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Pre-chamber ignition systems – development and application in the automotive industry

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This article reviews the latest literature on pre-ignition systems as an effective and future-proof lean-burn combustion technology. It presents the current state of knowledge on combustion characteristics and emissions, as well as the key advantages and challenges of pre-chamber ignition technology applications. The design and operation of turbulent jet ignition and pre-chamber combustion systems were discussed in detail. This ignition concept improves engine thermal efficiency by increasing ignition energy and flame surface area. This eliminates problems associated with engine knocking under heavy loads and at high engine speeds. Differences in the construction and operation of various types of pre-chamber ignition systems are presented. The fundamentals of spark-ignition systems with a pre-chamber are described, taking into account the various types of these systems and the factors that affect their operation. The article explains why the pre-chamber ignition concept, especially its passive version, is a promising alternative increasingly used in spark-ignition engines for passenger cars. It presents the prospects and further development of pre-chamber ignition systems. The application of pre-chamber jet ignition systems (turbulent jet ignition) in the automotive industry was also discussed, with examples provided.

Key words: *pre-chamber ignition systems, Turbulent Jet Ignition, internal combustion engines, engine efficiency, emissions*

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1. Introduction

Regulations limiting harmful emissions, including CO_2 emissions from ICEs (Internal Combustion Engines), are continually being increased. Combined with the growing global demand for energy, this calls for the development of technological solutions to improve the efficiency of piston-type internal combustion engines [62, 86].

Such an objective can be achieved by burning a lean mixture or a stoichiometric mixture using an EGR (exhaust gas recirculation) system. These strategies offer various advantages but also pose some challenges. Generally speaking, burning a lean mixture requires careful preparation by blending the fuel with air. In turn, high pressure in the intake system reduces pumping losses during the intake stroke. Increasing in the amount of operating substance in the cylinder lowers the peak combustion temperature, thereby significantly reducing heat losses. Using lean or ultra-lean fuel-air mixtures is a proven and effective strategy for reducing fuel consumption and emissions [86]. Operating the engine on a lean mixture ($\lambda > 1$) increases its efficiency by reducing heat loss through the combustion chamber walls, increasing the specific heat capacity and reducing pumping losses at partial load [3, 8, 12]. However, three-way catalytic converters pose a problem in this case, as they are incompatible with the lean-burn combustion concept in spark-ignition engines [84]. In this case, the permissible level of nitrogen oxide (NO_x) emissions can only be achieved by using an air excess ratio λ of 1.8–2.0 or higher [5]. This exceeds the stability limit of lean mixture combustion ($\lambda \sim 1.4$). This solution is associated with problems with ignition and flame propagation [26, 51]. Extremely lean mixtures can cause large differences between combustion cycles, leading to an increased probability of flame extinction or even ignition failure, reduced thermal efficiency and increased emissions of unburned hydrocarbons (UHC) [11, 26, 85].

Another frequently used strategy to improve the efficiency of SI engines is to maintain a stoichiometric air-fuel ratio ($\lambda = 1$) and use exhaust gas recirculation (EGR) to dilute the oxygen concentration in the in-cylinder mixture [16, 73]. This strategy enables the use of three-way catalytic converters, which significantly reduce NO_x emissions [16, 86]. The issue is that the exhaust gas recirculation (EGR) rate is essential for reducing NO_x emissions to levels that comply with current emission standards. Without an exhaust gas after-treatment system, the exhaust gas recirculation rate is approximately 50 percent. This leads to the same problems encountered when increasing the air-to-fuel ratio. These problems include variability of the combustion process between cycles, difficulties with flame propagation, and misfires [12, 40]. Beyond that, EGR reduces the tendency to knock at low engine speeds and high loads and improves fuel economy [25].

The results of previous studies [64, 69] have shown that the main obstacles to the combustion of a lean mixture, regardless of the combustion strategy employed, are the increased energy required to initiate combustion and the low flame propagation speed. Consequently, the greatest challenge to the widespread adoption of lean-burn technology is developing an ignition system that reliably ignites such a mixture. In ICEs, a high ignition energy and a localized ignition source are required to ignite and burn the lean mixture effectively.

Another, equally significant obstacle to improving the thermal efficiency of spark-ignition (SI) engines is known as knocking. This type of abnormal combustion significantly reduces the performance and reliability of spark-ignition engines [22, 81]. Many methods for reducing knock have been developed. However, they all have disadvantages,

including reduced engine thermodynamic efficiency, high cost, and other undesirable side effects. For this reason, ignition timing is usually retarded to prevent engine knocking, thereby delaying the combustion phase. One reason for the low thermal efficiency of spark-ignition engines is that they operate on a stoichiometric mixture. The need to maintain a stoichiometric air-to-fuel ratio stems from the need to maintain an appropriate flame propagation speed. The goal is to to ensure high combustion efficiency when using a three-way catalytic converter to effectively control exhaust emissions [12]. The previously discussed lean-burn combustion strategy is a highly effective and promising approach to reducing CO_2 emissions in both spark-ignition engines and future hybrid gasoline engines [21, 39]. However, during lean combustion, both flame kernel growth and flame propagation slow down. This is due to the reduction in laminar flame velocity. This significantly prolongs combustion time, leading to incomplete combustion and large cycle-to-cycle variations that negatively impact engine efficiency. Increasing ignition energy with high-efficiency ignition systems is both desirable and necessary. This solution simultaneously reduces knock and enables operation under lean-burn conditions, even with an excess of air and a λ ratio greater than 2. The high-energy ignition system also allows for shortening the ignition delay, achieving ignition closer to TDC, and accounting for changes in fuel mixture motion and homogeneity. In recent years, there has been a growing interest in the development, research and testing of innovative, cutting-edge ignition technologies [52] – Fig. 1.

Generally speaking, ignition systems can be divided into two types: point ignition and space ignition. Point ignition systems include single-spark, multi-spark, twin-coil, and laser ignition. In space ignition, a larger portion of the fuel charge is ignited. Compared to point ignition systems, space ignition systems such as prechamber ignition, corona ignition and microwave ignition are distinguished by higher ignition energy and a shortened flame path [77]. The advantages of space ignition systems include, first of all, shorter combustion time, greater stability and higher combustion efficiency. Space ignition systems include plasma igniters [34], laser-induced ignition [54], corona spark plug systems [35], and pre-chamber ignition systems [20, 35, 38, 42, 65].

The pre-chamber ignition system, also known as Turbulent Jet Ignition (TJI), is a promising ignition strategy that enables spark-ignition engines to operate under lean or diluted conditions while maintaining efficient combustion. The combustion process initiated by the TJI system differs significantly from that initiated by conventional combustion in compression-ignition engines. A spark plug first ignites the combustible mixture in the pre-chamber. The rise in pressure in the pre-chamber, caused by the rapid spread of the flame, results in hot products and active radicals entering the main chamber through the pre-chamber orifices. The high turbulence intensity and the numerous ignition points generated by turbulent flows promote intense, rapid and complete combustion in the main chamber. The main benefits of using this strategy include shortening the combustion process, improving combustion stability, and increasing combustion efficiency. Consequently, the pre-chamber ignition system, particularly in its passive form, represents a promising alternative for future spark-ignition engines intended for passenger cars [12, 67].

