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Experimental Study on Comparison of Flame Propagation Velocity for the Performance Improvement of Natural Gas Engine

Jin Do Chung and Dong Soo Jeong*
Dept. of Environmental Eng., Hoseo University, Asan 336-795, Korea
**Korea Institute of Machinery & Materials, Daejeon 305-343, Korea*
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Natural gas possesses several characteristics that make it desirable as an engine fuel ; 1)lower production cost, 2)abundant commodity and 3)cleaner energy source than gasoline.
Due to the physics characteristics of natural gas, the volumetric efficiency and flame speed of a natural gas engine are lower than those of a gasoline engine, which results in a power loss of 10-20% when compared to a normal gasoline engine.

This paper describes the results of a research to improve the performance of a natural gas engine through the modification and controls of compression ratio, air/fuel ratio, spark advance and supercharging and method of measuring flame propagation velocity. It emphasizes how to improve the power characteristics of a natural gas engine. Combustion characteristics are also studied using an ion probe. The ion probe is applied to measure flame speed of gasoline and methane fuels to confirm the performance improvement of natural gas engine combustion characteristics.

Key Words : Engine performance, Flame propagation, Velocity, Ion Current, Supercharging effect

1. Introduction

Modern society is suffering from are pollutions which is the by-product of fast industrial development. As the large part of air pollutions are from vehicles using petroleum based fuels, it is urgent to develop alternative fuel engines with lower exhaust emissions in a viewpoint of environmental protection. Natural gas engine is now one of best candidates being developed as alternative fuel engines.

Natural gas engine converted from gasoline engine shows the power decrease of 15-20% in a condition of wide open throttle when compared to original gasoline engine. One reason of this power decrease is that the volumetric efficiency of gaseous fuel is lower than that of liquid fuel. The other reason is that the flame speed of methane air mixture is lower than that of gasoline-air mixture by Karim and Ali[1], Baets[2], Perry et al[3].

Thermal losses are higher in natural gas engine than in gasoline engine because of lower flame speed in gasoline engine. These losses are especially higher for lean methane-air mixture because the flame speed of natural gas engine is more sensitive to air-fuel ratio than that of gasoline engine by Bahram[4], Karim and Wierzba[5].

In order to understand the combustion characteristics of natural gas fuel, Karim et al[6]. studied combustion process of a methane fueled engine when employing plasma jet ignition, and Charlton et al[7]. conducted experiments and simulations for lean burn of natural gas engine.

Since the octane number of natural gas is higher than that of gasoline, natural gas is more preferable to be used in higher compression ratio or supercharging (turbocharging) where knocking is a limiting factor. Higher compression ratio, supercharging or spark timing advance are common methods used in natural gas engine to compensate for the power de-

Corresponding Author : Jin Do Chung, Dept. of Environmental Eng., Hoseo University, Asan 336-795, Korea
Phone: +82-41-540-5743
E-mail: jdchung@office.hoseo.ac.kr

crease coming from the use of gaseous fuel.

The flame propagation velocity has been defined as the velocity of the unburned gases through the combustion wave in the direction normal to the wave surface. Various measurement techniques for this quantity have been developed. Some common techniques are briefly discussed below. For more detailed information on techniques for measuring the speed and structure of flames, is referred by researchers, Glassman, Gaydon and Wolfhard, Beer and Chiger, and Kanury[8].

There are five basic type of experiments to measure flame propagation velocities. These are (1) the Bunsen-burner method, (2) the transparent-tube method, (3) the constant-volume bomb method (4) the high speed camera method, and (5) Laser doppler velocimeter method.

This study employs supercharging to boost the power output of natural gas engine to the level of the corresponding gasoline engine. The effect of air fuel ratio on engine performance is also studied for various fuels. To comparatively study combustion characteristics of natural gas engine, the flame speed of both fuels is measured using ion current method which utilizes the electrical nature of flame.

2. Combustion of Methane and Ion in The Flame

From the chemical reaction of methane, CH_4 and O_2, the combustion of methane is defined as follows;

$$CH_4 + O_2 \rightarrow CH_3 + H_2O_2 \quad (1)$$

The fuel with structural formulas of Cm-Hn undergo chain reactions in the flame region and produces OH.

$$CH_4 + OH \rightarrow CH_3 + H_2O \quad (2)$$

When the gases in the premixed flame(or diffusion flame) region are under thermal equilibrium state in the combustion of hydro-carbon based fuel, it is well known that the concentration of ions in the region are much higher than the expected value.

