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Combustion stability control of gasoline compression ignition (GCI) under low-load conditions: A review

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Abstract

With greater energy pressure and stricter emission standards, increasing power output and reducing emissions of engines are simultaneously required. To achieve this, considerable researches are motivated. In recent years, key and representative developments in the field of high-efficiency and clean engines have been carried out. Among them, a low temperature combustion concept called gasoline compression ignition (GCI) is widely considered by universities and research institutions around the world, since it has the potential to achieve ultra-low NO_x and soot emissions while maintaining high thermal efficiency. However, GCI combustion mode has certain issues to be solved, such as combustion instability under low-load conditions. Therefore, this paper reviews the experimental, computational and optical studies on the combustion stability control of GCI combustion mode during low loads and describes the recent progress to improve combustion stability as well as points out the future work finally.

Keywords: gasoline compression ignition, intake heating, intake boost, spark assistance, internal exhaust gas recirculation, injection strategy, gasoline additive

1 Introduction

Internal combustion engines, currently the most efficient thermal machines, are widely used in transportation, engineering equipment, agricultural machinery and other fields. Generally speaking, compression ignition (CI) engines have the advantage of high thermal efficiency with the disadvantage of increased NO_x and soot emissions because of the spray diffusion combustion of the locally over-rich air–fuel mixture as compared to the stoichiometric combustion of gasoline engines, as shown in Fig. 1. For CI engines, an evident trade-off relationship exists between these two emissions, but how to break through the compromise has always puzzled us.

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Fig. 1 Traditional diesel fuel injection and NO_x and soot generation area [1].

In recent years, with the increasingly serious problems of energy shortage and environmental pollution, the developments in the regulations of both engine efficiency and emissions have been carried out. For example, the China Phase 4 fuel consumption limits for passenger cars have been released which states that the average fuel consumption has no permission to exceed 5 L/100 km by 2020 [2]. In December 2016, China 6 light-duty vehicle regulations were issued by the Ministry of Environmental Protection, and the emission limits of the major pollutants such as CO, HC, NO_x and PM were reduced dramatically by about 50% compared with China 5 [3]. Thus, the application of exhaust emission aftertreatment systems is essential. However, the complex aftertreatment systems including Selective Catalytic Reduction (SCR), Diesel Particulate Filter (DPF), Diesel Oxidation Converter (DOC) and so on have problems in terms of their cost and durability [4–14].

From the above, it can be seen that there is an urgent need to seek an ideal combustion technology for better efficiency and emission performances, and a series of advanced combustion concepts have been proposed since the end of 1970s with the purpose of minimising the reliance on aftertreatment systems [15–18]. In 1979, the concept of Homogeneous Charge Compression Ignition (HCCI) was first proposed by Onish et al. [16] for gasoline applications, and it was found that the stable combustion was achieved in the full operation range with a compression ratio of 7.5:1 over speed range from 1000 to 4000 rpm.

Based on the previous research, HCCI combustion is characterised by the fact that the air and fuel are fully premixed before combustion starts and the mixture auto-ignites simultaneously at multi-points. Therefore, HCCI combustion, which combines the advantages of traditional gasoline engines and diesel engines [19], can achieve high thermal efficiency compared to diesel and smokeless combustion engines such as gasoline engines. Meanwhile, the lean homogeneous mixture is burned at a lower temperature, resulting that the emission of NO_x is also extremely low, as shown in Fig. 2.

Unlike the conventional combustion, however, the start of HCCI combustion is established by the auto-ignition chemistry of the air-fuel mixture, resulting in difficulty in controlling combustion phasing. Moreover, the problem of extending operation range, one aspect is the quasi-constant volume combustion leads to a high heat release rate (HRR), which prevents HCCI combustion from expanding to higher loads, has been regarded as a challenge in the practical HCCI combustion system. Due to the relatively low burned gas temperature, HCCI engine encounters a major difficulty in achieving stable and complete combustion in low-load operation as well as auto-ignition during cold start. Then an increasing number of relevant researches on HCCI combustion have been conducted. For example, a diesel HCCI, allowing intake air to be preheated, was conducted by Ryan et al [15]. It was found that the low emission of soot and the complete combustion were obtained in the low-load operation since relatively high intake temperatures had the potential to alleviate the problem of fuel condensation on the surface of manifold during the intake process. In addition, it was found that the absolutely homogeneous

