An Ultra-Lean Premixed Compression-Ignition Engine Concept and its Characteristics

Masahiro Furutani, Yasuhiko Ohta, Masaaki Kono, Mamoru Hasegawa
Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan

Abstract

Premixed compression ignition of lean mixtures has allowed us to overcome the lean flammability limit of spark-ignition engines. The purpose of this paper is to propose a novel concept of “Ultra-lean Premixed Compression-Ignition Operation”, and to describe the engine characteristics. To realize the engine operation, autoignition timing should be controlled. A combination of two different fuels enables us to control the autoignition timing. A low-octane liquid fuel is injected into a homogeneous high-octane gaseous fuel/aer mixture just before the intake valve. For an operating condition of speed and load an optimal combination of fuel amounts can be found, i.e. the optimal octane value of the total charge and the optimal total amount of fuels can be selected separately. Drastic reduction of soot and NOx emissions are accomplished, as well as a lower fuel consumption compared to those of conventional engines. The more octane-number difference exists between high- and low-octane fuels, the more torque can be obtained. However, some amount of high-octane fuel might not participate in the engine operation due to its poor self-ignition tendency, which results in a lower hydrocarbon or exhaust emission than a spark-ignition operation. The multi-fuel ability is another characteristic of this engine. Hydrogen can be used as a high-octane fuel along with this concept, but the power output is insufficient compared to the case used the propane as a high-octane fuel. Temperature measurement using thermal-inertia-compensated fine thermocouples shows that the low NOx emission concentration is mainly owing to the hot flame temperature lower than the popular propagating flames or diesel-engine flames.

1. Proposing Concept

A novel concept “Ultra-lean Premixed Compression-Ignition Operation” (1, 2) proposed by the present authors has several promising characteristics, such as lower NOx emission, high efficiency and multi-fuel capability. Premixed compression ignition is an only method to overcome the lean flammability limit of premixed spark ignition engines. Ignition timing, however, will be kept away from artificial control. Autoignition timing should always be controlled in the real engines. Amount of intake air is fixed because of no throttle valve in this concept as shown in Fig. 1. Fuels are the only control measures. A combination of two different-octane fuels enables us most easily to control the autoignition timing. A low-octane liquid fuel is injected into a homogeneous high-octane gaseous fuel/aer mixture just before the intake valve. For an operating condition of speed and load an optimal combination of fuel amounts can be found, i.e. the optimal octane value of the total charge and the optimal total amount of fuels can be selected separately.

2. Confirmation Experiments

The schematic of experimental apparatus is shown in Fig. 2. A single cylinder diesel, Yanmar L60ADD, 4 stroke, air cooled, 273 cm3 displacement volume, was used to confirm the proposed concept. The combustion chamber was simplified to a pancake type. The compression ratio ε is 14.3. A pressure transducer, a quartz window for luminescence, and a fine-wire thermocouple probe for gas temperature were installed on the cylinder head. A spark plug could be also equipped to carry out spark-ignition operations which gave us reference engine performances to be compared to the premixed compression-ignition data. The engine was connected to an AC dynamometer to absorb the engine power output as well as to enable motoring operations without a break.

Fig. 1 Lean premixed compression-ignition-engine concept Procedure required for ignition timing and output torque controls
The engine speed is 600 r.p.m. Cylinder-head temperature is fixed at 80 °C.

A high-octane gaseous fuel and a low-octane liquid fuel are used to establish an ultra-lean premixed compression-ignition operation. A gaseous fuel is introduced continuously upstream of the intake manifold for making a homogeneous lean mixture. A liquid fuel is supplied by an electronic fuel injector, which is installed downstream of the intake manifold. The injection timing of liquid fuels is fixed during the intake stroke at the 25 degrees after the TDC. Propane (RON: 112), n-pentane (RON: 62) or hydrogen is the high-octane fuel.

n-Heptane (RON: 0) or n-hexane (RON: 25) is prepared as the low-octane fuel.

Cool-flame appearance and hot-flame ignition are recognized by the light-emission detection using a photomultiplier tube (Hamamatsu Photonics: R5600-03) through a blue glass filter (Toshiba: V-42).

The tail-pipe exhaust emissions, carbon monoxide, hydrocarbon and the nitric oxides, are measured with a CO-HC, and a NOx analyzer. More detailed exhaust gas composition is analyzed with a gas chromatograph (Shimadzu: GC-4BP) having a TCD and a FID detector. Temperature of in-cylinder charges is measured using a 12.5 μm K-type fine-wire thermocouples, where the thermal inertia is compensated, though the compensation is not large.