Combustion systems utilizing a pre-chamber and ignition via a turbulent jet of the burning mixture in spark-ignition engines can be used to extend the operating range on a lean mixture. They also help to reduce the tendency towards knocking and its severity under high loads and at high engine speeds, as well as increasing the rate of fuel combustion in the main combustion chamber. However, despite the increased combustion rate, knocking remains a significant limitation at low engine speeds and high engine loads [6, 7]. In compression-ignition engines, indirect injection can extend the time available for the mixture to form before combustion begins. It can also be used to optimize the timing and limit extreme pressure peaks in controlled mixed combustion. Ignition systems with a pre-chamber ensure stable combustion even when using alternative fuels and can help reduce emissions of NO_x, HC, CO and CO_2 thanks to more efficient combustion at low temperatures [6, 67].

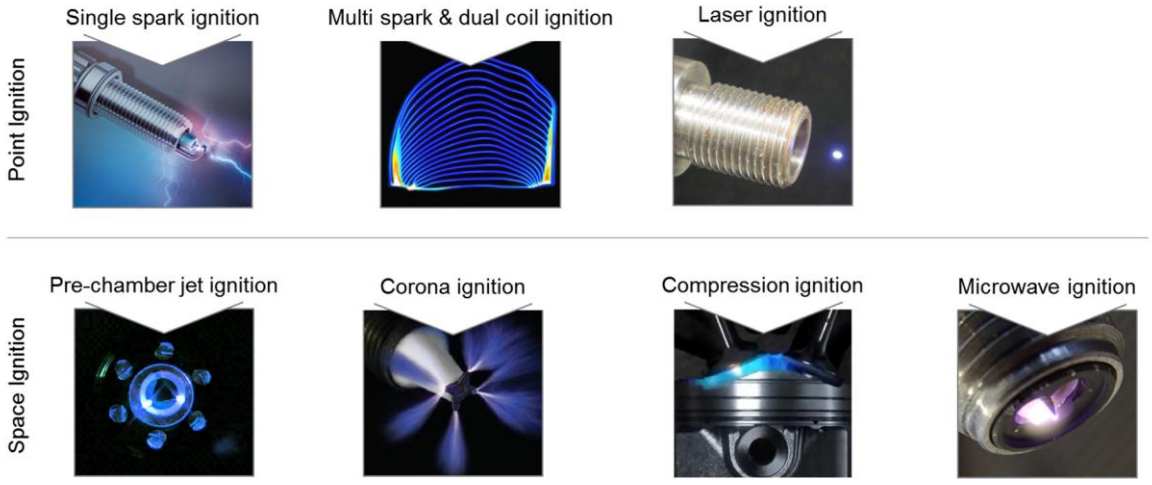


Fig. 1. Various ignition systems for both categories, point and space ignition [43]

2. Turbulent Jet Ignition pre-chamber combustion systems

2.1. Design and operation

The concept of ignition in a pre-chamber is also often described as Turbulent Jet Ignition (TJI) [3, 65]. This ignition concept uses a conventional electric spark system to ignite a small amount of the fuel-air mixture in a separate, small volume (pre-chamber) that is 2–3% of the volume of the main chamber. The pre-chamber (Fig. 2) is connected to the main combustion chamber via a set of channels and outlet ports [65]. Combustion raises the pressure in the pre-chamber, causing jets of the burning combustible mixture to be ejected from the pre-chamber into the main chamber [27]. This forces combustion to begin in multiple locations within the main chamber volume [14, 27, 28]. Under appropriate conditions, combustion in the main chamber is characterized by very low dispersion, and its speed is much higher than that of conventional spark ignition systems [2, 14]. A faster combustion process reduces the tendency for knocking. This allows for an increase in the compression ratio and, consequently, an increase in the engine thermal efficiency [15].

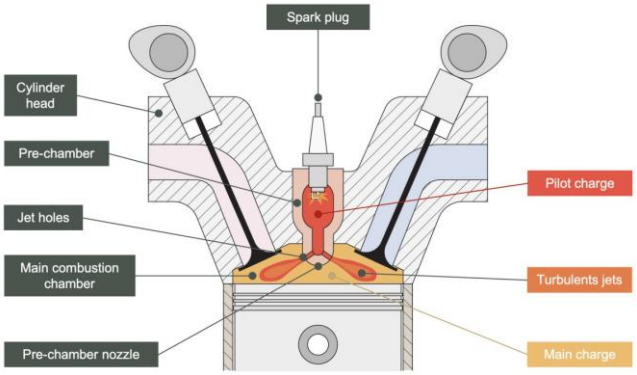


Fig. 2. Basic configuration of an ignition pre-chamber [32]

In the main chamber, the mixture is burned from the outside to the center (Fig. 3a). In this way, the flame reaches the areas that are usually most prone to knocking much sooner, such as the top piston ring [56]. In this combustion process, which is approximately 30% shorter than that in a conventional combustion chamber, the center of heat release can be shifted by approximately 4-5° CA [56]. This allows for a higher compression ratio, reducing fuel consumption at partial load.

Unlike conventional spark ignition, in the case of pre-chamber ignition, the intensity of knock combustion does not decrease with the subsequent heat release (Fig. 3b). The intensity of knocking combustion remains at a relatively high level, just below the required limit (100%) – Fig. 3b.

However, in pre-chamber ignition, the pre-chamber overpressure generates a pressure wave or pressure surge as the combusting air-fuel mixture passes through the nozzles. This pressure wave travels from the pre-chamber flow channels throughout the combustion chamber and then reflects off the walls. Unlike in knock combustion, the pressure spikes caused by ignition in the pre-chamber are detected as pressure oscillations in the cylinder immediately after ignition. However, the pressure fluctuations occurring in the pre-chamber are caused solely by gas dynamics and – unlike those resulting from knocking – are not caused by the irregular release of heat, which is harmful to the engine. Clearly distinguishing knocking combustion from pressure oscillations in the pre-chamber at any operating point can be challenging, however [56].

Higher fuel injection pressure in the pre-chamber improves the quality of the mixture formed. This leads to increased combustion stability of a lean mixture in the main chamber [72]. The optimal timing for fuel injection into the pre-chamber occurs midway through the compression stroke. This utilizes airflow (air blast) at increasing velocity during the compression stroke, which facilitates the formation of a stratified mixture in the pre-chamber, with a richer upper layer and a leaner lower layer. The pre-chamber nozzle design must be compatible with the main chamber design. The most important factor is selecting the optimal nozzle angle to allow the jet from the pre-chamber to travel farther before reaching the wall of the main combustion chamber. This helps to maximize the ignition capability of ultra-lean mixtures [72].

a) b)