Fig. 2 Equivalence ratio—local temperature space diagram of different combustion modes [20].

mixture was difficult to be formed in the actual working process due to the thermal stratification of the charge in cylinder [21]. But Hwang et al. [22] have found that the non-absolutely homogeneous mixture precisely reduces the HCCI combustion rate, which is beneficial to achieve mild combustion under high-load conditions, and the combustion efficiency is also improved owing to the existence of thermal stratification at low loads. Besides, the quasi-homogeneous premixed gas by early fuel injection is moved to cylinder and thus can also avoid high NO_x and soot formation rates. This prompted a trend in the engine research community to study Premixed Charge Compression Ignition (PCCI) [23, 24].

The early fuel injection strategy is carried out by Nakagome et al. [25] to achieve PCCI, supplemented by a proper proportion of exhaust gas recirculation (EGR). Based on the optimised results, it is found that PCCI with properly stratified mixture is an effective approach to control the combustion process while the operation range can be expanded to higher loads. However, ‘wet wall’ is observed owing to the low-pressure and low-temperature environment in cylinder during the early fuel injection.

To avoid the occurrence of ‘wet wall’, the coupling of the fuel injection event and the combustion one is desired. In 2003, the multi-pulse injection strategy called MULINBUMP, combining premixed combustion with ‘lean diffusion combustion’, has been proposed by Su et al. to achieve PCCI without wetting the wall by the fuel [26]. To achieve PCCI, multi-pulse fuel injection, which could decrease emissions of NO_x and soot, is adopted in light-duty diesel engines. Besides, integrated with the hybrid enhanced combustion chamber and high-pressure fuel injection, the rapid mixing can be achieved under medium and high loads. Consequently, the high-efficient and clean combustion of the PCCI engine over the full load range is realised by MULINBUMP system. In addition to MULINBUMP system, Partially Premixed Combustion (PPC) is proposed to avoid the problem of ‘wet wall’ due to the fuel injection timing prior to CI combustion but after HCCI combustion. It is found that the combination of mixture stratification and fuel injection timing is worked out for the auto-ignition process and combustion process; thus a series of studies have been conducted in the diesel PPC [27, 28].

But the diesel fuel with low volatility and having cetane number greater than 40 is very prone to auto-ignition before a sufficient premixing of fuel and air, which results in locally rich mixture regions that lead to the soot formation. The primary conclusion from experimental investigation is that diesel fuel is not well suited for PPC operation without high injection pressure and high level of EGR, while the optimised composition of fuel is able to play a role in the phase of reaction and mixing of fuels. Without high levels of EGR, so as to avoid the appearance of ‘wet wall’ associated with early injection of diesel fuel, a promising strategy known as gasoline PPC is proposed by Kalghatgi et al. in 2006 [29, 30], also referred to as GCI. Before gasoline is compression-ignited on a high-pressure common rail diesel engine, the properly stratified mixture has been formed through multiple injections to control the combustion process [31]. Moreover, high thermal efficiency is achieved owing to the mixture having a suitable equivalence ratio [32]. Based on the previous research, GCI combustion concept has gained considerable attention because of the great advantages in simultaneously maintaining high thermal

efficiency and achieving low emissions of NO_x and soot. For example, the successful GCI operation from low load to high load has been conducted by Johansson et al. [33]. At the load of 20 bar indicated mean effective pressure (IMEP), multiple injection strategies are adopted to achieve stable combustion with high pressure and EGR rate of about 50%, maintaining low emissions of NO_x (0.3g/kwh) and soot ($<2\text{FSN}$), with high indicated thermal efficiency (57%). To obtain the insights into the in-cylinder low-temperature combustion process, further investigation of GCI mode is done rapidly by research institutions such as Deron University in Sweden [34], University of Wisconsin [35], Tsinghua University [36] and so on. Moreover, the third-generation Gasoline Direct Compression Ignition (GDCI) test engine of Delphi using GCI combustion has been achieved without combustion mode switching during the whole operation range using gasoline with octane number (RON) of 91, which meets the Tier 3 emissions standards combined with thermal efficiency up to 42%.