In the region of flame, ions mainly produced by chemical ionization usually positive and negative ion produced.

Equation (3) developed that positive ions become as following equation (3) was-tested analysed, Deckers et al.[9].

$$CH + O \rightarrow CHO^+ + e \quad (3)$$

$$CHO + H_2O \rightarrow H_3O^+ + CO \quad (4)$$

$$H_3O^+ + K \rightarrow K^+ + H_2O + H \quad (5)$$

Knewstubb et al.[10] suggested that C_3H_3+ ion production process.

$$C_2H_2 + CH^+ \rightarrow C_3H_3^+ + e^- \quad (6)$$

And, Fontijn et al.[11] developed using mass analysis that negative ions exist O^-, OH^-, C_2^-, C_2H^-, O_2^-, CNO^-, NO_2^-, C_2H^-, C_3HO^-, and $HCNO_2^-$, in the flame of $C_2H_2^-/O_2$.

The example of negative ion is following.

$$CH + HO_2 \rightarrow CHO^+ + OH^- \quad (7)$$

But generally negative ion is nearby reaction zone of flame. Therefore most of the negative ion is produced another medium instead of reaction. Positive ion in the flame is H_3O^+, $C_3H_3^+$, CHO^+. Among these, H_3O^+ in the flame of hydrocarbon exists extremely high.

3. Experimental Apparatus and Methods

3.1. Engine Performance Test

Specifications of an engine used in engine performance test are shown in Table 1. Fig. 1 shows the

Table 1. Engine Specifications

Engine Type	4cyl., Water Cooled.
Compression Ratio	9.5 : 1
Displacement(cc)	1468
Bore x Stroke(mm)	75.582
Max. Output(ps/rpm)	68/5000
Max. Torque(kg-m/rpm)	10.67/2500

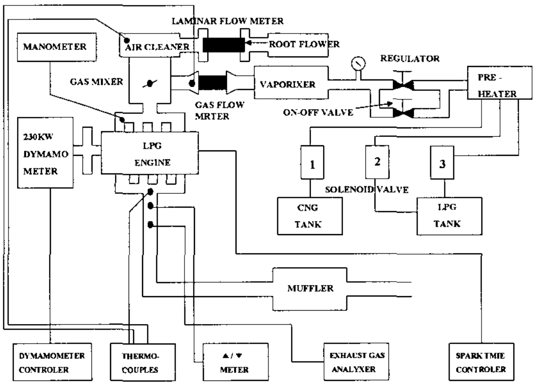

Fig. 1. Engine test apparatus.

Table 2. Experimental Apparatus

	Measuring Item	Model
Dynamometer	Torque, rpm Spark Advance, Cooling Water Temp. Air & Fuel Flow-Rate etc.	230kw, Eddy Current Type
A/F Ratio Meter	Excess Air Ratio	Lamdscan, Cussons
Gas Flow Meter	Methane Flow Rate	Digital Mass Flow Meter, Japan.
Supercharger	-	Root Blow Type, Korea

Table 3. Test Matrix

Compression Ratio	9 : 1
Engine Speed(rpm)	1500, 2000, 2500, 3000, 3500
Throttle Opening	WOT
Excess Air Ratio	0.8, 1.0, 1.2
Spark Timing	MBT

Table 4. Specifications of an Engine used for Ion Current Test

Engine Type	1cyl, Air cooled.
Displacement(cc)	433
Compression Ratio	4.5 : 1
Max. Output(ps/rpm)	8.0/1800
Valve Arrangement	L-head camshaft
Length of Connecting Rod(mm)	133

schematic diagram of engine test set-up. Table 2 explains the experimental apparatus. Test conditions are shown in Table 3.

3.2. Ion Current Test

Table 4 provides the details of the engine used for ion current test. Fig. 2 shows the schematic diagram

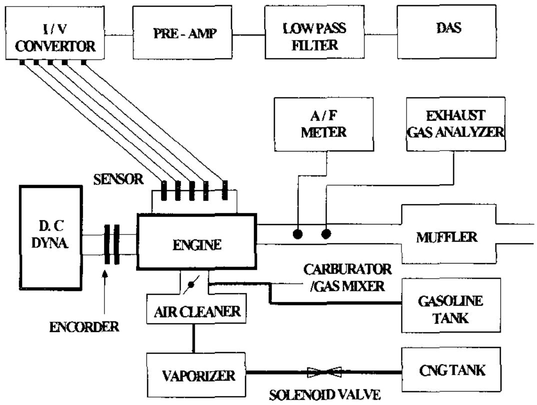

Fig. 2. Schematic diagram of the experimental set up for Ion current.

