1.4G Japan
Combustion Enhancement of Very Lean and Diluted SI Engine Using a Novel Ignition System with Repetitive Pulse Discharges

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Purpose

The decrease in inflammability on the fuel leaner side can cause many problems, such as decreased engine power, deteriorated fuel economy, increased pollutant emissions, and generated noise.
To solve these problems, new enhanced ignition systems have been proposed, for example, plasma jet igniters*1, laser ignition*2, rail plug*3, etc. But there is still more work to be done on commercial use.

***1 Dale, J.D., Oppenheim, A.K., "Enhanced ignition for I.C. engines with premixed gases", Trans. SAE, Paper810146, Vol.90, pp.606-621, (1981).**
***2 Dale, J.D., Smy, P.R., Clements, R.M., "Laser Ignited Internal Combustion Engine – An Experimental Study", SAE Paper No.780329, (1978).**
***3 Hall, M.J., Matthews, R.D., Ezekoye, O.O., "Railplug Ignition Operating Characteristics and Performance: A Review", SAE Paper No.2007011832, (2007).**

In order to improve inflammability, we investigate feasibility of using a newly developed small-sized IES (inductive energy storage) circuit for ignition system.

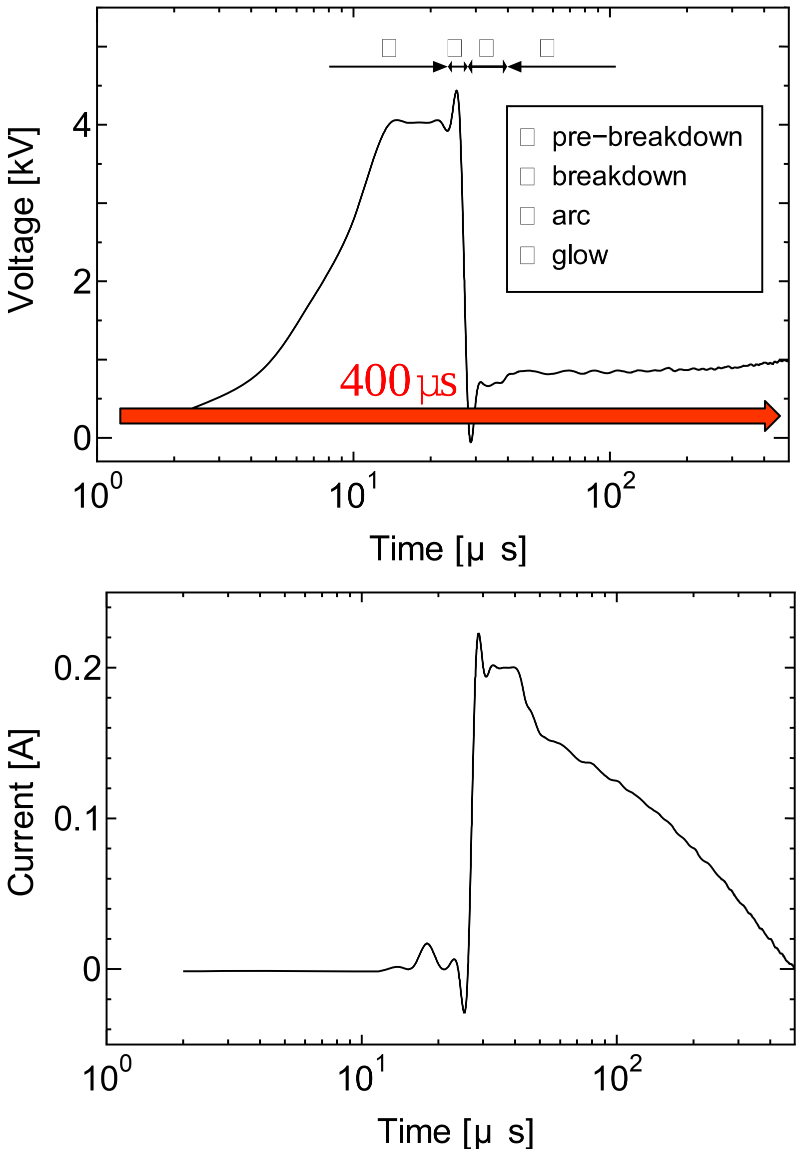
Features of IES circuit

1. The IES circuit can generate repetitive nanosecond pulse discharges, which consists of streamer discharges and arc discharges.

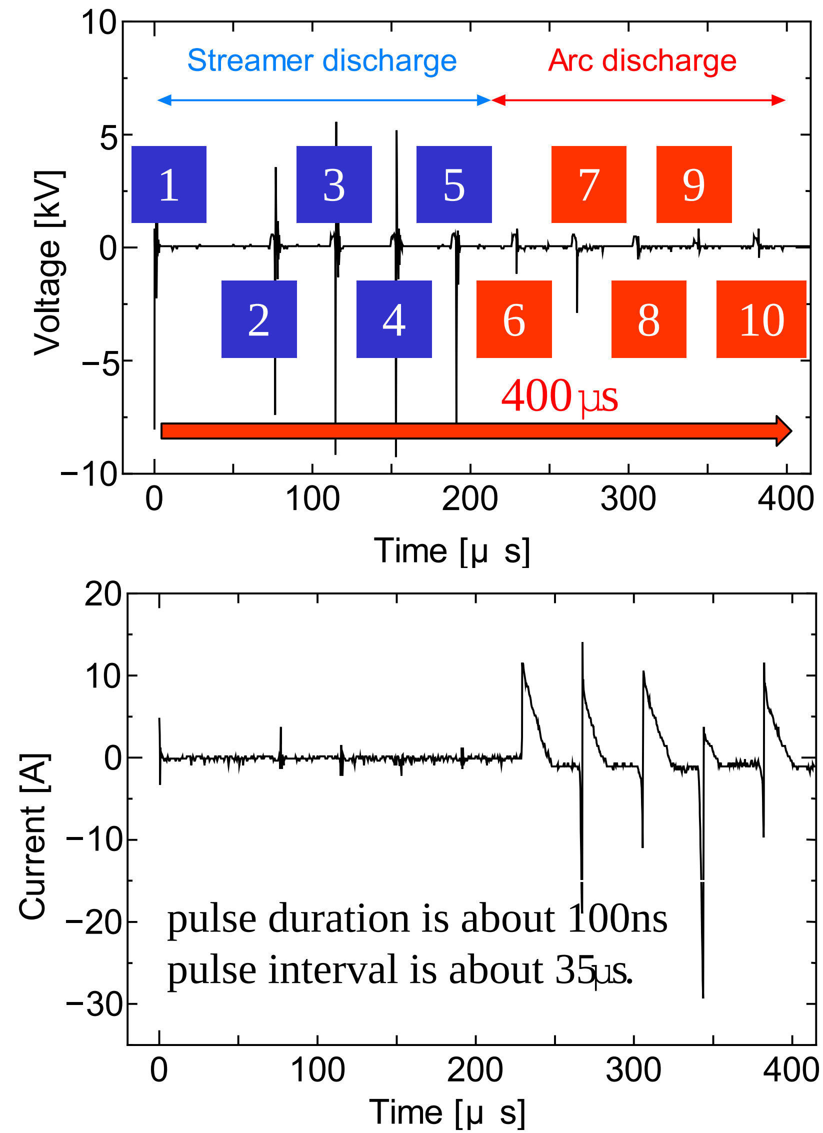
2. This IES circuit can generate the high rise-up voltage (dV/dt) pulses.

3. This IES circuit enables us to change various settings, such as pulse duration, pulse interval, and number of pulses.

4. This circuit can operate with low-voltage power supply as low as car battery.



Conventional ignition system (CIC)



10 pulses of IES circuit (PRD10)

Purpose

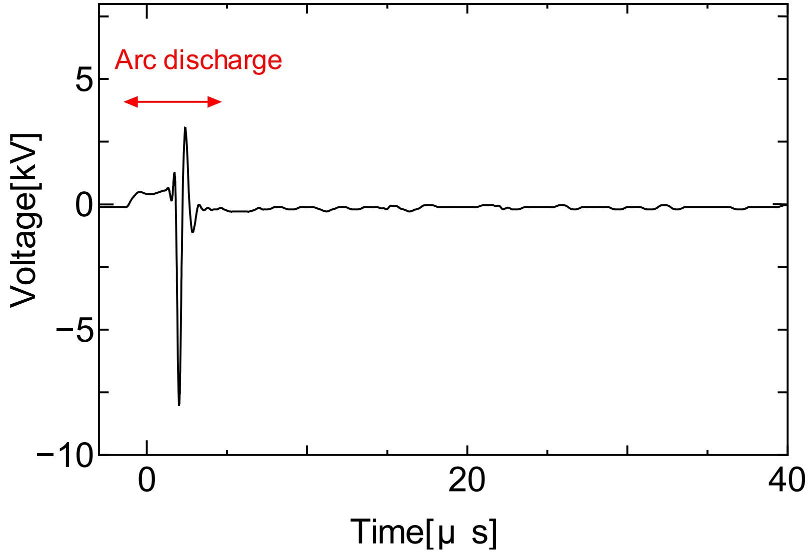
In order to improve inflammability, we investigate feasibility of using a newly developed small-sized IES (inductive energy storage) circuit for ignition system.

In this study, we investigated

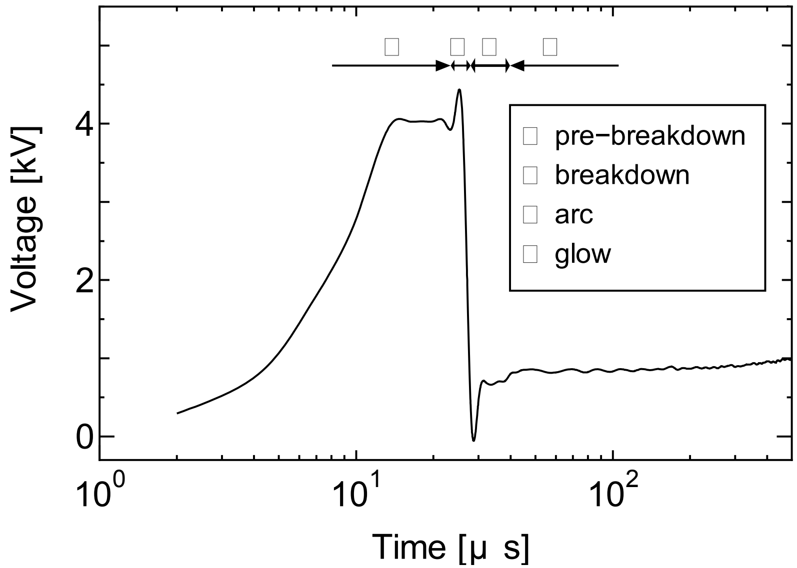
1. basic ignition characteristics of IES circuit, compared with conventional ignition system,
2. improving mechanisms for inflammability by IES circuit,
3. the effect of repetitive pulse discharges on the inflammability
4. Application to a SI (Spark Ignition) engine.

Experiment 1

Investigation of the ignition characteristics of IES circuit (SD1), by comparing it with conventional ignition system (CIC) in terms of single pulse discharge.

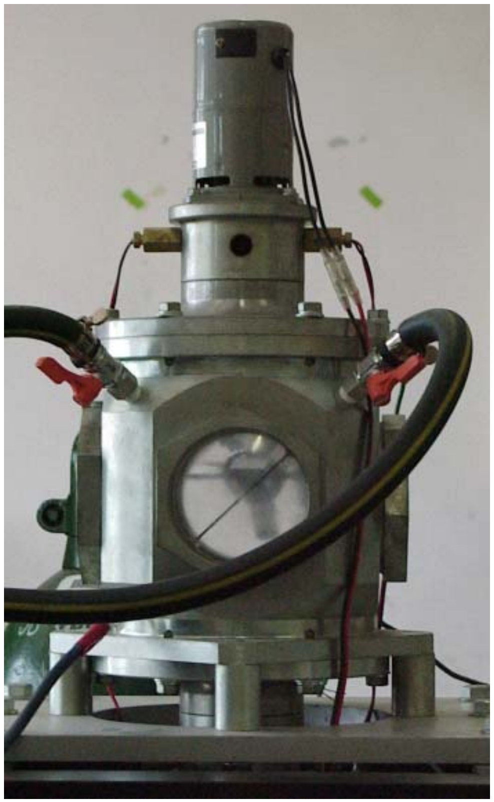


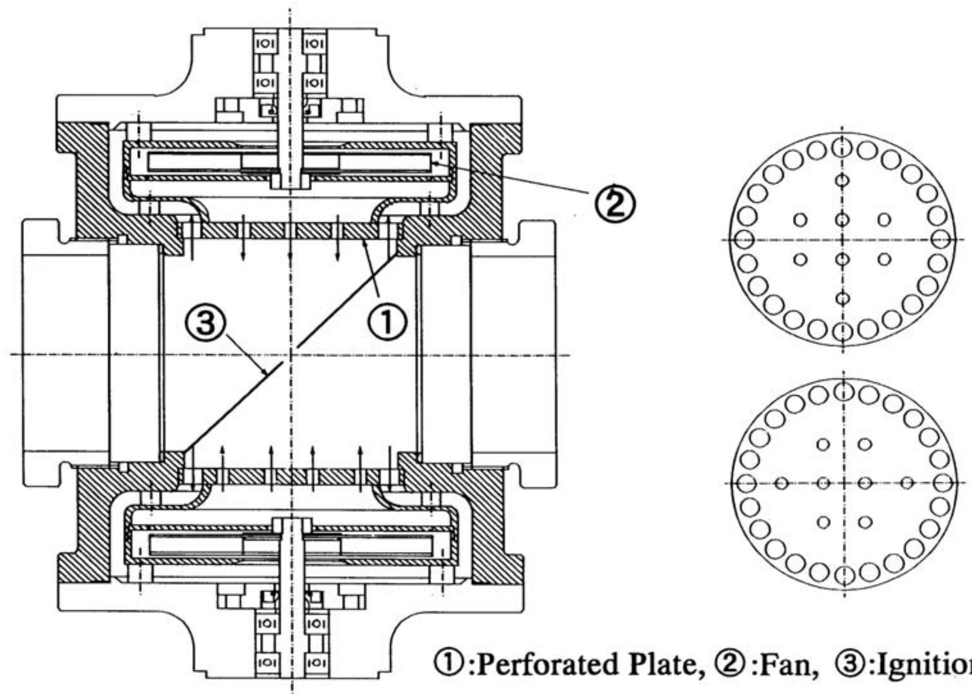
Single pulse of IES circuit (SD1)



Conventional ignition system (CIC)

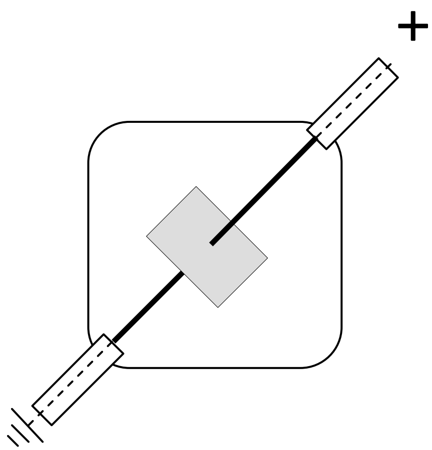
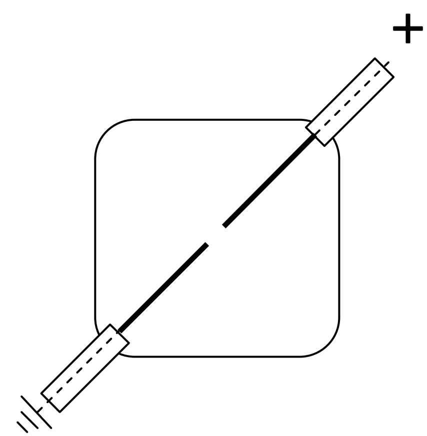
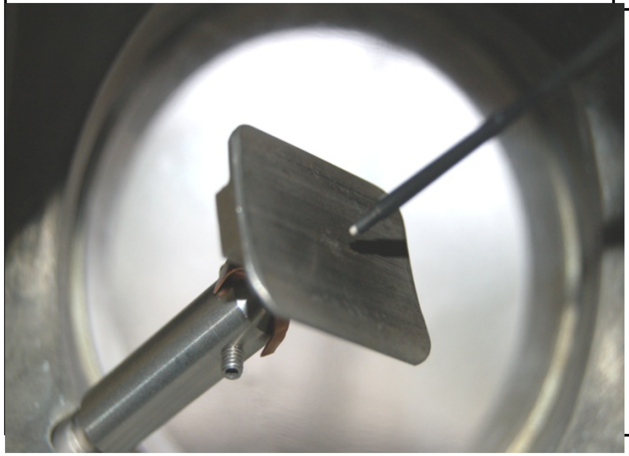
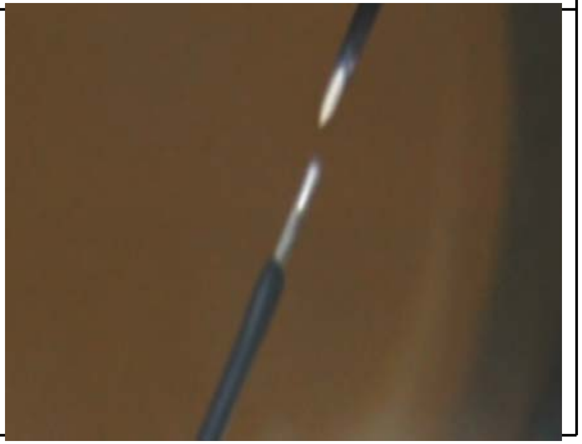
Combustion Chamber





①:Perforated Plate, ②:Fan, ③:Ignition Plug

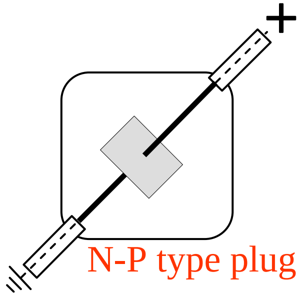
Ignition plug

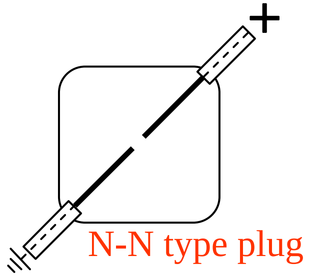
needle-to-plate N-P type	needle-to-needle N-N type
	
	

Experimental procedure

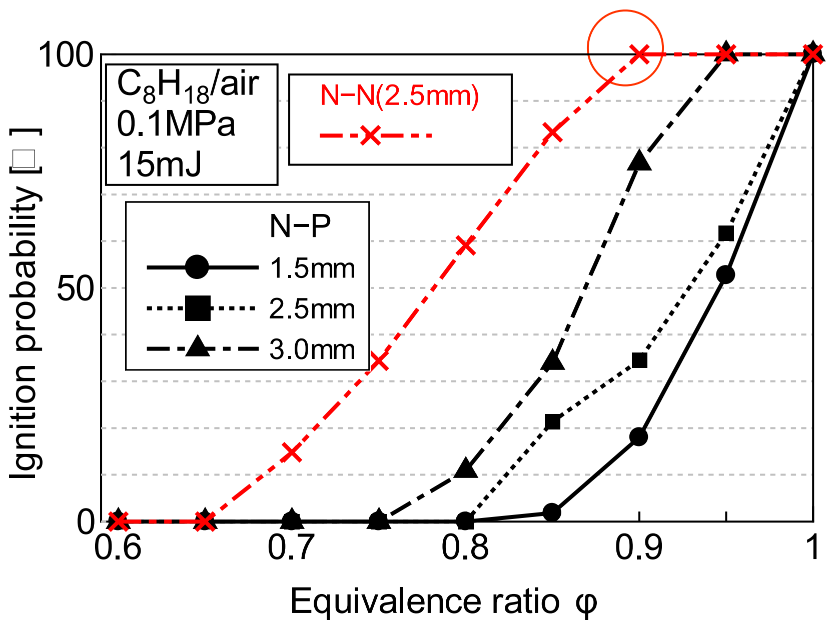
In order to clarify the ignition properties, we investigated the ignition probability, which was defined as the ratio of number of igniting the whole flame to total number of experiments for each condition, and ignition delay time, which was defined as the interval between the ignition current trigger and the time at which the pressure rose to 10% of its maximum pressure.

Experiments were carried out 10 to 100 times for each condition with almost the same ignition energy. The spark gap was set to be 1.5, 2.5 or 3.0 mm for N-P type plug, while 2.5 mm for N-N type plug. The averaged ignition energies supplied were estimated to be about 15 mJ and 20 mJ for SD1 and CIC, respectively.



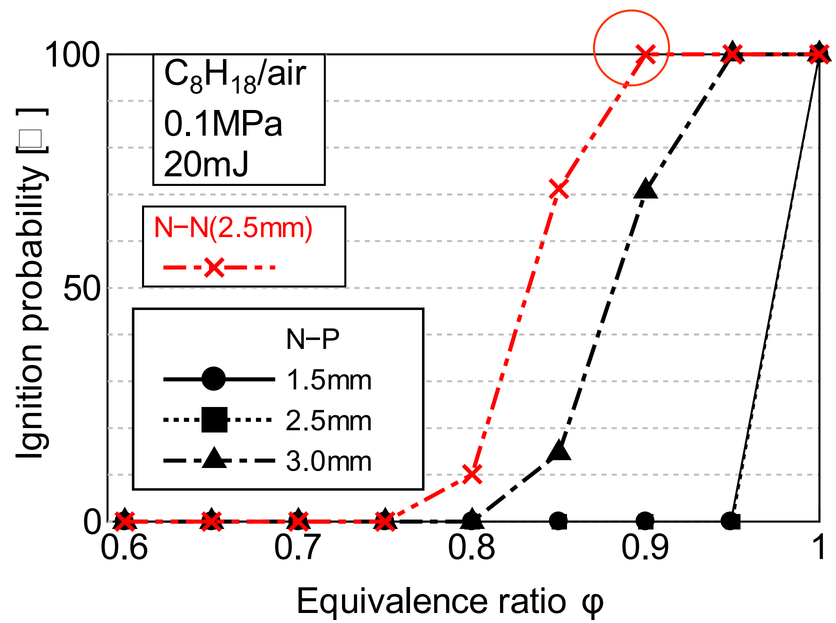


Ignition probability for IES circuit and conventional ignition circuit



Single discharge (SD1) by IES circuit

$\phi_{\text{lim}} = 0.9$



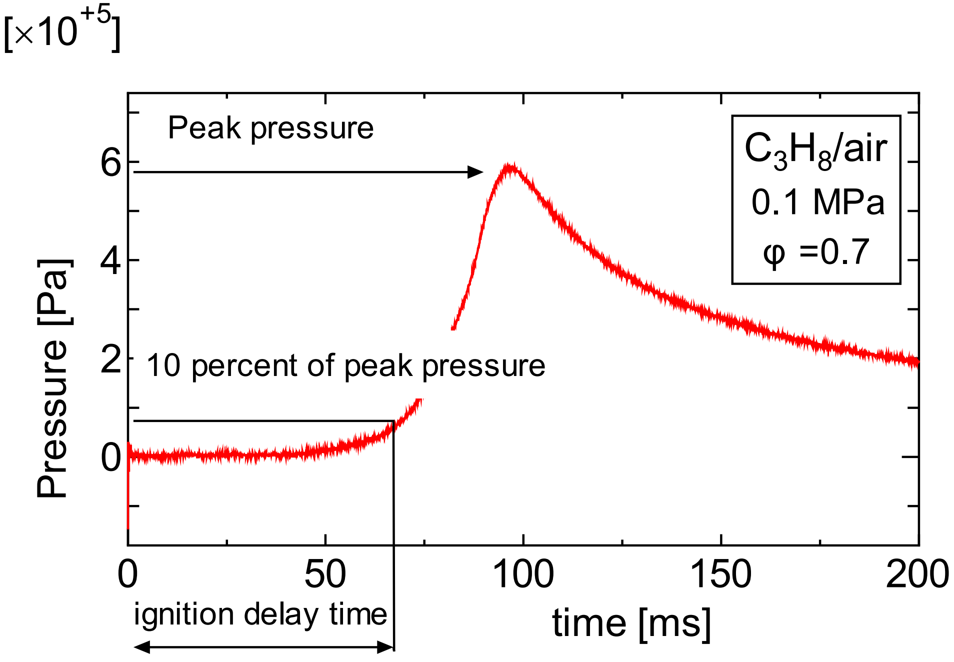
Conventional ignition circuit (CIC)

$\phi_{\text{lim}} = 0.9$

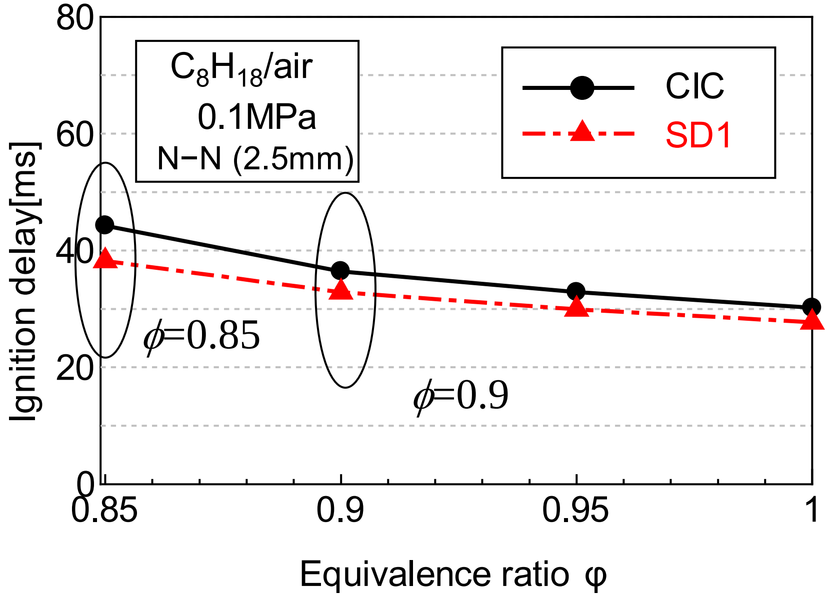
These conclude that single pulse discharge (SD1) produced by IES circuit has better inflammability than conventional ignition system (CIC).

Ignition Delay Time

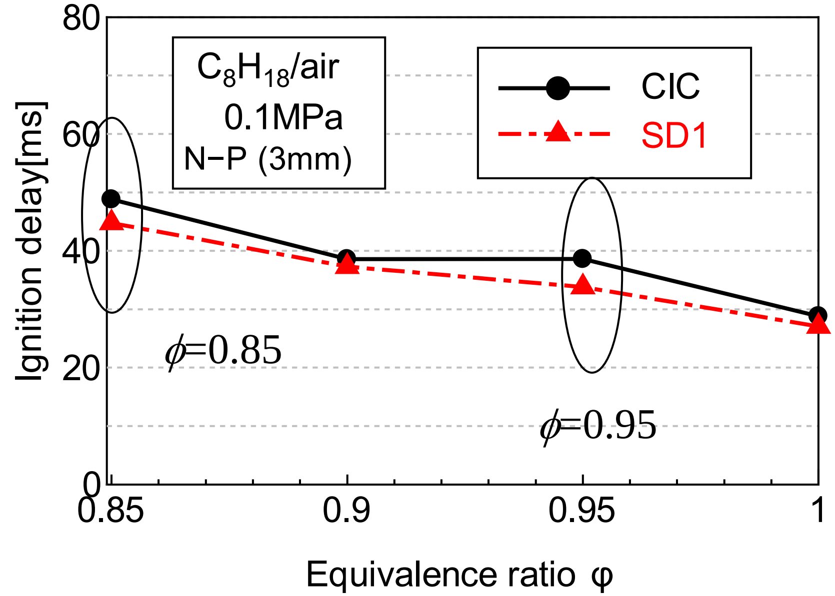
defined as the interval between the ignition current trigger and the time at which the pressure rose to 10% of its maximum pressure.



N-N type plug (2.5mm)



N-P type plug (3mm)



Δt_{ig}= 44ms

Δt_{ig} = 38ms

14% improve

Δt_{ig}= 36ms

Δt_{ig} = 33ms

8% improve

Δt_{ig}= 49ms

Δt_{ig} = 44ms

11% improve

Δt_{ig}= 39ms

Δt_{ig} = 33ms

15% improve

In conclusion, single pulse discharge (SD1) produced by IES circuit can reduce the ignition delay time (that is, improve the initial combustion phase) compare with conventional ignition system (CIC).

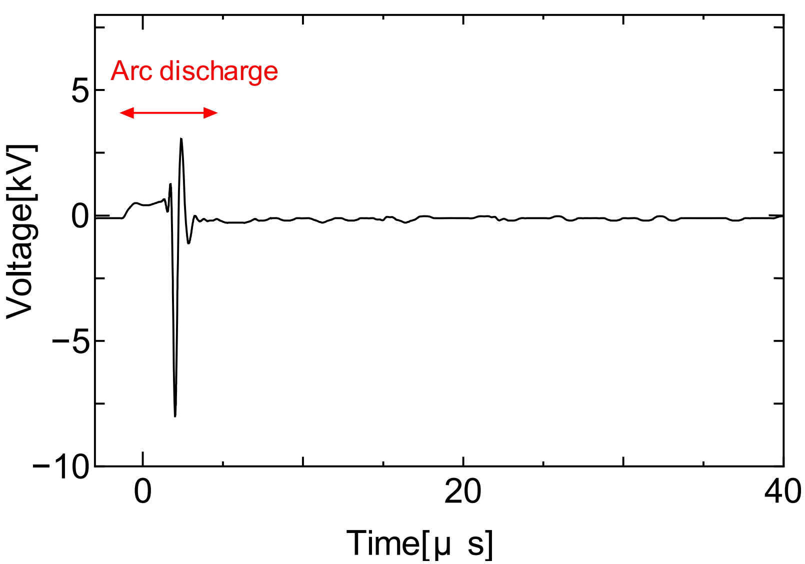
Experiment 2

We investigated the mechanisms for improving the inflammability with IES circuit, compared with conventional ignition system.

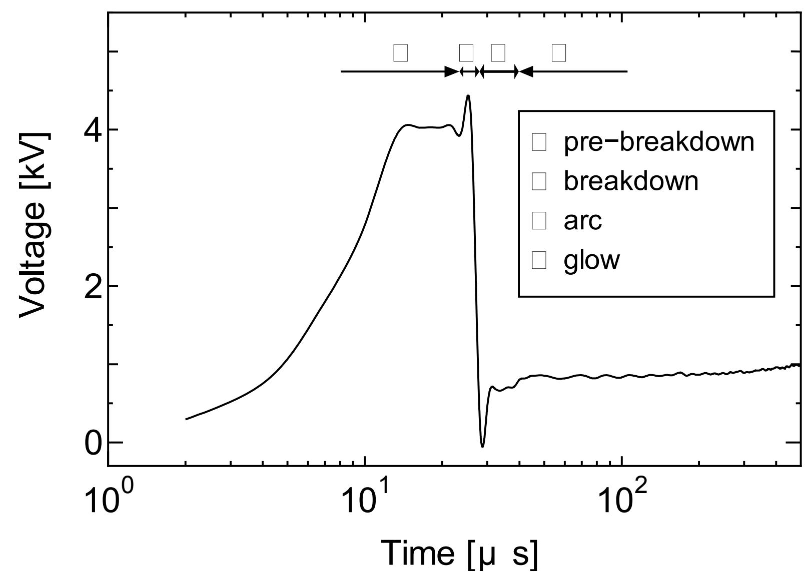
The IES circuit produced by far shorter arc discharge than that produced by the conventional ignition system, meaning that the shorter duration arc discharge can improve the inflammability, although they can supply almost the same energy.

Experimental procedure

The flames were observed using schlieren system with a high speed camera (40,500 pictures per second).

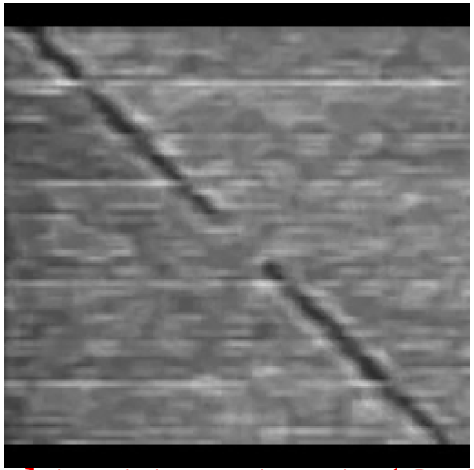


Single pulse of IES circuit (SD1)



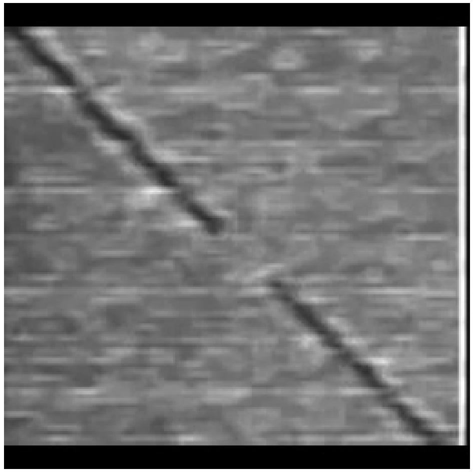
Conventional ignition system (CIC)

Schlieren photographs for C_3H_8-air with ϕ=0.8



Flame kernel is found to develop along the electrode and get a spherical shape.

Conventional ignition circuit (CIC) Total energy: 20mJ

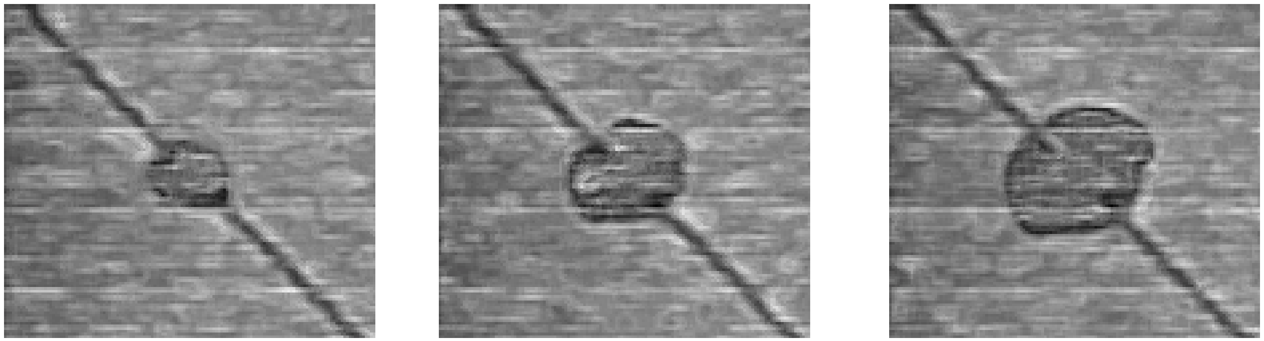


Flame kernel develops into a torus and located far away from electrode

Single discharge (SD1) by IES circuit Total energy: 16mJ

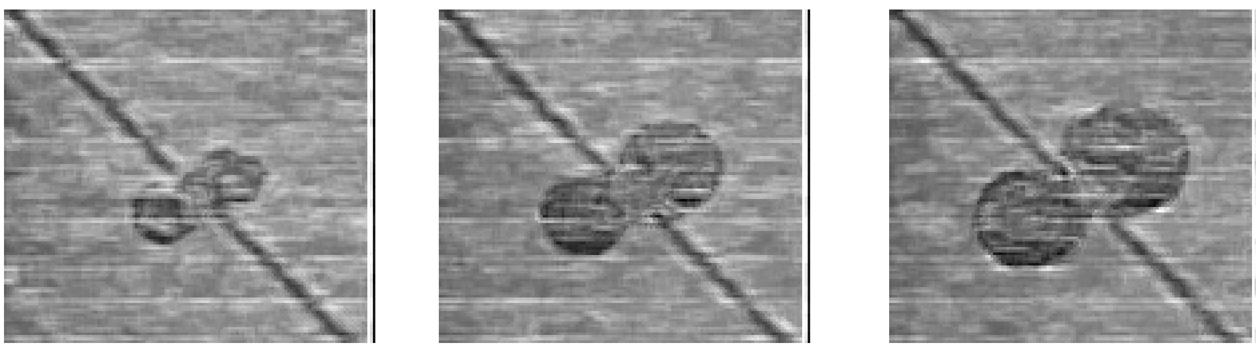
Schlieren photographs for C_3H_8-air with $\phi=0.8$

0.5ms 1.7ms 2.9ms



Flame kernel is found to develop along the electrode and get a spherical shape.