A recent research has shown that by the year 2040, the demand for diesel and jet fuels will increase by 70%, which would be a result of an increase in the number of passenger cars to 1.6–1.9 billion, but the demand for gasoline would not change much, as shown in Fig. 3. Based on the experimental results by Johansson et al., the RON range of gasoline fuels from 70 to 85 is proved to be optimum for GCI operations, as shown in Fig. 4, because gasoline fuels with higher RON are prone to cause unstable combustion at low loads [32, 37, 38]. Meanwhile, a large amount of surplus ‘low-octane gasoline’ is produced by the refining industry, which provides opportunities for the development of GCI combustion technology.

Fig. 3 Forecast of demand for different fuels [39].

Fig. 4 Variation law of stable operating conditions with octane number [33].

However, the obstacles including high level of unburned fuel, limit of low-load range and difficulty during cold start operation must be overcome before GCI combustion can be fully realised in commercial applications. These could be attributed to the fact that the peak burned gas temperature is too low at low loads and cold start in GCI engines to consume much of the unburned fuel, which results in higher levels of HC and CO emissions compared with the conventional combustion. In addition, the unstable combustion under low-load conditions is frequent owing to the poor trait of gasoline's spontaneous combustion, the locally lean mixture, as well as the low-temperature and low-pressure environment in cylinder.

In summary, how to improve the combustion stability of GCI combustion under low-load conditions, or rather expand the low-load limit has become a crucial problem to be solved [40].

2 Evolution in control strategies

To avoid the drawbacks previously mentioned, the combustion control strategies of GCI engines are studied and the results show that the engine performance is mainly dependent upon the initial thermodynamic state of the reactants [41, 45], the mixture concentration distribution [29, 46] and the fuel reactivity [47, 48]. Therefore, the obvious ideal strategies would be to find a hybrid type by controlling influencing factors to improve the combustion and emission characteristics comprehensively [40, 49–54]. Specifically, there are mainly several types of measures to improve the combustion stability under low-load conditions: (1) intake heating [42, 51, 55–57], (2) intake supercharging [44, 58], (3) spark-assisted ignition [59, 60], (4) internal EGR (In-EGR) [61–63], (5) injection strategy [63–65] and (6) gasoline additive [66, 67].

2.1 Effects of initial thermodynamic state of reactants

The control of the initial thermodynamic state of the reactants offers the potential for the increase of compression ratio and the extension of the low-load limit of GCI combustion consequently, including four specific technologies: intake heating, intake boost, spark assisted ignition and In-EGR.

An increasing intake temperature can satisfy the temperature requirement of spontaneous ignition, while the lower equivalence ratio can be achieved by intake boost, both of which can make efforts to start the combustion under low-pressure and low-temperature environment successfully. If necessary, spontaneous ignition can also be significantly improved by spark assistance. Besides, the remarkable improvement of in-cylinder temperature can be attained by internal EGR, which is beneficial to improve the combustion characteristics.

2.1.1 Intake heating

To overcome the difficulty in spontaneous ignition of gasoline fuel under low-load conditions, it is desirable to directly heat the intake air, so that the air–fuel mixture can reach the spontaneous combustion temperature near TDC [68]. According to the literature of Nicolao [69], it can be concluded that higher intake temperature shows a drawback in cylinder filling because of the lower air density; however, it improves the engine performance since the positive impact on the combustion rate is more significant than the negative one on volumetric efficiency. Adam et al. [70] examined the operating characteristics of a multi-cylinder CI engine with 92 RON gasoline fuel at low speeds and loads, and the effect of intake temperature is presented in Fig. 5. It is clear that increasing the intake temperature can lead to an advanced 50% fuel cumulative heat release time (CA50) and lower HC emissions.