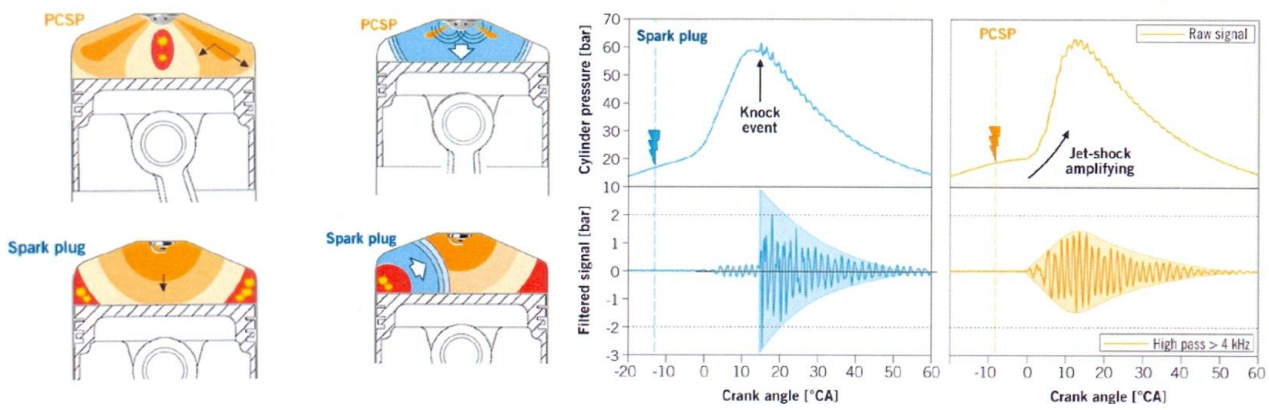


Fig. 3. a) knock mitigation with passive pre-chamber ignition (PCSP) compared to conventional spark plug, b) physical principle and pressure traces for PCSP-specific pressure oscillations compared to knocking combustion with conventional spark plug [56]

The TJI process can be divided into the following stages: mixture enrichment, thermal effects and chemical effects. As shown in Fig. 4a, the most important heat-transfer phenomena associated with flame propagation within the chamber are thermal and hydrodynamic quenching. Thermal quenching occurs due to rapid heat transfer to the pre-chamber material's surface as the flame passes through the nozzle. Hydrodynamic quenching occurs when the flame mixes with the cool, lean mixture entering the main chamber – Fig. 4a [37, 84].

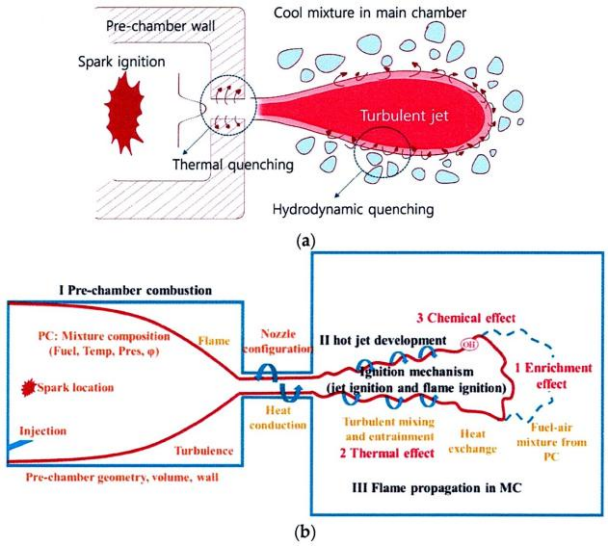


Fig. 4. Operating mechanisms of TJI in pre-chamber spark-ignition engines, a) quenching. b) overview of turbulent jet ignition process [37, 84]

The two-stage combustion process in the main chamber consists of a jet-dominant, controlled-mixing phase and a flame propagation phase. The combustion intensity influences the jet-dominant, controlled-mixing phase in the prechamber. The flame propagation phase, in turn, depends on the mixture reactivity in the main chamber, driven by the mass flow within the cylinder and the accompanying turbulence – Fig. 4b [54, 76, 82, 84]. Undulations on the outer surface of the flame characterize the conical, turbulent flame jet ejected from the pre-chamber. The outer part of the jet serves as an ignition source for the mixtures in the main chamber, thereby enabling multiple ignition points.

A large pre-chamber volume provides more ignition energy and more intense charge movement within the combustion chamber. However, it requires more fuel and increases heat loss through the walls [29].

The geometry of the ducts connecting the pre-chamber to the main chamber, and the temperature of the pre-chamber walls, influence the chemical reactivity and temperature of the exhaust gas streams, and thus the ignition process of the mixture in the main combustion chamber [29].

Changing the nozzle diameter while keeping the pre-chamber volume constant affects the combustion time, with little effect on NO_x emissions [57].

A comparison of the performance of an engine using conventional spark ignition with that of an engine using a pre-chamber ignition system showed that, in the case of the latter, an 18 percent improvement in fuel economy can be achieved [6, 80] thanks to the engine running on lean mixtures. The lean combustion concept is often employed with alternative fuels. Furthermore, the combustion characteristics in an engine with a pre-chamber ignition system depend on the fuel used [1, 31, 49, 50]. It has been shown that the extent of the lean-burn limit depends largely on the fuel type in the main chamber, specifically on its minimum ignition energy [24, 80]. According to the classification shown in Fig. 5, once a spark has ignited the mixture in the pre-chamber, it may undergo a further combustion process either in so-called passive pre-chambers or in active pre-chambers. When burning a very lean mixture in the main combustion chamber, an active pre-chamber is required to enrich the fuel mixture externally. This allows a stoichiometric or slightly richer mixture to be achieved in the pre-chamber without disrupting the homogeneous, lean mixture in the main combustion chamber. Dosing can be carried out either by a non-return valve or by a separate injector. Active pre-chambers can be supplied with both liquid and gaseous fuel.

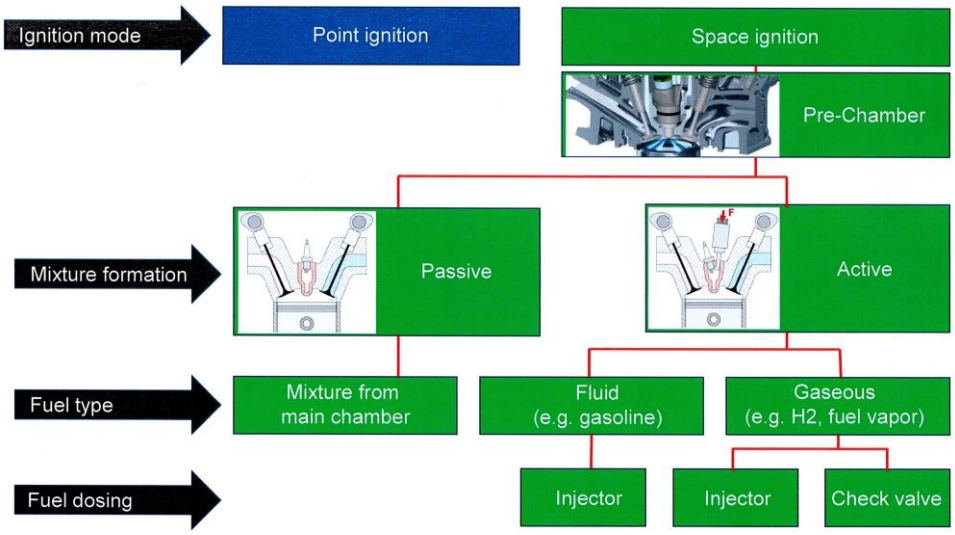


Fig. 5. Classification of different pre-chamber configurations

2.2. Types of pre-chamber ignition systems

Pre-chamber ignition systems can be divided into active [28, 66] (or scavenged) and passive (or unscavenged) systems [23, 48, 76]. Figure 6 compares the operating principles of active and passive pre-chamber ignition systems with those of a conventional spark-ignition engine.