Conventional ignition circuit (CIC) Total energy: 20mJ



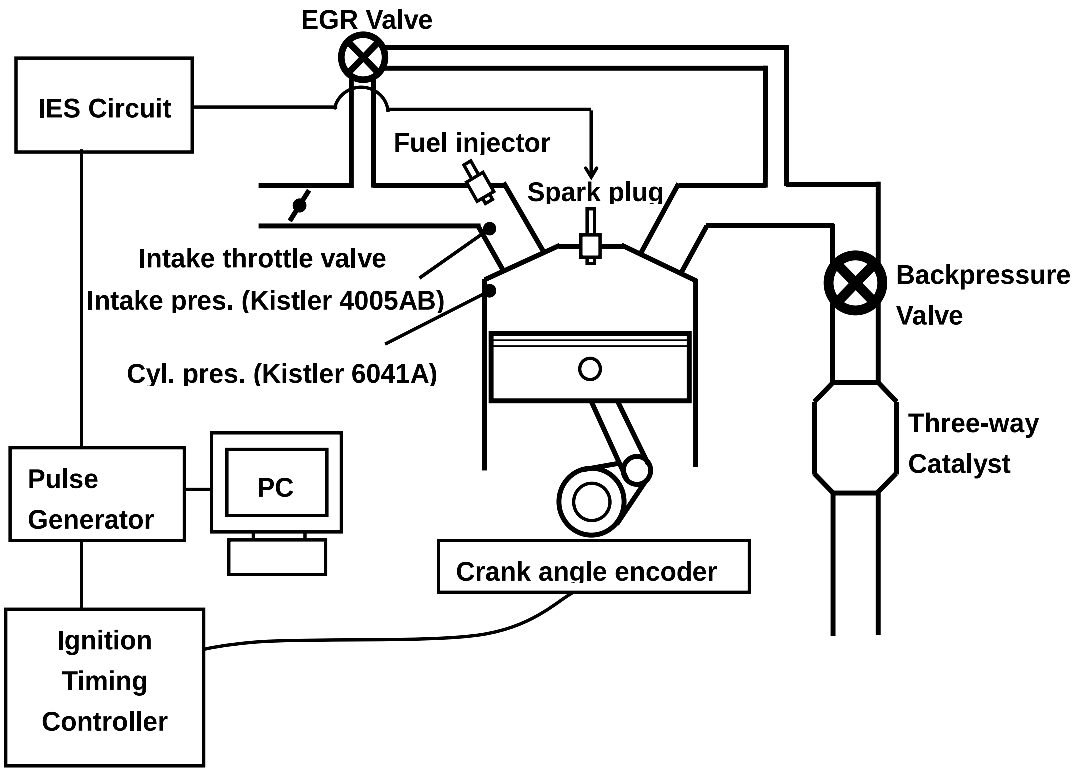
Flame kernel develops into a torus and located far away from electrode

Single discharge (SD1) by IES circuit Total energy: 16mJ

Experiment 3

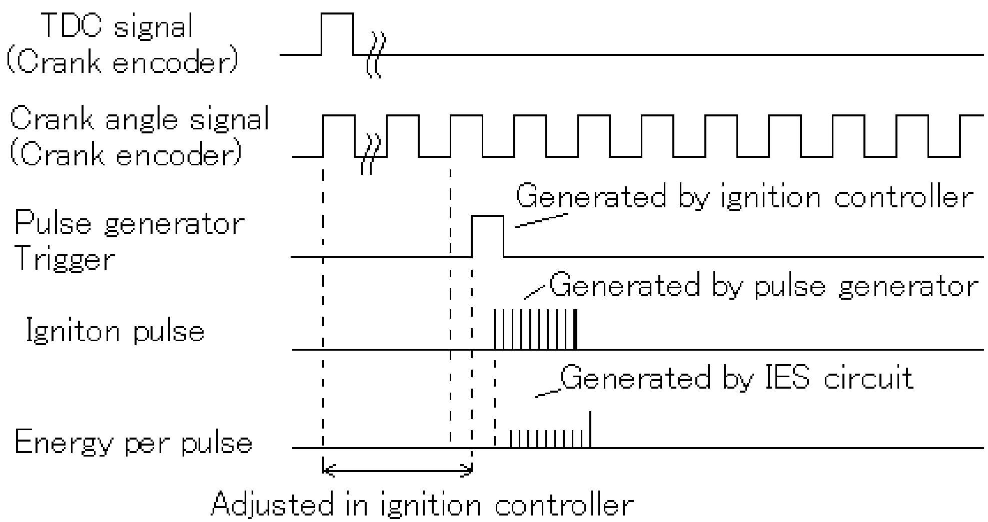
This ignition system was applied for a single-cylinder gasoline engine. The extension limit of lean combustion and EGR dilution combustion and using this system was examined.

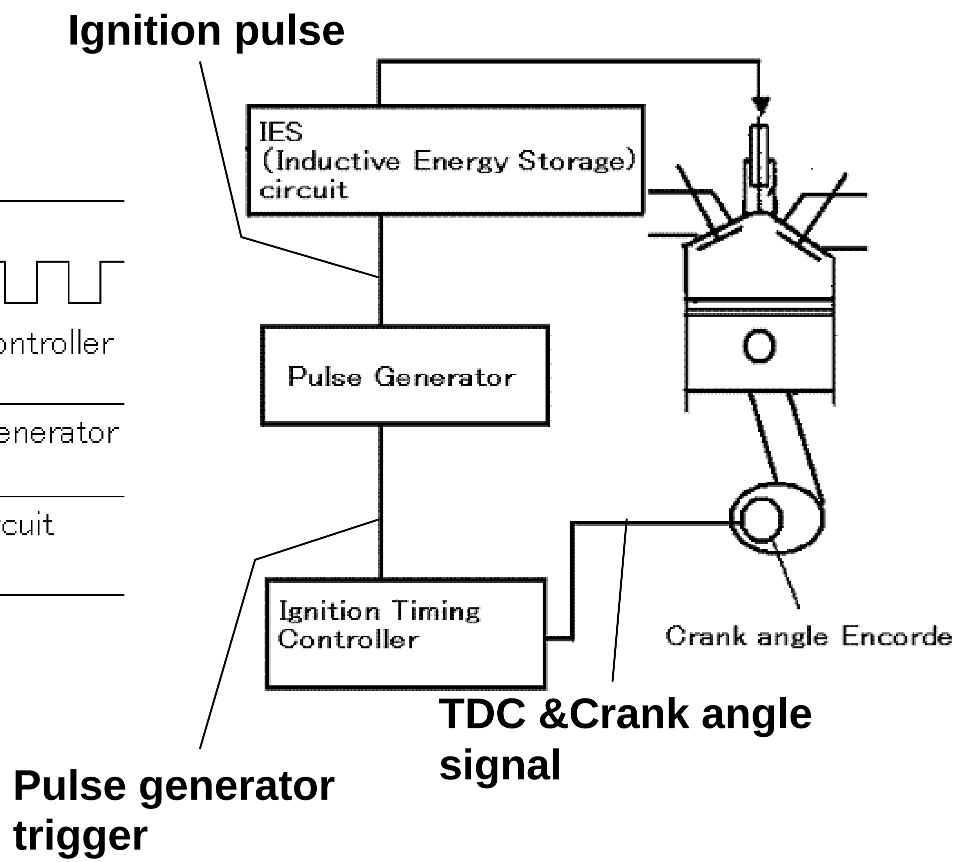
Experimental Apparatus



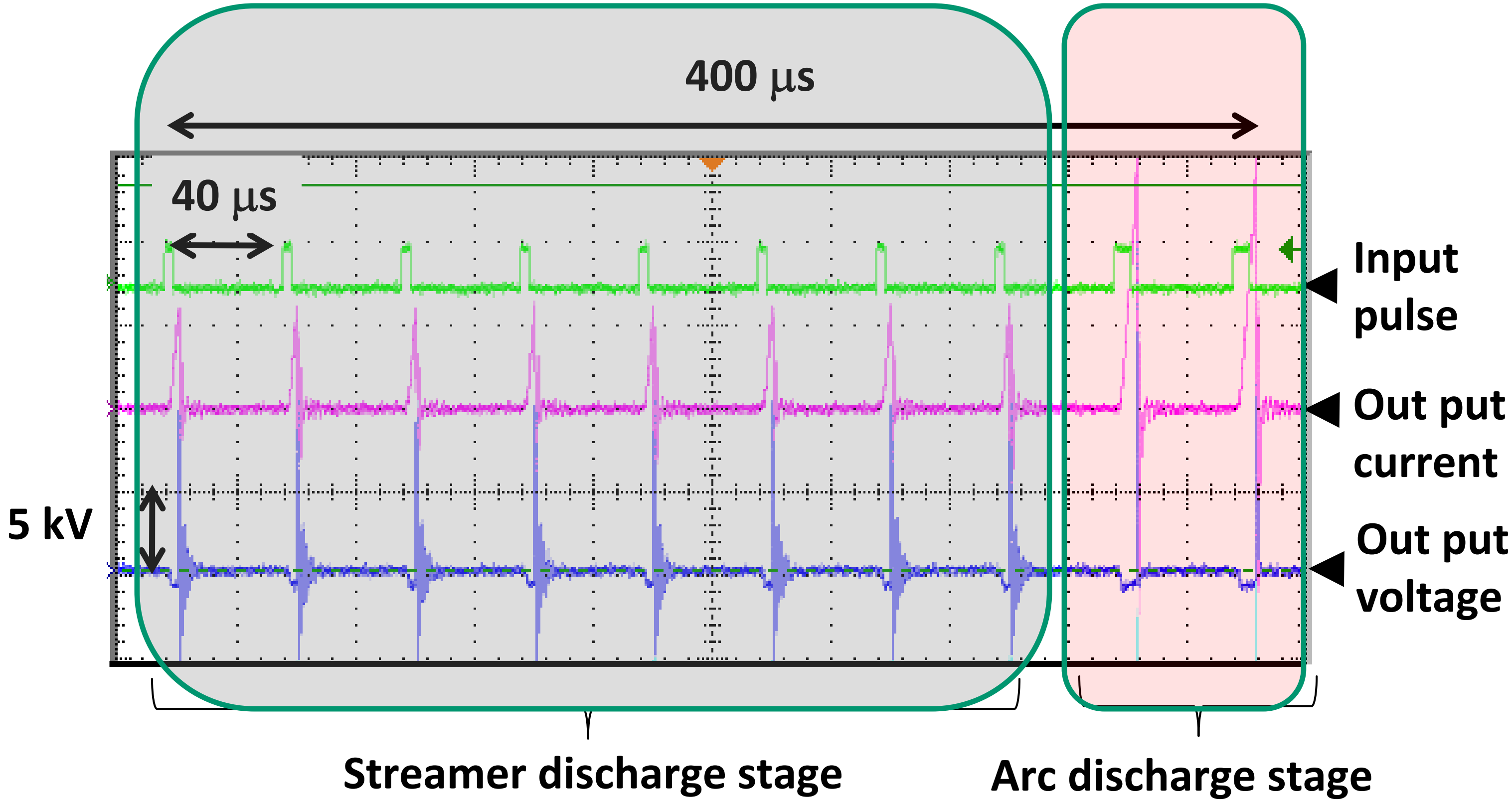
Engine type	4-stroke single cylinder
Bore × Stroke	ϕ75 × 60 mm
Compression ratio	10.5
Displacement vol.	265 cc
Fuel supply	Port injection

Ignition System





Discharge Pattern

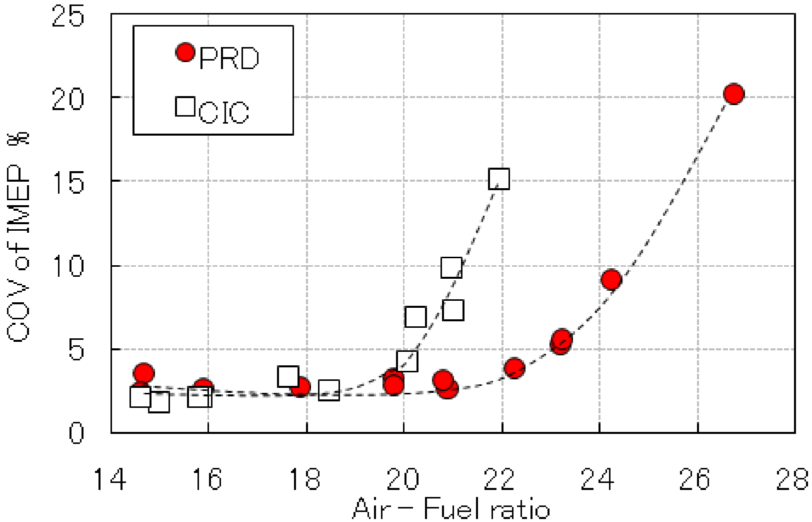


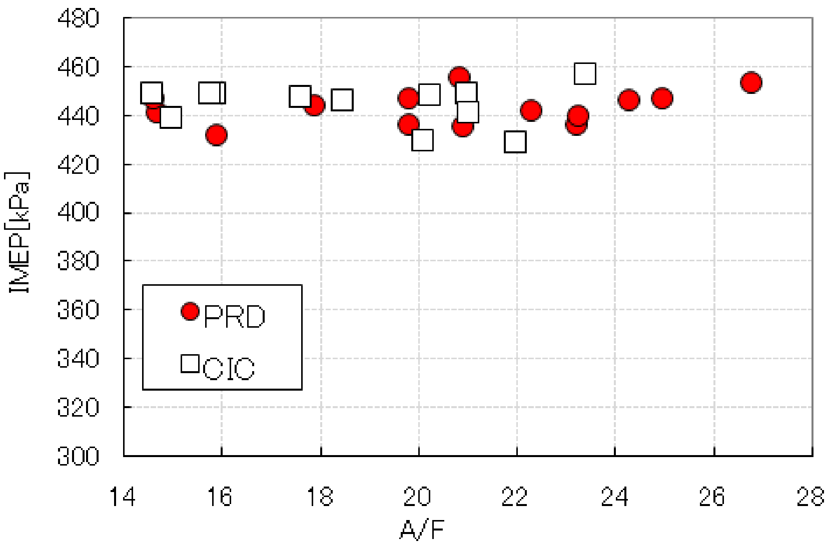
●objective□
Multiple low temperature plasma causes chemically active species and the following arc discharge would confirm stable ignition.

Experimental conditions

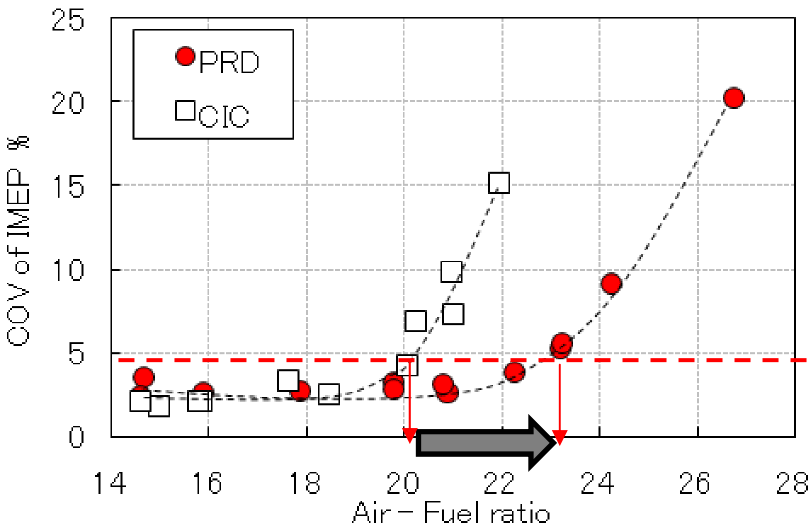
	Lean limit test	EGR limit test
Engine speed	1000 rpm	1000 rpm
IMEP	440 kPa	630 kPa
A/F	**14.6 ~ 27**	14.6
EGR ratio	0 %	**13 % ~ 23 %**
Fuel	Gasoline (RON91)	Gasoline (RON91)
Ignition timing	MBT	MBT

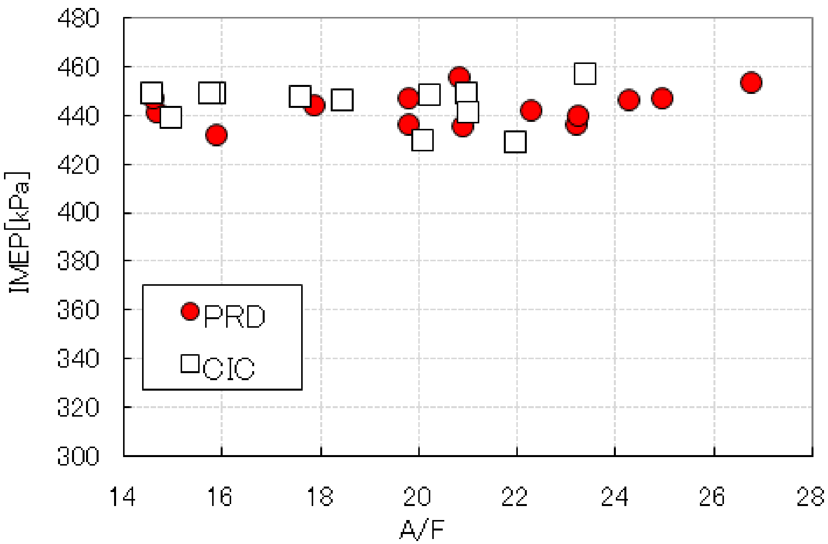
Extension of lean combustion limit by low-temperature repetitive discharges – IMEP fixed conditions





Lean Limit Test – IMEP at 440 kPa

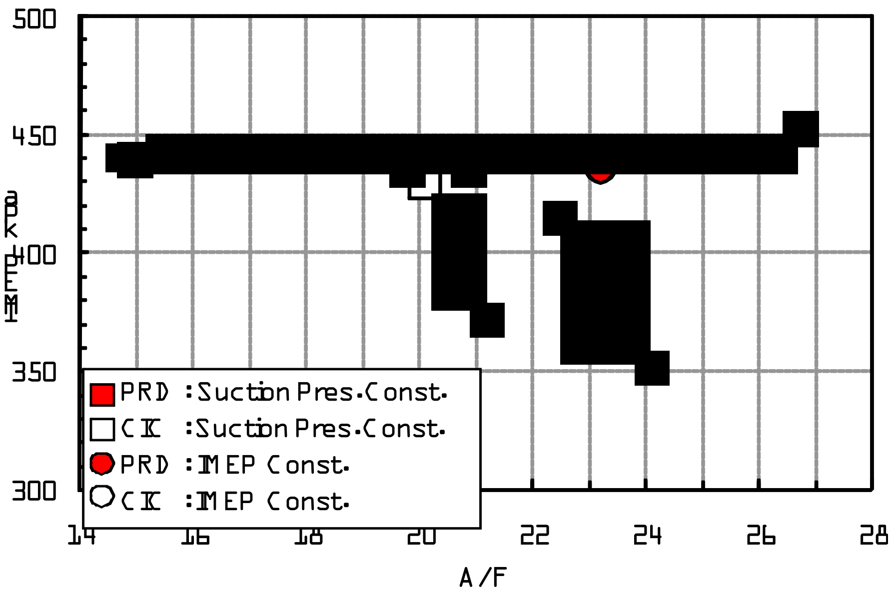




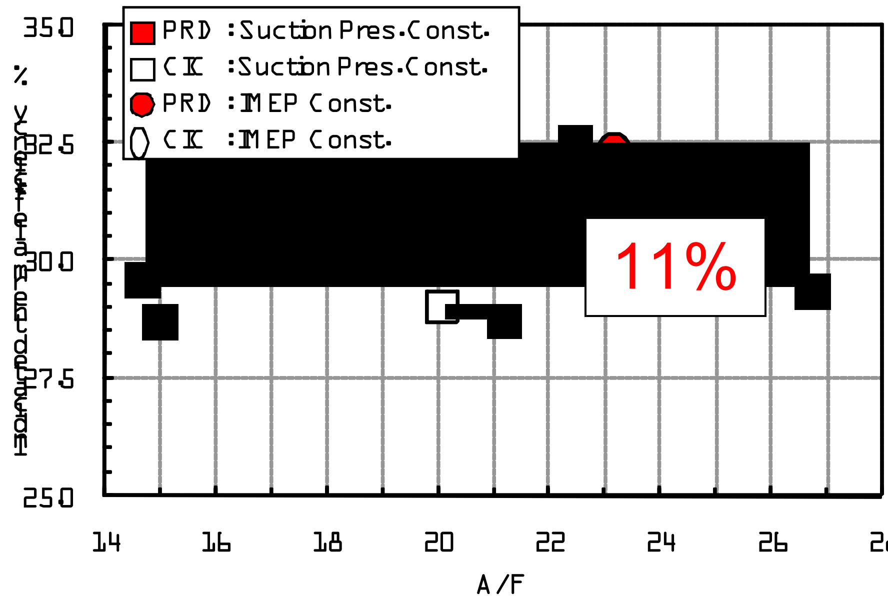
Limit□Cov of IMEP < 5%

A/F = 20□A/F = 23

Effect of ignition system on thermal efficiency – IMEP fixed conditions



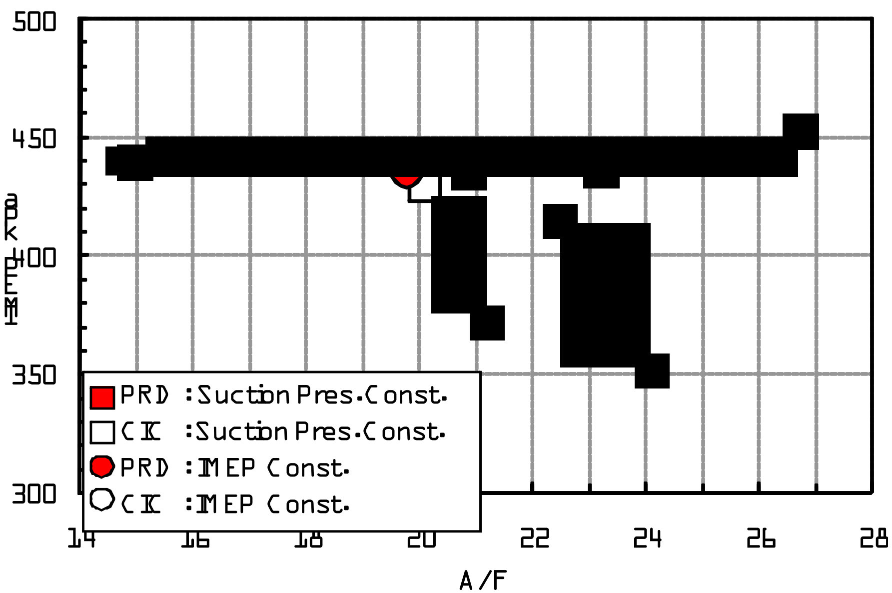
(a) IMEP vs A/F



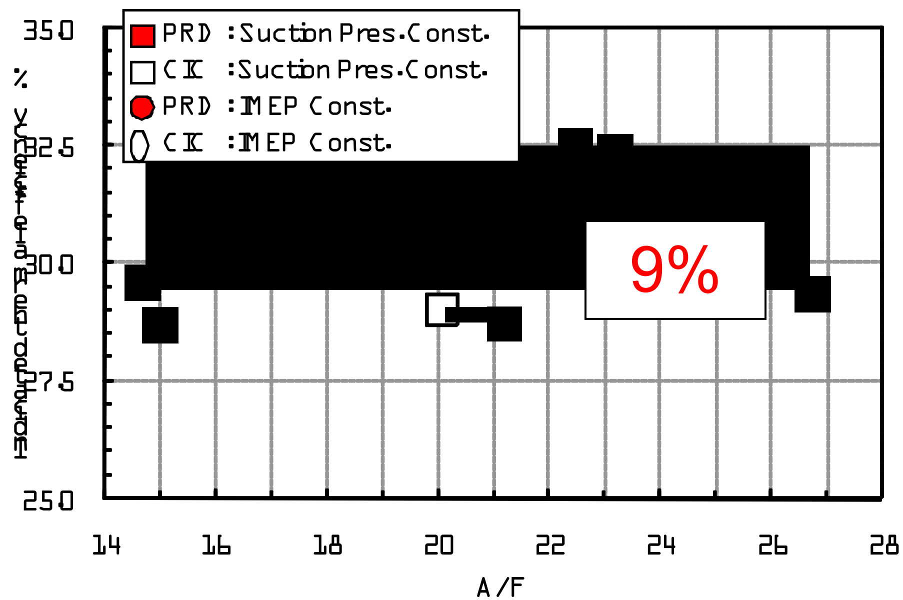
(c) Indicated thermal efficiency vs A/F

At the same IMEP of 440 kPa, PRD with A/F = 23 is better than of CIC with A/F = 20 by 11%.

Effect of ignition system on thermal efficiency – A/F fixed conditions



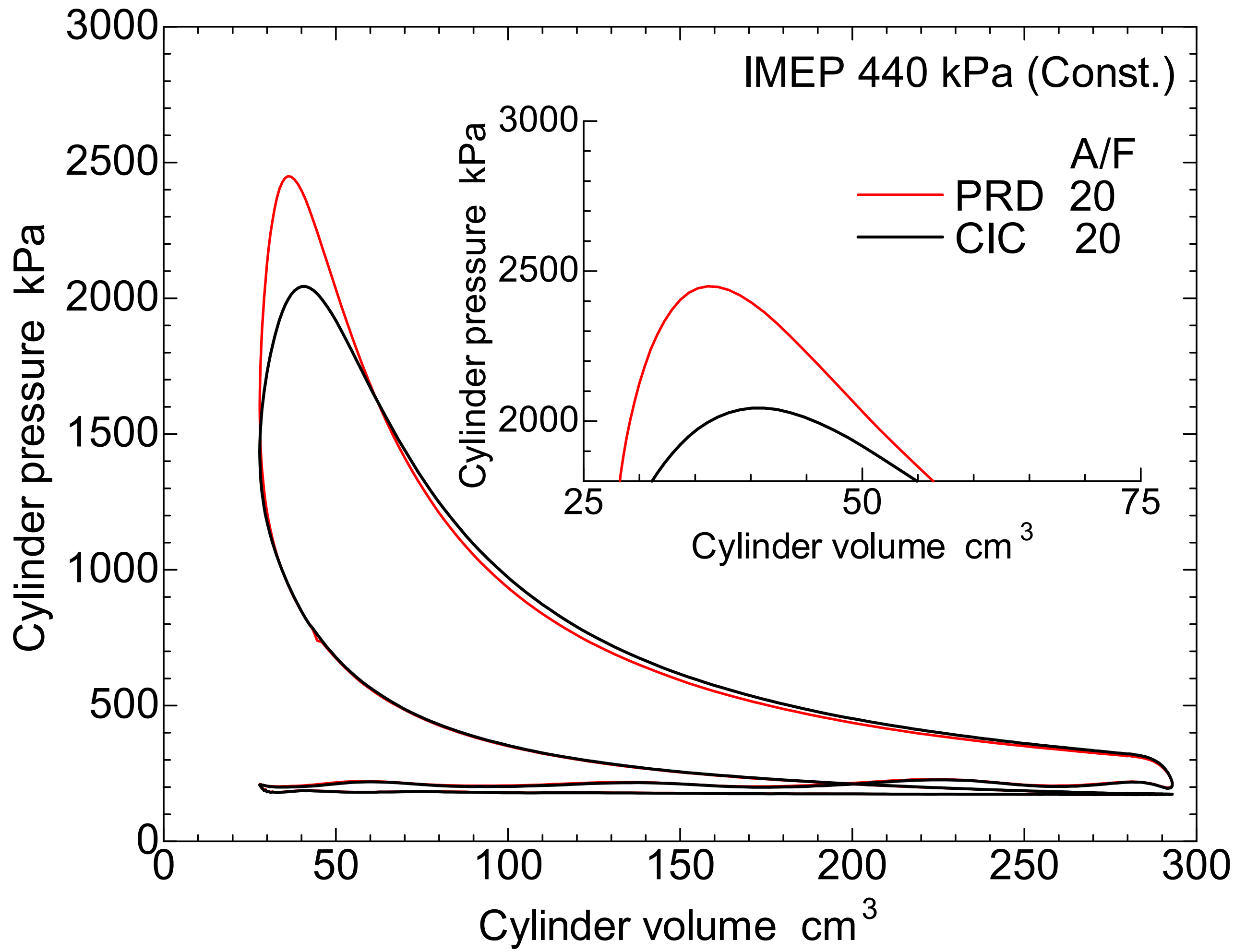
(a) IMEP vs A/F



(c) Indicated thermal efficiency vs A/F

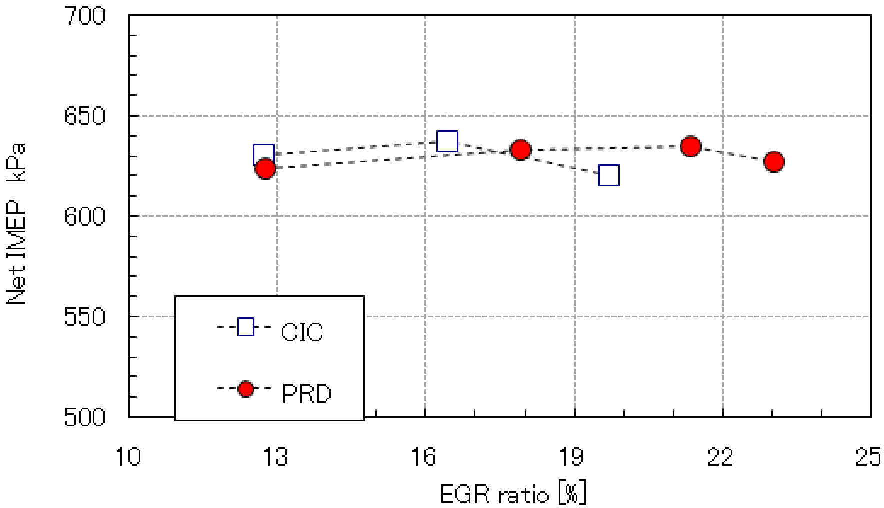
At the same A/F at 20, PRD shows better efficiency than CIC by 9%

Effect of ignition system on thermal efficiency – IMEP fixed conditions

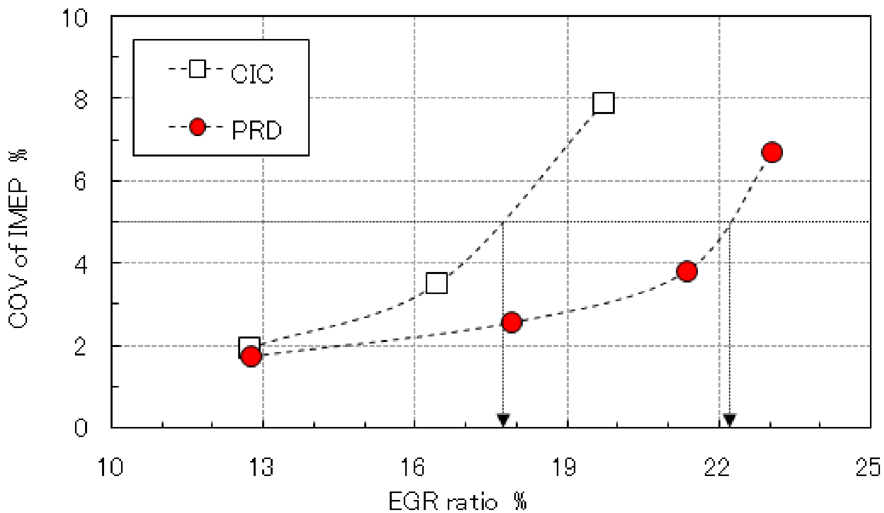


- Increased degree of constant volume combustion → increase of thermal efficiency

EGR Dilution Limit Test –IMEP at 630 kPa



IMEP 630 kPa const.
Ignition timing□MBT



Limit□COV of IMEP < 5 %

EGR rate 17□→22 %

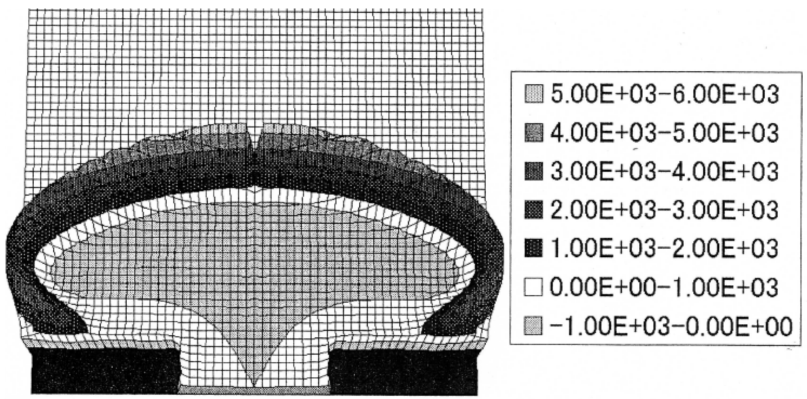
Conclusions

1. The lean combustion limit was tested using both the repetitive pulse ignition system and a conventional ignition system. The lean limit was extend from 20 in A/F using a conventional system to 23 using the repetitive pulse system, keeping the COV of IMEP under 5%. Thermal efficiency was improved by 11%. Even when the same A/F conditions at 20, the repetitive pulse ignition system showed better thermal efficiency by 9%.

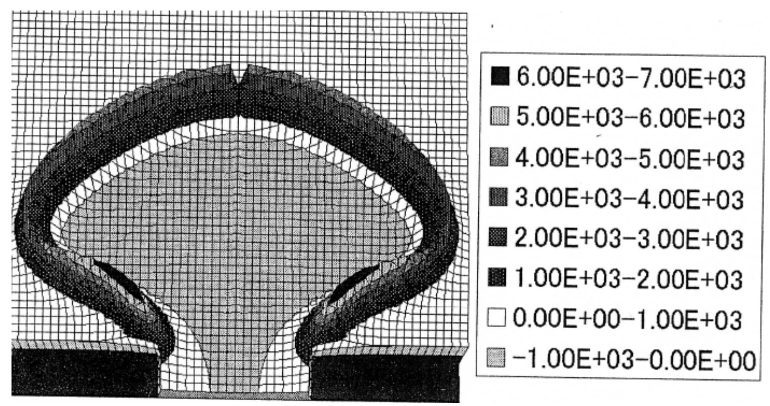
2. The repetitive pulse ignition system extended the diluted combustion limit from 17% to 22% and also improved thermal efficiency by about 5% compared to a conventional system. This is due to that the combustion speed is enhanced and the degree of constant volume is increased.

The mechanism about the developed different flame kernels, depending on the time during which energy was supplied, based on the result of Tsue and Kono' group

Calculated heat release distributions



(a) Ratio of capacity spark energy 20% corresponding to longer duration



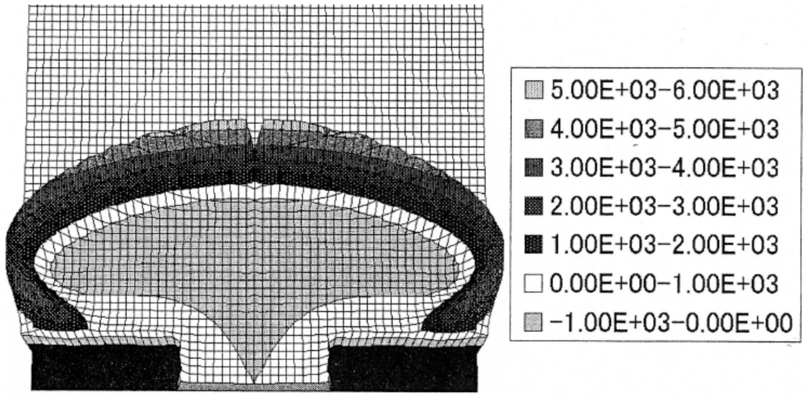
(b) Ratio of capacity spark energy 80% corresponding to shorter duration

Tsue, M., Kono, M., J., Combust. Soc. Japan, Vol.48, No.145, (2006).

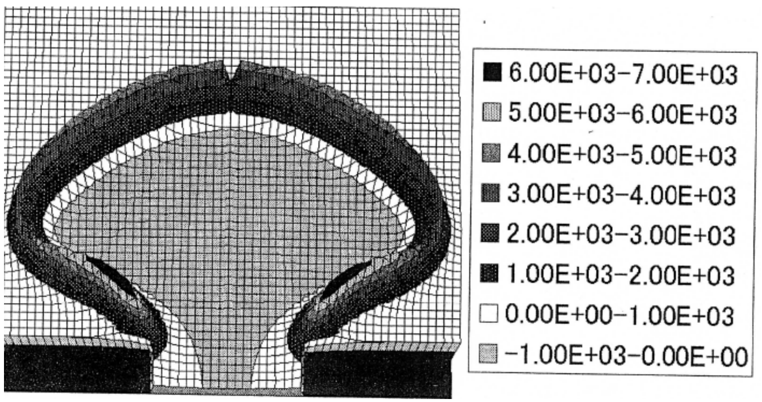
he short duration arc discharges can produce a larger flame kernel and located far away from the electrodes, which can results in the higher inflammability.

As for this different flame kernel development, they have reported that the gaseous flow motion near the spark gap induced by shock wave caused by spark discharge affects the formation process of the flame kernel.