The influence of an increase of intake temperature on the combustion characteristics and operating range of GCI combustion mode was performed on a modified single-cylinder diesel engine by Xiao et al. [71]. In addition to the effect on combustion characteristics, as shown in Fig. 6, the lower load limit of GCI combustion mode under stable conditions is significantly reduced with the intake temperature raised from 323 to 403 K, which demonstrates that increasing intake temperature is one of the important factors for extending the lower load limit.

In the growing literature, An et al. [72] conducted experiments on an optical engine to obtain the insights

Fig. 5 Effect of an increase of intake temperature on BMEP, CA50, HC and NO_x [70].

Fig. 6 Operating conditions of GCI combustion at different intake temperatures [71].

into the sensitivity of GCI combustion mode to intake temperature under low-load conditions. It was found that 70°C is considered to be the minimum intake temperature for a single injection strategy to maintain stable combustion, as shown in Fig. 7, CA50 within the target range and smaller cycle coefficient of variation (CoV) are also obtained. Furthermore, the intake temperature continued to be increased, and neither stability nor IMEP can be significantly improved, while a misfire would occur if the intake temperature continued to be reduced.

Besides, because of the combination of low combustion temperature and high heat transfer loss, GCI engine has severe problem in firing during cold start operation. To deal with the issue, intake heating was used by Zhou et al. [73]. Pre-heating air inlet to 35°C and 55°C by means of air inlet heaters showed a failed cold start at 35°C but the first ignition cycle was successfully started at 55°C; after only four combustion cycles of the engine, IMEP and CA50 stabilised. However, the intake heating after the start process is unnecessary to achieve stable operation.

2.1.2 Intake boost

Increasing the intake pressure can increase the pressure and the oxygen content in the cylinder, which improves the combustion stability effectively under low-pressure environment. For a GCI engine, higher pressure has also shown significant effect on the control of combustion phasing and the operation range extension to lower loads.

Using single injection strategy, Adam et al. [73] showed that CA50 as well as HC, CO and NO_x emissions could be controlled by changing intake pressure. By altering the intake pressure from 0.8 to 0.96 bar at a fixed

Fig. 7 Effect of temperature and SOI on combustion characteristics. (a) CA50 (b) CoV (c) maximum in-cylinder pressure (d) IMEP [72].

intake temperature of 95°C without loss of power approximately, the advanced CA50 and the decreased HC and CO emissions are able to be obtained. In addition, changes of CA50 and emissions in Figs. 5 and 8 indicate that the dependence on the combination of high temperature and high pressure is obvious. To maintain a constant combustion performance, the decrease in intake pressure needs to be compensated by an increase in intake temperature and vice versa.

And then, Solaka et al. [33] found that despite fuels with different RON values had different low-load limits for stable combustion, sufficient intake pressure allows these fuels to burn stably under the load condition with an IMEP of 0.2 MPa. Moreover, the dependence of low-load limit extension on intake pressure decreases gradually with the reduction of RON. Similarly, Zhang et al. [75] found that the successful GCI operating range can be extended to lower load as the intake pressure increased on a single-cylinder diesel engine equipped with electro-hydraulic variable valves. As shown in Fig. 9, when a lower In-EGR rate is employed, supercharging can enable gasoline with RON of 93 to achieve efficient and clean combustion at an IMEP of about 0.47 MPa.

2.1.3 Spark assistance

Unlike spark ignition (SI) and CI engines, the GCI engine does not have a direct measure to control the start-of-combustion and has a poor property in auto-ignition due to the low fuel reactivity [76]. The spark assistance, which can lead to a faster chemical reaction process and shortened ignition delay, is regarded as an important technology to control the ignition at low-load boundary by Xie et al. [77]. Compared with the conventional CI mode, the ignition guidance can organise and control the auto-ignition and combustion process more effectively.

Fig. 8 Effect of an increase of intake pressure on BMEP, CA50, HC and NO_x [74].