In a passive system with a pre-chamber, the fuel-air mixture around the spark plug forms during the compression stroke, as fuel is forced from the main chamber into the pre-chamber through passages connecting the two chambers. In the active configuration, an additional fuel injector [48, 73] is fitted in the pre-chamber.

Consequently, in an active ignition system with a pre-chamber, fuel is supplied to the pre-chamber via an injector or a check valve. In the pre-chamber, a stoichiometric or fuel-rich mixture forms near the spark plug, regardless of the main-chamber mixture composition. In the main chamber, the required air-fuel ratio – a lambda value in the range of 2.0 to 2.4 for petrol – is achieved by the main injector metering the fuel. Under lean-burn conditions, when the air-to-fuel ratio in the main combustion chamber is significantly greater than 1, the high reactivity of the burning mixture flowing through the channels from the pre-chamber promotes ignition in the main combustion chamber. Other benefits of using this active pre-chamber ignition system include charge stratification and significant reduction of HC and NO_x emissions [6, 28]. Moreover, the active pre-ignition chamber system is characterized by a high combustion rate [28, 71] and low variability of combustion processes between cycles [56]. It also allows the engine to operate under very lean combustion conditions [14]. However, the big challenge is to atomize the fuel well in the small pre-chamber and then vaporize the gasoline very quickly within the pre-chamber's very limited volume. The atomized fuel wets the chamber walls, which retain a significant portion of the fuel. This complicates the control of the effective composition – enrichment of the pilot dose- and leads to increased particulate emissions. Consequently, this necessitates installing a particulate filter in the exhaust system. However, a significant disadvantage of active pre-chambers is that they can only be used in engines operating with excess air.

The passive system simplifies the design by eliminating the need for an additional fuel injector located in the pre-chamber. This reduces assembly and packaging costs in the main combustion chamber, making it an attractive solution for passenger cars. In this case, no additional fuel is added to the pre-chamber, so its air-to-fuel ratio is not directly controlled. Fuel is injected solely into the main chamber, using either indirect fuel injection (PFI) or direct injection (DI). In engines with port fuel injection (PFI), the λ ratio is similar in both chambers, i.e., the pre-chamber and the main chamber. In direct-injection (GDI) engines, the difference in the λ ratio between the chambers can be indirectly influenced by adjusting the relative position of the pre-chamber and the injector [60]. The fuel-air mixture flows into the prechamber through channels connecting the two chambers. Therefore, the geometry of the prechamber and connecting channels plays a key role in the initiation of combustion, its course, and the flame propagation rate [28, 60, 71]. In the case of a passive system, some aspects of its operation still require detailed study and optimization. For example, the prechamber purge and filling processes, which depend on gas transfer between the prechamber and the main chamber, require further investigation.

Furthermore, the limitations of this concept regarding maximum air dilution and/or EGR [30, 70]. The ignition efficiency of passive pre-chambers is hampered by residual exhaust gas remaining in the pre-chamber, especially at low loads. These residual exhaust gases significantly impede ignition of the fuel in the pre-chamber and make it much more difficult, or even impossible, to intentionally dilute the mixture charge in the main chamber via EGR. Under real conditions, dilution of the charge in the main chamber via EGR also dilutes the pilot charge in the pre-chamber in the same proportion [13, 30, 70]. The additional charge on the EGR system is due to residual exhaust gases that remain in the pre-chamber. The spread between work cycles increases significantly. In the pre-chamber, there is a continuous alternation between fast and slow combustion [4, 83]. The main combustion chamber absorbs these instabilities but also amplifies them. Combustion becomes less efficient because EGR dilutes the ignition charge, making the turbulent flows through the passages connecting the pre-chamber to the main chamber less intense and cooler.

A passive pre-chamber creates a dead space, making it difficult to remove residual exhaust gases between cycles. The total amount of residual exhaust gases retained in the pre-chamber is slightly influenced by the engine load. The lower the engine load, the less fresh air enters the engine cylinder and the greater the relative proportion of residual exhaust gases remaining in the pre-chamber, regardless of its volume.

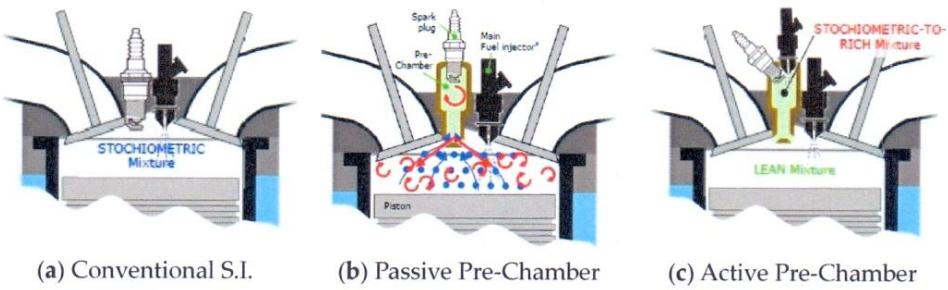


Fig. 6. Comparison of the operating principles of active and passive pre-chamber ignition systems with those of a conventional SI engine [73]

At low and medium engine loads, when most of the fuel is burned, the share of residual exhaust gases in the pre-chamber can reach 30–40% or even more [9, 79]. Such levels make ignition and combustion in the pre-chamber unstable and inefficient. Therefore, at low engine loads, the benefits of using passive pre-chambers are small or even inferior to those of conventional spark ignition. Another problem and limitation of passive pre-chambers is the difficulty in cold starting the engine. As the main chamber charges the pre-chamber, some of the vaporized fuel condenses. The reason for this is that the fuel flowing through the still-cold channels between the chambers and coming into contact with the cold internal walls. This depletes the pre-chamber fuel mixture, making it too lean to ignite [9, 55, 61].

To resolve the issues described above, it is essential to install a spark plug in the main chamber to assist ignition. This solution applies to engines from the Stellantis group – specifically the Maserati Nettuno and Hurricane 4 units.

Another problem associated with the use of a passive ignition system in the pre-chamber is the difficulty in heating the exhaust catalyst. The use of a spark plug in the main chamber allows the system to return to a more conventional operating mode [45, 61, 68].

In small-displacement engines that frequently operate under high loads, passive pre-ignition within the chamber can be used to advantage. In this case, a higher compression ratio can be utilized, or an overly rich mixture can be avoided. However, this advantage applies to high-performance vehicles such as the BMW M2, M3, and M4 – the S58 engine starting in July 2026.

2.3. Further development of pre-chamber ignition systems

For over a decade, there has been intensive development of various pre-chamber ignition system concepts. One of the more interesting concepts is Jetfire® Ignition, which has been under development since 2010 by Mid Michigan Research/Jetfire® Power, LLC [46]. A distinctive feature of the fourth-generation Jetfire® Ignition system is a mechanical pre-chamber air management system operated by concentric camshafts and electric phasers – Fig. 7.