Calculated heat release distributions



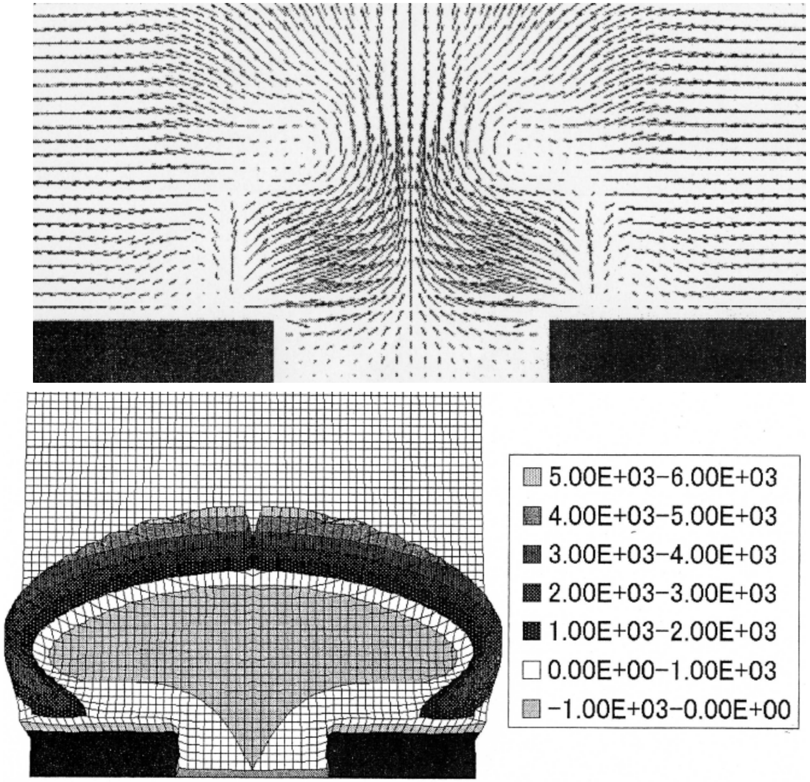
(a) Ratio of capacity spark energy 20% corresponding to longer duration



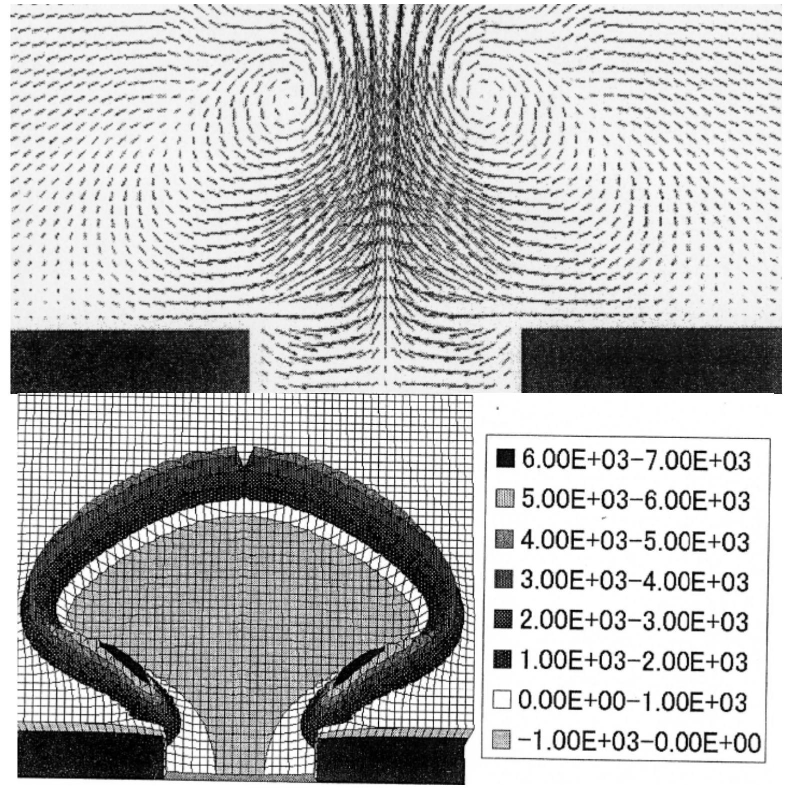
(b) Ratio of capacity spark energy 80% corresponding to shorter duration

Tsue, M., Kono, M., J., Combust. Soc. Japan, Vol.48, No.145, (2006).

Calculated velocity distributions



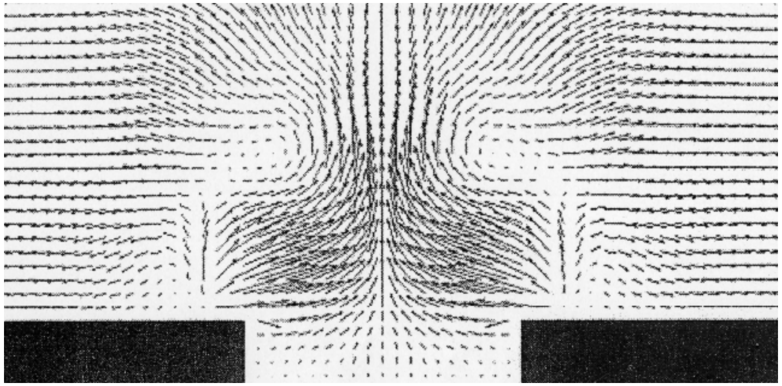
(a) Ratio of capacity spark energy 20% corresponding to longer duration



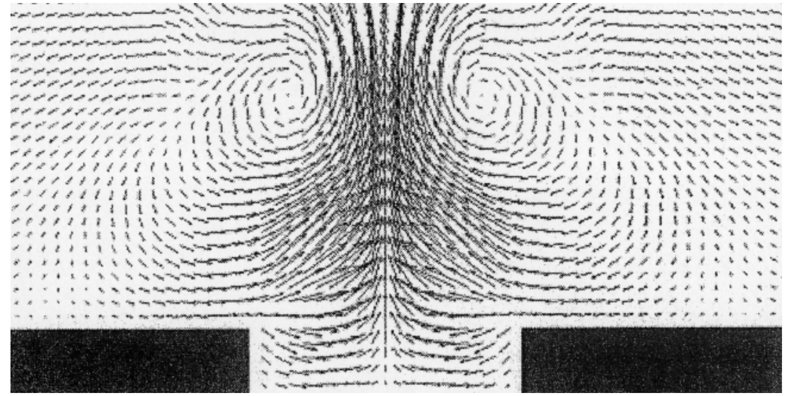
(b) Ratio of capacity spark energy 80% corresponding to shorter duration

Tsue, M., Kono, M., J., Combust. Soc. Japan, Vol.48, No.145, (2006).

Calculated velocity distributions

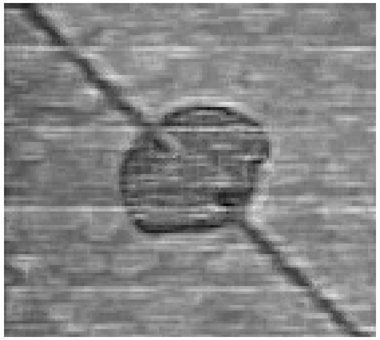


(a) Ratio of capacity spark energy 20% corresponding to longer duration

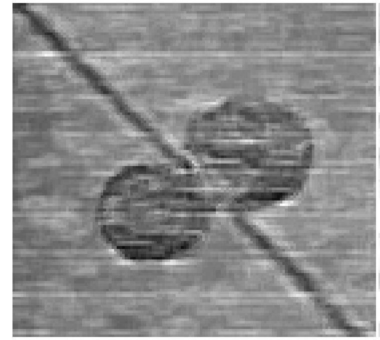


(b) Ratio of capacity spark energy 80% corresponding to shorter duration

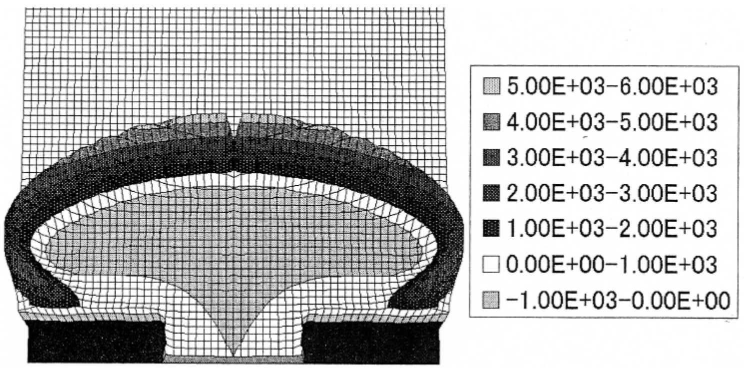
A sudden pressure rise in the spark gap due to spark discharge can generate a spherical shock wave, which create gas flow motion like this figure.
The flame kernel is initially spherical, and the maximum temperature region is located in the center of the spark gap.
Then, the flame kernel is moved by these flow motions.
If the ignition energy is supplied in the shorter time interval, the higher energy densities and temperature gradients are achieved, which lead to the stronger shock wave. Consequently, the generation of gaseous motion is promoted, which makes flame kernel away from electrodes.



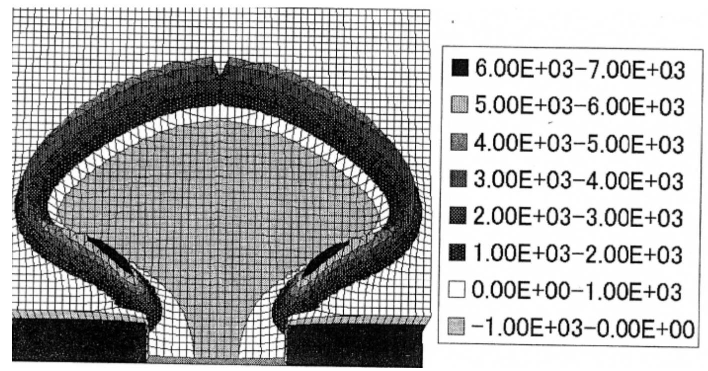
Conventional ignition circuit (CIC)



Single discharge (SD1) by IES

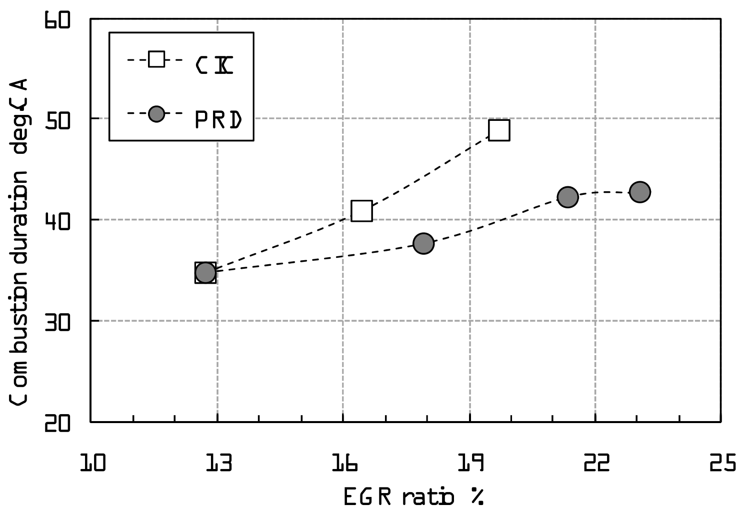


(a) longer duration

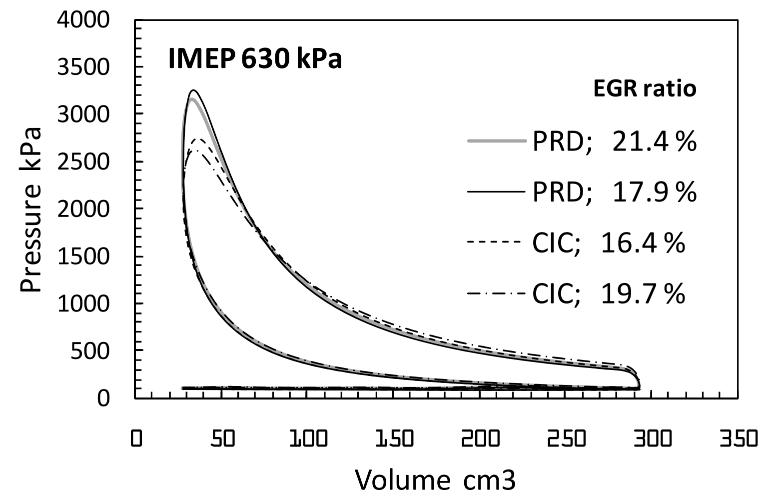


(b) shorter duration

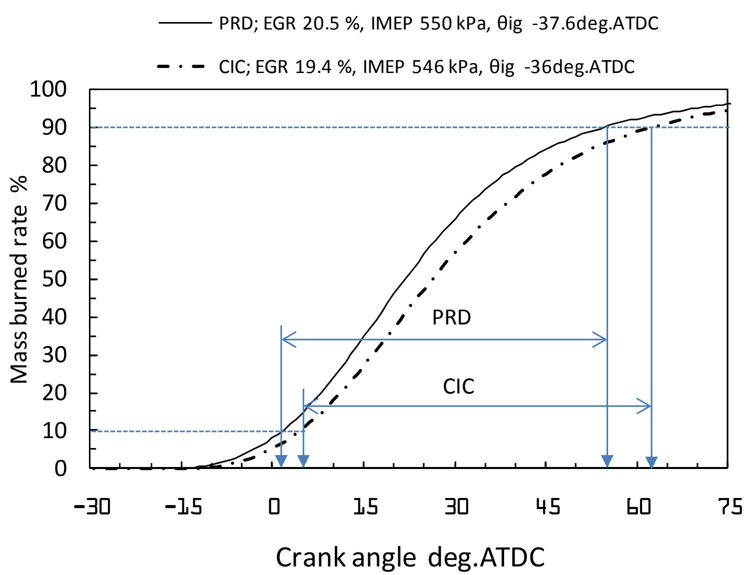
As the flame kernel is located far away from the electrodes, heat loss to the electrodes becomes smaller.
In addition the larger flame kernel becomes, the higher inflammability becomes, because of larger effective gas volume exposed to ignition and higher energy transfer efficiency.



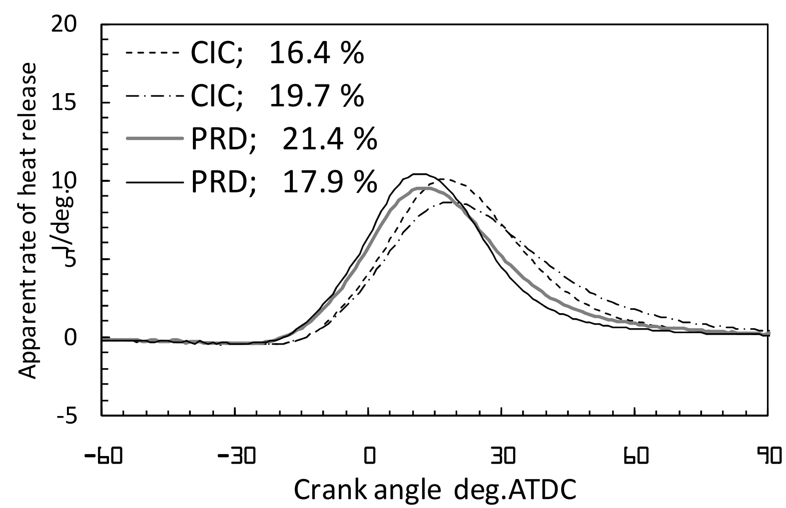
CIC
PRD
Combustion duration degCA
EGR ratio %



IMEP 630 kPa
EGR ratio
PRD; 21.4 %
PRD; 17.9 %
CIC; 16.4 %
CIC; 19.7 %
Pressure kPa
Volume cm3

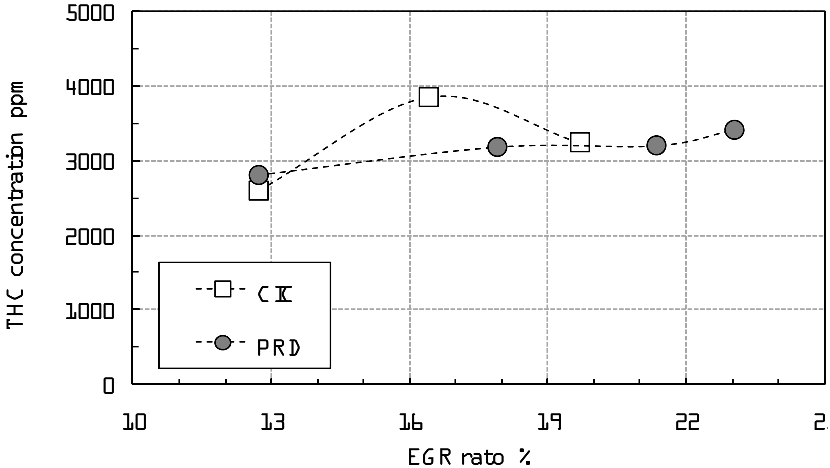


PRD; EGR 20.5 %, IMEP 550 kPa, θig -37.6deg.ATDC
CIC; EGR 19.4 %, IMEP 546 kPa, θig -36deg.ATDC
Mass burned rate %
PRD
CIC
Crank angle deg.ATDC

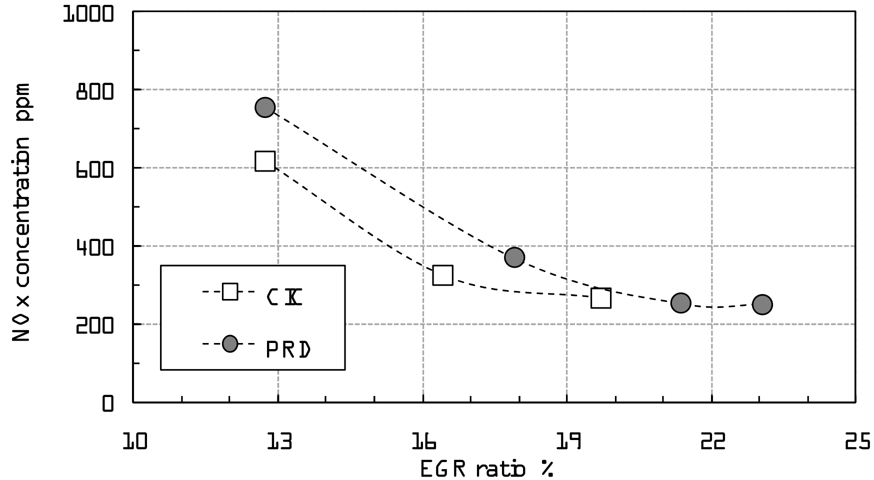


CIC; 16.4 %
CIC; 19.7 %
PRD; 21.4 %
PRD; 17.9 %
Apparent rate of heat release J/deg.
Crank angle deg.ATDC

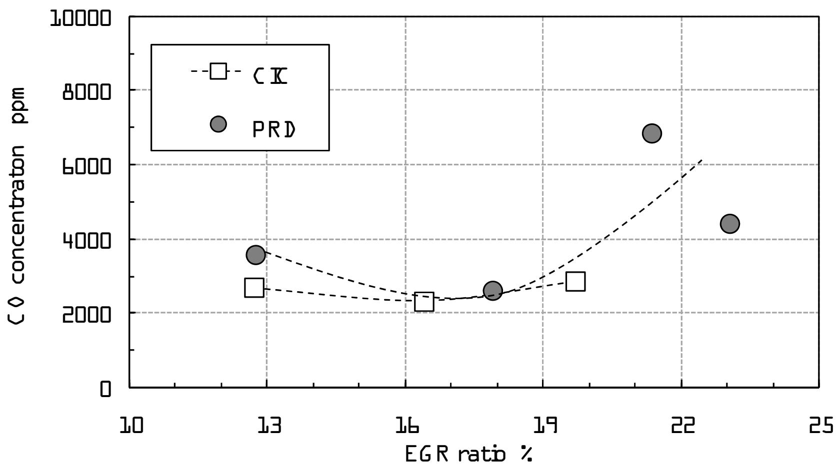
EGR[illegible]



THC concentration ppm
5000
4000
3000
2000
1000
0
10
13
16
19
22
2
EGR rato %
CK
PRD



NOx concentration ppm
1000
800
600
400
200
0
10
13
16
19
22
25
EGR ratio %
CK
PRD



CO concentraton ppm
10000
8000
6000
4000
2000
0
10
13
16
19
22
25
EGR ratio %
CK
PRD

Experimental procedure

- Two types of ignition systems were used
  - (1) conventional ignition circuit (CIC)
  - (2)10pulses of IES circuit (PRD), which consists of 8 streamer discharges and 2 arc discharges.
- The engine speed was fixed at 1000 r/min.
- Two types of engine operation were conducted;
  - (1)keeping the suction pressure at 70 kPa
    - to control the suctioned air amount
  - (2)keeping IMEP at 440 kPa
    - to control the engine load.
- At each condition, the ignition timing was taken at MBT.
- The supplied energy was estimated to be around 140 mJ/cycle for both ignition systems.

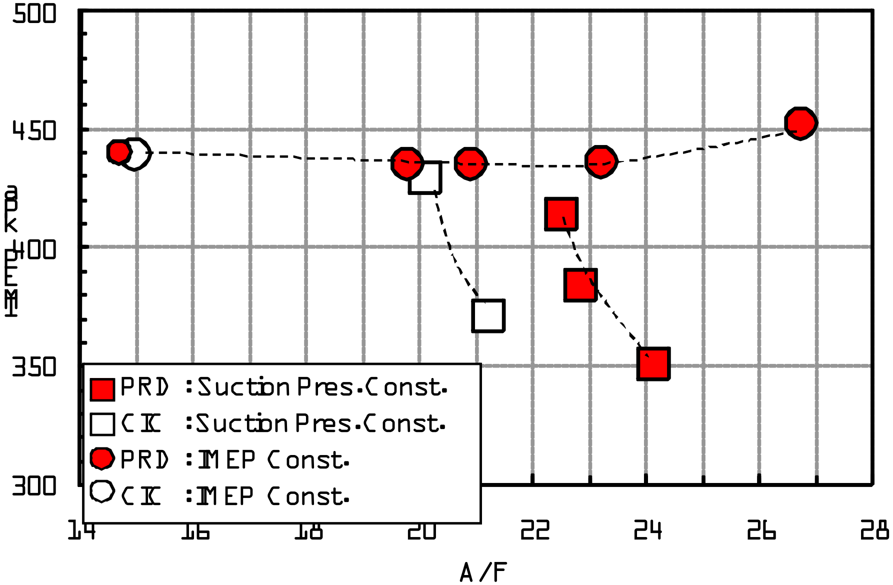
Test engine

Test Engine	
single-cylinder four-stroke port-injection gasoline engine	
The bore x stroke	75 x 60 mm
displacement volume	265 cc
compression ratio	10

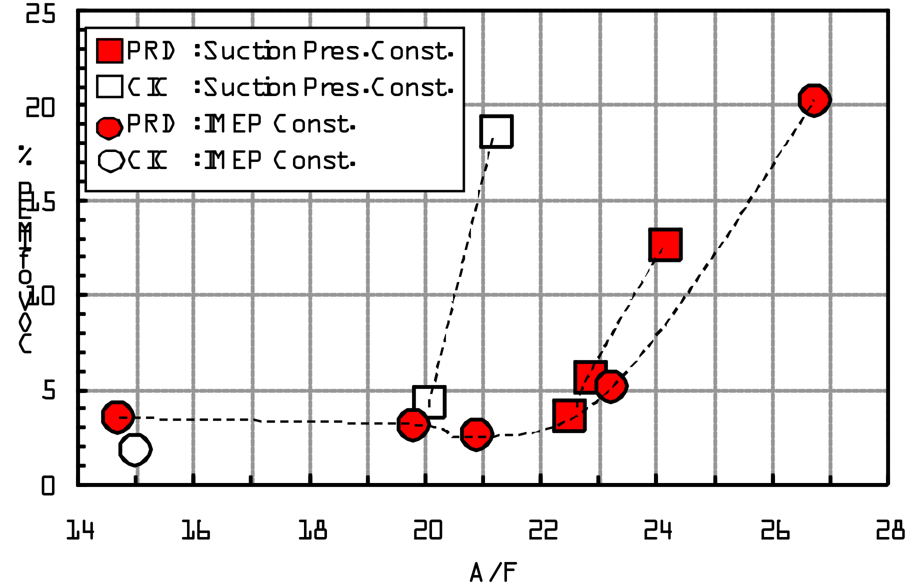
A conventional spark plug was used .

The spark gap was 0.5 mm for CIC

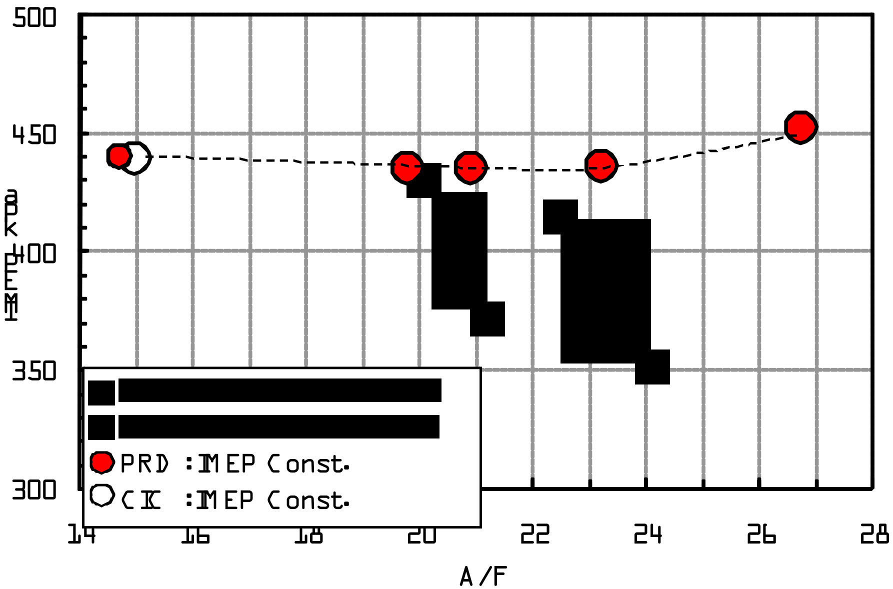
1.5mm for PRD



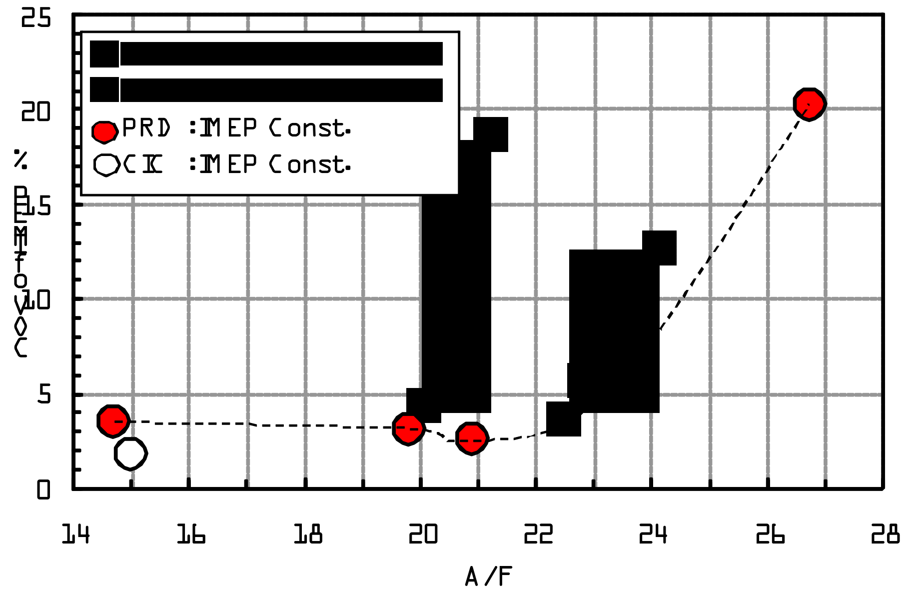
(a) IMEP vs A/F



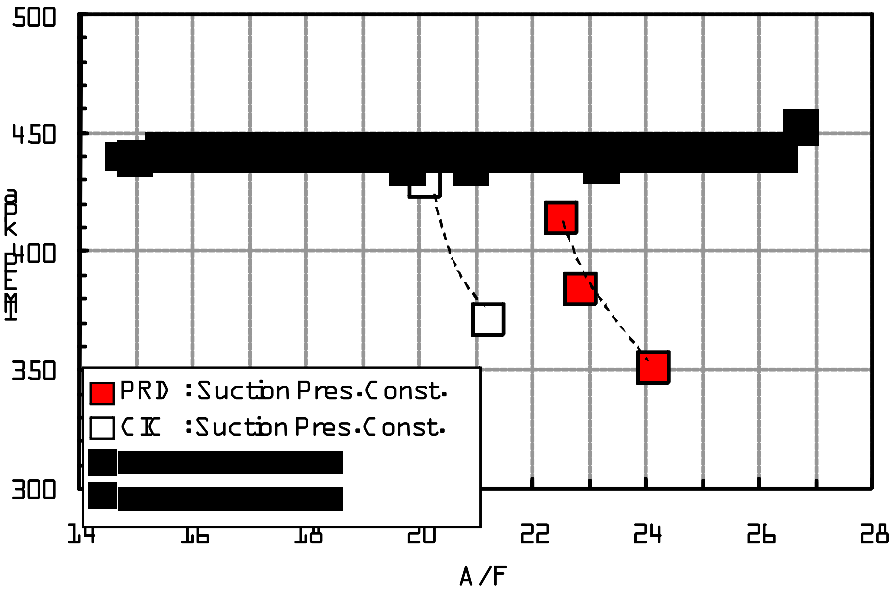
(b) COV of IMEP vs A/F



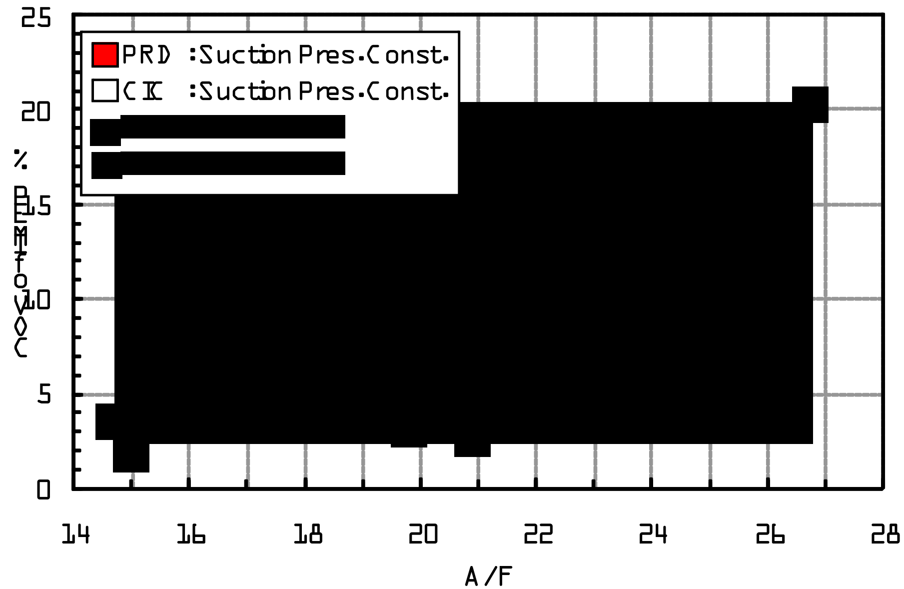
(a) IMEP vs A/F



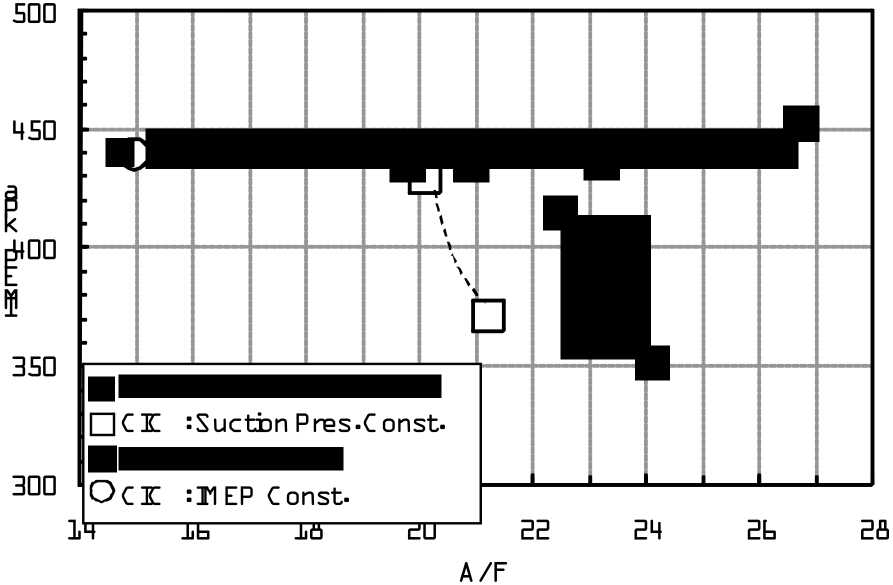
(b) COV of IMEP vs A/F



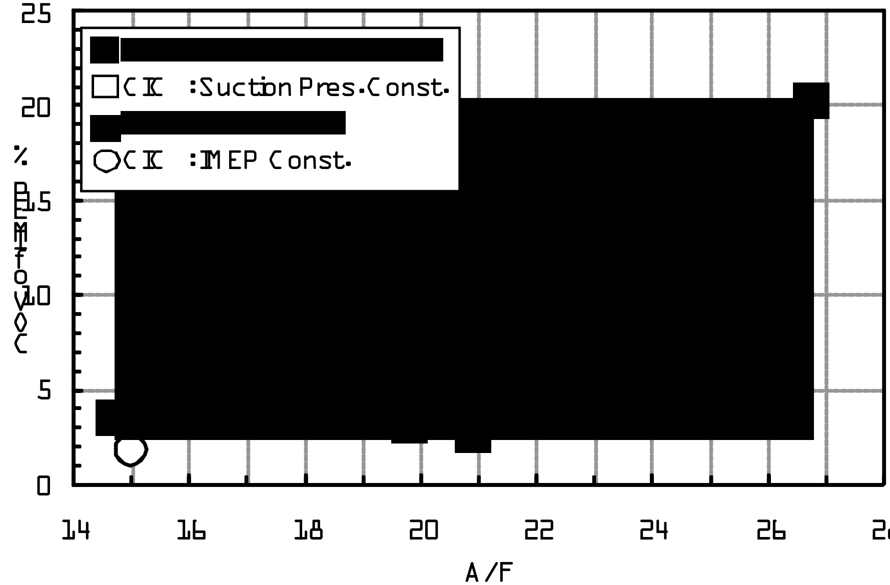
(a) IMEP vs A/F



(b) COV of IMEP vs A/F

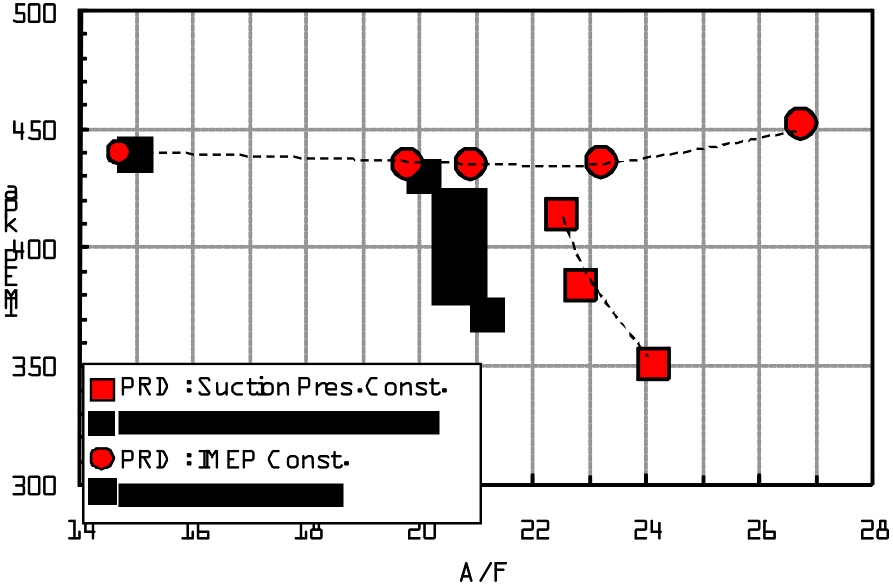


(a) IMEP vs A/F

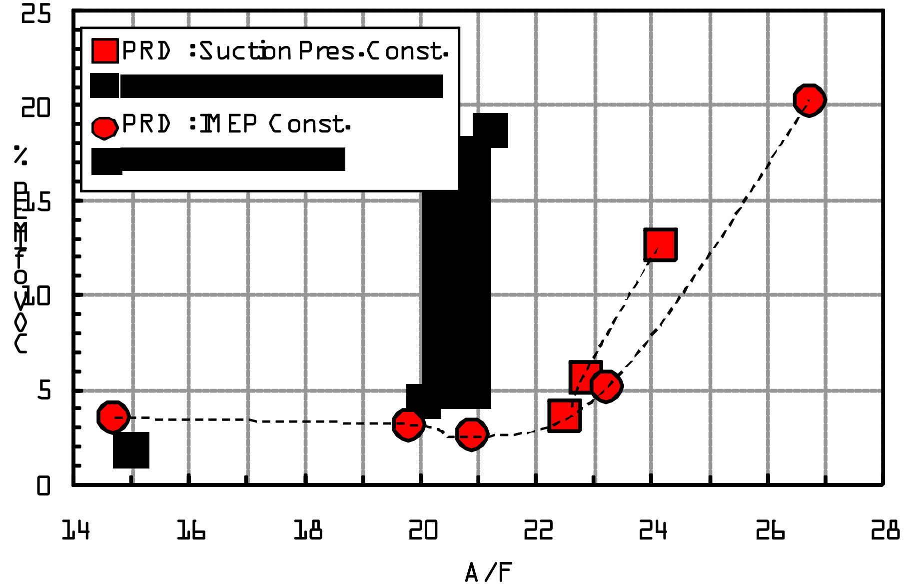


(b) COV of IMEP vs A/F

The conventional system (CIC) can be operated up to 20 in A/F due to engine instability (COV < 5%)

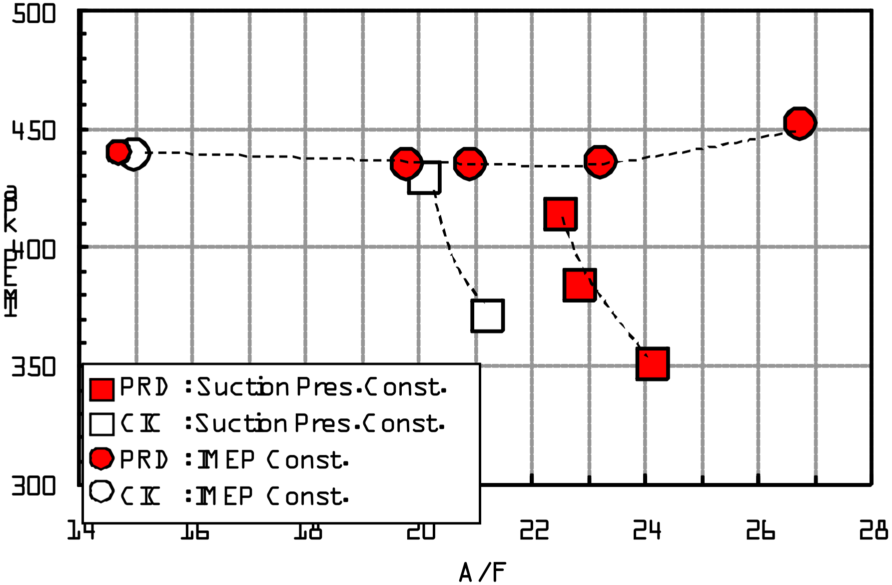


(a) IMEP vs A/F

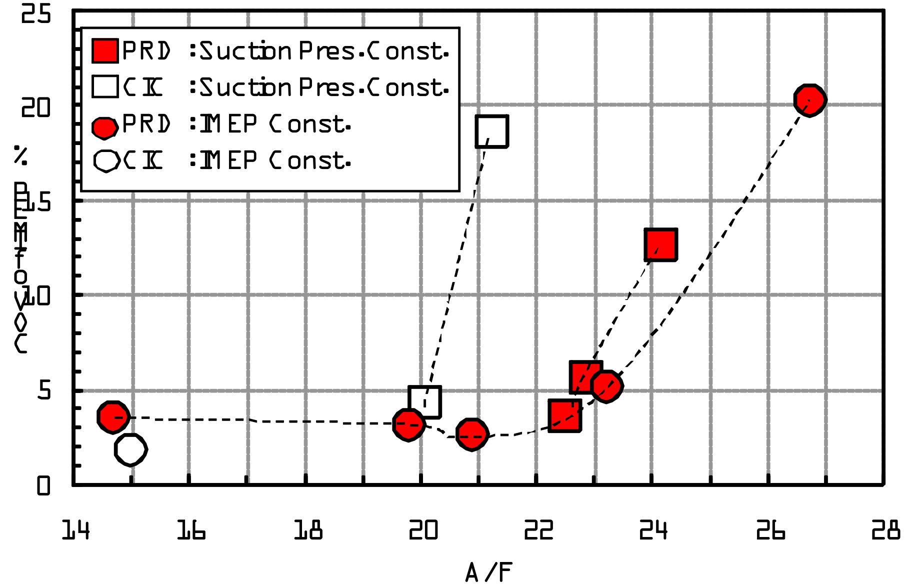


(b) COV of IMEP vs A/F

PRD can be operated up to 23.