3. Results and Discussion

Ultra-Lean Burn Engine

Leaner mixture ignitions can be obtained only by the piston compression of the mixtures even than the normal flammable limit. Hot-flame onset was observed up to the equivalence ratio 0.1 in a rapid compression machine when the mixture is n-butane/O2/Ar (3). Compression-ignition histories of pressure and blue-light emission are shown in Fig. 3 for a nearly lean-limit of n-heptane ignition. This case is also beyond the normal flammable limit of n-heptane. In the figure, pressure development swings upwards and blue-light emission traces downwards. Hot-flame pressure-rise rate is mild compared to stoichiometric spark knocking or diesel ignition. The first blue-light emission is a proof of cool flame appearance; the blue luminescence will degenerate once and a little while. Following strong luminescence is due to the hot flame generation. In this case, the net power output could not be obtained though the hot flame is established, because the ignition timing is not adequate, located ahead from TDC; no ignition-timing control procedure is introduced. If the overall octave number of the charge can be adjusted, an adequate ignition timing will be given.

Typical example of "controlled" ultra-lean premixed compression-ignition operation is shown in Fig. 4. The high-octane gaseous fuel is propane and the low-octane liquid fuel n-heptane. Adequate fuel amount combinations forced the hot-flame onsets to appear near the TDC, though the engine output torque varies. Engine operation in a wide range of output can be available by this procedure. The countermeasure to meet the required torque is adjusting the total amount of both fuels. When a higher torque is required, fuel amount must be increased. The same ratio between both fuels will result in the hot flame appearance earlier than TDC, and reduced thermal efficiency. The ratio of high-octane fuel must be raised at same time as increasing the total amount of fuels.

Figure 5 shows the relation between equivalence ratio and indicated mean effective pressure obtained in the propane/n-heptane premixed-compression-ignition operation, compared to the conventional propane spark-ignition operation.
The premixed compression-ignition operation can be available as low as the equivalence ratio 0.2. The indicated mean effective pressure for the premixed compression-ignition operation is higher than the extrapolated value of spark-ignition operation, which indicates higher thermal efficiencies.

Higher Hydrocarbon Exhaust Emission
An important drawback of the premixed compression-ignition operation is the high hydrocarbon emission tendency; thousands ppm order of magnitude. Carbon monoxide and total hydrocarbon included in the exhaust gases are shown in Fig. 6. Carbon monoxide decreases as the equivalence ratio increases, on the other hand, no dependence on equivalence ratio for the total hydrocarbon emission. Exhaust hydrocarbon species were specified by gas chromatography and are shown in Fig. 7. The sampled conditions are indicated by the characters A, B, C and D in Fig. 5. The equivalence ratio of n-heptane/air is 0.23 at A, B and C, and that of propane/air is 0.19 at A, 0.12 at B, and 0.10 at C. At condition D, the equivalence ratio of n-heptane related is 0.28, propane related 0.05. The total amount of fuel are same between conditions C and D. The highest hydrocarbon emission is the propane exhausted at conditions A, B and C. Hydrocarbon emission of the premixed compression-ignition operation originates in the misfire of high-octane fuel. Propane itself does not ignite under the present compression ratio (ε = 14.3) and propane related equivalence ratio. The octane number of pentane is lower than that of propane. The high-octane fuel was changed to pentane from propane, and the low-octane fuel hexane. But, this fuel combination made the stable operation difficult. An available operation was only at the equivalence ratio 0.29 and octane number 50.

The tail-pipe emission of the hydrocarbon and the carbon monoxide are plotted in Fig. 6. Comparing between propane/n-heptane and pentane/hexane cases at the same equivalence ratio, the amount of total hydrocarbon of pentane/hexane case is reduced to 60% of propane/n-heptane case. It can be presumed that some amount of high-octane fuel might not participate in burning due to its poor self-ignition nature, which results in a higher hydrocarbon exhaust emission than a spark-ignition operation.

It is necessary to use a high-octane fuel as high as possible and a low-octane fuel as low as possible to obtain a wide range of engine operation. The more octane-number difference exists between high- and low-octane fuels, wider operation range and higher torque can be obtained. However, higher octane character will result in the higher hydrocarbon exhaust emission.