What is more, it has been proved that the spark plug has the potential to achieve good phasing control in a variety of working conditions, which allows spark-assisted ignition have a better commercial application prospect; for example, Mazda SkyActiv-X is actually a spark-assisted GCI engine. However, there are no more commercial applications due to the immature technologies.

Persson [78] pointed out that spark-assisted compression ignition (SACI) can increase the possible operating range without switching to SI combustion mode. At the constant intake temperature, spark-assisted combustion is prone to be a means of direct control of combustion phasing, and at different intake temperatures, the advanced spark is considered to be able to compensate for the reduction of intake temperature.

As described above, the spark discharge serves a function in auto-ignition in low-load boundary region and has the potential for the control of auto-ignition timing. The effects of spark assistance on GCI mode were further investigated by Pastor et al. [79] by means of UV-visible spectrometry. The test results showed that the first flame core after the spark discharge appeared and began to develop as a premixed flame front. That is because the in-cylinder temperature and pressure are increased by the flame propagation to ignite the unburned mixture, and the second stage of combustion was characterised by a more pronounced HRR and faster reaction rate. The conclusion was also certified by Benajes et al. [80]; as shown in Fig. 10, it can be seen evidently that spark assistance, as an appropriate method, is able to control combustion process in time and space. And illustrated in Fig. 11, the use of spark assistance and double injection strategy reduces CoV and increases IMEP in GCI engines under low-load conditions.

2.1.4 Internal EGR

As one of the most promising strategies for the control of GCI combustion, In-EGR attracts an increasing attention. High-temperature exhaust gas is trapped by In-EGR technology, which results in a reduction in incomplete combustion products. Apart from this, the initial thermodynamic state of the working fluid in the cylinder can be improved by high-temperature residual gas and reform the fuel to form a lot of small molecules with high reactivity, such as O, H, OH and so on [82].

In-EGR can be realised by negative valve overlap (NVO), exhaust valve rebreathing (2EVO) or intake valve rebreathing (2IVO) by adjusting the intake or exhaust valves. The NVO strategy is obtained by closing the exhaust valve in advance, which increases residual gas and then leads to significantly higher temperature in the cylinder. At the same time, the mixing time can also be controlled by regulating the histories of in-cylinder temperature and pressure, which makes effects on emission performance of GCI combustion under low loads. To achieve In-EGR, NVO strategy was used by Borgqvist et al. [83], and the results showed that the trapped hot residual gas had a positive effect on the extension of lower load limit, while a minimum attainable load of 1.75 bar IMEP was achieved consequently.

By reopening the exhaust valve during the intake stroke, 2EVO can be achieved to promote the natural

Fig. 9 Effect of fuel injection timing, internal EGR rate and excess air coefficient λ on indicated thermal efficiency and average indicated pressure under different intake pressures [75].

ignition of the air–fuel mixture and accelerate the response of the aftertreatment equipment. Zhang et al. [75] studied the potential of 2EVO for combustion and emission control on a diesel engine using gasoline with RON of 93. It was shown that the 2EVO has the potential to improve the combustion performance with an increased intake boost. When the engine speed was 1500 r/min and the circulating fuel quality was 11.6–22.2 mg, the low-load limit of GCI engines can be extended to 1.5 bar IMEP with the intake pressure of 1.5 bar.

The 2IVO strategy is realised by reopening the intake valve, thus part of the exhaust gas will be discharged into the intake duct first, and then enters the cylinder together with the fresh air during the intake stroke. Fessler and Genova investigated the influence of 2IVO strategy on engine performance in a four-cylinder diesel engine, and the reduced HC emissions and shortened engine warm-up time could be obtained in a low-temperature environment [75]. In addition, it was found by Balaji [84] that 2IVO had a higher potential to rise the In-EGR rate than 2EVO, while a higher NO_x reduction efficiency can be obtained, as shown in Figs. 12 and 13.

Fig. 10 Influence of spark assistance on combustion [80].

Fig. 11 Effect of spark assistance on CoV under different injection strategies [81].