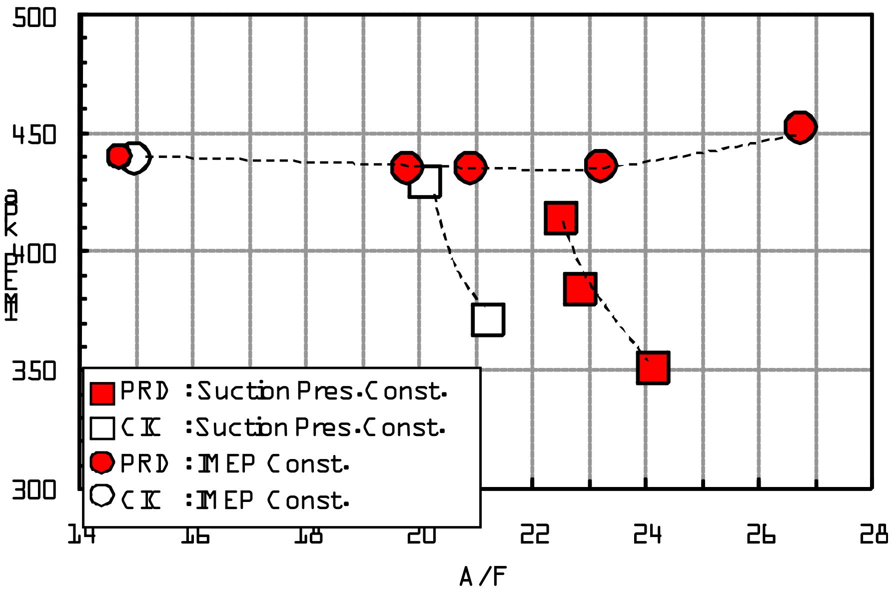


(a) IMEP vs A/F

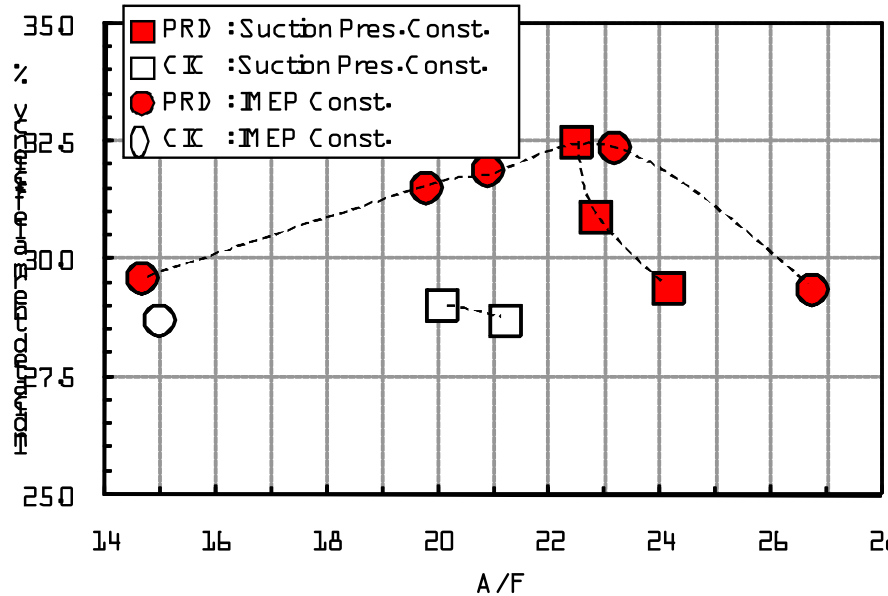


(b) COV of IMEP vs A/F

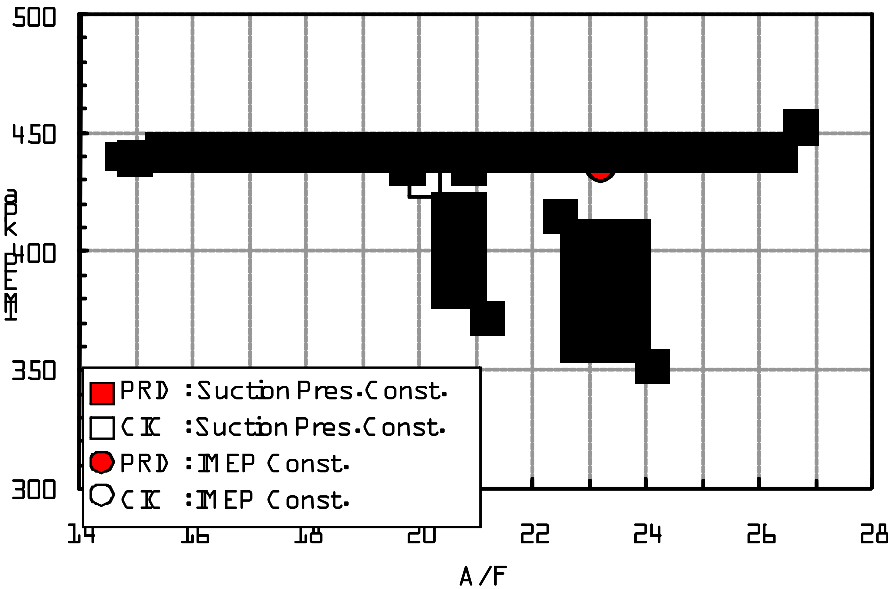
The Repetitive pulse discharges were found effective also for a SI engine.



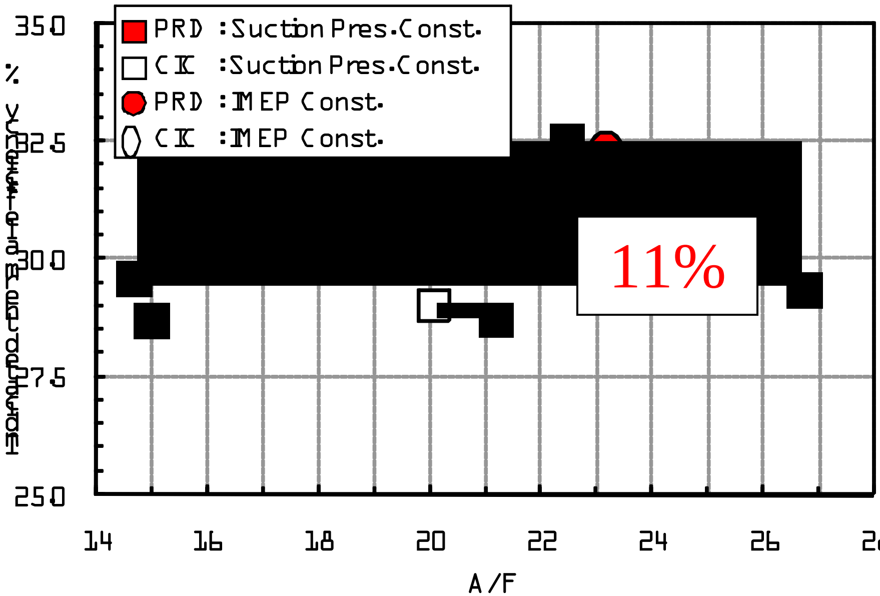
(a) IMEP vs A/F



(c) Indicated thermal efficiency vs A/F

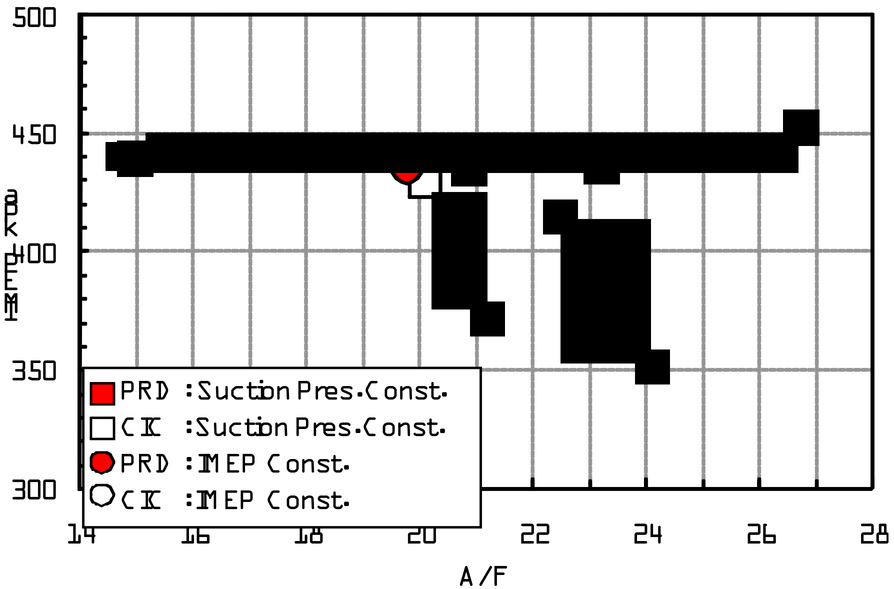


(a) IMEP vs A/F

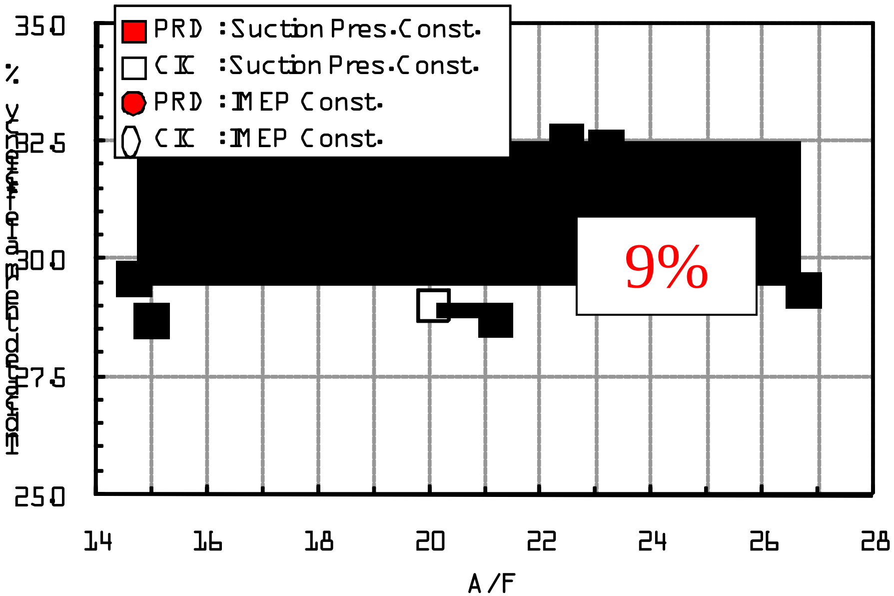


(c) Indicated thermal efficiency vs A/F

At the same IMEP of 440 kPa, PRD with A/F = 23 is better than of CIC with A/F = 20 by 11%.

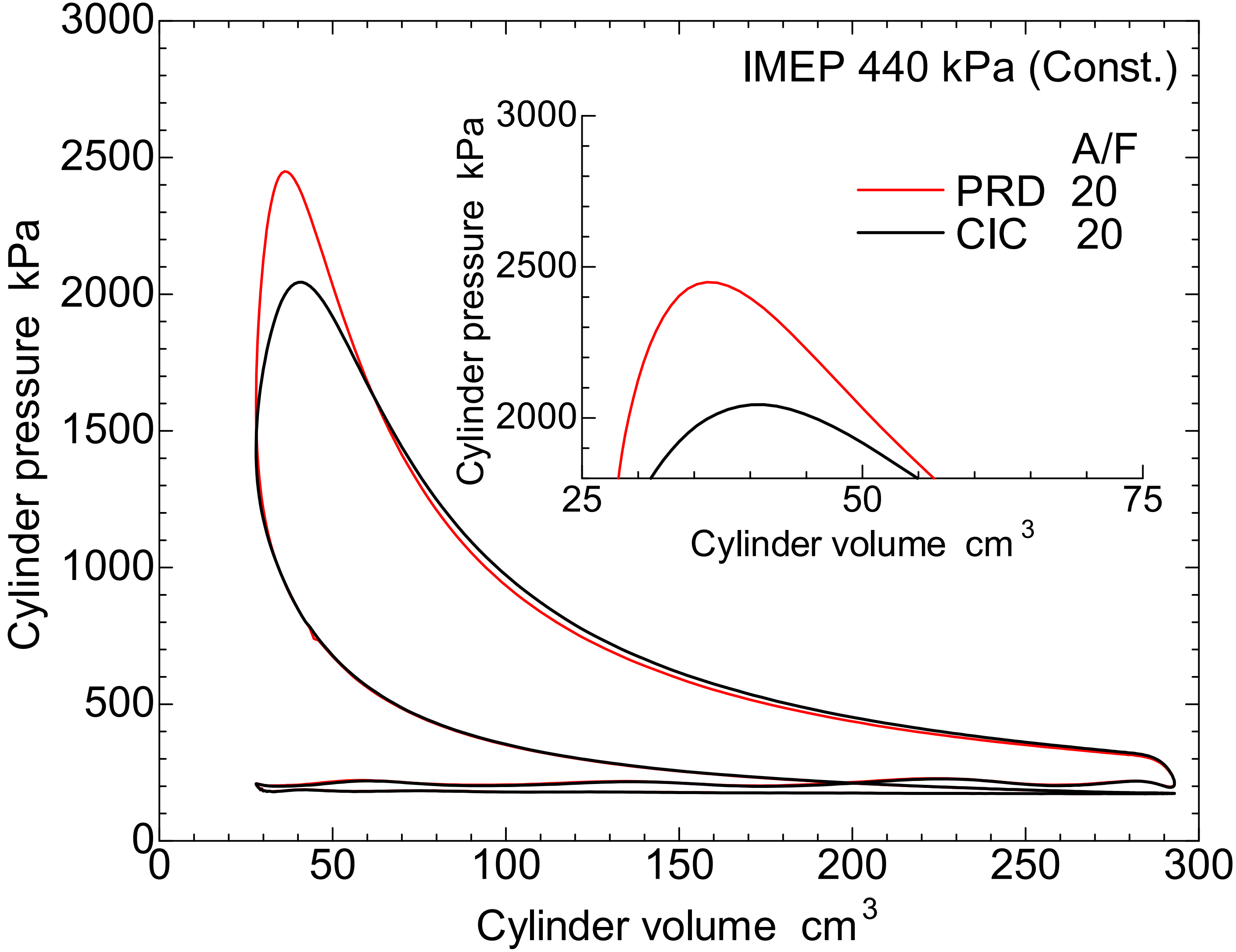


(a) IMEP vs A/F



(c) Indicated thermal efficiency vs A/F

At the same A/F at 20, PRD shows better efficiency than CIC by 9%



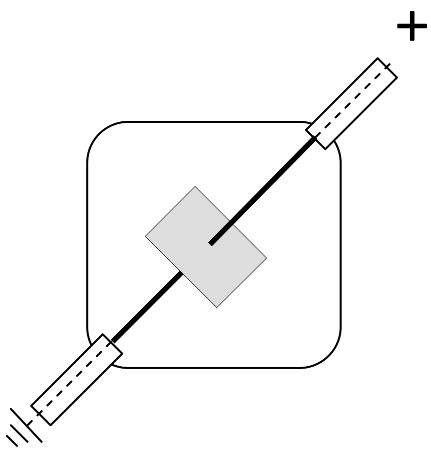
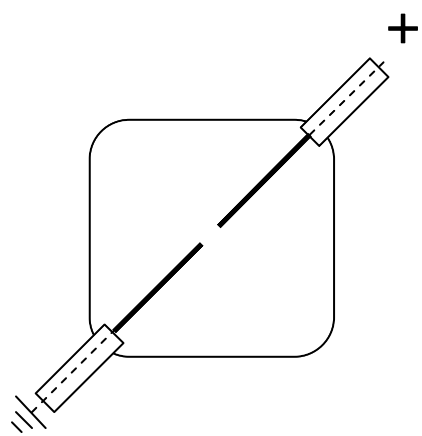
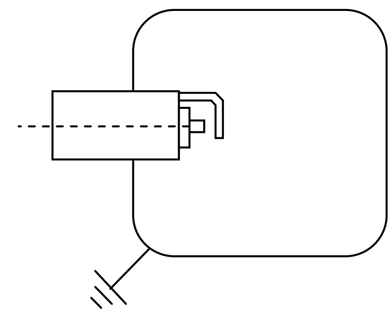
Comparison of in-cylinder pressure vs Cylinder volume

higher degree of constant volume

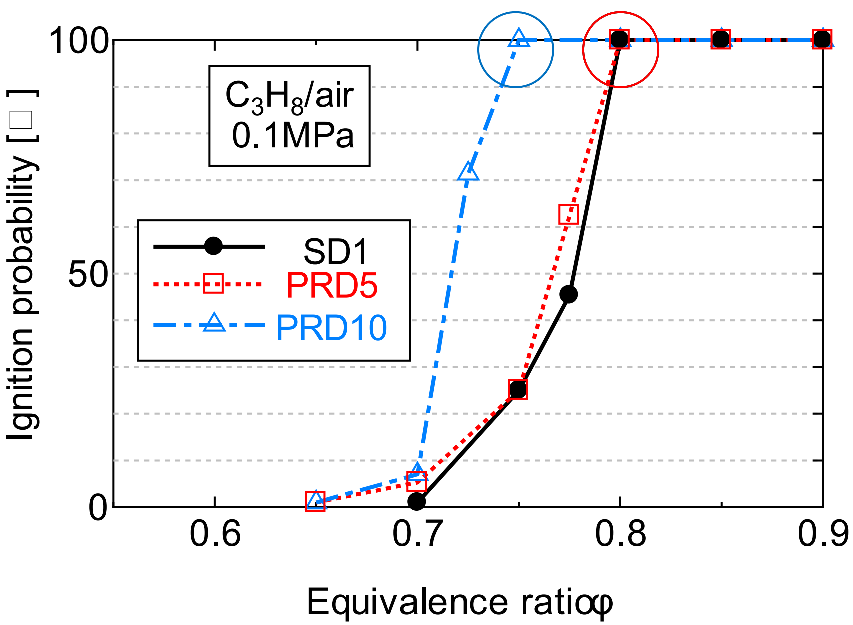
Conclusions

1. Single pulse discharge produced by IES circuit has better inflammability than conventional ignition system.
2. The short duration arc discharges by IES circuit can produce a larger flame kernel and located far away from the electrodes, which can results in the higher inflammability.
3. Repetitive pulse discharges can extend the flammability limit at both normal and elevated pressures and this tendency becomes more remarkable as the number of pulses increases.
4. Repetitive pulse discharges were applied to a SI engine. Compared to the original performance using CIC, the lean-limit was extended from 20 to 23 in A/F. Thermal efficiency was improved by 11%.

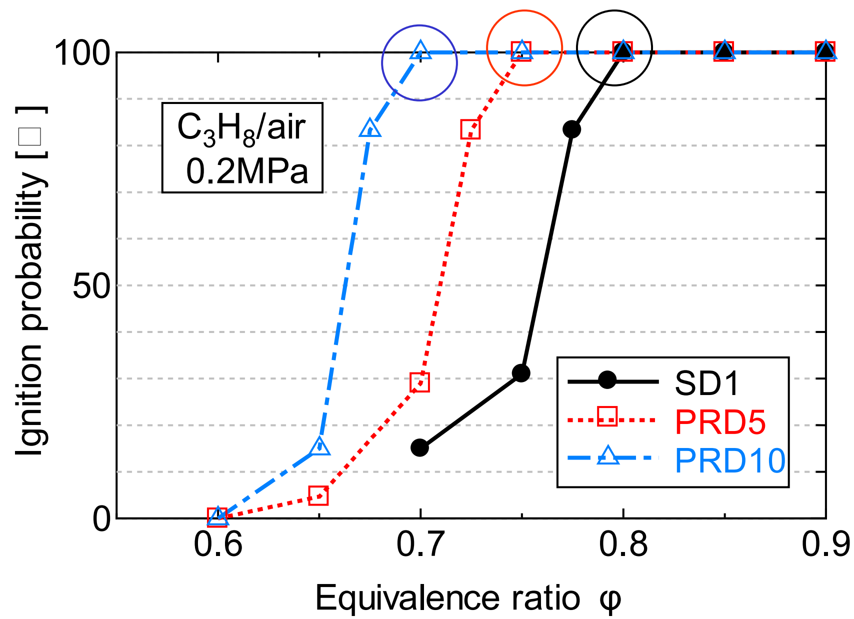
Ignition plug

needle-to-needle N-N type	needle-to-plate N-P type	convention ignition plug
		
		

0.1MPa



0.2MPa

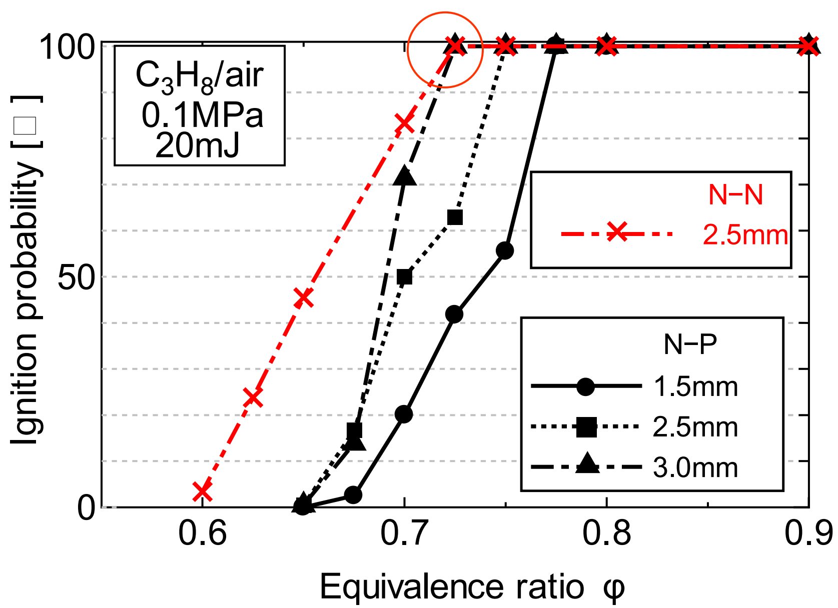


$\phi_{lim} = 0.75$ | $\phi_{lim} = 0.8$ | $\phi_{lim} = 0.8$

$\phi_{lim} = 0.7$ | $\phi_{lim} = 0.75$ | $\phi_{lim} = 0.8$

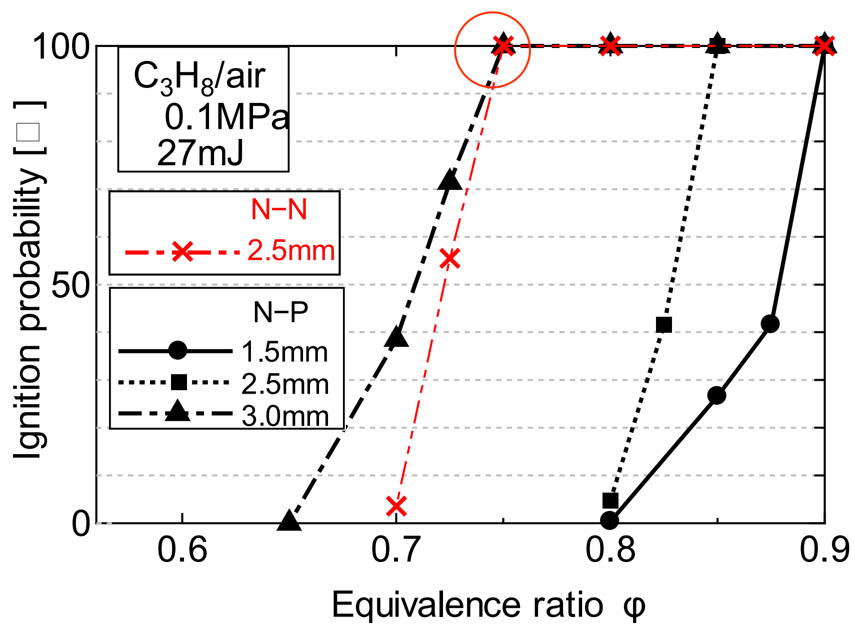
These conclude that repetitive pulse discharges can extend the flammability limit at both normal and elevated pressures and this tendency becomes more remarkable as the number of pulses increase.

Ignition probability for IES circuit and conventional ignition circuit



Single discharge (SD1) by IES circuit

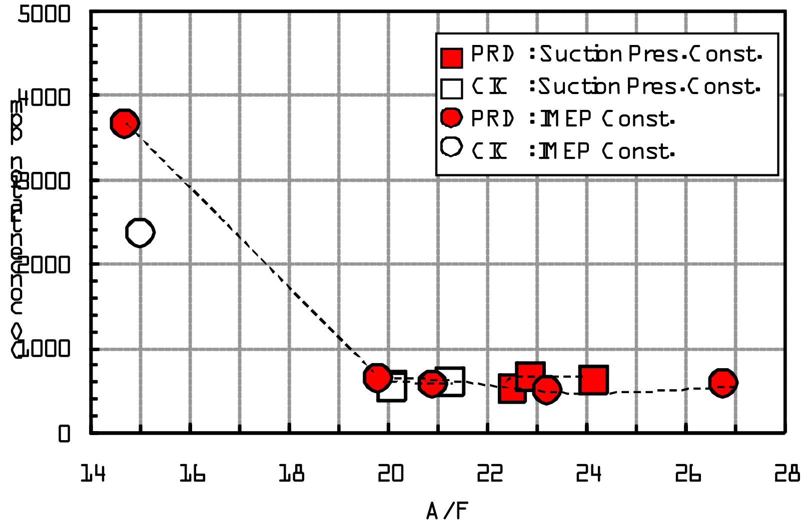
$\phi_{\rm lim}$= 0.725



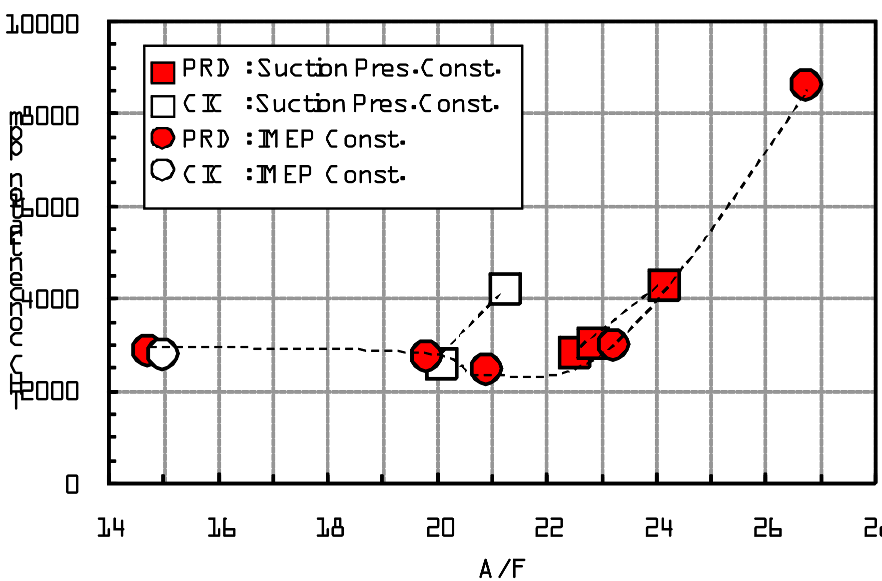
Conventional ignition circuit (CIC)

$\phi_{\rm lim}$= 0.75

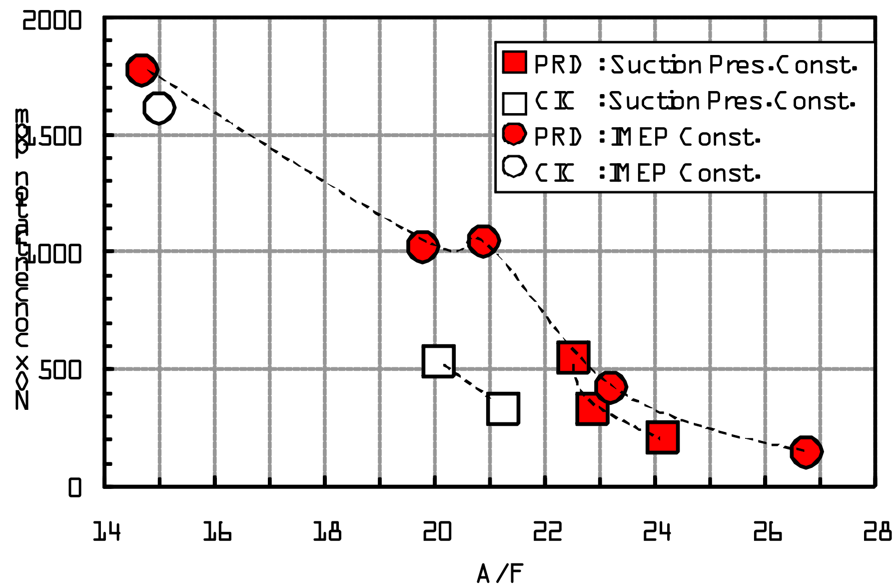
These conclude that single pulse discharge (SD1) produced by IES circuit has better inflammability than conventional ignition system (CIC).