Thyssen Krupp Dynamic Components' ConCam technology provides a highly efficient method for controlling air flow to the pre-chamber. Figure 8 illustrates the sequence of events occurring in the Jetfire® ignition system, including those in the pre-chamber and the main chamber [5, 46, 59]. First, purge air is fed into the pre-chamber (1) to remove any residual gases. Next (2), fuel is injected into the pre-chamber, where it mixes with the air to form a rich mixture, which is then ignited by a spark. This triggers the combustion process in the pre-chamber (3). The air-diluted combustion mixture is discharged through connecting ducts into the main chamber.

Residual gases will be burned later in the main chamber. All fuel deposited on the pre-chamber walls is vaporized and mixed with the reaction mixture (4). During this process, a reaction mixture is formed (5). It is then forced through the openings in the Jetfire® pre-chamber housing into the main chamber (6). The fuel, air, and diluent mixture (residual and EGR) is ignited in the main chamber (7). The combustion products formed in the main chamber are then directed back to the pre-chamber (8). The cycle repeats when the purified air and the unburned reactants remaining in the main chamber are forced into the pre-chamber (9 and 10). Test results to date indicate significant improvements in fuel efficiency as the system evolves. Tests have used various fuels, including kerosene, gasoline, diesel, and hydrogen. Engine efficiency with the Jetfire® Ignition system has been as high as 48.5% when fueled with gasoline and over 49% when fueled with hydrogen fuel.

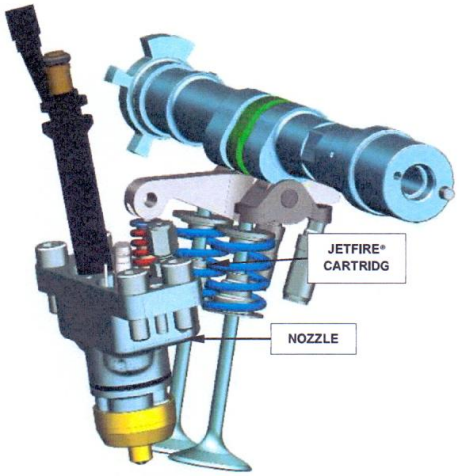


Fig. 7. Jetfire® Ignition with cam purge valve actuation and no independent control from intake valves [46]

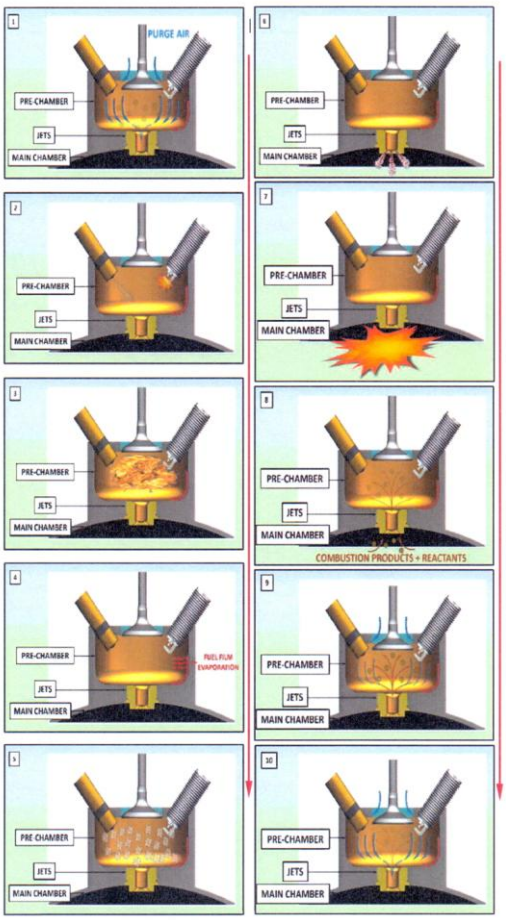


Fig. 8 Jetfire® Ignition system operation [44]

Since 2018, an international project has been developing a pre-chamber ignition system called Valvijet [28]. The goal of Valvijet is to develop an improved pre-chamber ignition system for low-fuel engines, leveraging a set of technologies (PFI, TJI, turbocharging, VVT). Valvijet combines an active pre-chamber with "air/fuel injection" (Fig. 9).

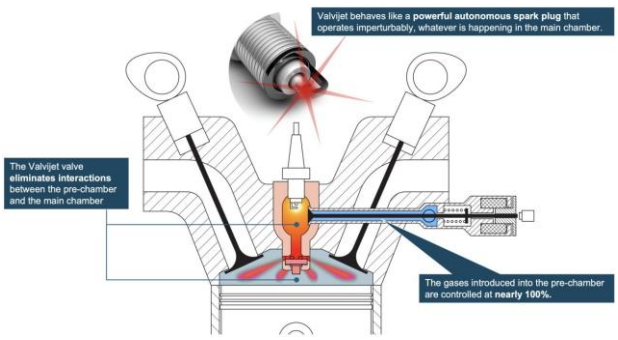


Fig. 9. Construction diagram of the Valvijet system [32]

This concept is the only one to date that avoids both the limitations of passive pre-chambers and the application limitations and disadvantages of active pre-chambers with fuel-only injection. The introduction of the fuel-air mixture into the pre-chamber of the Valvijet system ensures a stable stoichiometric composition ($\lambda = 1$). This fuel dose is then diluted solely by the non-reactive, oxygen-free exhaust gas recirculation (EGR) system. This combustion-mixture formation enables the reduction of nitrogen oxides with a simple three-way catalytic converter [32].

Since the main fuel charge has a stoichiometric composition but is strongly diluted by EGR, injecting fuel into the pre-chamber alone is insufficient to achieve proper combustion. It is essential to supply the required amount of air to the pre-chamber to ensure there is sufficient oxygen for combustion. Typically, the pilot charge energy is only 1.5% to 4% of the total combustion energy produced during one cycle. The more EGR dilutes the main chamber mixture charge, the greater the ignition energy must be. Therefore, the greater the pilot charge energy must be. The optimal air-to-fuel ratio in the pilot dose is approximately 11.3:1. This corresponds to an equivalence factor of $\varphi = 1.3$ or lambda $\lambda = 0.77$ [32].

The burning fuel-rich pilot dose generates a high flame velocity in the pre-chamber and produces numerous reactive intermediates (H, O, OH, CH, CO, H_2, C_1–C_2 radicals). Due to turbulent flow, these substances are transferred through the channels connecting both chambers to the main chamber, thereby supporting the combustion of the main dose, which EGR strongly dilutes. This enables rapid and homogeneous combustion of the main mixture, with very limited potential for knocking.

However, simultaneous injection of air and fuel into the pre-chamber requires solving numerous challenges, the most important of which are:

- Compressing air to pressures above 30 bar over a wide flow range. The compressor used must be highly efficient and durable [32]
- Preparing the fuel-air mixture at high pressure while preventing gasoline re-liquefaction [32]
- The pilot mixture must be fed into the pre-chamber with high precision. This is due to the narrow angular range within which it can be fed into the pre-chamber, which is limited to a few degrees of crankshaft rotation. This requires developing a suitable injector [32].

In the case of engines fitted with a pre-chamber, compliance with the above requirements has a decisive influence on the stoichiometric composition of the mixture and the combustion process in the main combustion chamber, which are necessary for the proper functioning of three-way catalytic converters. It is assumed that the main mixture is highly diluted by EGR, thereby ensuring high efficiency throughout the entire operating range.