Fig. 12 Predicted NO_x with 2IVO strategy [84].

However, numerous studies [73, 85, 86] have shown that the flame propagation velocity in the cylinder increases first and then decreases as the In-EGR rate increases, due to the competition of heating effect and dilution and specific heat capacity. For example, Zhu et al. [40] investigated the effects of In-EGR rate and intake pressure on combustion efficiency and indicated thermal efficiency. As shown in Fig. 14(a), the improved combustion efficiency and combustion stability are obtained as In-EGR rate increases, while the In-EGR plays a leading role in the heating of the mixture. However, when the In-EGR rate exceeds 57.5%, the dilution and specific heat capacity effects are more important, which result in poor combustion and emission performance. If the intake pressure is further increased, coupled with an increased oxygen content of the mixture, it is beneficial to further improve the combustion, as shown in Fig. 14(b).

Fig. 13 Predicted NO_x with 2EVO strategy [84].

Fig. 14 Effect of EGR rate and intake pressure on combustion efficiency and indicated thermal efficiency [40].

Simultaneously, an evident increase of NO_x emission is also observed as the load decreased and the fraction of In-EGR increased. Besides, an increase in the specific heat capacity of the mixture occurred due to the excessive residual exhaust gas, which led to a poor combustion stability. While the external intercooled EGR (Ex-EGR) is further coupled, the combustion temperature and oxygen concentration can be reduced, thereby suppressing the production of NO_x .

The effects of In-EGR (2IVO strategy) and Ex-EGR on CI engine combustion were investigated by Dittrich et al. [87]. The experimental results showed that low CO and HC emissions could be achieved by In-EGR and Ex-EGR at 2 bar BMEP, and the coupling of In-EGR and Ex-EGR could break through the compromise between NO_x and fuel economy. Similarly, Zhang et al. [85] studied the influence of coupling strategy under low-load conditions. As a result, an increase of In-EGR ratio can reduce HC and CO emissions; however, the improvement effect is gradually weakened while the ratio of Ex-EGR is increased, but higher thermal efficiency can be obtained. Compared with the In-EGR strategy, the internal and external EGR coupling strategy can achieve a significant improvement in the emission performance of GCI combustion mode in the whole operating conditions.

2.2 Effects of mixture concentration distribution

According to the optical experiment results, the GCI mode is a 'combination' of multi-point spontaneous combustion and flame propagation [88], and the ideal mixture stratification makes efforts to spontaneous ignition of the GCI mode. Under low-load conditions, low-temperature and low-pressure are obtained owing to the relatively poor spontaneous combustion characteristic of the mixture, which makes it difficult to form an ignition point. Therefore, it can be concluded that improving the mixture stratification can play an important role in the low-temperature environments.

Spontaneous ignition in GCI combustion mode usually occurs in the regions where the equivalence ratio is close to 1 and the temperature is high. Thus, the combustion process can be improved by organising the mixture concentration and temperature distribution in the cylinder. Realising the cooperative control of the fuel injection and the thermodynamic state in the cylinder through a reasonable fuel injection strategy is an important entry point to improve the combustion stability of GCI combustion mode under low-load conditions.

In the researches of the technologies for improving combustion stability of GCI combustion mode at low loads, the reasonable fuel injection strategy has always been the focus, and it is in the stage of continuous development and progress. According to the specific combustion conditions, the flexible fuel-injection strategies are adopted to control in-cylinder combustion in experiments [72, 89]. Moreover, the concentration distribution of the mixture, the ignition timing and the combustion phasing are effectively controlled by reasonably designing the number of injections, the timing of pilot-injection and the ratio of pilot-injection quantity. Thus, the mixture can be fully burned, so that the GCI combustion method can achieve lower NO_x and soot emissions in a wider range of working conditions, while obtaining higher thermal efficiency.

2.2.1 Injection strategy

Above all, the control of injection pressure had been regarded as one of the most effective injection techniques to control charge thermal stratification and concentration. The main reason behind the progressive injection pressure increase in GCI engines is the increased spray kinetic energy, which can promote the droplet fragmentation, evaporation and air–fuel mixing, as well as ensure a better combustion process and lower emissions.