(d) CO concentration vs A/F

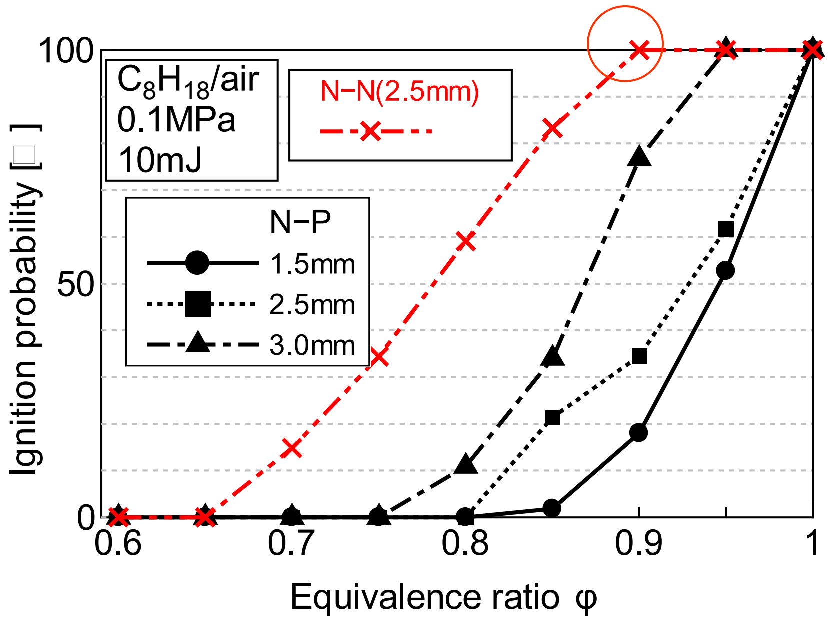


(e) THC concentration vs A/F



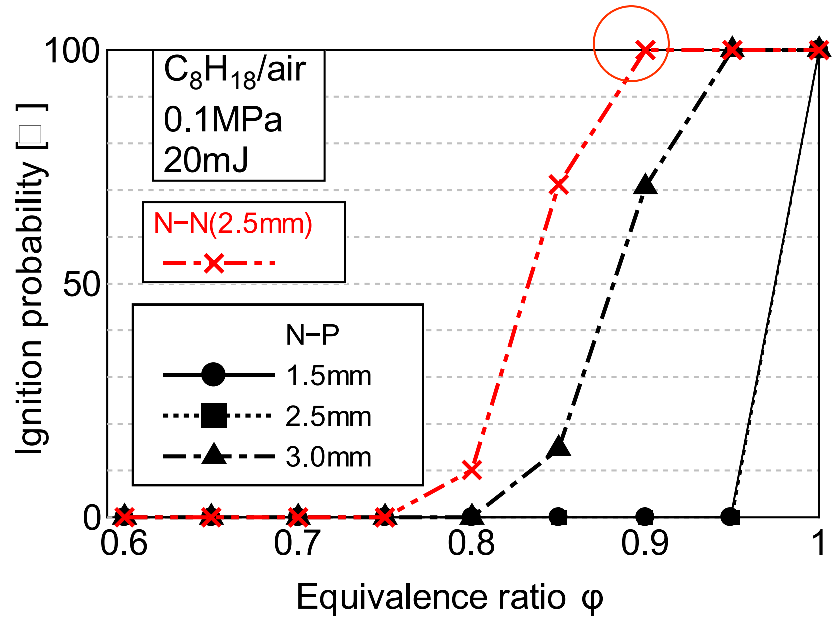
(f) NOx concentration vs A/F

Ignition probability for IES circuit and conventional ignition circuit



Single discharge (SD1) by IES circuit

$\phi_{\rm lim}$= 0.9

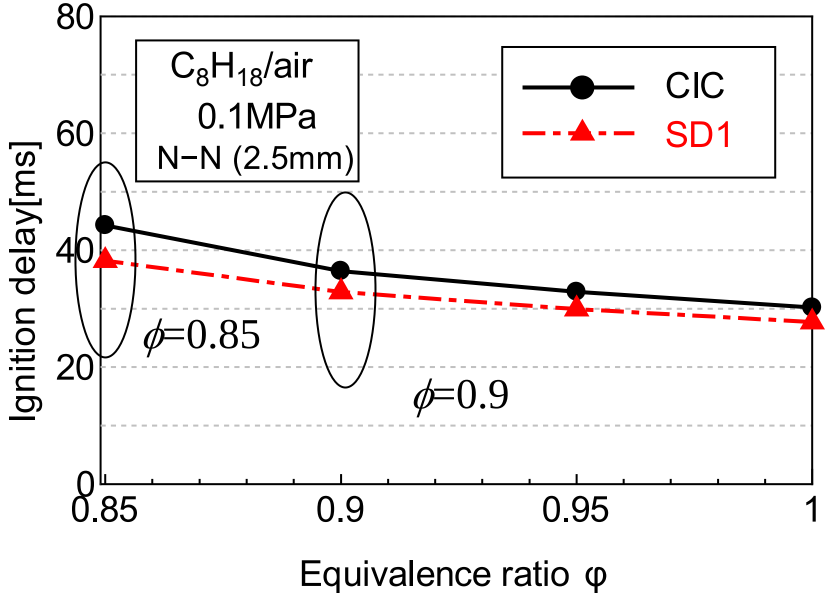


Conventional ignition circuit (CIC)

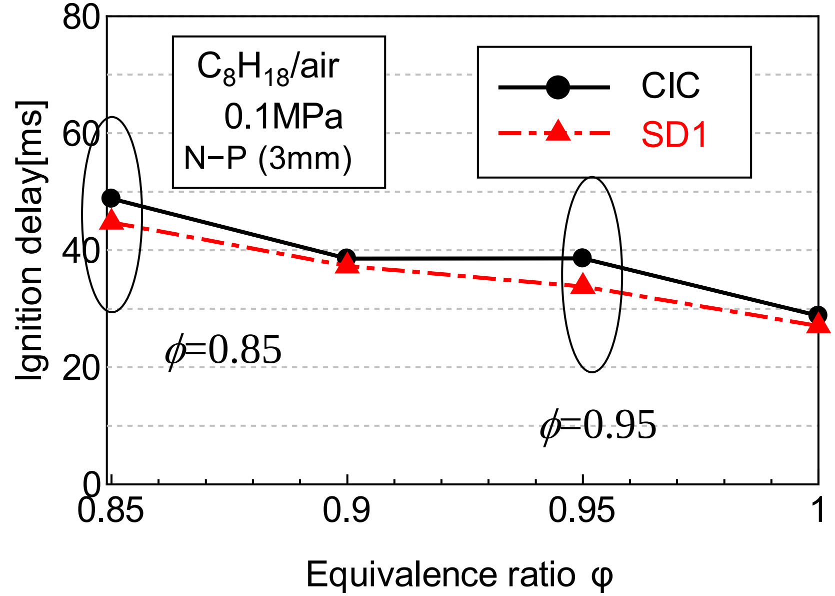
$\phi_{\rm lim}$= 0.9

These conclude that single pulse discharge (SD1) produced by IES circuit has better inflammability than conventional ignition system (CIC).

N-N type plug (2.5mm)



N-P type plug (3mm)



Δt_{ig}= 44ms

Δt_{ig} = 38ms

14% improve

Δt_{ig}= 36ms

Δt_{ig} = 33ms

8% improve

Δt_{ig}= 49ms

Δt_{ig} = 44ms

11% improve

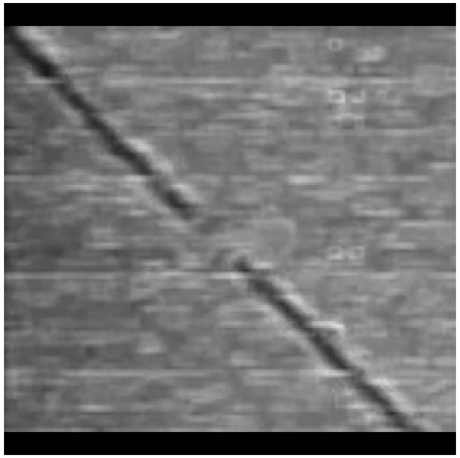
Δt_{ig}= 39ms

Δt_{ig} = 33ms

15% improve

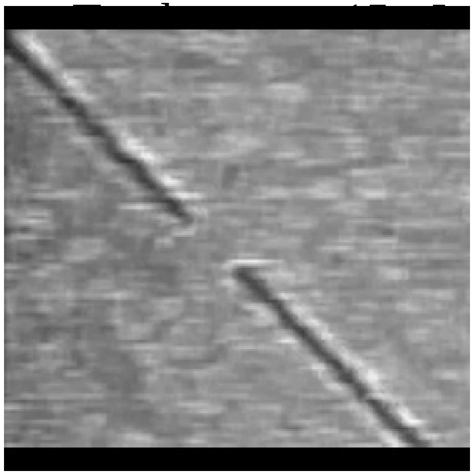
In conclusion, single pulse discharge (SD1) produced by IES circuit can reduce the ignition delay time (that is, improve the initial combustion phase) compare with conventional ignition system (CIC).

Schlieren photographs for C_3H_8-air with ϕ=0.8



flame kernels of repetitive pulse discharges by IES circuit are found to be ellipsoidal

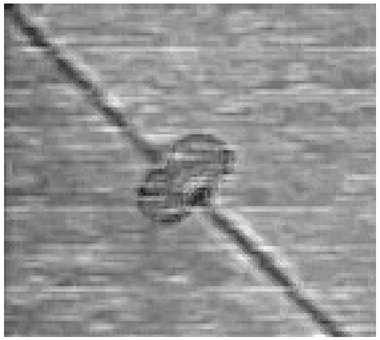
5 repetitive discharges (PRD5) 2 streamer discharges and 3 arc discharges



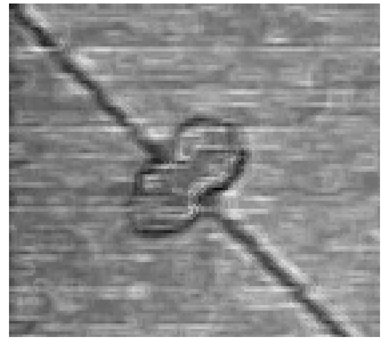
10 repetitive discharges (PRD10) 7 streamer discharges and 3 arc discharges
Total energy: 15mJ

Schlieren photographs for C_3H_8-air with ϕ=0.8

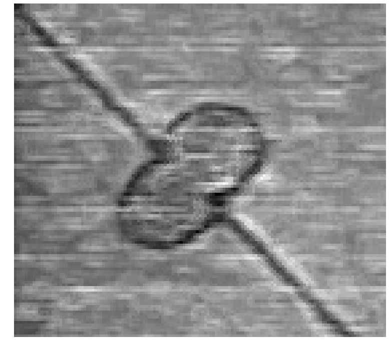
0.5ms



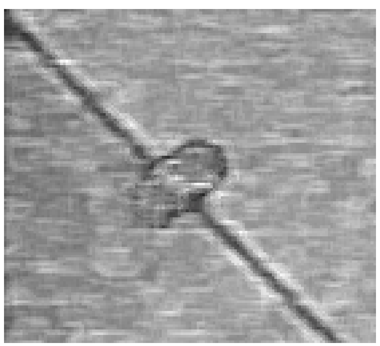
1.7ms

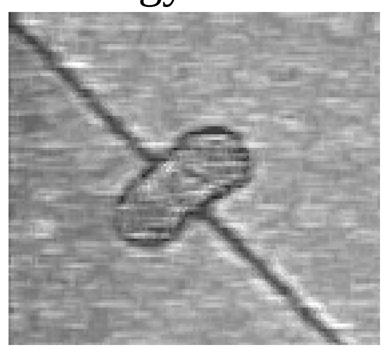


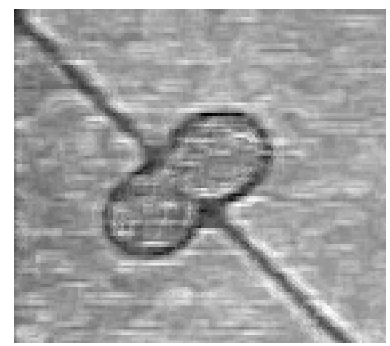
2.9ms



5 repetitive discharges (PRD5) 2 streamer discharges and 3 arc discharges
Total energy: 15mJ



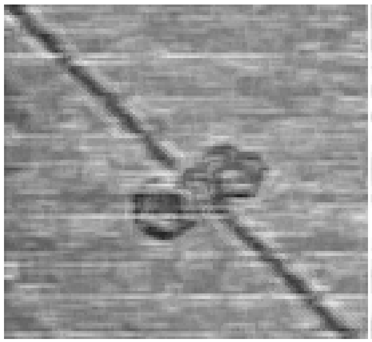




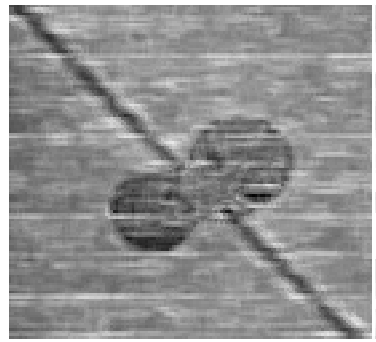
10 repetitive discharges (PRD10) 7 streamer discharges and 3 arc discharges
Total energy: 15mJ

Schlieren photographs for C_3H_8-air with ϕ=0.8

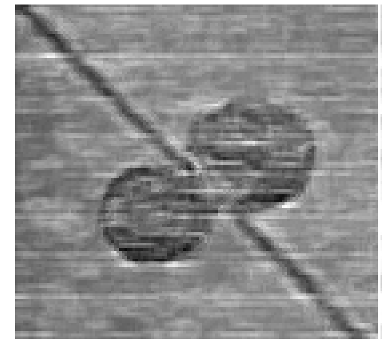
0.5ms



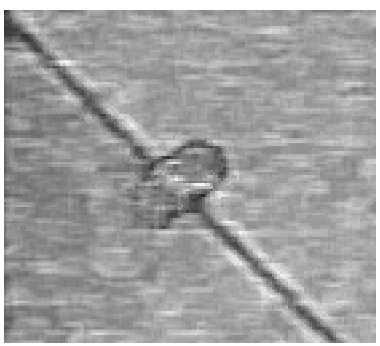
1.7ms

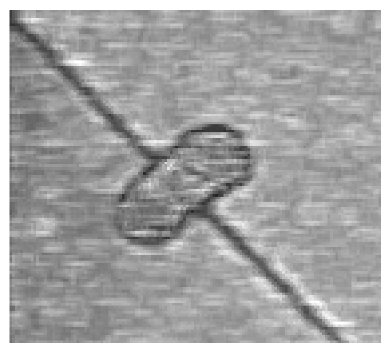


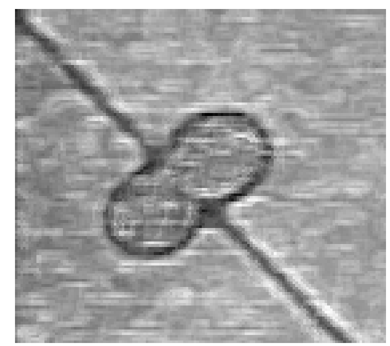
2.9ms



Single discharge (SD1) by IES circuit Total energy: 16mJ





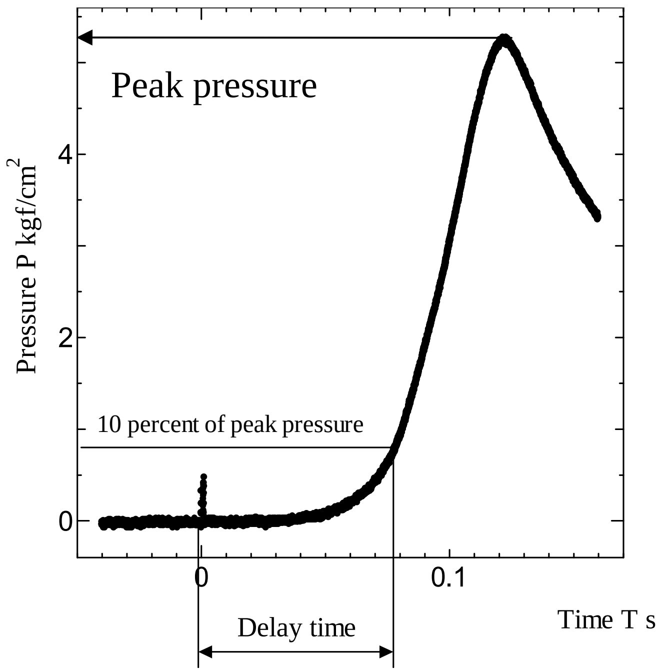


10 repetitive discharges (PRD10) 7 streamer discharges and 3 arc discharges
Total energy: 15mJ

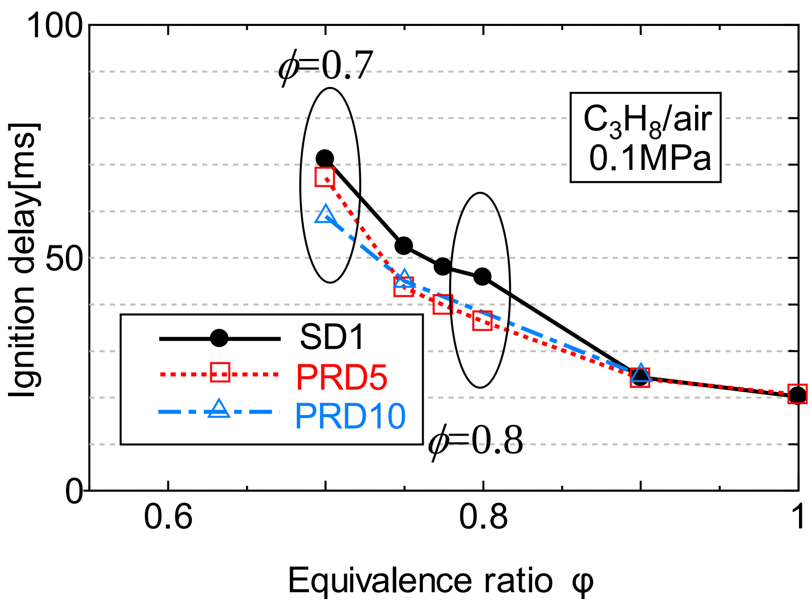
Experiment 3

Ignition Delay Time

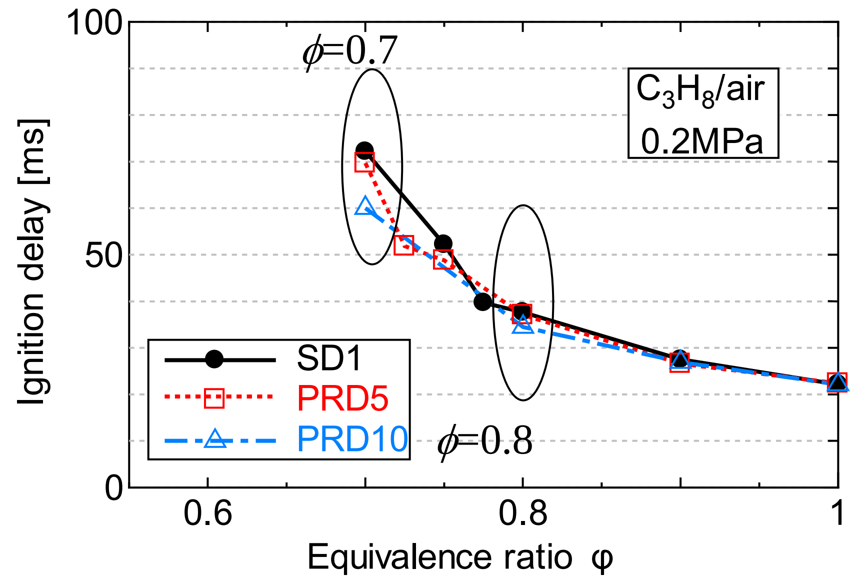
defined as the interval between the ignition current trigger and the time at which the pressure rose to 10% of its maximum pressure.



0.1MPa



0.2MPa



Δt_{ig}= 71ms

Δt_{ig} = 67ms

Δt_{ig} = 59ms

17% improve

Δt_{ig}= 46ms

Δt_{ig} = 36ms

Δt_{ig} = 34ms

17% improve

Δt_{ig}= 72ms

Δt_{ig} = 70ms

Δt_{ig} = 60ms

17% improve

Δt_{ig}= 38ms

Δt_{ig} = 37ms

Δt_{ig} = 34ms

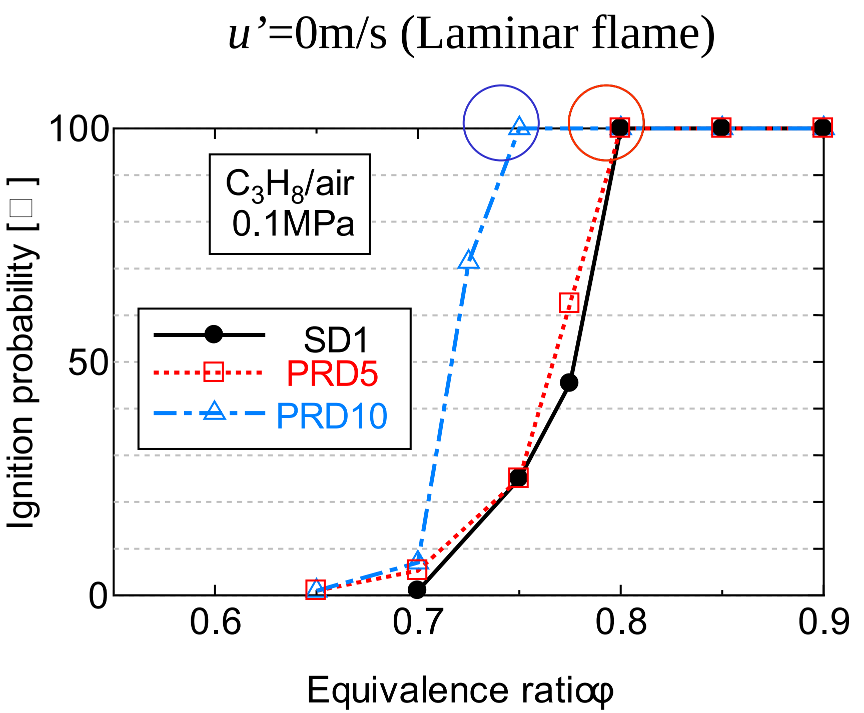
11% improve

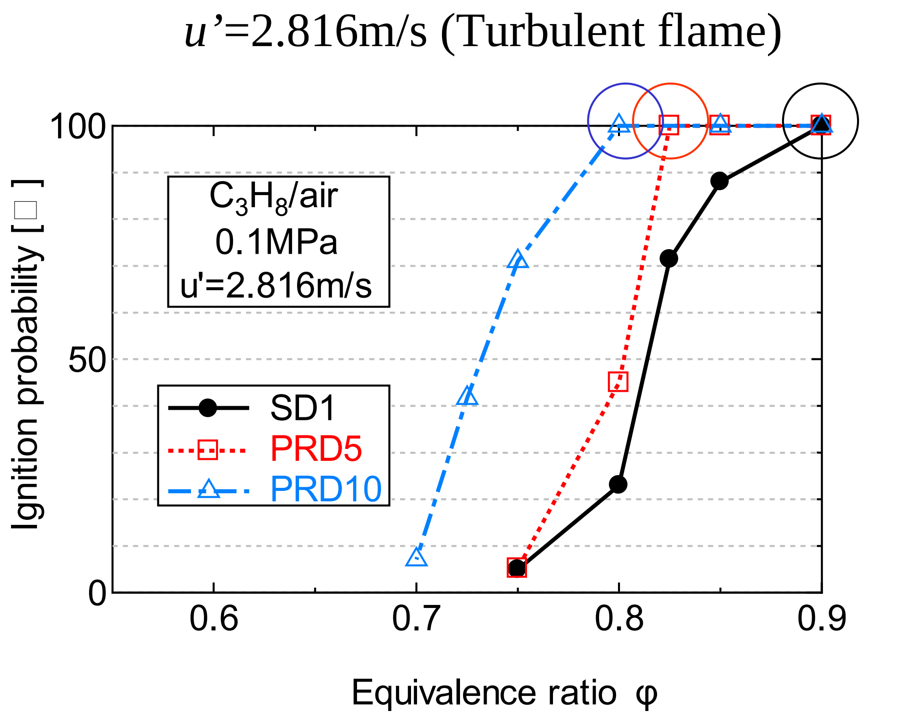
In conclusion, repetitive pulse discharges can reduce the ignition delay time (that is, improve the initial combustion phase) in the fuel lean region at both normal and elevated pressures and this tendency becomes more remarkable as the number of pulses increases.

Experiment 4

Investigation of the effect of the discharge types on the lean flammability limit and the initial combustion phase subject to turbulence.

Flammability Limit under Turbulence





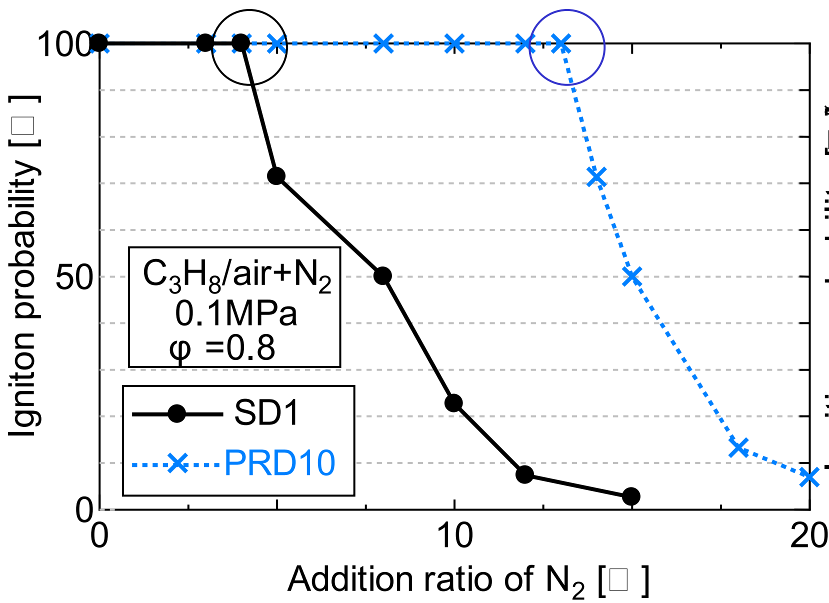
$\phi_{lim} = 0.75$ | $\phi_{lim} = 0.8$ | $\phi_{lim} = 0.8$ | $\phi_{lim} = 0.8$ | $\phi_{lim} = 0.85$ | $\phi_{lim} = 0.9$

These conclude that repetitive pulse discharges can extend the flammability limit for turbulent combustion as well as laminar combustion, and this tendency becomes more remarkable as the number of pulses increases.

Experiment 5

Investigation of the effect of the discharge types on the lean flammability limit and the initial combustion phase for mixtures diluted by inert gases.

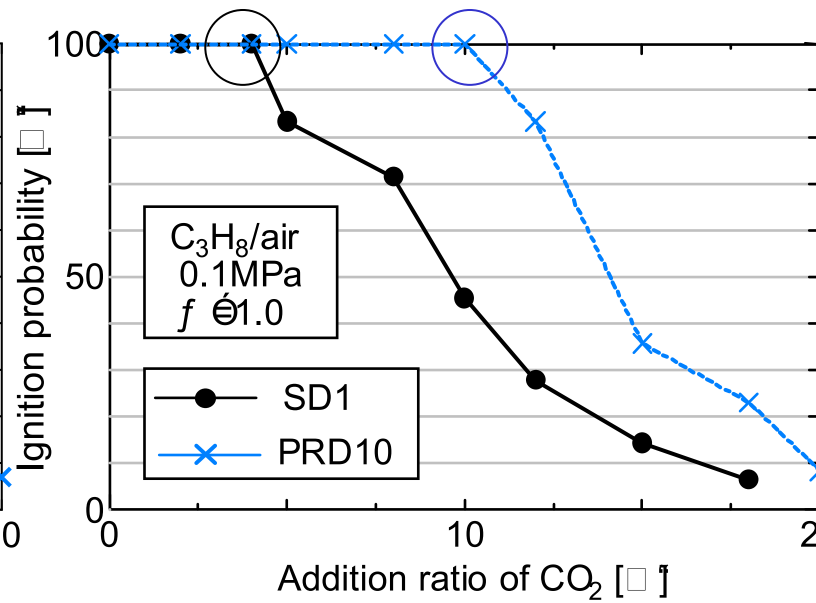
N_2 dilution



X_{lim}= 4%

X_{lim}= 13%

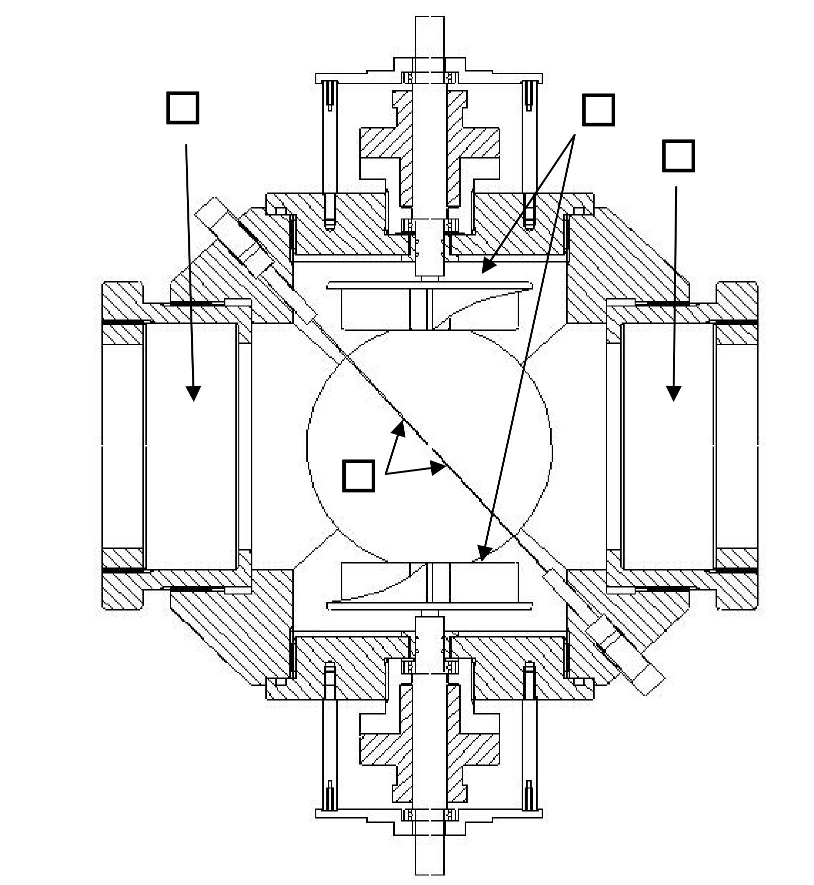
CO_2 dilution

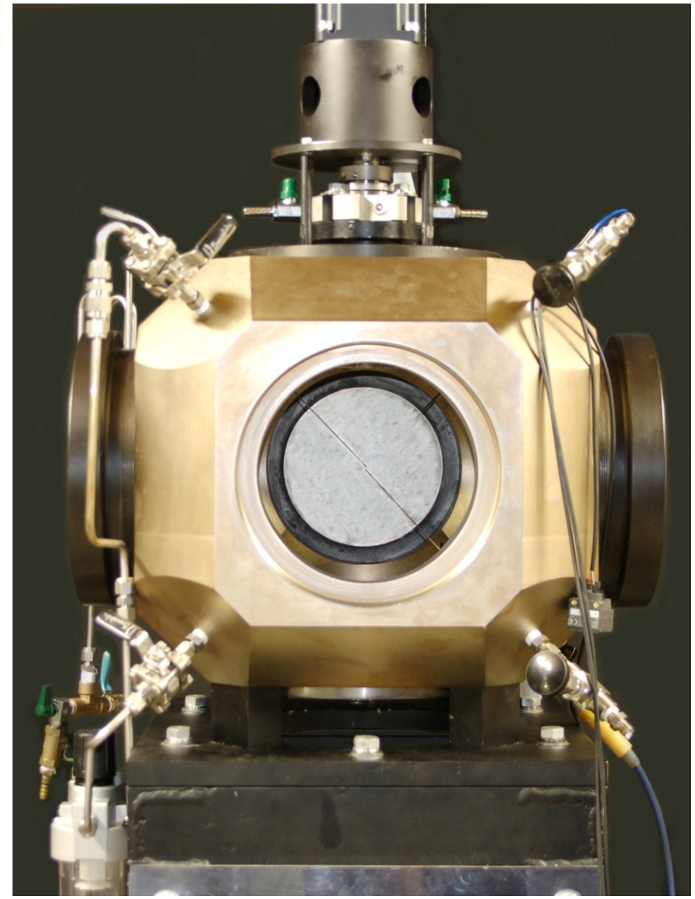


X_{lim}= 4%

X_{lim}= 10%

These conclude that repetitive pulse discharges can improve inflammabilities of mixture diluted by N_2 and CO_2,





□Observation window
□Ignition plug
□Fan

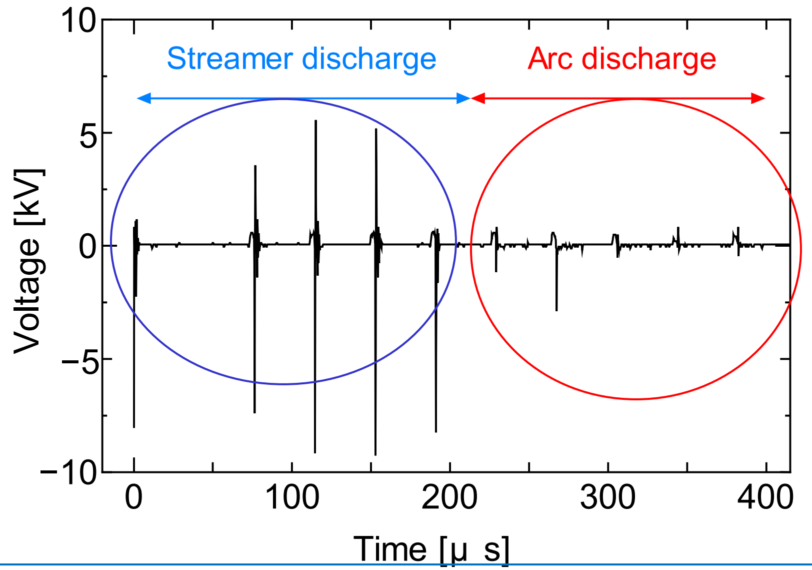
Mixtures

$$\mathrm{C_3H_8} + X_0\left(\mathrm{O_2} + 3.76\mathrm{N_2}\right)$$

ϕ Equivalence ratio $\qquad \phi = \dfrac{5}{X_0}$

Initial pressure was set at 0.1 MPa or 0.2 MPa,

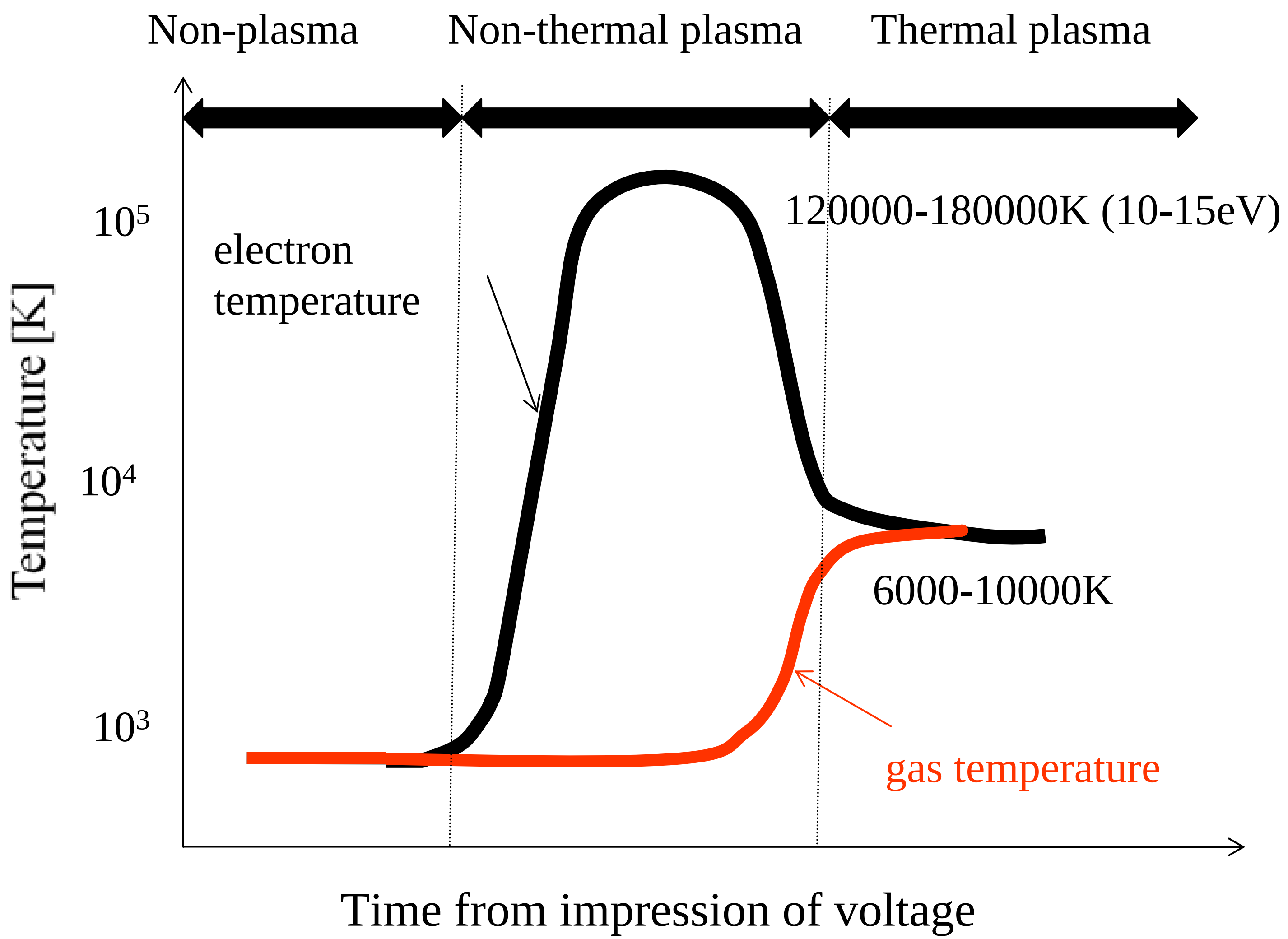
Expected mechanisms which can result in improvement of inflammability



1. The streamer discharges with high dV/dt occur several times from the beginning, whose pulse duration of 10 ns to 200 ns employed here is expected to generate active species related to combustion process efficiently.

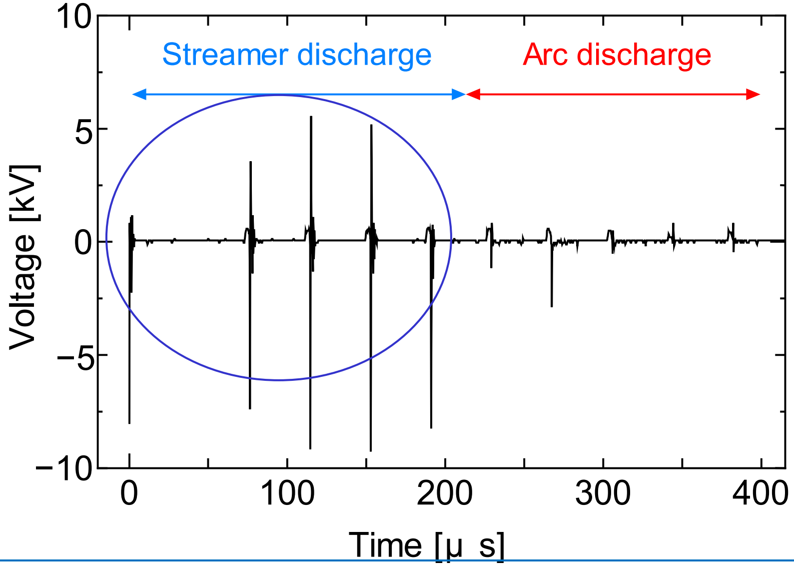
2. After that, nanosecond arc discharges occur also several times, which can create higher energy density and temperature gradient. This leads to transferring generated energy into a combustible mixture with smaller heat loss.