The final version of the Valvijet is characterized by the following features and advantages [32]:

- Each pre-chamber of the cylinder head houses only one injector. This is a Valvijet fuel-air mixture injector that can be installed horizontally under the intake manifold (Fig. 10). It is equipped with a long, thin nozzle.
- The Valvijet system includes a fuel-air mixer that delivers a pilot mixture to the engine's pre-chambers. Air and fuel are supplied to the mixer in precisely controlled proportions, with an accuracy of (±2%). A turbine rotates continuously inside the mixer chamber, homogenizing the fuel-air mixture [32].

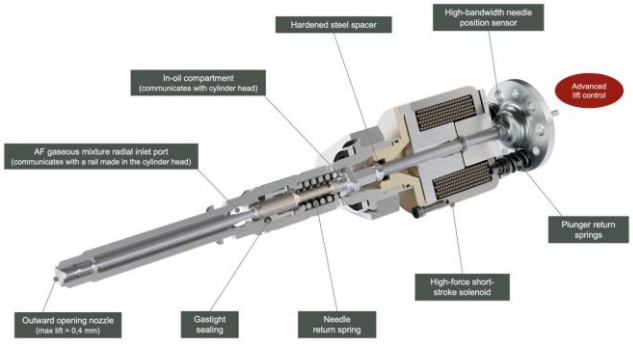


Fig. 10 Valvijet A/F injector [32]

- The Valvijet system does not require a high-pressure fuel pump. The Valvijet mixer itself generates the fuel pressure necessary to create the fuel-air mixture. Furthermore, the Valvijet mixer guarantees fuel-air mixture enrichment with an accuracy of ±2% and very good mixture uniformity across the entire operating range and under all conditions [32].
- All injectors in the engine cylinders' pre-chambers are supplied by the same fuel and air source. Therefore, there are no differences in the mixture composition between the individual pre-chambers of the engine [32].
- The Valvijet system utilizes a magnetic non-return valve situated at the bottom of the pre-chamber, surrounded by the outlets of the turbulent-flow channels for the burning mixture. When the solenoid check valve is closed, the pre-chamber and the main chamber are isolated from one another. When this valve is open, gases

can flow through the channels from the smaller chamber to the larger one.
- The solenoid valve closes as a result of the simultaneous, combined effect of the magnetic field and the pressure difference between the chambers.
- The overall enrichment of the fuel mixture in the engine's main chamber is controlled without affecting the operation of the pre-chamber. This allows λ to be maintained at 1 and the required exhaust gas temperature to be maintained for the three-way catalytic converter to operate correctly. Adjustment of the global mixture enrichment is performed solely by the main MPFI injectors [32].

This pre-chamber ignition system configuration, called Valvijet, meets all the functions and requirements necessary to achieve highly efficient, fully controlled stoichiometric combustion of a TJI engine.

3. The automotive use cases of pre-chamber jet ignition systems (Turbulent Jet Ignition)

3.1. Turbulent Jet Ignition in F1 engines

In 2014, Formula 1 adopted regulations limiting fuel flow to a maximum of 100 kg/h to meet global environmental policy goals. Consequently, engine development has had to focus on generating as much energy as possible from a limited amount of fuel, which can only be achieved by increasing the combustion efficiency.

Lean-burn combustion is very complex to implement, particularly due to the increased risk of knock. Consequently, engine manufacturers began seeking ways to improve the ignition process and better control flame propagation. In 2014, Mercedes introduced turbulent jet ignition (TJI) technology in its engines, and Ferrari followed in 2015. Given that F1 regulations limited the number of injectors used in combustion chambers to one, and the same applied to spark plugs in F1 engines, passive pre-chamber ignition technology was developed. Passive pre-chamber ignition features a simple design. It can improve combustion speed and reduce the tendency to knock. By utilizing passive ignition in the pre-chamber, it is possible to increase the engine's compression ratio and accelerate the combustion phase under partial-load conditions. Furthermore, in the operating mode where the throttle is fully open (WOT), the mixture enrichment can be reduced. Therefore, a system with a passive pre-chamber is a beneficial solution for engines with a high compression ratio, which often operate under heavy loads. A passive pre-chamber increases combustion speed; however, the mixture in this chamber cannot be enriched. Furthermore, the lean-burn limits in a passive pre-chamber cannot be extended compared with those for conventional spark ignition [3, 63].

The technical solutions used in F1 engines are kept strictly confidential, but the most likely pre-chamber ignition system and turbulent jet ignition (TJI) technology are presented below – Fig. 11 [33].

As shown in Fig. 11, according to Article 5.10.2 of the F1 technical regulations, the pre-chamber contains a spark plug and a single injector. The injector presumably creates a predetermined amount of fuel-air mixture (lean) in the pre-chamber, which is then sprayed into the main chamber. The pre-chamber is then filled with a rich mixture, which is ignited by the spark plug. Once combustion is initiated, the rich, partially burned mixture passes through the pre-chamber's channels, creating plasma jets on the nozzle's other side (in the main combustion chamber). These jets reach the piston, primarily at the outer edge, igniting the remaining mixture. This creates several ignition zones arranged around the main combustion chamber. This facilitates ignition of the mixture, increases the combustion rate, ensures a more stable combustion process, and reduces the likelihood of knocking. Whilst conventional ignition occurs at the center of the cylinder, in the case of jet ignition, it is initiated primarily on the outer part of the charge and progresses towards the center. This allows for significantly more efficient combustion of the fuel mixture, enabling the engine to produce more power whilst generating far fewer combustion by-products. Figure 12 shows the combustion process in a 2017 Honda RA617H F1 engine.

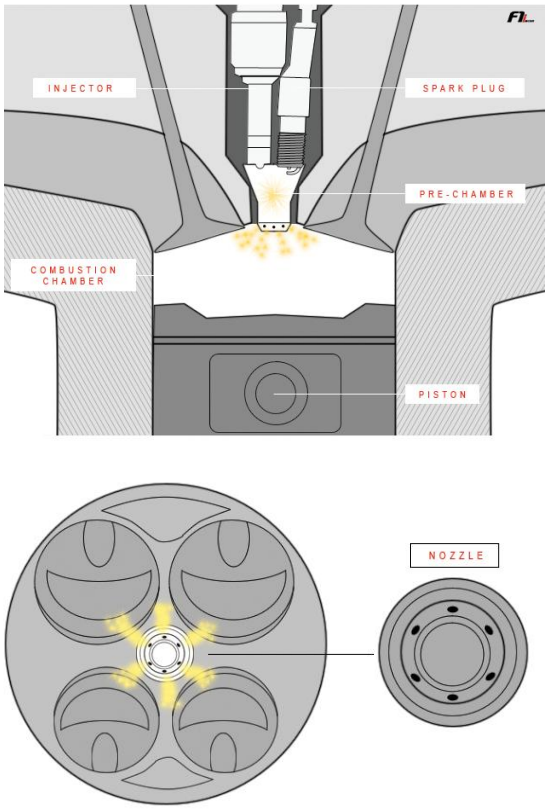


Fig. 11. Pre-chamber combustion in an F1 engine [33]

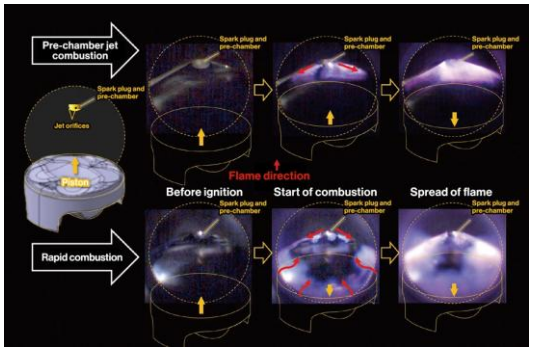


Fig. 12. Combustion process in a 2017 Honda RA617H F1 engine [33]

3.2. Zenvo Aurora (MAHLE)

MAHLE (MAHLE Jet Ignition® system) was the first company to introduce and popularise a pre-chamber ignition system in Formula 1 engines. The company also designed and built the engine for the Zenvo Aurora hypercar [10]. It was a turbocharged V12 engine with a displacement of 6.6 liters, fitted with four turbochargers, delivering a maximum power output of 932 kW and a maximum speed of 9800 rpm – Fig. 13.