The influence of injection pressure (600/1000 bar) on the combustion performance and emissions of GCI engines with biodiesel/gasoline blends was investigated by Sakda et al. [90]. It was found that the complete combustion can be achieved under high injection pressure while engine speed was fixed at 1200 rpm. Subsequently, Mao et al. [91] and Zheng et al. [92] revealed that injection pressure became one of the most important factors to promote air–fuel mixing because of the reduced ignition delay in GCI combustion mode without EGR, as shown in Fig. 15.

In addition, Ciattí et al. [93] found the quasi-homogeneous mixture formed by the second injection in the double-injection strategy has higher reactivity, which ensures stable operation under low-load conditions. Based on the research, a simulation experiment was carried out by Zhu et al. [51] to study the influence of single/double injection strategy on the combustion stability of a GCI engine under low-load conditions. In this study it was found that near TDC, the high-temperature regime in the cylinder was concentrated in the middle of the combustion chamber. However, a large amount of fuel was directly injected into the lower-temperature area near the bottom wall of the combustion chamber owing to the single injection strategy. Therefore, the consistency between the rich gas zone and the high-temperature zone in the cylinder was poor and resulted a poor spontaneous ignition. Compared with the single injection strategy, the use of double injection strategy can effectively control the distribution of the mixture in the cylinder and improve the consistency of the above two zones, as shown in Fig. 16. But, as the engine load further decreased, the number of fuel injections should be changed from two to one to control the in-cylinder mixture concentration distribution, because the combustion efficiency of the single injection strategy is higher than that of the double one.

An [74] and Johansson [72] et al. studied the sensitivity of GCI combustion mode to injection strategy and intake temperature under low-load conditions on an optical engine. It was shown that compared with the single injection strategy, multiple injection strategy can reduce the requirement of stable combustion for intake temperature, and the lower limit of stable combustion was reduced from 70°C to 50°C. On this basis, as the injection pressure increased, the stability and combustion performance were further improved.

Similarly, Goyal et al. [89] investigated the effect of injection strategies by means of hydroxyl (OH) self-luminescence technology on combustion stability. The results also verified that the minimum intake temperature for stable combustion under a single injection strategy was significantly higher than the one required for multiple injection strategy to achieve stable combustion, since an earlier ignition and a higher flame propagation velocity were obtained by multiple injection strategy. The ignition process of single injection is composed of

Fig. 15 Effect of injection pressure on combustion [91].

the emergence of multiple ignition points and the propagation of isolated spontaneous combustion flames. The flame merging process of double injection has been done in advance due to the faster air-fuel mixing rather than the obvious isolated spontaneous flame propagation. Also, the results have proved that the double injection has the potential to achieve more stable combustion.

2.3 Effects of fuel reactivity

According to Ref. [94–96], the poor combustion stability and narrow operation range of GCI combustion mode caused by gasoline with low cetane number can be improved by means of modifying fuel composition and reactivity.

2.3.1 Gasoline additive

Manente et al. [33] investigated the effect of gasoline with different octane numbers on the variation of stable operating load range of GCI engine. Stable combustion can be achieved when used fuels with RON below 70, as shown in Fig. 4. An extension in the lower load limit of the stable operation was also shown by further increasing the RON of fuels.

To improve auto-ignition and combustion stability, high reactivity gasoline-like fuels are proposed that gasoline as a raw material to blend other additives with different reactivity such as diesel, n-butanol, ethyl levulinate, biodiesel and so on.

The effect of fuel reactivity on GCI combustion under low-load conditions was studied by Adams et al. [97],

Fig. 16 Effect of single and double injection on combustion at 13 mg/cycle [51].

and the results showed that the addition of 5% and 10% biodiesel to gasoline significantly reduced ignition delay and accelerated combustion compared with pure gasoline operation. Meanwhile, the requirements for the intake temperature (15°C and 30°C, respectively) can be effectively reduced by adding biodiesel, and the combustion stability was also improved as the blending ratio increased.