Streamer discharges and Arc discharges



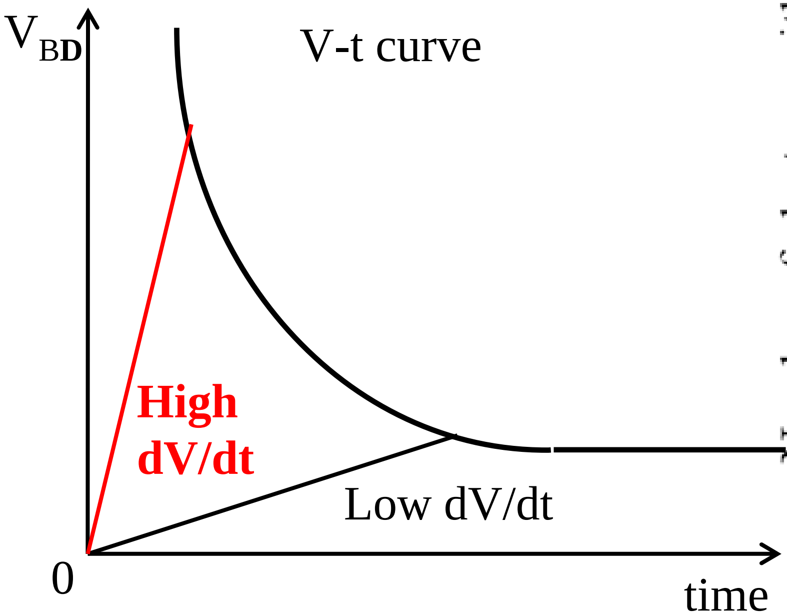
SAE 2008-01-0466, T.Shiraish, et. al

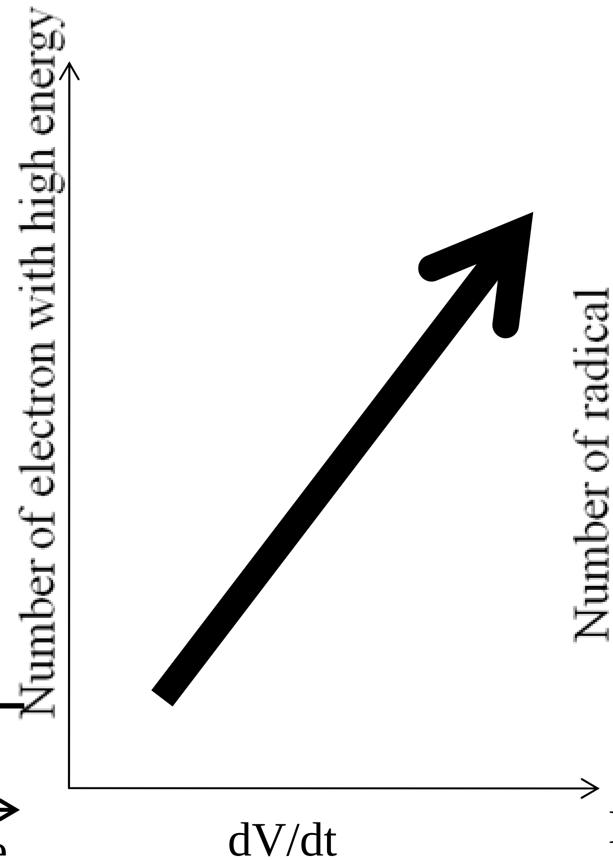
Expected mechanisms which can result in improvement of inflammability

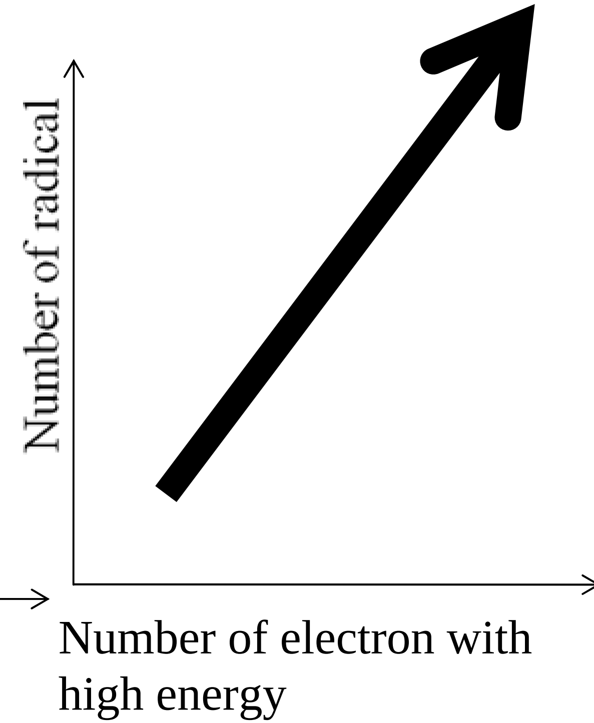


1. The streamer discharges with high dV/dt occur several times from the beginning, whose pulse duration of 10 ns to 200 ns employed here is expected to generate active species related to combustion process efficiently.

About streamer discharges

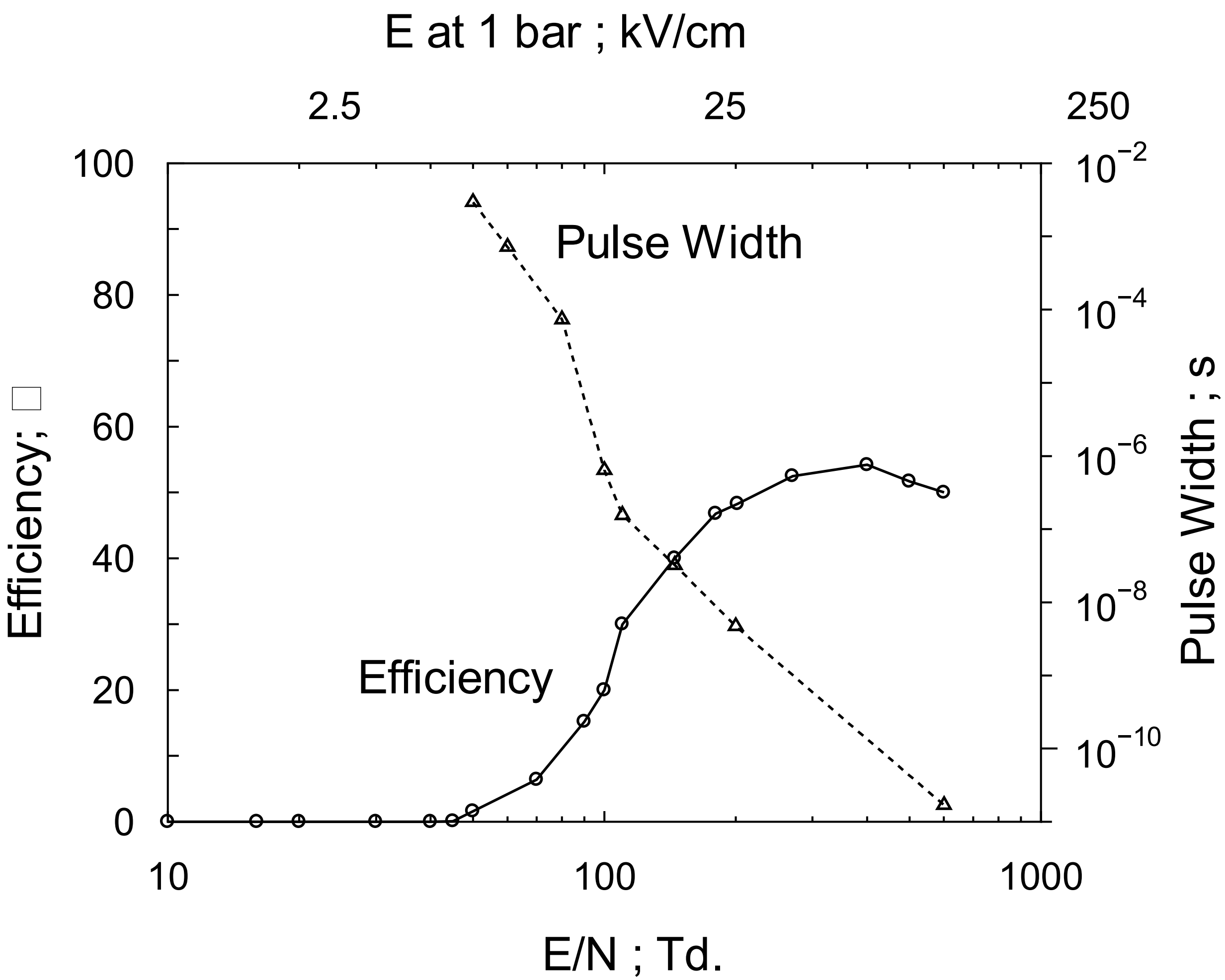






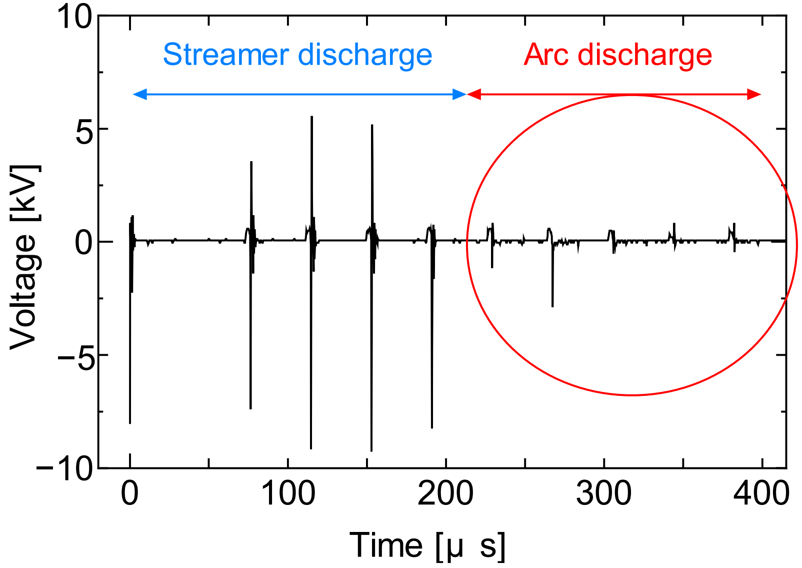
The streamer discharges with high dV/dt can generate active species efficiently.

About streamer discharges



Lowke, J.J., Morrow, R.,"Theoretical Analysis of Removal of Oxides of Sulphur and Nitrogen in Pulsed Operation of Electrostatic Precipitators", IEEE Trans. Plasma Sci., Vol.23, pp.661-671, (1995).

Expected mechanisms which can result in improvement of inflammability

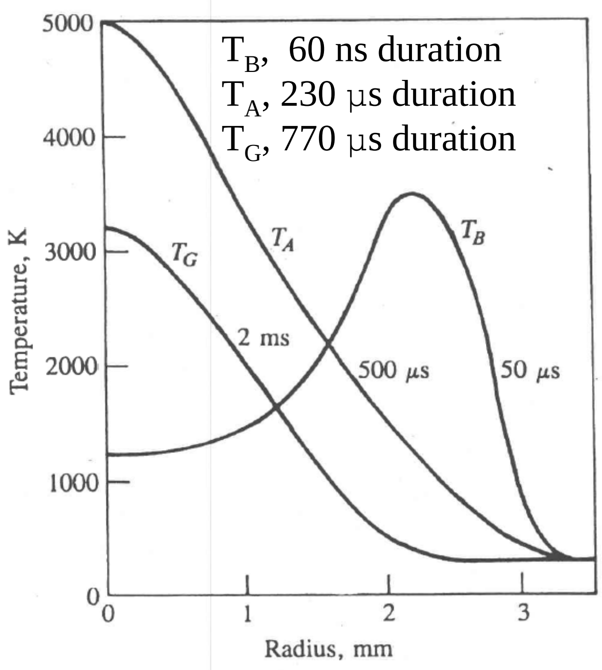


2. After that, nanosecond arc discharges occur also several times, which can create higher energy density and temperature gradient. This leads to transferring generated energy into a combustible mixture with smaller heat loss.

About short duration arc discharges

Maly has found the inflammability can be increased with decreasing the time interval in which the ignition energy is supplied. He attributed this to the formation of larger plasma radii, which increase reaction rates, reduce total burn times, and lower any adverse effects.

With these findings, he concluded that practical systems have to be optimized for transferring the energy in extremely short time intervals which is possible by suitable layouts. He and his college developed breakdown spark system, which is referred to as VFZ.
Maly's study has been important to clarify the fundamental phenomena of ignition, but short duration ignition like breakdown ignition systems have not yet been introduced on production engines.



Radial temperature profiles at selected times after spark onset for three different ignition systems.

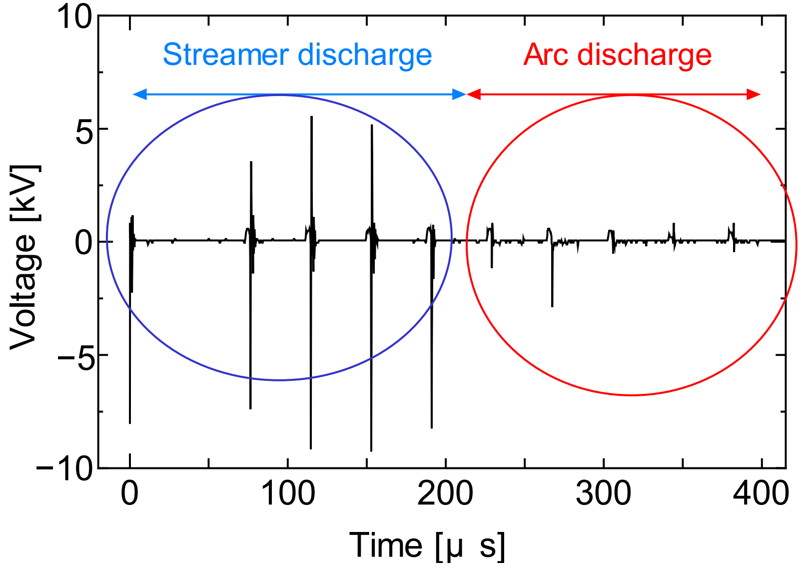
Shorter duration ignition is found to produce a larger plasma, earlier, with a steep temperature front.

Thus it creates favorable conditions for transferring heat and radicals to the surrounding unburned mixture.

In addition, heat loss to the electrodes becomes smaller because the flame kernel is located far away from the electrodes

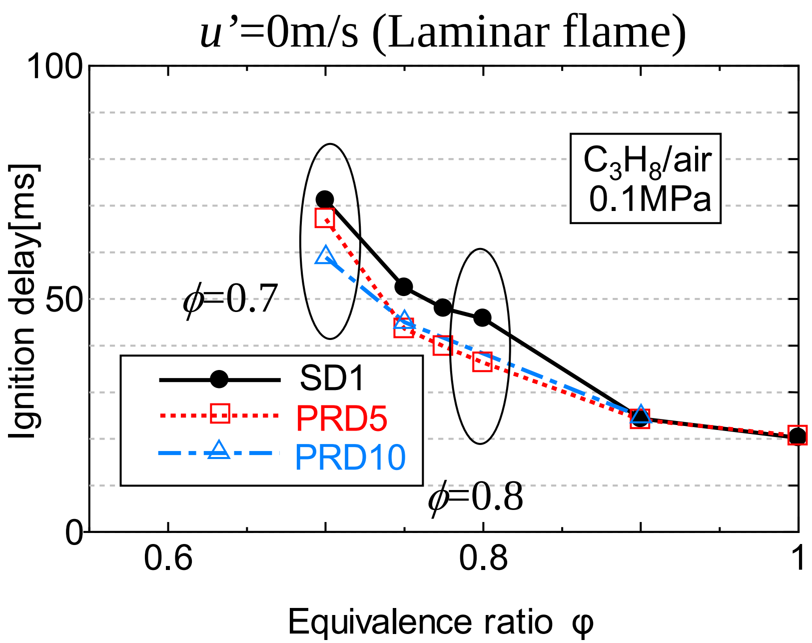
Maly, R., "Spark Ignition: Its Physics and Effect on the Internal Combustion Engine", Fuel Economy in Road Vehicles Powered by Spark Ignition Engines, Plenum Press, pp.91-148, (1984).

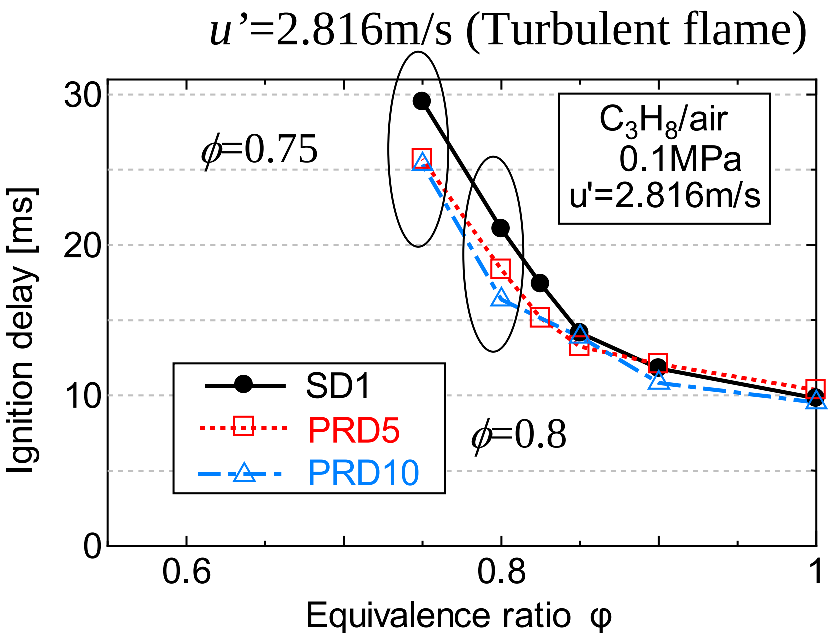
Expected mechanisms which can result in improvement of inflammability



1. The streamer discharges with high dV/dt can generate active species efficiently.

2. The short duration arc discharges can produce a larger flame kernel, which causes less heat loss, and larger effective gas volume exposed to ignition.





Δt_{ig} = 71ms

Δt_{ig} = 67ms

Δt_{ig} = 59ms

17% improve

Δt_{ig} = 46ms

Δt_{ig} = 36ms

Δt_{ig} = 34ms

17% improve

Δt_{ig} = 30ms

Δt_{ig} = 26ms

Δt_{ig} = 25ms

17% improve

Δt_{ig} = 21ms

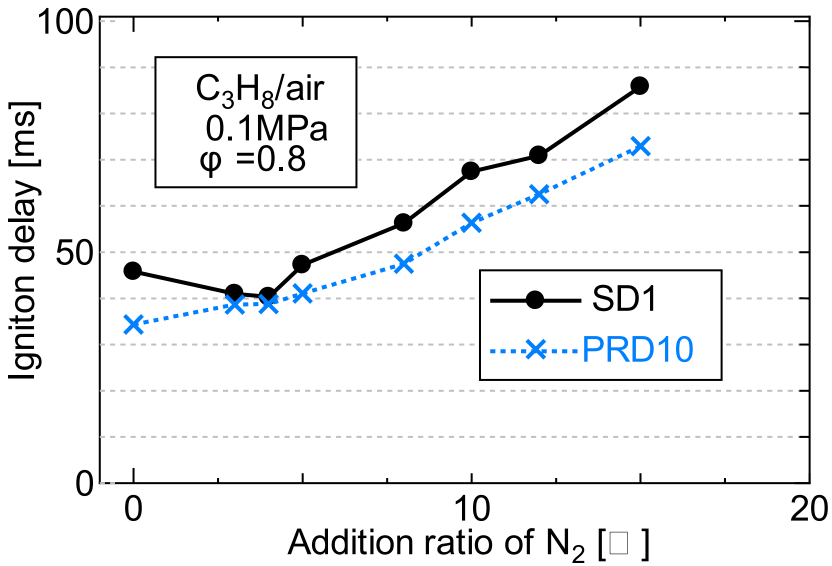
Δt_{ig} = 18ms

Δt_{ig} = 16ms

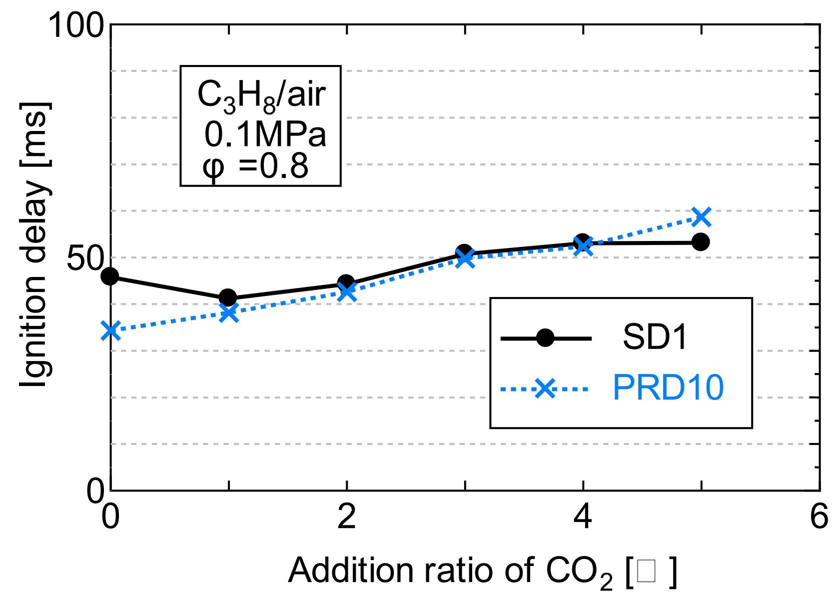
24% improve

In conclusion, repetitive pulse discharges can reduce the ignition delay time (that is, improve the initial combustion phase) for turbulent combustion as well as laminar combustion, and this tendency becomes more remarkable as the number of pulses increase.

N_2 dilution

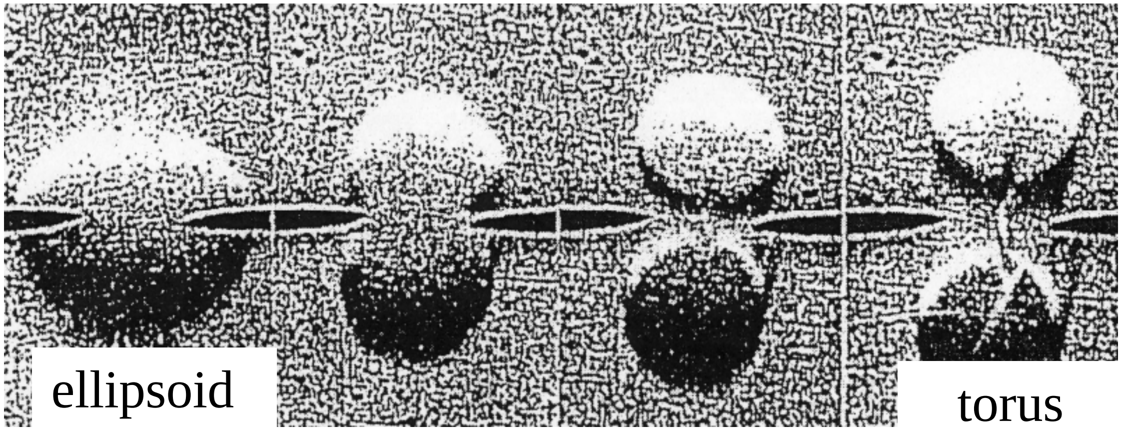


CO_2 dilution

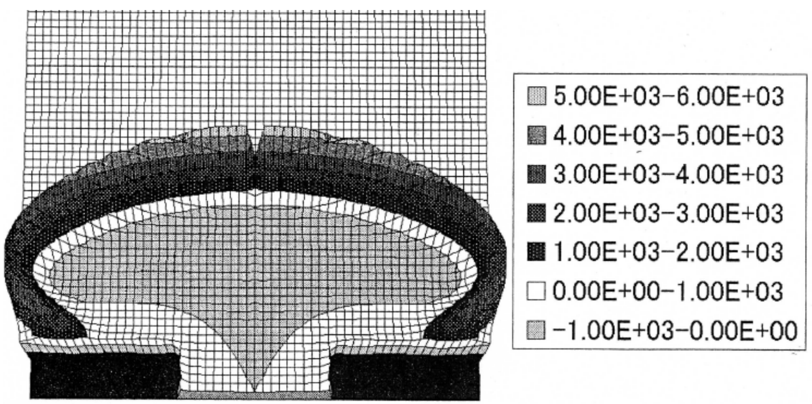


About short duration arc discharges

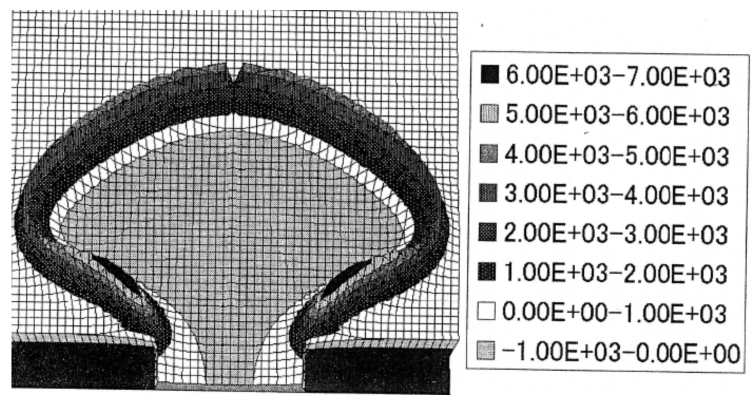
Schlieren photographs of flame kernels



Calculated heat release distributions



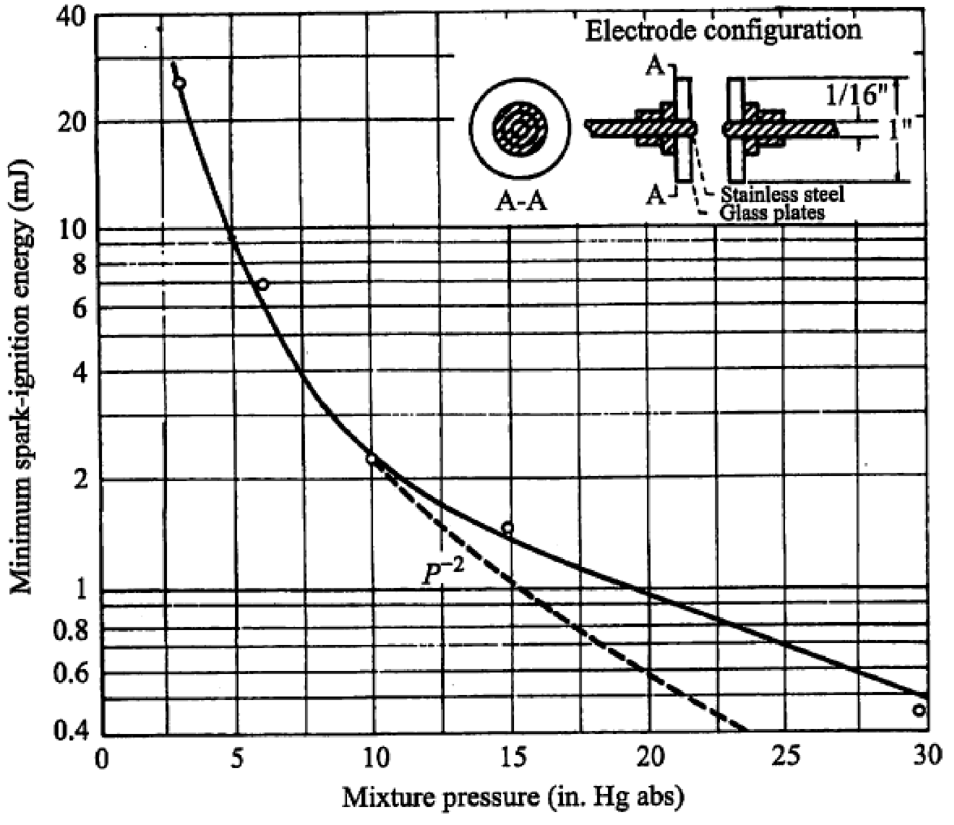
(a) Ratio of capacity spark energy 20% corresponding to longer duration



(b) Ratio of capacity spark energy 80% corresponding to shorter duration

Tsue, M., Kono, M., “A Numerical Simulation on Spark Ignition Process in Combustion Mixtures”, J. Combust. Soc. Japan, Vol.48, No.145, pp.257-264, (2006).

Effect of Pressure on minimum spark ignition energy



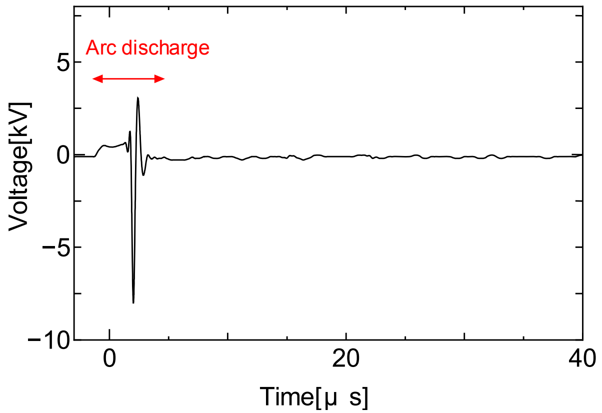
Turns, S.R., "Introduction to Combusiton", MaGraw-Hill, INC.

Experiment 5

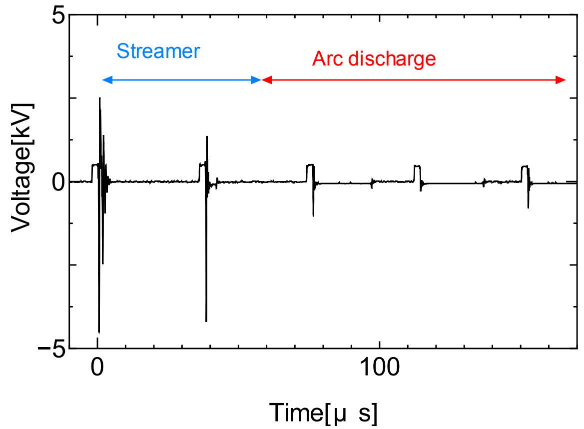
Ignition Delay Time under Turbulence

Experiment 2

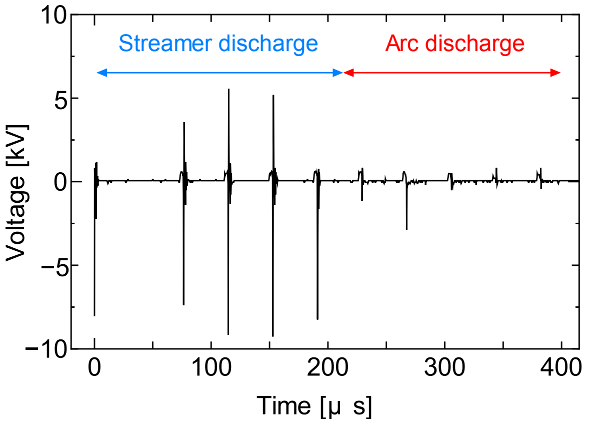
Flammability Limit at Normal Pressure



Single pulse of IES circuit (SD1)



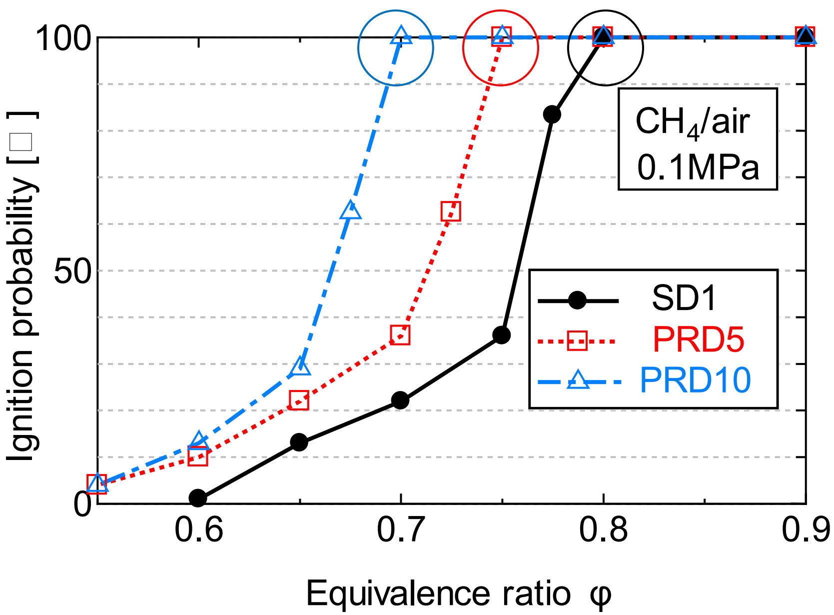
5 pulses of IES circuit (PRD5)



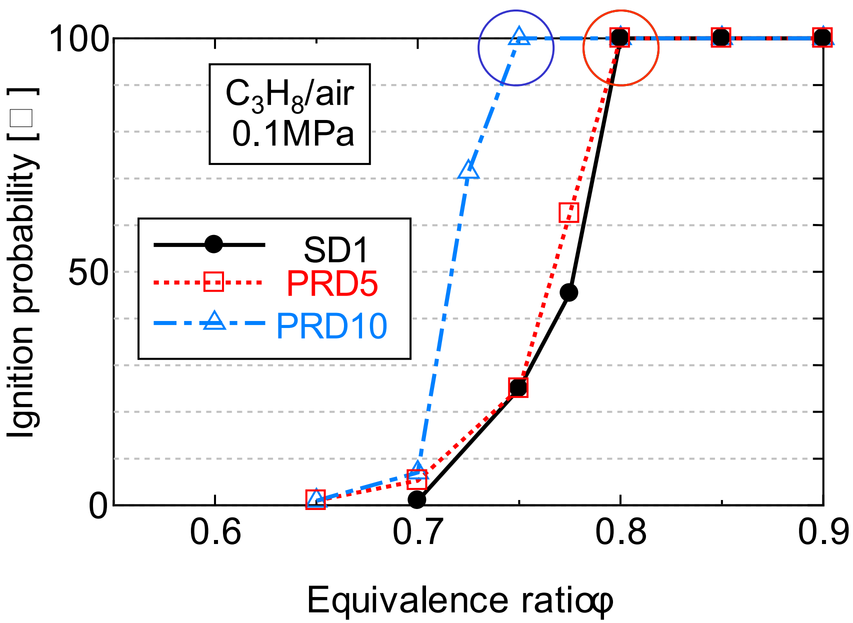
10 pulses of IES circuit (PRD10)

Experiments were carried out 10 to 100 times for each condition with almost the same ignition energy of about 30 mJ for N-P type plug.