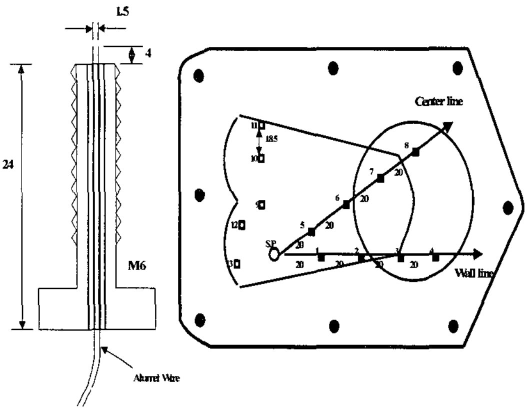

Fig. 3. Configuration & location of ion probe inserted in cylinder head.

of the experimental set-up for ion current measurement. Fig. 3 represents ion probe configuration and ion probe locations on the cylinder head, respectively. Table 5 shows measuring apparatus for ion current. Test conditions are shown in Table 6. It is very important to eliminate a noise signal in measuring a very sensitive ion current signal. Grounding of ion current from measuring system and engine needs to be done delicately. Natural gas, on the other hand,

Table 5. Experimental Apparatus for Ion Current Test

	Measuring Items	Model
Dynamometer	Torque, rpm	Plint
A/F Ratio Meter	Excess Air Ratio	Lamdascan Ⅲ cussons, England
Gas Flow Meter	CNG Flow Rate	Tokyo kiki. Japan
Ion Current Analyzer	Ion Current	Ost R&D, Korea

compositionally is primarily methane with some ethane and propane. The composition of natural gas will vary very widely, depending on the source. The composition of the natural gas used in both engine performance and ion current test, whose compositions are methane 93.0%, ethane 3.7%, propane 1.6%, nitrogen 1.0%, others 0.7%.

3.3. Ion Probe and Data Process

The ion probe for detecting the flame propagation velocity signals of flame lets was nickel-alumel wire of 0.2mm diameter and 4mm long, whose support tube was 6mm outer diameter. The probe was inserted into the combustion chamber in engine through the cylinder head fixed the screw. As the flame front propagated from the center of the combustion chamber and the probe was directed to the center of the chamber, it is not considered that the flame structure would be influenced by such a small probe mechanically. Moreover, as the probe has no externally supplied electric potential, electric influences on the flame structure was avoided.

In order to have exact understanding of the turbulent flames, a probe at 20mm from the spark plug point(which was located at the upper center of the combustion chamber) was used to detect flame signals from the turbulent flame of both fuels, at a turbulence intensity of 9.74m/s. in same type, Chung et al[13].

Since the flame propagation velocity also contains the ignition delay time, it is erroneous to obtain exact mean flame propagation velocity. However, relation flame propagation velocity can be compared between natural gas and gasoline as long as the identical test condition is satisfied. To control the difference of the flame propagation velocity caused by the fluctuation of cycle, mean flame propagation velocity is calculated from the eq. (8) using 9 consecution cycle as follows;

$$\overline{S_f} = \frac{1}{N} \sum_{i=1}^{n} S_{f,i} \qquad (8)$$

N : Number of cycle

i : Order of cycle

S_f : Flame propagation velocity

Table 6. Test Matrix for Ion Current Measurement

	Gasoline	CNG
Compression Ratio	4.5 : 1	4.5 : 1
Engine Speed(rpm)	1000, 1200, 1400, 1600, 1800	
Throttle Opening	WOT	
Excess Air Ratio	1	
Spark Timing	MBT	

4. Results and Discussion

4.1. Variations of Engine Characteristics with Methane and Butane Fuel

Torque and power variations of butane fueled engine for excess air ratio of 0.8, 1.0, 1.2 at wide open throttle and maximum brake torque (MBT) timing is shown in Fig. 4 in terms of engine speed.

