of future vehicle power systems. Diverse forms of power systems with zero emissions will coexistence in a mutually competitive relationship before the age of hydrogen energy commences.

One effective method to attain non-polluting clean automobile power system is a zero-emission ICE. It is also an effective approach to maintain the development of the traditional ICE, which chiefly includes the ICRC and APC engines. A high-efficiency APC engine can run in parallel with a pure-electric- or a fuel-cell-powered system. It offers an important technology path forward for the conventional ICE.

The recovery, utilization, capture, and storage of carbon dioxide remain as cogent objectives in implementing carbon-emission reductions in the transition from fossil fuel to hydrogen.

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