Flammability Limit at Normal Pressure



CH$_4$



C$_3$H$_8$

$\phi_{\mathrm{lim}} = 0.7$	$\phi_{\mathrm{lim}} = 0.75$	$\phi_{\mathrm{lim}} = 0.8$	$\phi_{\mathrm{lim}} = 0.75$	$\phi_{\mathrm{lim}} = 0.8$	$\phi_{\mathrm{lim}} = 0.8$

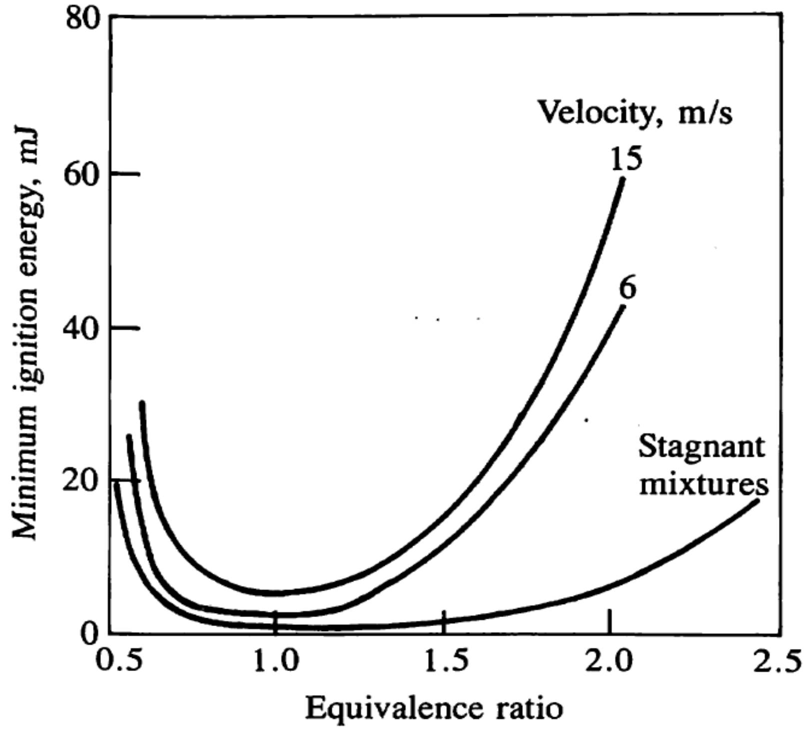
Mixtures

$$CH_4 + X_0\left(O_2 + 3.76N_2\right) \qquad \phi = \frac{2}{X_0}$$

$$C_3H_8 + X_0\left(O_2 + 3.76N_2\right) \qquad \phi = \frac{5}{X_0}$$

ϕ **Equivalence ratio**

Effect of mixture equivalence ratio and flow velocity on minimum ignition energy for propane-air mixtures at 0.17atm

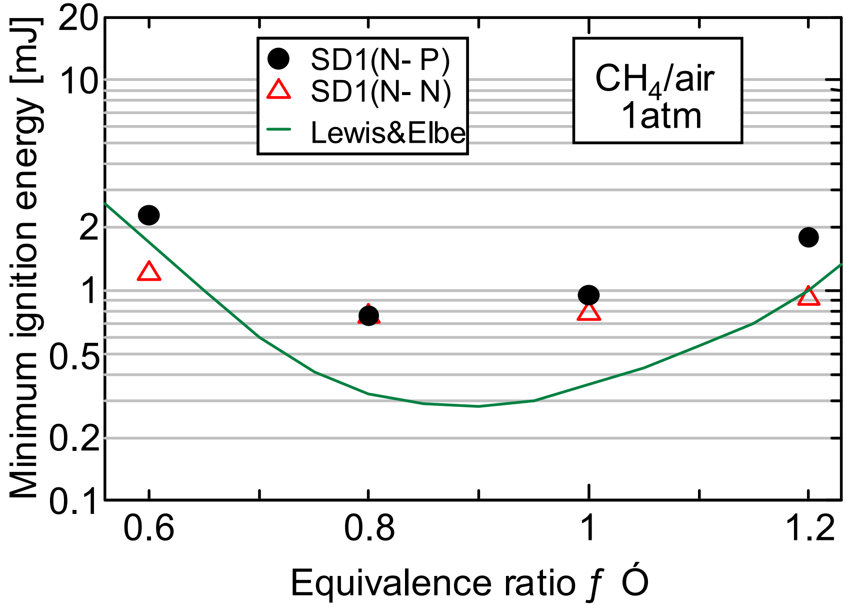


Heywood, J.B., “Internal Combustion Engine Fundamentals”, MaGraw-Hill, INC.

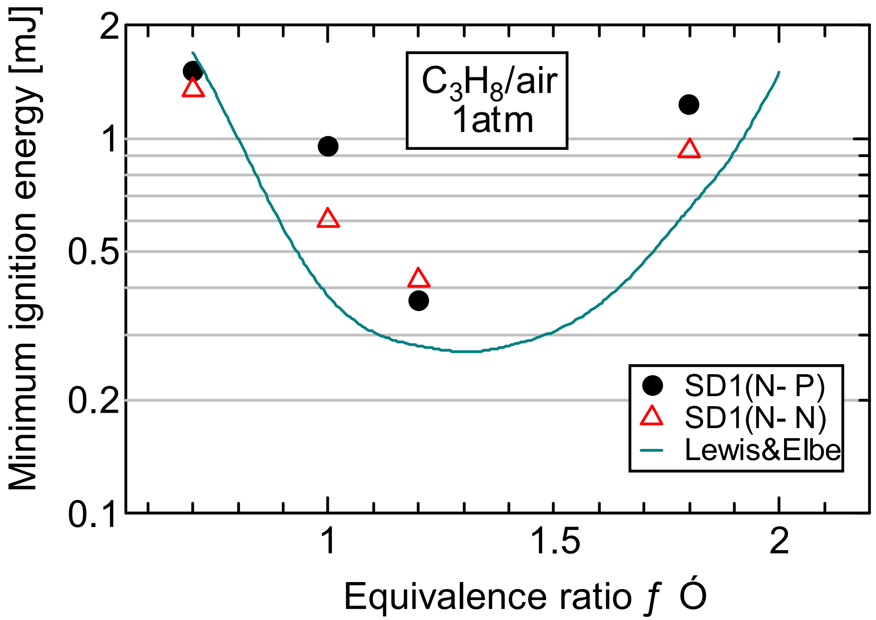
Experiment 1

Minimum Ignition Energy

Minimum Ignition Energy



CH_4



C_3H_8

Concepts

Energy distribution for breakdown, arc, and glow discharges†

	Breakdown, %	Arc, %	Glow, %
Radiation loss	<1	5	<1
Heat loss to electrodes	5	45	70
Total losses	6	50	70
Plasma energy	94	50	30

† Typical values, under idealized conditions with small electrodes.
Source: Maly and Vogel.[52]

Maly has summarized these fundamental aspects of spark discharge ignited flames as follows:
Of the total electrical energy supplied to the spark, only that fraction contained within the outer surface layer of the plasma (of thickness of the order of the inflammation zone) is available for initiating the flame propagation process. The energy density and the temperature gradient in the thin layer depend on the discharge mode. Highest energy densities and temperature gradients are achieved if the ignition energy is supplied in the shortest time interval .

Heywood, J.B., “Internal Combustion Engine Fundamentals”, MaGraw-Hill, INC.

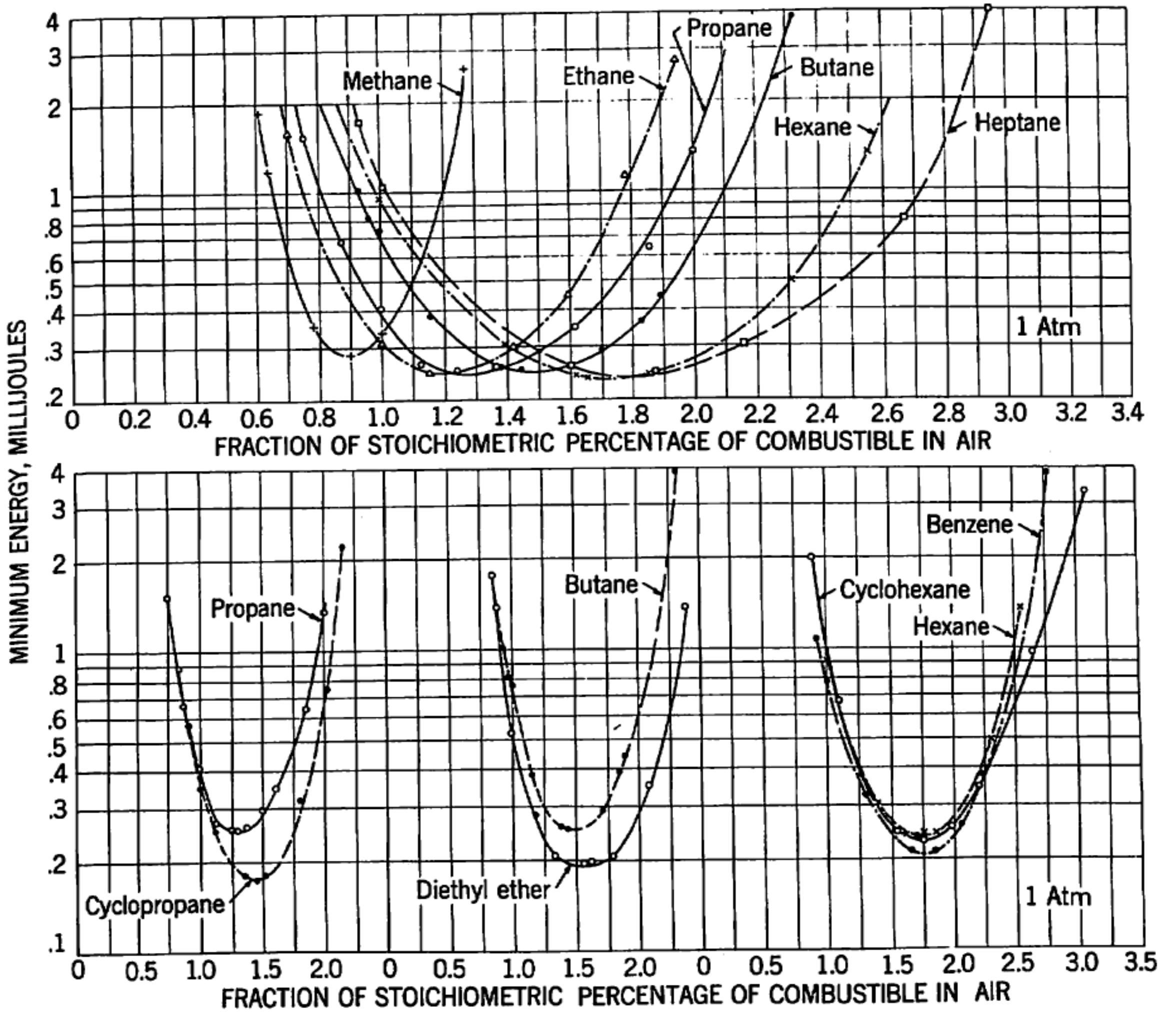
- Characteristics of streamer discharge
  - Multiple streamers of electrons
  - High energy electrons compared to sparks
  - Electrons not at thermal equilibrium with ions/neutrals
  - Ions stationary - no hydrodynamics
  - Low anode & cathode drops, little radiation & shock formation - more efficient use of energy deposited into gas

Features of this ignition system

1.Streamer discharge (Non-equilibrium plasma) to generate active species related to combustion process efficiently.

2.Arc with short duration

3.Repetative nano pulse to increase in ignition probability

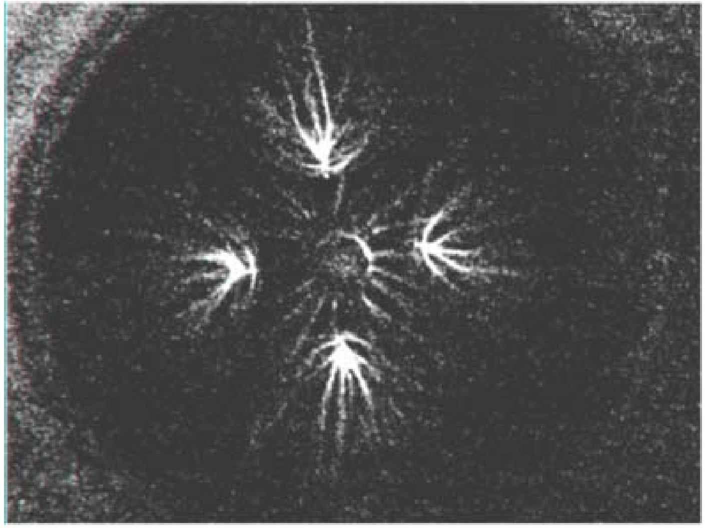


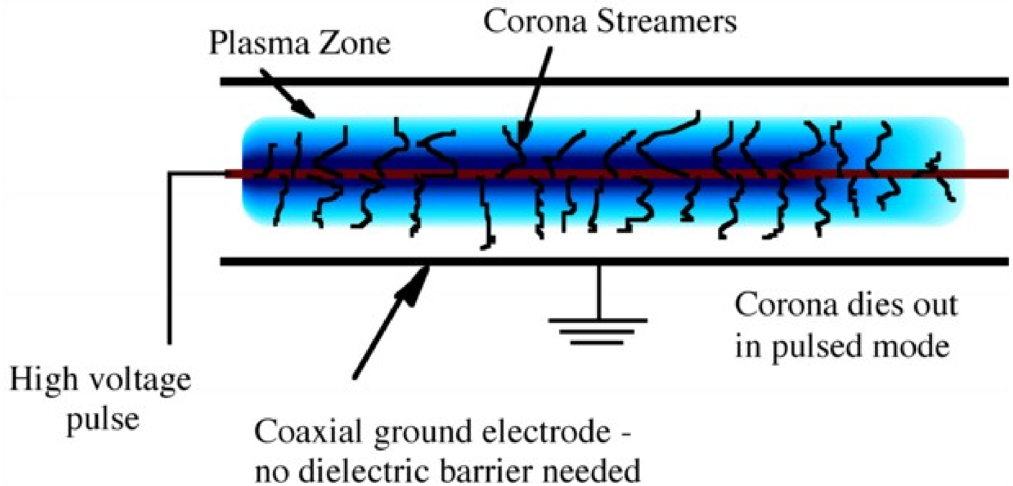
The minimum ignition energy as a function of equivalence ratio for air and various fuels

Lewis, B. and Elbe, G., "Combustion, Flames and Explosions of Gases", Academic Press, INC.

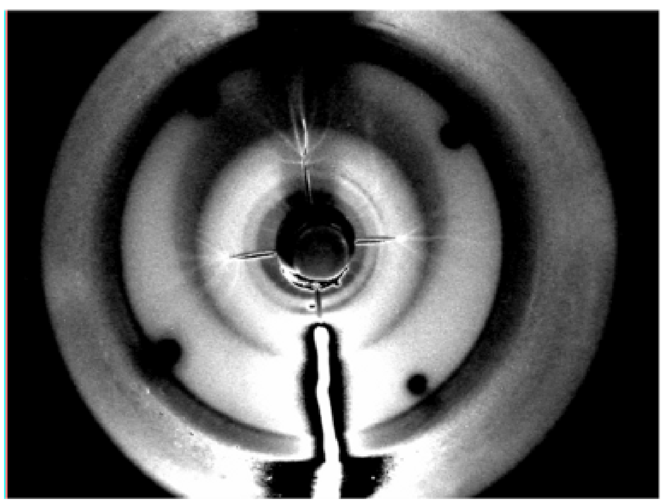
Future Work

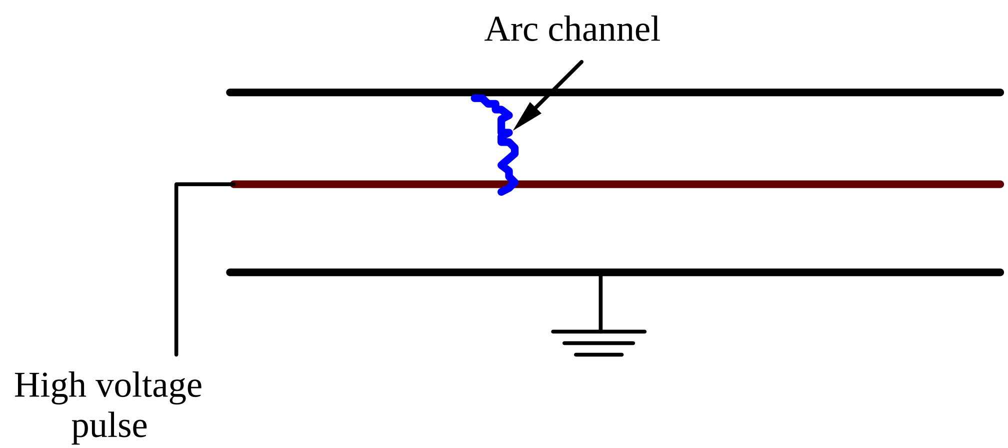
1. [illegible]
2. [illegible]
3. [illegible]
4. [illegible]





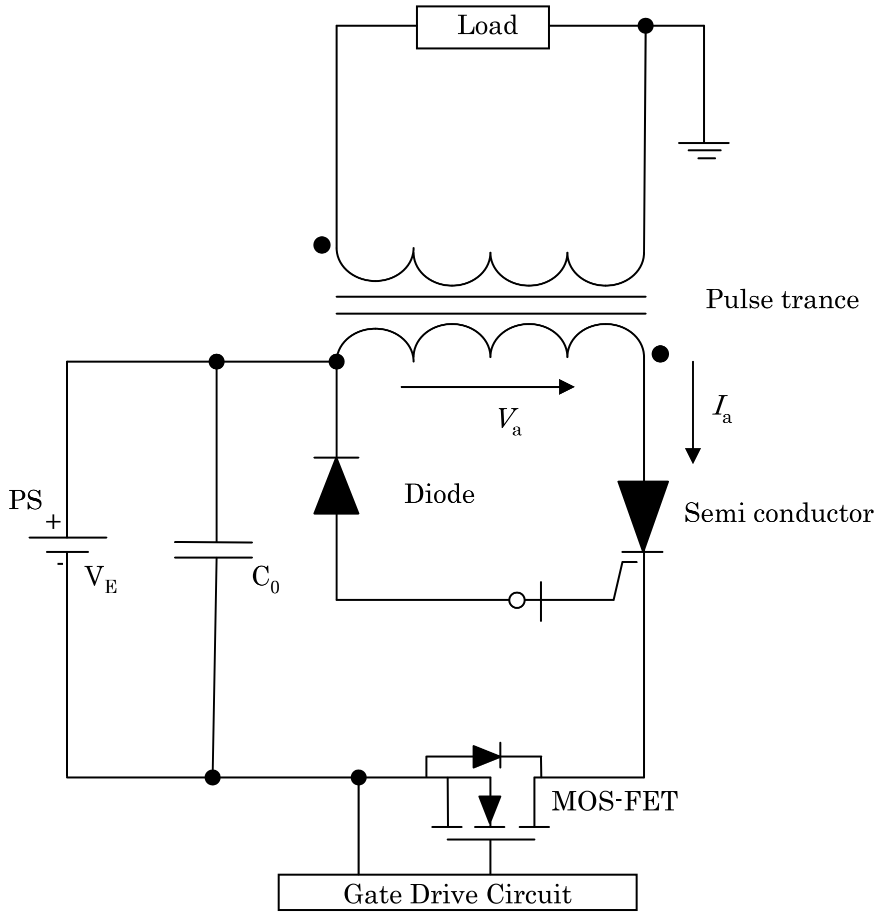
Corona phase (0 - 100 ns)





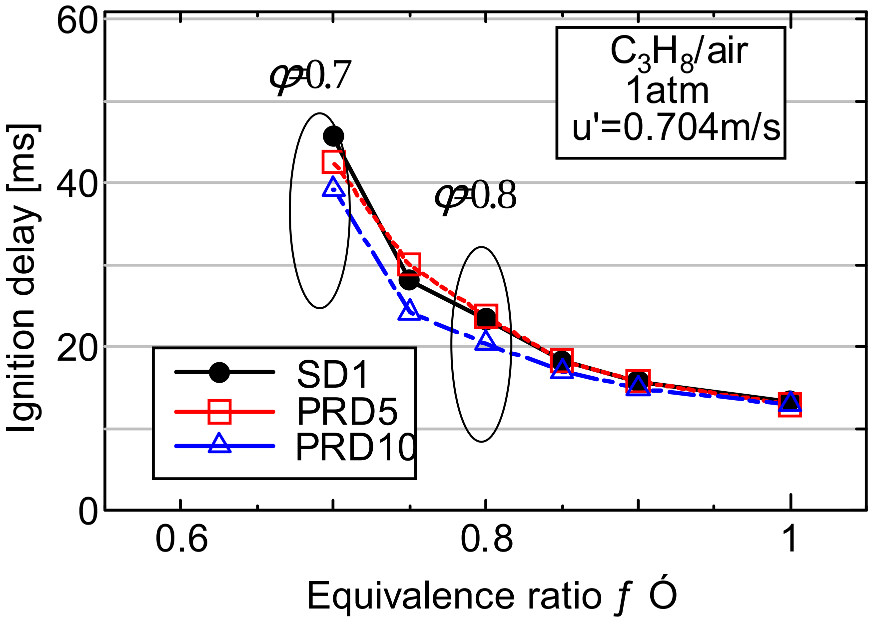
Arc phase (> 100 ns)

Basic IES circuit

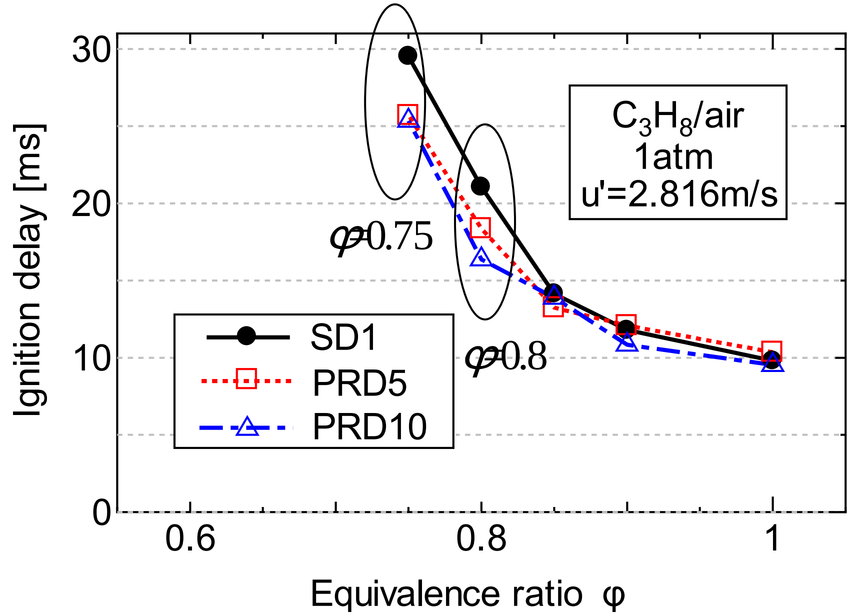


Ignition Delay Time under Turbulence

***u'*=0.704m/s**



***u'*=2.816m/s**



Δt_{ig}= 46ms

Δt_{ig} = 43ms

Δt_{ig} = 39ms

15% improve

Δt_{ig}= 23ms

Δt_{ig} = 23ms

Δt_{ig} = 20ms

13% improve

Δt_{ig}= 30ms

Δt_{ig} = 26ms

Δt_{ig} = 25ms

17% improve

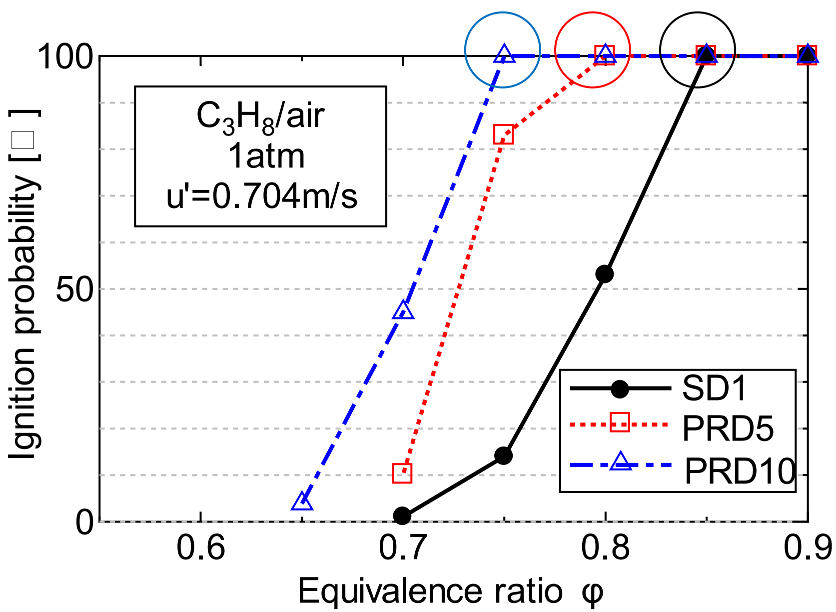
Δt_{ig}= 21ms

Δt_{ig} = 18ms

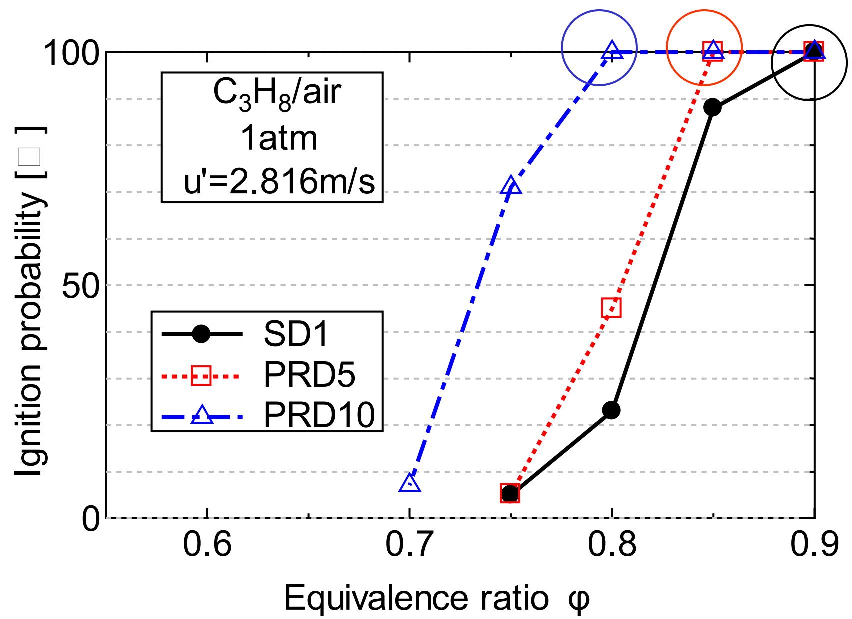
Δt_{ig} = 16ms

24% improve

Flammability Limit under Turbulence



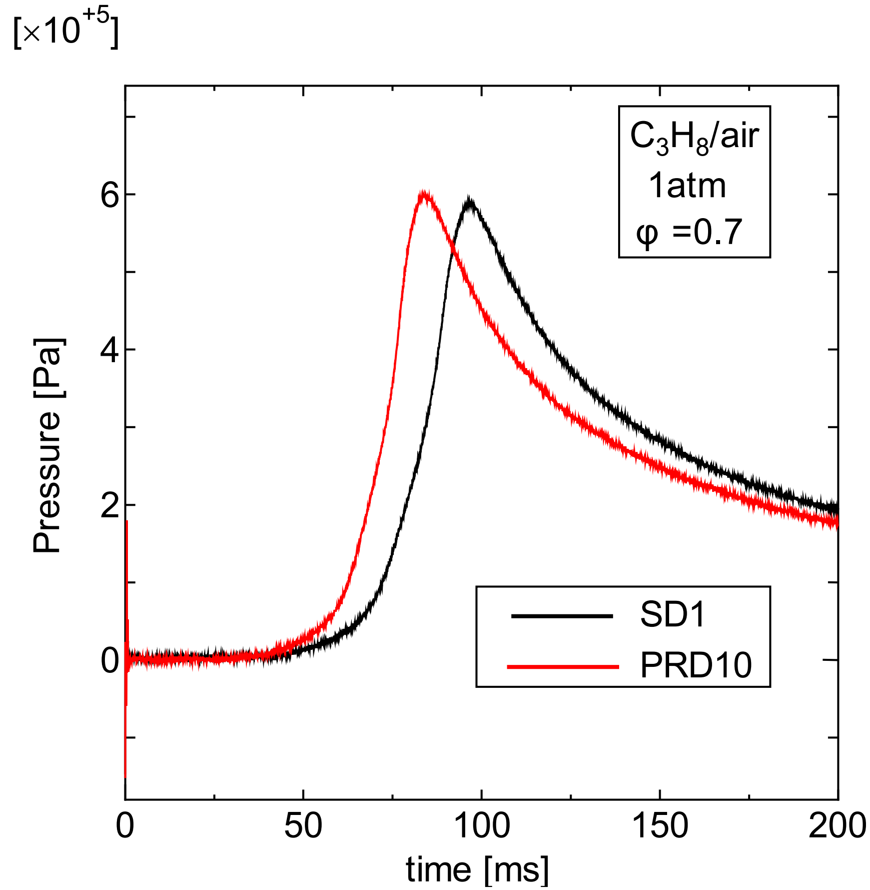
***u'*=0.704m/s**



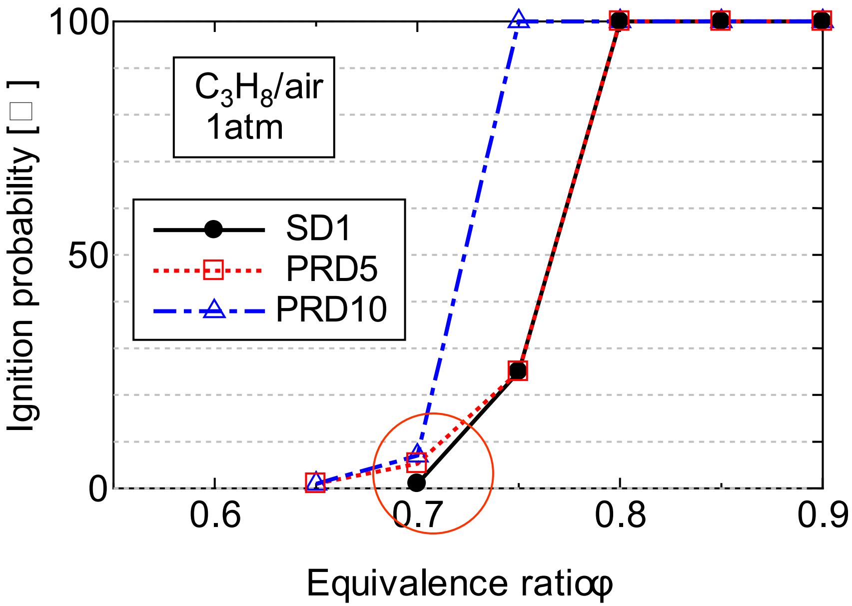
***u'*=2.816m/s**

$\phi_{lim} = 0.75$ | $\phi_{lim} = 0.8$ | $\phi_{lim} = 0.85$ | $\phi_{lim} = 0.8$ | $\phi_{lim} = 0.85$ | $\phi_{lim} = 0.9$

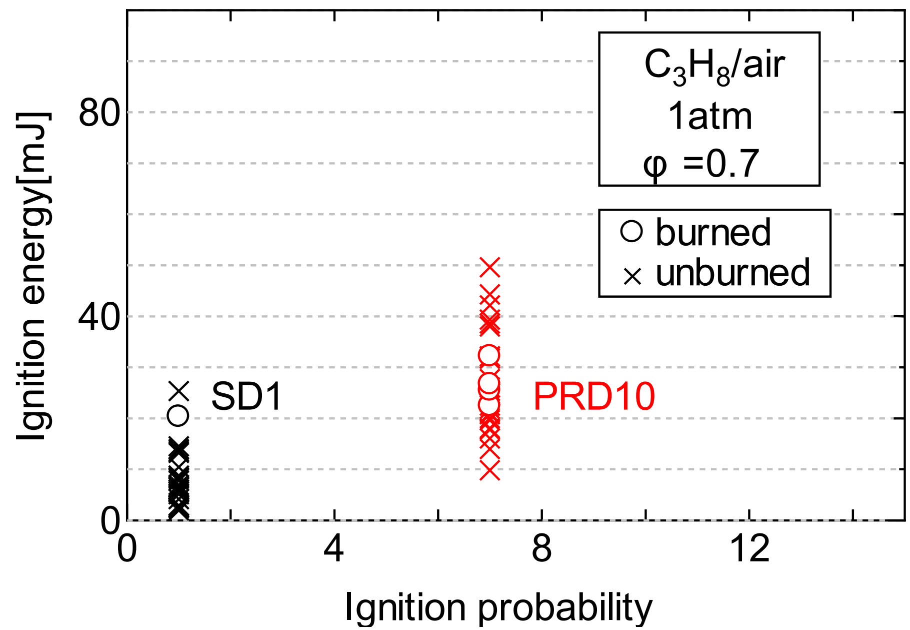
□□□□□□□□□□□□□□□□□□□□



[×10+5]
Pressure [Pa]
time [ms]
C3H8/air
1atm
φ =0.7
SD1
PRD10
0
2
4
6
0
50
100
150
200



100
50
0
0.6
0.7
0.8
0.9
Ignition probability [□]
Equivalence ratioφ
C_3H_8/air
1atm
SD1
PRD5
PRD10



80
40
0
0
4
8
12
Ignition energy[mJ]
Ignition probability
C_3H_8/air
1atm
φ =0.7
○ burned
× unburned
SD1
PRD10

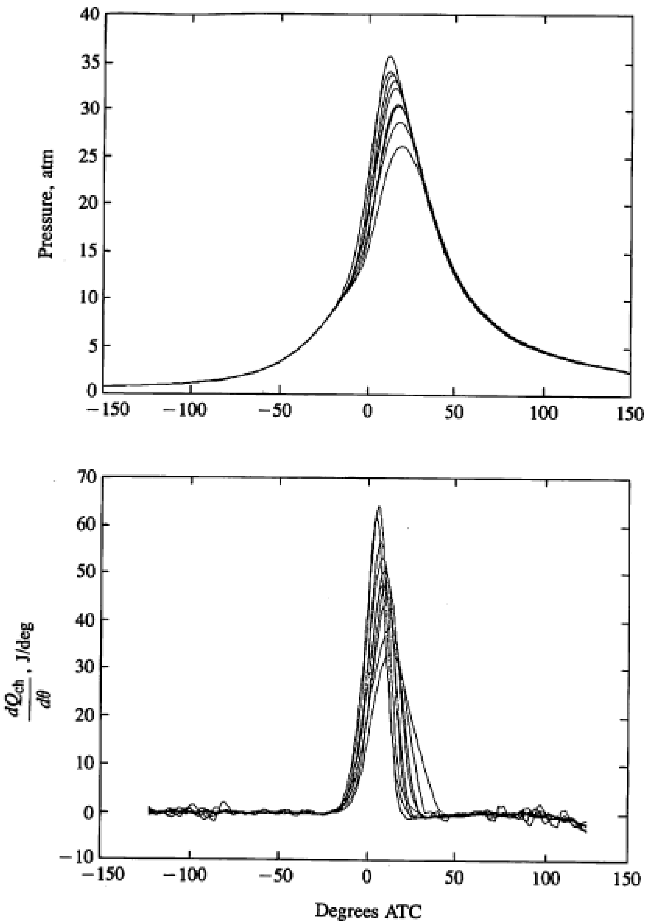


Fig.9-31 Measured cylinder pressure and calculated gross heat-release rate for ten cycles in single cylinder spark-ignition engine operating atl 500rev/min,

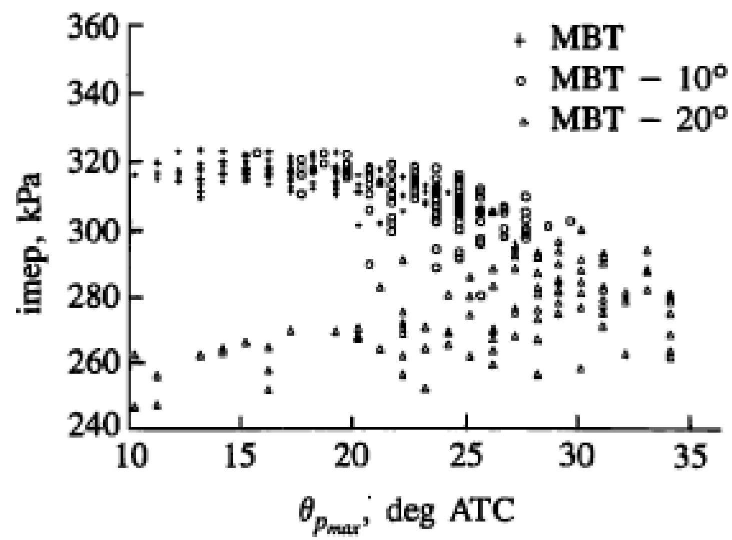
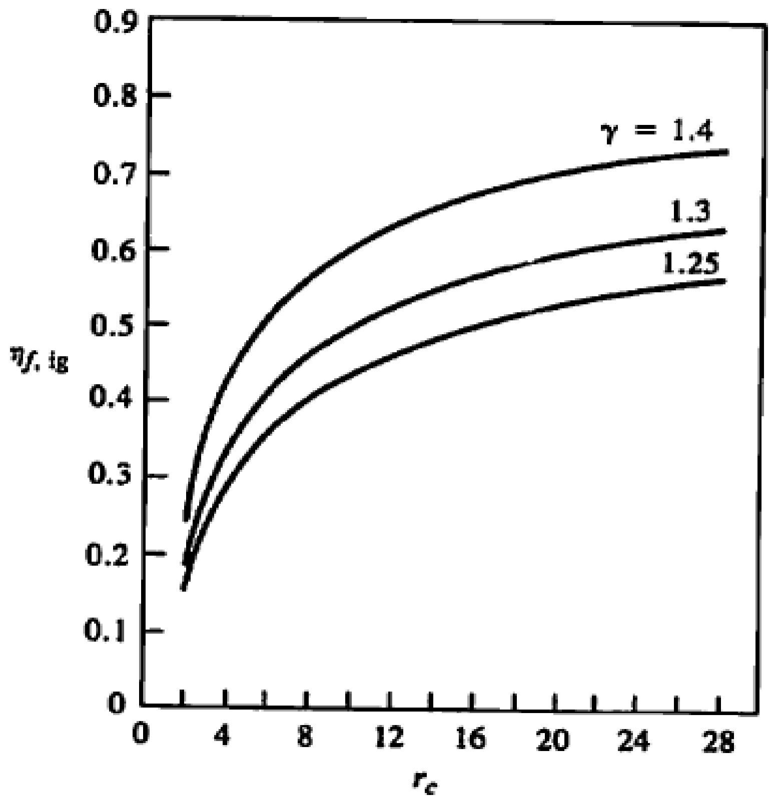


Fig.9-33 Individual-cycle indicated mean effective pressure versus θ_{pmax}

Heywood, J.B., “Internal Combustion Engine Fundamentals”, MaGraw-Hill, INC.



$$\eta_{f,i} = 1 - \frac{1}{r_c^{\gamma-1}}$$

Fig.5-5 Ideal gas constant-volume cycle fuel conversion efficiency as a function of compression ratio

Heywood, J.B., "Internal Combustion Engine Fundamentals", MaGraw-Hill, INC.