Fig. 5 shows torque and power variations of methane fueled engine for same conditions as above. Both figures show that torque at λ=1 is largest. For λ=1.2, power decrease in the higher speed is larger than that

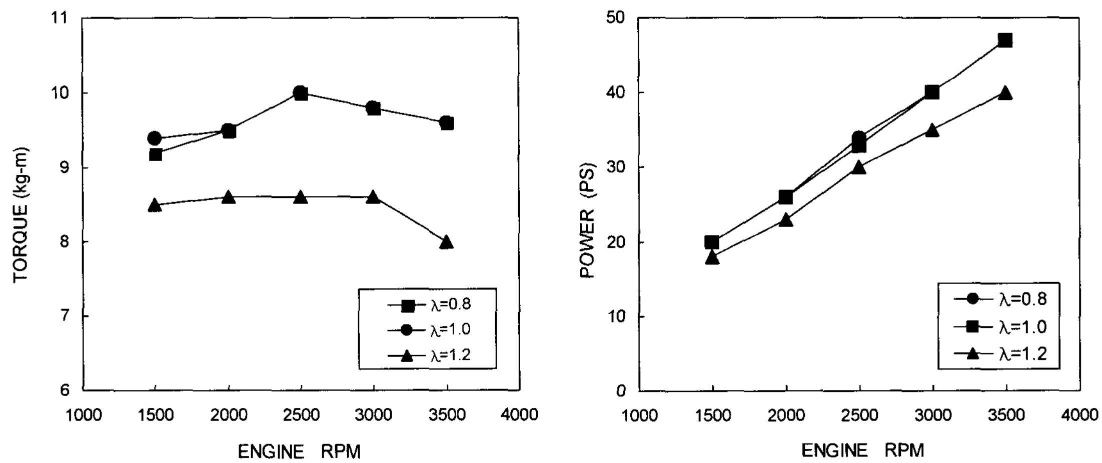

Fig. 4. Torque & Power variation of butane fueled engine for λ=0.8, 1.0 & 1.2.

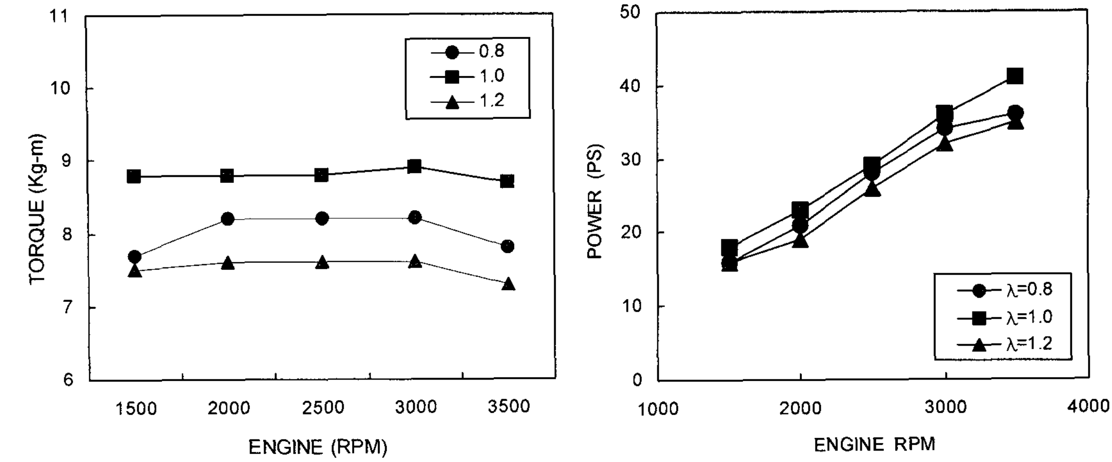

Fig. 5. Torque & power variation of methane fueled engine for λ=0.8, 1.0 & 1.2.

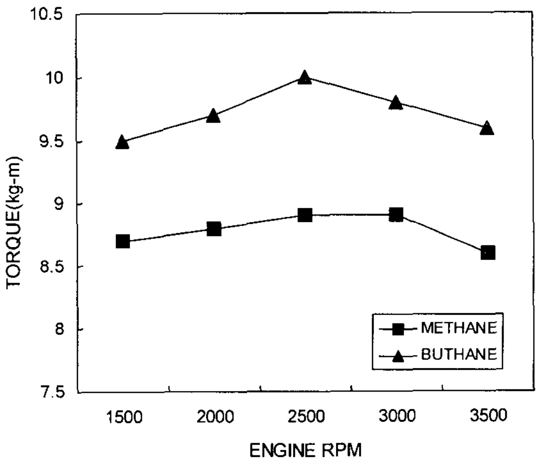

Fig. 6. Torque comparison at λ=1.0.