In addition, Wang et al. [98] studied the effects on low-load GCI combustion performance by blending diesel fuel. Blends of 80% and 90% gasoline (G80 and G90) by volume were used to modify the composition and reactivity of the fuels, as shown in Fig. 17. It was seen that the ignition delay was reduced substantially while the minimum of achievable load was extended to 0.7 bar IMEP since the anti-knock index (AKI) of the 80% blend decreased. This was because the addition of highly reactive fuels increases the charge reactivity, which in turn enhances the ignition property.

Due to the fact that a portion of components have the ability to promote the heat release process of auto-ignition, the auto-ignition of gasoline in low-temperature environments can be controlled by adding ignition promoters, which can release active free radicals and other intermediates that are beneficial to cold start and low-load performance [99–101]. For example, as an ignition promoter, polyoxymethylene dimethyl ethers (PODE_n) is characterised by high cetane number, high oxygen content and high volatility. Therefore, combustion performance and soot emission can be effectively improved by adding PODE_n into gasoline. Ma et al. [102] investigated the combustion process of gasoline/PODE_n blends by means of high speeds imaging and the results are shown in Fig. 18. It is obvious that the decreased ignition delay from 3.8 to 2.0 ms are obtained with an increase of PODE_n proportion from 10% to 30% (GP10, GP20, GP30), because higher reactivity of these blends was obtained.

3 Conclusions and scope for future work

In recent two decades, advanced combustion concepts, with ‘pre-mixing and low-temperature combustion’ as the fundamental characters, have been vigorously developed and have become a key technical approach for

Fig. 17 Comparison of combustion performance and emissions between GP80 and GP90 [98].

Fig. 18 The combustion process of gasoline/PODE_n blends [102].

engines to meet the future emission regulations and the thermal efficiency targets [29]. Among them, higher efficiency and cleaner combustion can be achieved with GCI combustion mode by rationally organising the stratification of both mixture concentration and fuel activity. Compared with the other combustion concepts, it can be concluded that GCI combustion concept has considerable potential to achieve low emissions and high efficiency. However, the problems of combustion instability and high emission of incomplete combustion products, such as HC and CO under low-load conditions, have not been effectively improved until now. This paper reviews the research progress and current status of the existing technical approaches to improve the stability of GCI combustion mode under low loads. By summarising them, the following conclusions can be drawn.

- The development of CI engines is bound to move towards high efficiency, low emissions and affordable. There is no doubt that it is correct to study the mechanism of in-flight purification by relying as little as possible on expensive aftertreatment technologies.
- The essence of the improvement technologies of GCI combustion mode under low-load conditions is to improve the thermodynamic state in the cylinder under a fixed load and match it with the mixture

distribution.

- Intake heating, intake boost, spark assistance and internal EGR can improve the initial thermodynamic state of reactants effectively.
- Injection strategy is an important entry point to control the distribution of mixture concentration in the cylinder.
- Adding additives into gasoline can change the reactivity of fuel and extend the lower limit of the stable combustion load of the GCI combustion method.
- Different compromises have diverse applications. Coupling control of a series of strategies has the potential to achieve stable combustion under low loads.

3.1 Scope for future work

This review demonstrates that it is possible to achieve high efficiency, low NO_x and soot emissions in GCI combustion mode, and it would have room for further improvement, as shown below.

1. There is an interdependent ‘combination’ between engine and fuel, that is, the improvement of combustion stability under low-load conditions must come from the joint improvement of engine and fuel.
2. Improvement technology, used in GCI combustion mode under low-load condition, should be studied in three major directions: extending the lower load limit of stable combustion, improving efficiency and reducing emissions.
3. There are several points that may be taken into account:
 - (a) Optimise injectors and injection systems to match reasonable fuel injection strategies.
 - (b) Use ‘turbocharger + supercharger’ to obtain high supercharge.
 - (c) Increase compression ratio of engine to improve the thermodynamic conditions.

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