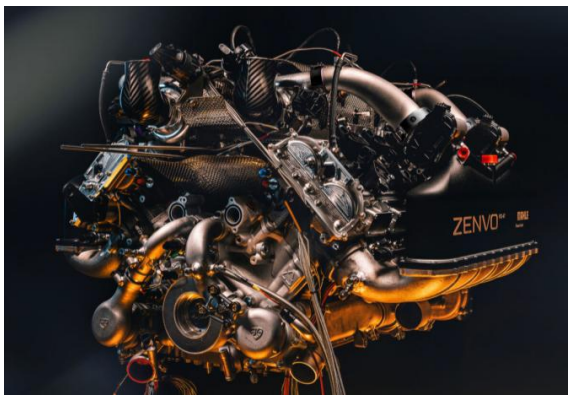


Fig. 13. Zenvo Aurora (MAHLE) V12 engine [10]

The engine utilizes passive ignition technology in the pre-chamber (the MAHLE Jet Ignition® system), enabling maximum power at a stoichiometric air-to-fuel ratio. The combustion chamber architecture is a conventional four-valve, open-roof design. In addition to an auxiliary spark plug, which is used during catalytic converter deactivation and low-load operation, the main combustion chamber also features a direct fuel injector and a pre-chamber – Fig. 14.

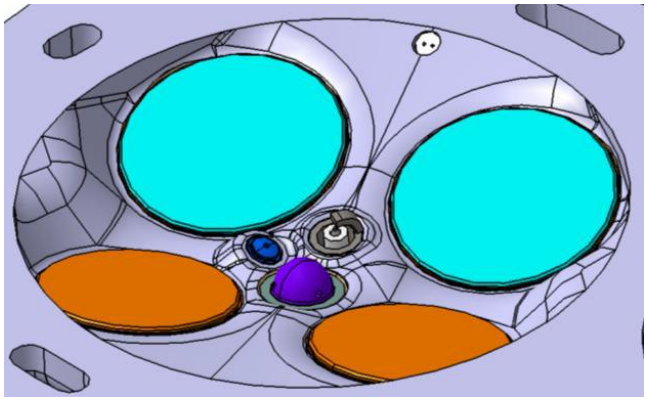


Fig. 14. Combustion chamber with MJI pre-chamber, auxiliary spark-plug and direct fuel injector - Zenvo Aurora (MAHLE) V12 engine [10]

The passive pre-chamber ignition system (MAHLE Jet Ignition®) used in the engine employs a very small secondary pre-chamber. Once the mixture charge in the auxiliary chamber has been ignited, the burning streams are rapidly ejected into the main combustion chamber through a multi-orifice nozzle. This chamber design minimizes heat loss thanks to its compact size and small internal surface area, combined with the small nozzle diameters, which aid the flame-extinguishing process. Streams of the burning mixture can penetrate deep into the main chamber and ignite the main charge in several places. The advantage of the passive MJI system in this high-performance application is increased combustion velocity, which offers two significant benefits. Firstly, a higher combustion rate reduces the residence time of the flue gases in the combustion chamber. Consequently, this reduces the engine's tendency to knock, which allows for a higher compression ratio. A higher compression ratio also means a higher expansion ratio, helping to lower the mixture temperature in the cylinder before the exhaust valve opens. Secondly, faster combustion ensures that even at high engine speeds, combustion is completed well before the exhaust valve opens. This ensures that exhaust gas temperatures remain within acceptable limits [10, 19, 20].

3.3. Maserati (Nettuno)

The Maserati Nettuno V6 engine, with a 90-degree angle, twin-turbocharged, a displacement of 2992 cm^3, and a compression ratio of 11.0:1, develops a maximum power of 544 kW at 7500 rpm. The engine utilizes passive pre-chamber ignition technology (Maserati Twin Combustion (MTC)) – Fig. 15. This pre-chamber design, derived from Formula 1 engine technology, ensures significantly more efficient and complete combustion of the fuel-air mixture in the cylinder and greatly reduces the likelihood of pre-ignition. In the Maserati Nettuno engine, the pre-chamber has a capacity of 15 cm^3. From there, the mixture enters the large chamber through six nozzles, each approximately 1 mm in diameter. A spark plug has been fitted in the main combustion chamber to assist ignition. This additional ignition source is used at low and medium engine speeds.

Both spark plugs (in both chambers) can operate synchronously, but they do not have to. Ignition can occur in close succession, depending on how quickly the mixture must be burned under the given circumstances. For example, retardation is used when the engine is cold and the catalytic converter needs to be warmed up quickly. The calibrated channels in the pre-chamber regulate both the flow of fresh mixture into the pre-chamber and the flow of the burning mixture into the main combustion chamber.

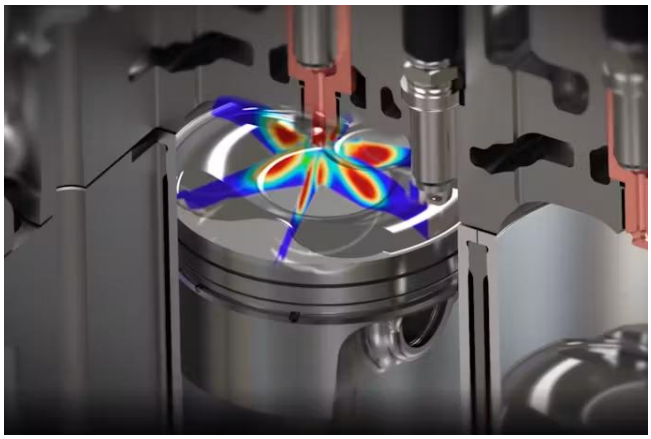


Fig. 15. Pre-chamber combustion in Maserati Nettuno engine [58]

The Nettuno engine is also equipped with a dual injection system that combines direct and indirect injection. Both sets of injectors are supplied with fuel at a high pressure of 350 bar (5076 psi), and the injection strategy is

modified depending on engine load and operating conditions, similar to pre-ignition. The most important advantage of this combustion concept is that it increases engine performance whilst reducing fuel consumption [44].