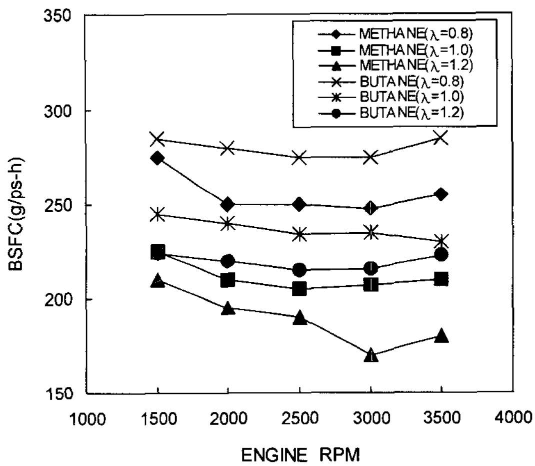

Fig. 7. BSFC Comparison at for λ=0.8, 1.0 & 1.2 for methane and buthane.

in the lower speed.

Fig. 6 shows that the power output of methane fueled engine is about 10% less than butane fueled engine at λ=1.0. This power decrease is due to slower flame speed and lower volumetric efficiency of gaseous fuel. Among the above 10% power decrease, the power decrease due to lower volumetric efficiency, is estimated to be 7.5% and the remainder appears to be due to lower flame speed. It is similar results that previous researcher, Kang et al.[14].

4.2. Brake Specific Fuel Comsumption (BSFC)

The effect of various fuels on BSFC at lof 0.8, 1.0 and 1.2 is shown in Fig. 7 in terms of engine speed. In general, BSFC of methane fuel is 8-13% lower than that of butane fuel. This comes from the difference of the heating value of the fuels (lower heating value : methane; 11954Kcal/kg, butane;10927Kcal/kg)

4.3. Engine Characteristic with Supercharging

Supercharging is commonly used to improve the performance of natural gas engine to the level of corresponding gasoline engine. Fig. 8, shows the effect of supercharging on engine torque, at λ=1. Where, methane+denotes supercharged methane fuel.

Without supercharging, methane fuel shows disadvantage of about 15% power decrease when compared to butane fuel. Supercharging of methane fuel boosts the power to the level of non-supercharging butane fuel. Fig. 9 shows the effect of supercharging on BSFC. Supercharging is proved to improve fuel economy.

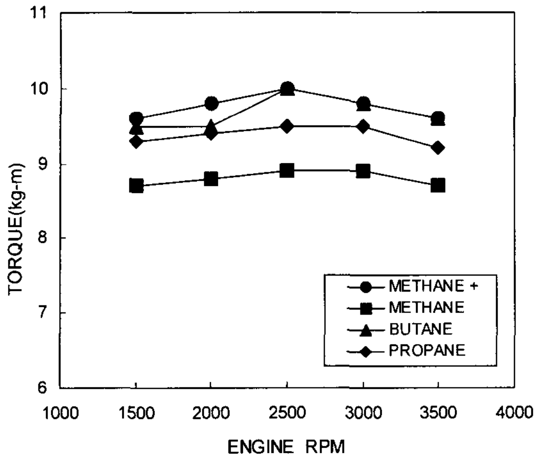

Fig. 8. Torque comparison for various fuels at λ=1.0.

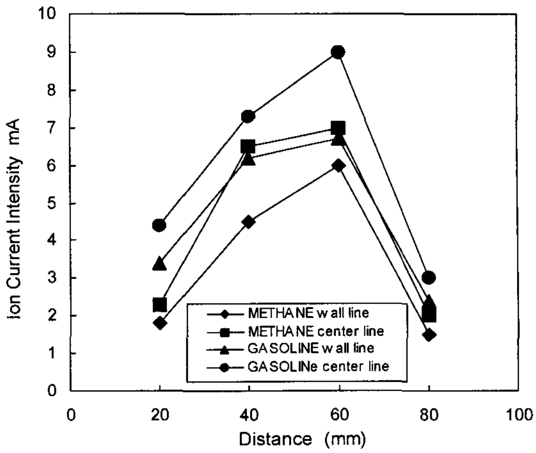

Fig. 10. Relation with ion probe location and ion current variation in comparison of gasoline & methane at λ=1.1.