Fig. 5  Operating range and power output of propane/n-heptane premixed compression-ignition operation

Fig. 6  CO and HC exhaust emissions of each fuel combination

Fig. 7  Exhaust species at propane/n-heptane premixed compression-ignition operation

Fig. 8  Premixed compression-ignition operation using hydrogen and n-heptane as fuels
Multi-Fuel Ability

The multi-fuel ability is another advantageous characteristic of this operation. Hydrogen can be used as a high-octane fuel along with this concept as shown in Fig. 8. Pressure-rise rate of the hydrogen fuel is also mild. However, the power output is insufficient compared to the case used the propane as a high-octane fuel. Figure 9 shows this situation. As a matter of course the hydrocarbon emission is reduced as shown in Fig. 6. It is shown here again that the more octane-number difference between high- and low-octane fuels will extend the operation range of the engine under this concept.

Reason of Low NOx Emission Characteristic

Tail-pipe NOx emission of spark-ignition operation with the identical engine configuration became maximum at the nearly stoichiometric mixture strength. Figure 10 demonstrates the low NOx emission characteristic of the lean premixed compression-ignition operation, compared to the spark-ignition operation. Only tens ppm order of magnitude NOx emission can be observed. Drastic reduction of NOx emission is accomplished compared to the conventional engine operations. It can be conjectured that the low NOx emission characteristic might be owing to NOx deoxidization in high hydrocarbon environment. Spatial temperature and concentration inhomogeneity would also be a contributor for low-NOx characteristic. No procedure to dispel these suspicions.

Temperature of the charge and its combustion products in the cylinder was measured using a thermal-inertia-compensated fine thermocouple. Figure 11 shows an example result associated with pressure histories. Fuel used is the typical primary reference fuel; the ratio of two fuels is fixed and the equivalence ratio only is changed, which results in no ignition-timing control. The highest temperature appeared was 1500 K under the equivalence ratio 0.35. A combustion under no NOx-generation-relating temperature is carried out in the lean premixed compression-ignition operation; which reminds us that the normal NOx frozen temperature would be about 1700 K.

It can be easily elucidated that the low NOx emission concentration of the lean premixed compression-ignition operation is mainly owing to the hot flame temperature lower than the popular propagating flames or diesel-engine flames, even though other contributing factors could not be neglected.

![Fig. 9 Operating range and power output of hydrogen/n-heptane premixed compression-ignition operation](image9)

![Fig. 10 Lower nitric oxide emission characteristic of premixed compression-ignition operation compared to the conventional operation](image10)

![Fig. 11 Temperature and pressure profiles of 50-primary reference fuel autoignition (ϕ = 0.25, 0.30, 0.35)](image11)

![Fig. 12 Nitric oxide emission characteristic of premixed compression-ignition operation (wide range of equivalence ratio), half throttle, compression ratio ε = 10.2](image12)
Nitric oxide emission characteristic of compression-ignition operation is measured in a wide range of equivalence ratio, $\phi = 0.25-1.35$ by using the 50-primary reference fuel and is shown in Fig. 12. Because a standard fuel is used, the ignition timing is not optimized. Only for this purpose, the compression ratio $\varepsilon$ was lowered to 10.2 and the throttle was set to be half to decrease the induced air, for fear the engine will be damaged by the severe knocking when the stoichiometric mixture was supplied. By adopting the compression-ignition operations nitric oxide emission can be reduced to less than 100 ppm when the mixture was set leaner than the equivalence ratio $\phi = 0.6$.

4. Concluding Remarks

A novel concept of “Ultra-lean Premixed Compression-Ignition Engine Operation” and its advantages will be summarized as the follows:

- A new engine concept is proposed
- Found out the ultimate lean operation limit of IC engines
- Realized ultra lean operation beyond present lean-burn SI engines
- Utilized preferable characteristic of compression ignition
- Higher thermal efficiency, more fuel economy
- Drastic reducing NOx emission
- NOx-free temperature combustion
- Multi-fuel operation capability
- Providing a replacement of conventional diesel engines
- Ability to set the burning air/fuel ratio lean artificially
  - Better than diesel
- No throttle; reduced pumping loss

To realize the engine operation, autoignition timing should be controlled, and two different-octane fuels should be used to control the auto-ignition timing at the present time. Another disadvantage is high hydrocarbon emission. No secondary fuel, i.e. another ignition promoter or new stimulus, and the pressure-rise-rate control at heavy duty condition would be the near-future subjects.

References