3.4. BMW S58 engine from July 2026

BMW M Ignite is the internal name for the passive pre-chamber ignition technology BMW is introducing into series production with the S58 engine. It is a 6-cylinder in-line engine with a displacement of 2993 cm³, used in the BMW M2, M3 and M4 models. This solution is designed to improve engine efficiency under high loads and meet the restrictive Euro 7 emissions standard, which will come into effect in November 2026. A key component of the BMW M Ignite system is the pre-combustion chambers integrated into the main combustion chambers of each engine cylinder. Each pre-chamber is connected to the main combustion chamber via transfer channels. The pre-chamber houses a spark plug and coil – effectively, two independent ignition systems in one engine. The main chamber also houses a spark plug.

At low and medium engine speeds, the combustion process proceeds conventionally, using a spark plug in the main combustion chamber. It is only at higher revs and under heavier engine loads that jet ignition from an additional, small combustion chamber is utilized. At that point, part of the mixture enters this small auxiliary chamber, where it ignites, and the burning mixture passes through connecting channels into the main combustion chamber to ignite the main part of the mixture.

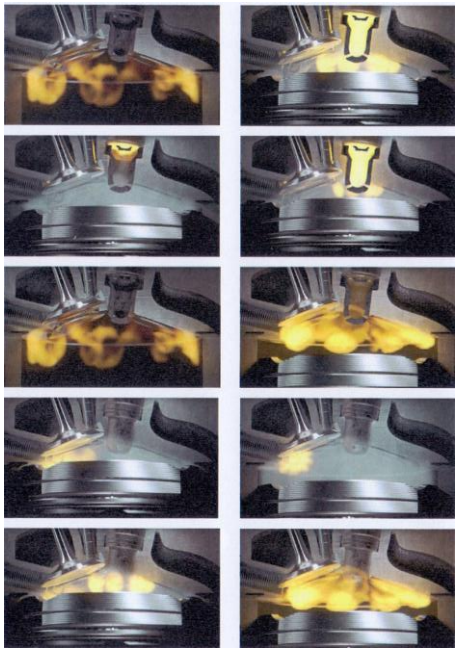


Fig. 16. The combustion process in the pre-chamber and main combustion chambers under various engine operating conditions [18]

These are so-called ignition jets that initiate combustion simultaneously at several locations within the main chamber. This significantly accelerates the combustion process and reduces the risk of uncontrolled spontaneous combustion, also known as knocking. An additional benefit is lower exhaust gas temperature, which translates into lower thermal loads and reduced NO_x emissions. This, combined with a higher compression ratio and variable-geometry turbochargers, helps to reduce fuel consumption. Figure 16 illustrates the combustion process in the pre-chamber and main chamber under various engine operating conditions. At low and medium engine speeds, a conventional spark plug mounted in the main combustion chamber ignites the mixture before the spark plug in the prechamber. At higher engine speeds and under heavier loads, ignition is initiated in the prechamber. The flames from the burning mixture enter the main chamber through channels connecting the prechamber to the main chamber, traveling at speeds close to the speed of sound. In this way, the mixture in the main combustion chamber, above the piston, is ignited at multiple points simultaneously. This enables a significantly higher combustion rate and prevents uncontrolled knocking.

3.5. Stellantis Hurricane 4 Turbo engine

The Hurricane 4 Turbo (GME-T4 Evo) engine from Stellantis is the first mass-produced engine to utilize the passive pre-chamber ignition and the turbulent jet ignition (TJI) technologies. A small pre-chamber was installed in the main combustion chamber of each cylinder. It was made of copper, as it achieves more efficient heat transfer than aluminum. Once the fuel-air mixture formed in the main combustion chamber via indirect fuel injection has been compressed, part of it is forced into the pre-chamber, where ignition takes place. Two spark plugs have been fitted to each cylinder, one in the auxiliary pre-chamber and the other in the main chamber. The flame formed in the auxiliary pre-combustion chamber passes through eight small holes, each 0.55 mm in diameter, into the main combustion chamber. Once in the main chamber, the flame front extinguishes. Partially burnt particles are now suspended in the main combustion chamber. When a spark is generated at the main spark plug, the particles ignite very quickly, accelerating the combustion of the fuel injected into the main combustion chamber via direct injection. Figure 17 shows the pre-chamber mixture formation system in the Hurricane 4 Turbo (GME-T4 Evo) engine.

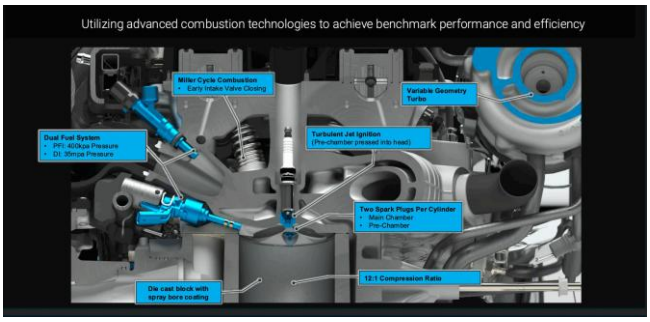


Fig. 17. Pre-chamber mixture formation system in the Hurricane 4 Turbo engine (GME-T4 Evo) [36]

Stellantis has combined passive pre-chamber ignition technology with turbulent jet ignition in the Hurricane 4 Turbo engine, using a Miller-cycle operating strategy. This strategy closes the intake valves earlier, optimizing engine efficiency and reducing emissions. This allows the Hurricane 4 Turbo to use a compression ratio of 12:1 without the risk of knocking when running on 87-octane gasoline.

4. Conclusions

- The pre-chamber ignition strategy relies on turbulent jet ignition (TJI). The key components of a TJI engine are the spark plug, a small-volume combustion chamber, and one or more channels through which the burning mixture from the pre-chamber flows into the main chamber.
- Spatial ignition initiated by combustion in a pre-chamber remains a forward-looking, evolving technology. It transforms the methods and strategies for initiating and sustaining ignition, as well as the combustion process. It also has the potential to improve the efficiency of spark-ignition engines.
- The use of pre-chamber ignition in spark-ignition engines represents a promising, forward-looking alternative that reduces fuel consumption and, consequently, CO_2 emissions. However, improvements are needed to mitigate the negative effects of pre-chamber ignition, including increased erosion of engine components and increased hydrocarbon emissions.
- Pre-chamber ignition is not a new technology, but there are still significant challenges to be resolved, such as engine operation when cold, engine operation under low load and at low revs, and mixture preparation in the pre-chamber.
- Pre-chamber ignition systems in spark-ignition engines make it possible to extend the engine's operating range to include lean and very lean mixtures, reduce the tendency towards knocking and its severity, as well as increase the combustion rate of the fuel-air mixture and improve the engine's thermal efficiency.
- Differences in pre-chamber volume, fuel supply and ignition strategies, and channel configuration lead to a variety of combustion systems within the pre-chamber. These offer similar advantages but are adapted and optimized for the combustion of different fuels fed into the main chamber, which vary in composition and in the preparation of the combustible charge for ignition.

Nomenclature

DI	direct injection
EGR	exhaust gas recirculation
GDI	gasoline direct injection
ICE	internal combustion engine
PFI	port fuel injection
SI	spark ignition
TDC	top dead center
TJI	Turbulernt Jet Ignition
UHC	unburned hydrocarbons
VVT	variable valve timing
WOT	wide open throttle

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