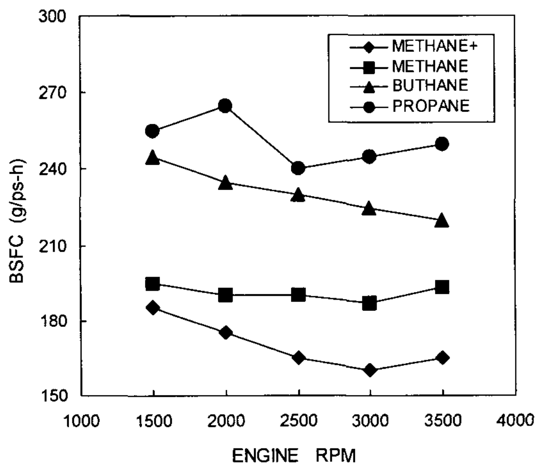

Fig. 9. BSFC comparison for various fuels at λ=1.0.

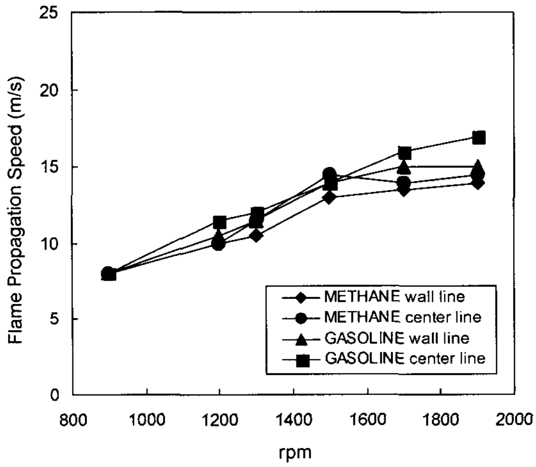

Fig. 11. Relation with flame propagation speed and RPM.

Supercharging is therefore very effective in improving the engine performance and fuel economy of gas fueled engine.

4.4. Ion Current Measurements

The flame speed of methane-air mixtures is known to be slower than that of gasoline air mixtures. In this study, the flame speeds of both fuels in the engine have been measured by using ion probe which utilizes the electrical nature of flame. Fig. 10 shows variations of ion current density as a function of ion probe location for both fuels. Ion density in the vicinity of spark plug is about 35% higher along the center line than along the wall line. It is due to quenching effect by the cylinder wall. The difference of ion current density between gasoline and methane-air mixtures is due to the difference of ionized species in the reaction zone.

Fig. 11 shows the calculated mean flame propagation speed from the ion current measurements for each probe. Under 1200rpm, the flame speed is about the same in both fuels. It shows that results by the Kido and Huang[12]. Over 1300 rpm, the flame speed of gasoline is however a little higher than that of methane. The difference in the higher engine speed is due to the lower flame speed of methane-air mixtures than that of gasoline-air mixtures. However, similar flame speed characteristics in the lower engine speed needs to be studied further

5. Conclusions

Fuel supply system of gasoline engine is converted for the engine to be used for both liquid and gaseous fuels. Supercharging is employed to compensate for the power decrease occurring when using gaseous fuels. The effect of air fuel ratio and supercharging on engine performance is examined for various fuels. The flame speed of both fuels is also measured. This study concludes as follows :

1) The ion current method is adequate to the results of a research to compare the flame propagation velocity between methane gas and gasoline in order to improve the performance of natural gas combustion efficiency. BSFC is lower for methane fuel than for butane fuel due to the larger lower heating value of methane fuel. The power output of the engine is the highest at $\lambda = 1$ for both fuels.
2) The power output of methane fuel is 11-20% lower than that of butane for same conditions. This power decrease is severer in the high engine speed for lean mixtures. Supercharging boosts the power output for methane-air mixtures to the level of butane fuel(10-13% increase). BSFC is slightly better with supercharging. Supercharging is therefore effective method to improve the engine performance when using gaseous fuels.
3) Flame speed of gasoline fuel is higher than that of methane fuel in the high engine speed. Both flame speeds are however about the same in the low engine speed. The thickness of the turbulent flame zone, the separation distance between successive flamelets and the number of flamelets in the flame reaction zone are receiving careful study.

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