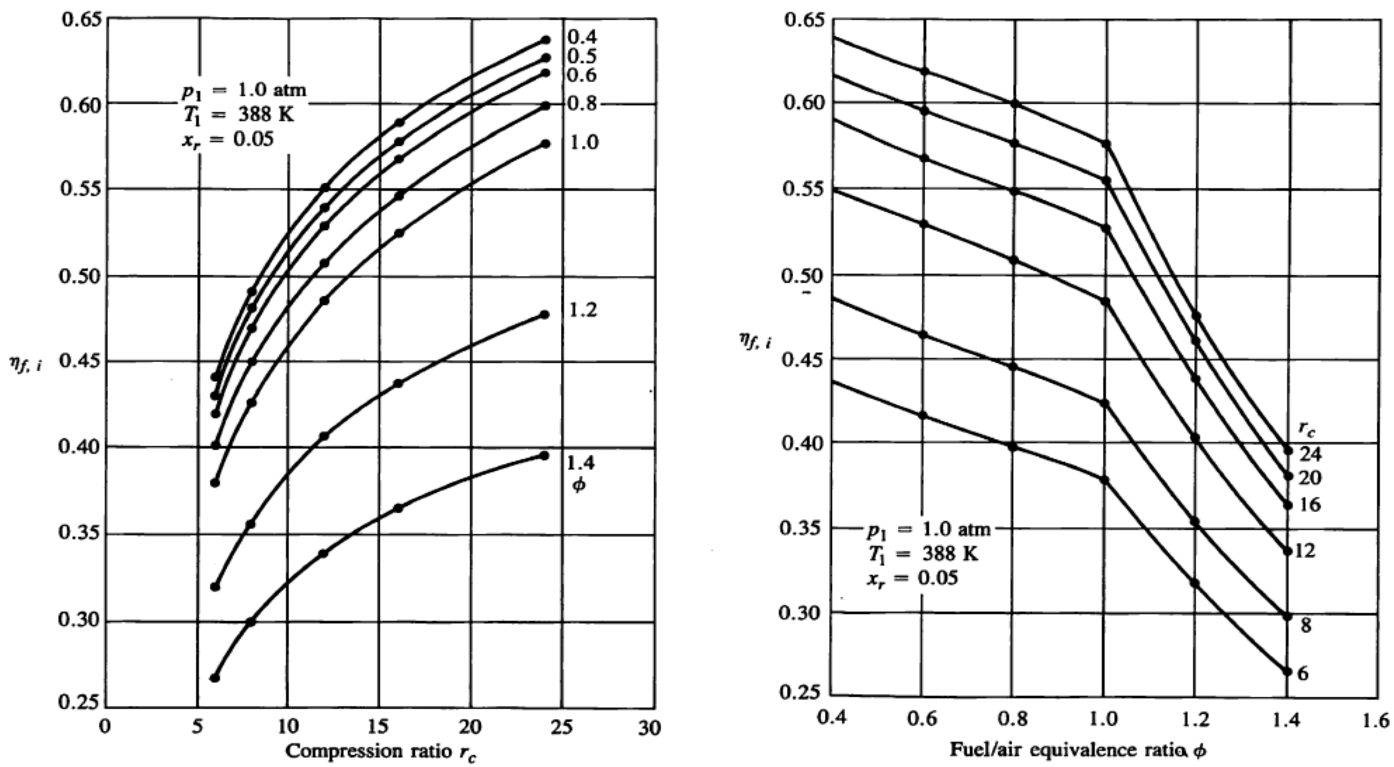


Fig.5-9 Fuel-air cycle results for indicated fuel conversion efficiency as a function of compression ratio and equivalence ratio Fuel: octane

Heywood, J.B., “Internal Combustion Engine Fundamentals”, MaGraw-Hill, INC.

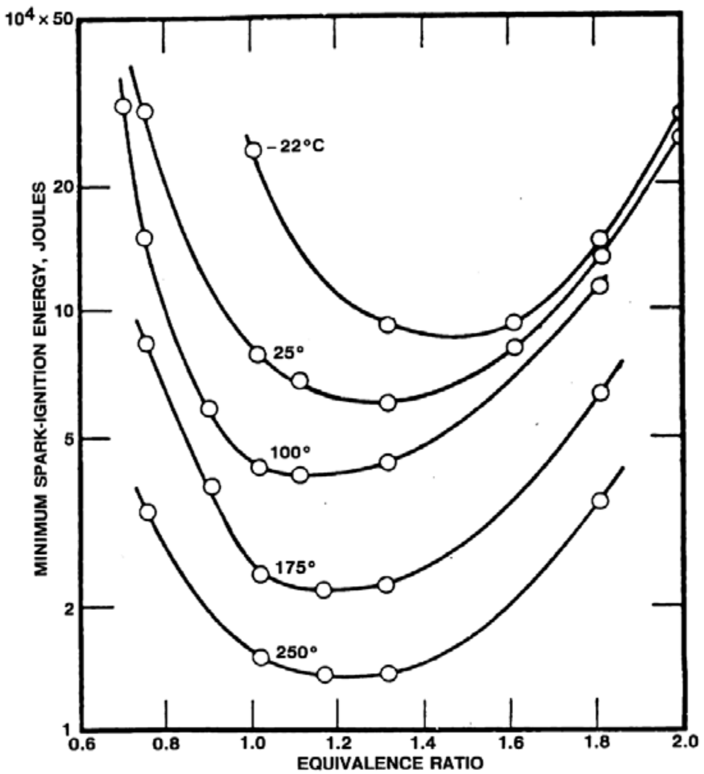


Fig.177 Effect of initial temperature on minimum spark-ignition energy for n-pentane-air mixtures

Lewis, B. and Elbe, G., “Combustion, Flames and Explosions of Gases”, Academic Press, INC.

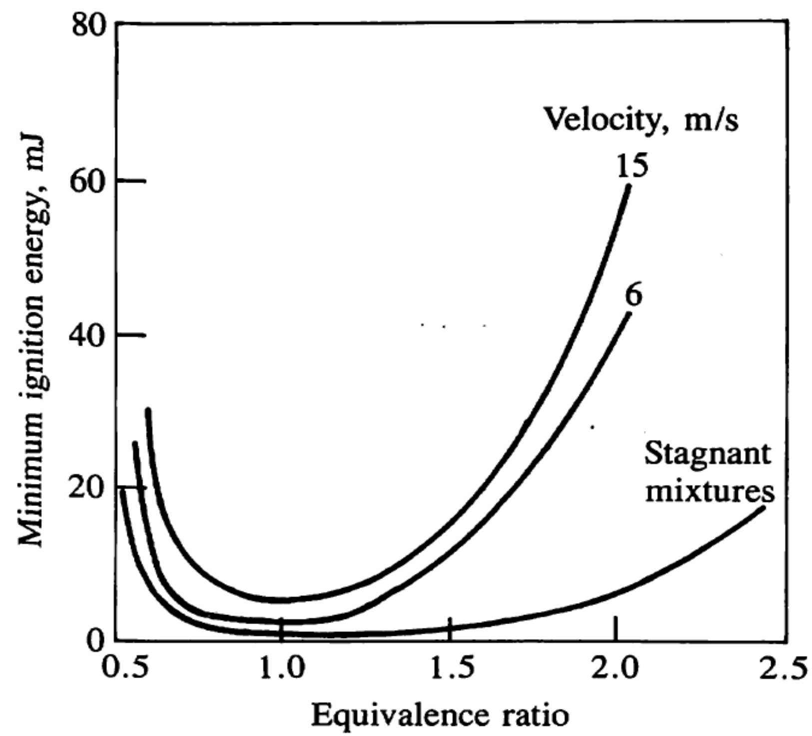


Fig.9-45 Effect of mixture equivalence ratio and flow velocity on minimum ignition energy for propane-air mixtures at 0.17atm

Heywood, J.B., “Internal Combustion Engine Fundamentals”, MaGraw-Hill, INC.

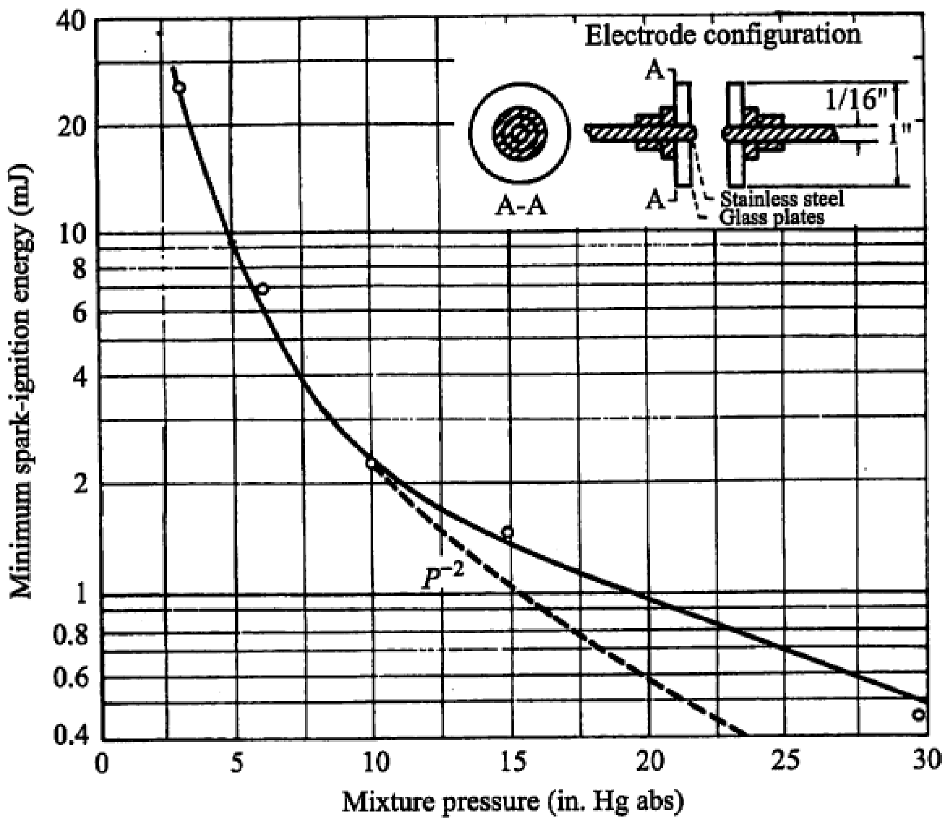


Fig.8.21 Effect of pressure on minimum spark-ignition energy

Turns, S.R., “Introduction to Combusiton”, MaGraw-Hill, INC.

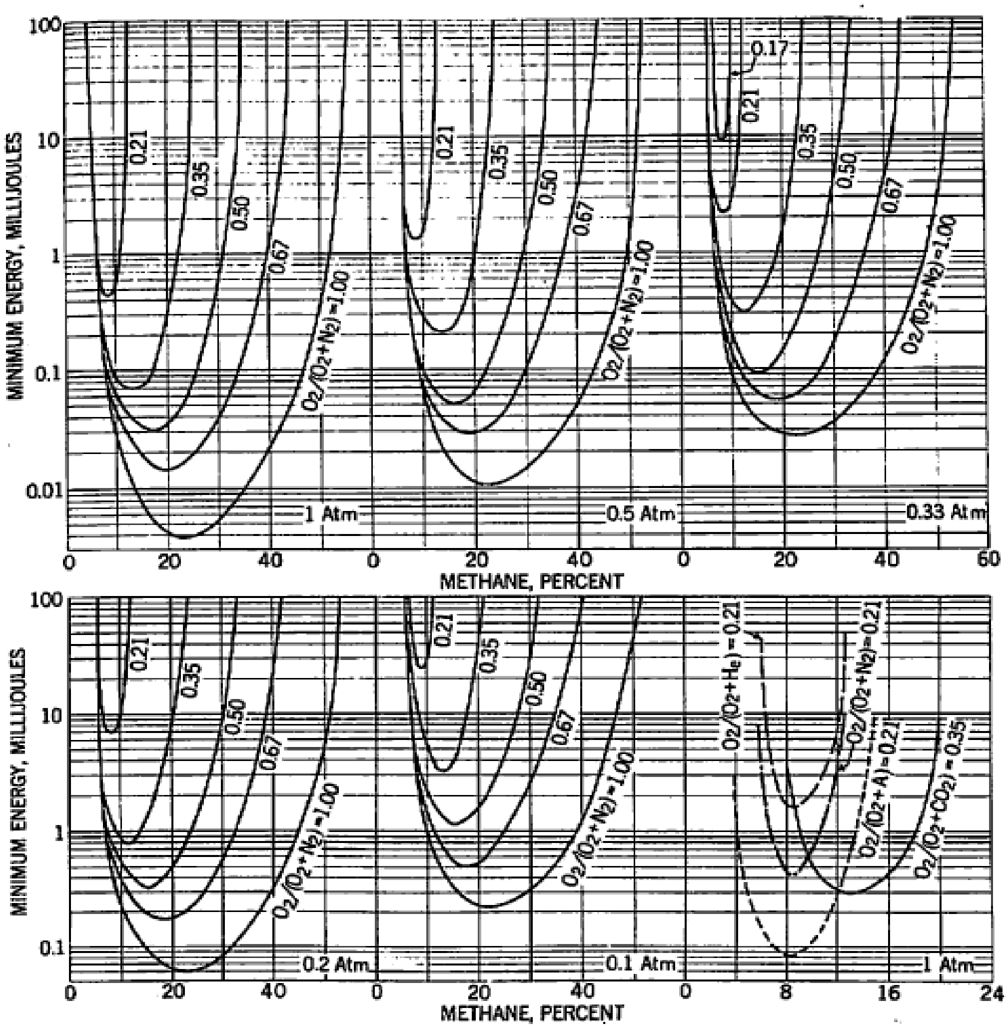


Fig.167 Minimum spark ignition energies in millijoules of methane, oxygen and nitrogen

Lewis, B. and Elbe, G., “Combustion, Flames and Explosions of Gases”, Academic Press, INC.

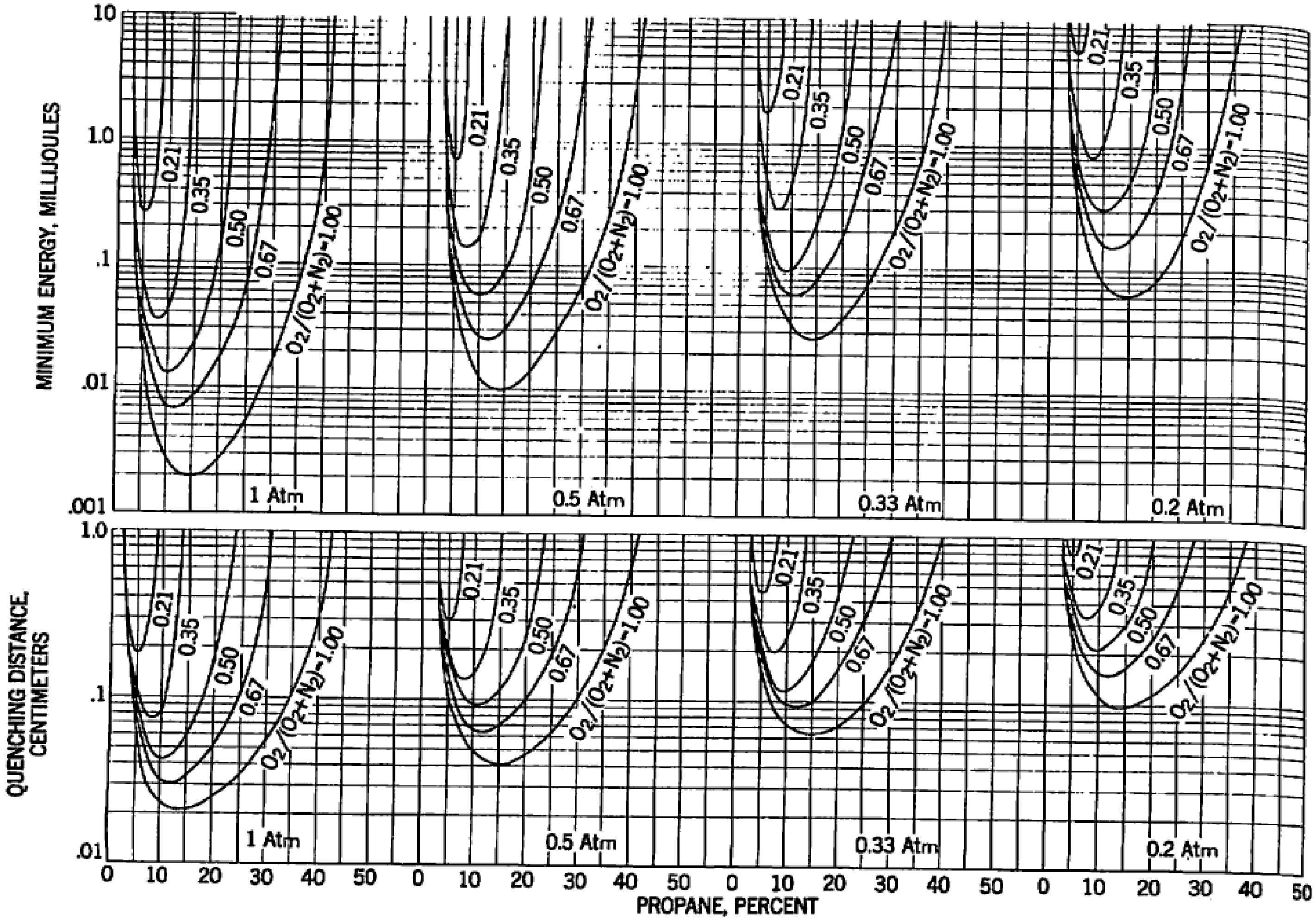


Fig.170 Minimum spark ignition energies in millijoules of propane, oxygen and nitrogen

Lewis, B. and Elbe, G., “Combustion, Flames and Explosions of Gases”, Academic Press, INC.

Energy distribution for breakdown, arc, and glow discharges†

	Breakdown, %	Arc, %	Glow, %
Radiation loss	<1	5	<1
Heat loss to electrodes	5	45	70
Total losses	6	50	70
Plasma energy	94	50	30

† Typical values, under idealized conditions with small electrodes.
Source: Maly and Vogel.[52]

Heywood, J.B., "Internal Combustion Engine Fundamentals", MaGraw-Hill, INC.

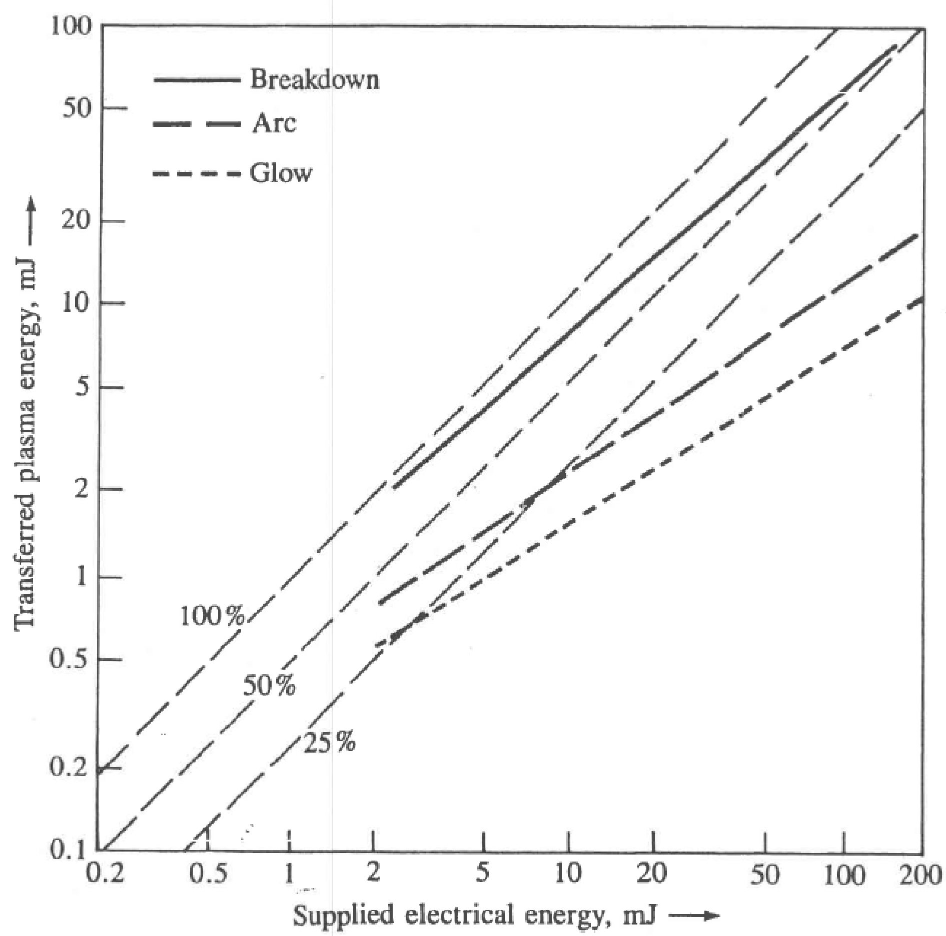
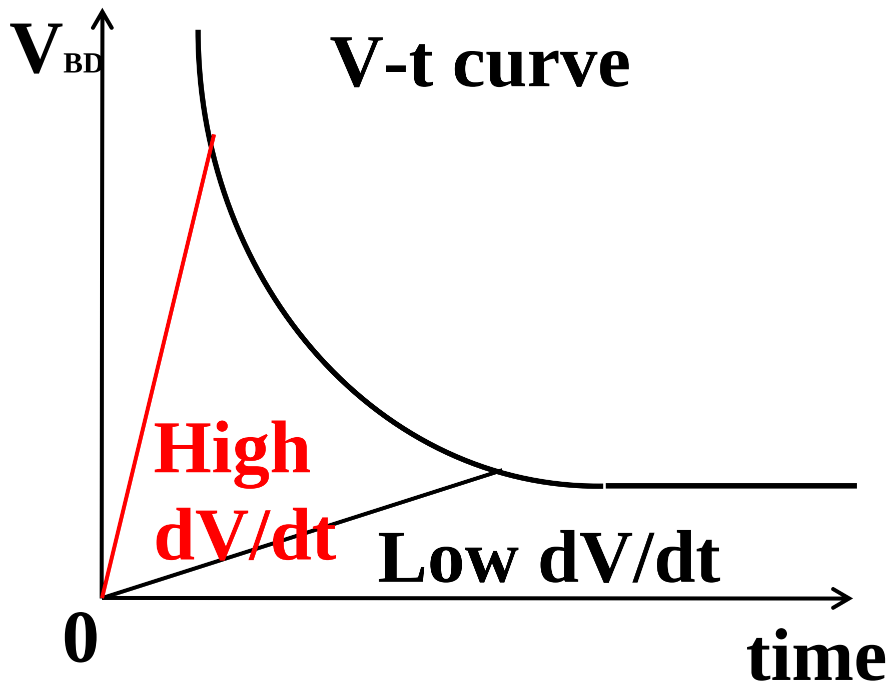


Fig.9-40 Energy transferred to the spark kernel as a function of supplied electrical energy for breakdown, arc, and glow discharges.

Heywood, J.B., “Internal Combustion Engine Fundamentals”, MaGraw-Hill, INC.



V_{BD}
V-t curve
High
dV/dt
Low dV/dt
0
time

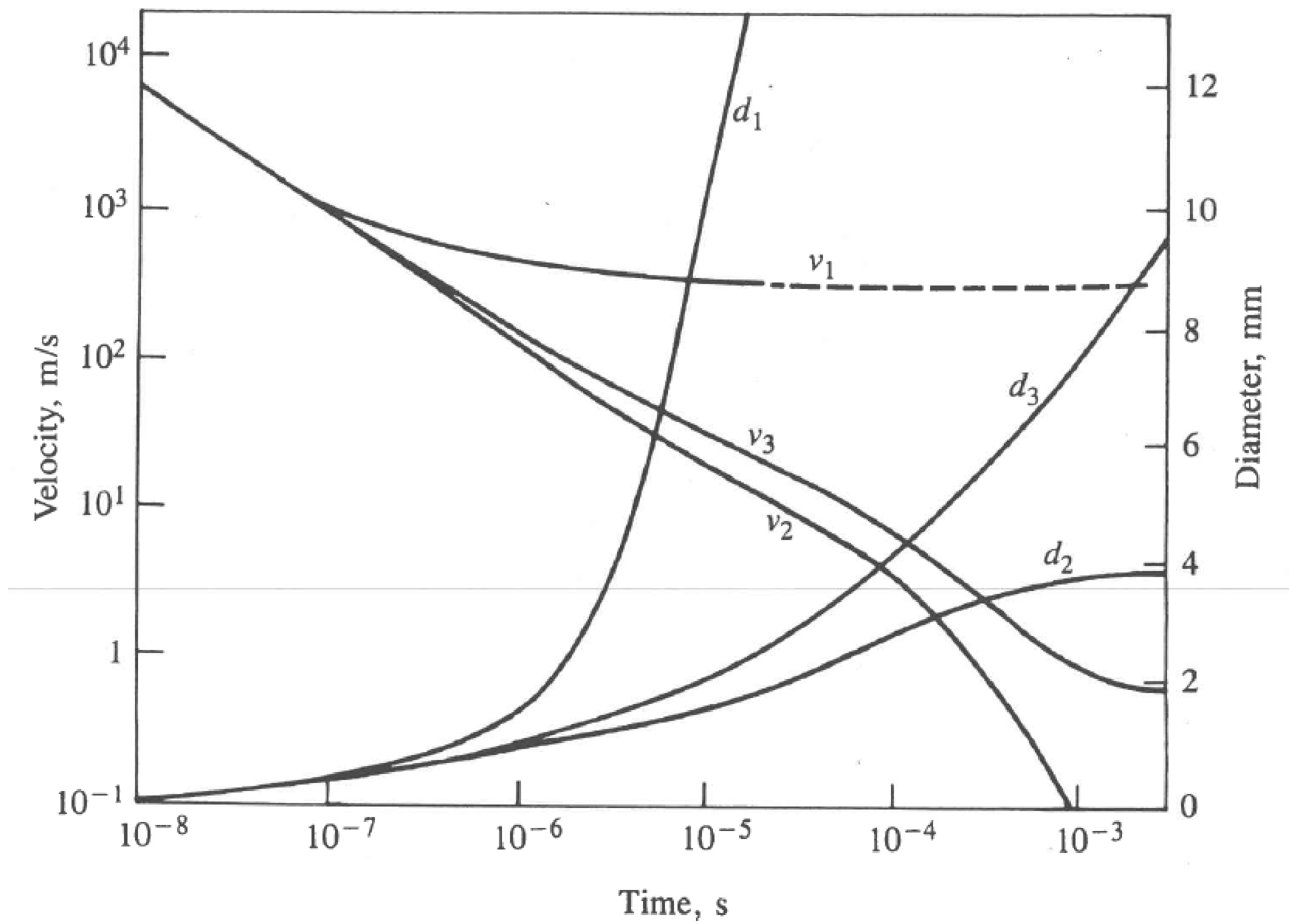


Fig.9-41 Diameters (d) and expansion velocities (v) of volumes activated by a capacitive-discharge ignition system: 3mJ electrical energy, 100 μs duration. Subscripts denote: 1, shock in air at 1atm; 2, plasma in air at 1atm; 3, electrical and chemical plasma in stoichiometric methane-air mixture at 1atm.

Heywood, J.B., "Internal Combustion Engine Fundamentals", MaGraw-Hill, INC.

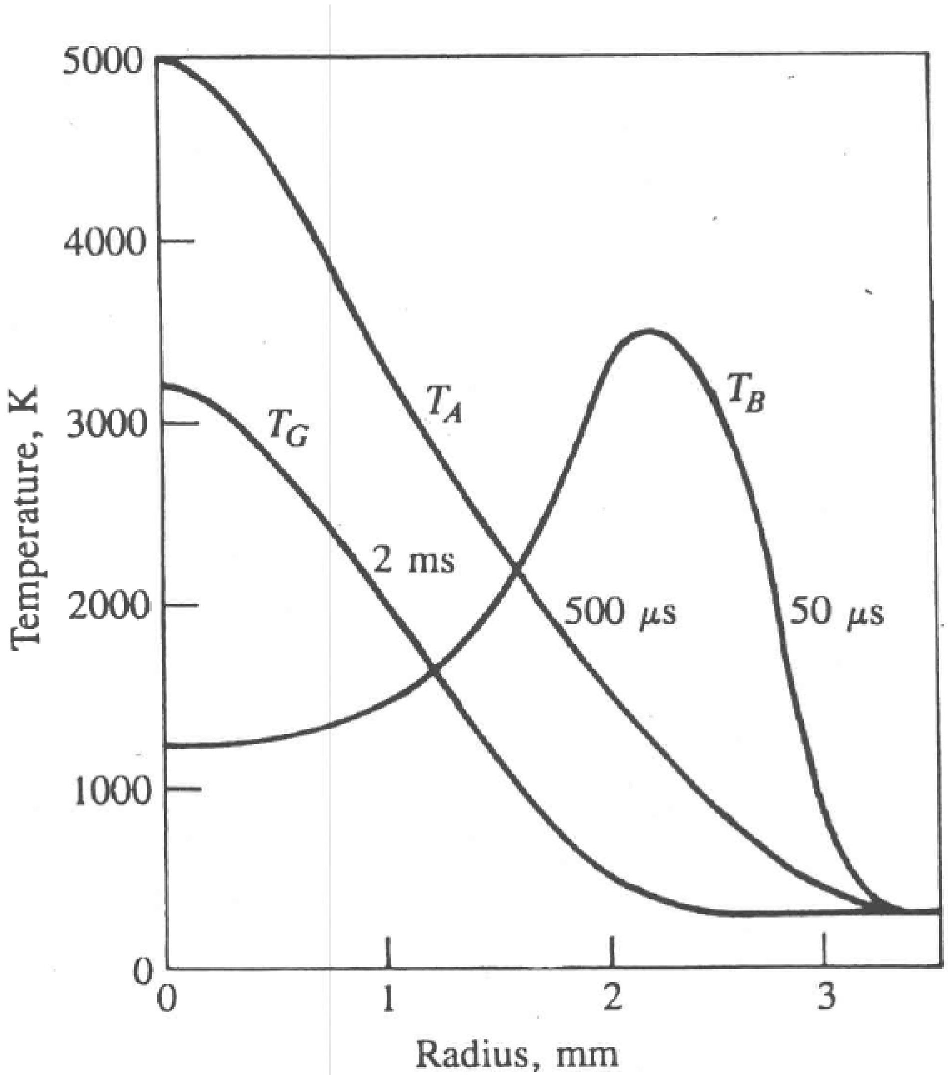


Fig.9-42 Radial temperature profiles at selected times after spark onset for ignition systems with different electrical energies and discharge times in air at 1atm. T_B, breakdown discharge, 30mJ energy 60ns duration; T_A, capacitive discharge, 3mJ energy, 100μs duration with superimposed current arc of 2A, 30mJ energy, for 230 μs; T_G, capacitive-discharge system, 3mJ energy, 100μs duration with superimposed current glow discharge of 60mA, 30mJ energy, for 770 μs duration.

Heywood, J.B., “Internal Combustion Engine Fundamentals”, MaGraw-Hill, INC.

Equilibrium composition of stoichiometric isooctane-air combustion products

	Temperature, K†			
Species	2000	3000	4000	5000
CO	2.4(−3)	6.1(−2)	9.4(−2)	9.0(−2)
CO_2	1.2(−1)	5.7(−2)	5.0(−3)	3.5(−4)
H	2(−5)	9.7(−3)	1.2(−1)	1.9(−1)
H_2	6.1(−4)	1.5(−2)	2.4(−2)	3.5(−3)
H_2O	1.4(−1)	1.0(−1)	1.1(−2)	1.2(−4)
N	*n*	1(−5)	6.6(−4)	1.2(−2)
NH	*n*	*n*	2(−5)	6(−5)
NO	5.7(−4)	1.5(−2)	2.9(−2)	1.7(−2)
N_2	7.3(−1)	6.9(−1)	5.7(−1)	5.1(−1)
O	1(−5)	8.6(−3)	9.8(−2)	1.6(−1)
OH	4.5(−4)	2.2(−2)	3.3(−2)	5.6(−3)
O_2	1.1(−3)	2.3(−2)	1.7(−2)	2.2(−3)

† At 4 atm pressure: mole fractions, $9.0(-2) = 9.0 \times 10^{-2}$. $n = <5 \times 10^{-6}$

Heywood, J.B., "Internal Combustion Engine Fundamentals", MaGraw-Hill, INC.

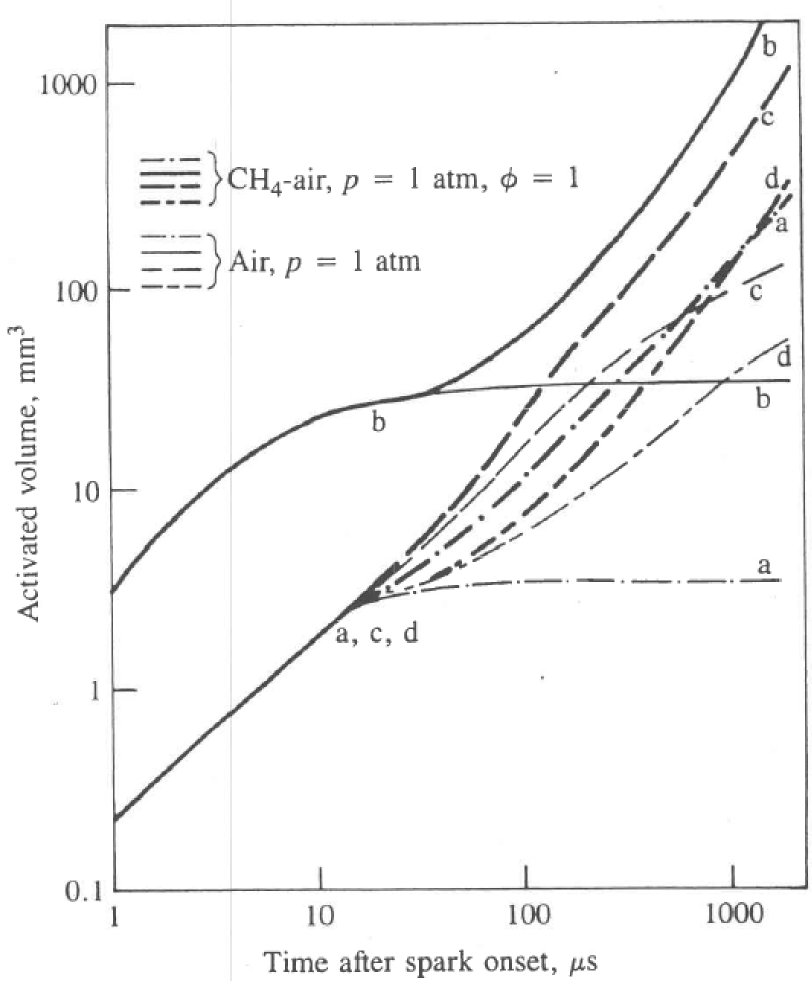


Fig.9-43 (a) Size of discharge-activated volume as function of time for several types of discharge in air and in stoichiometric methane –air mixture at 1tatm. a: CDI, 3mJ energy, 100 µs duration; b: breakdown discharge, 30mJ energy, 20ns duration; c: CDI plus arc discharge, 1.5A, 40V, 500 µs duration; d: CDI + glow discharge, 30mA, 500V, 2ms duration.

Heywood, J.B., “Internal Combustion Engine Fundamentals”, MaGraw-Hill, INC.

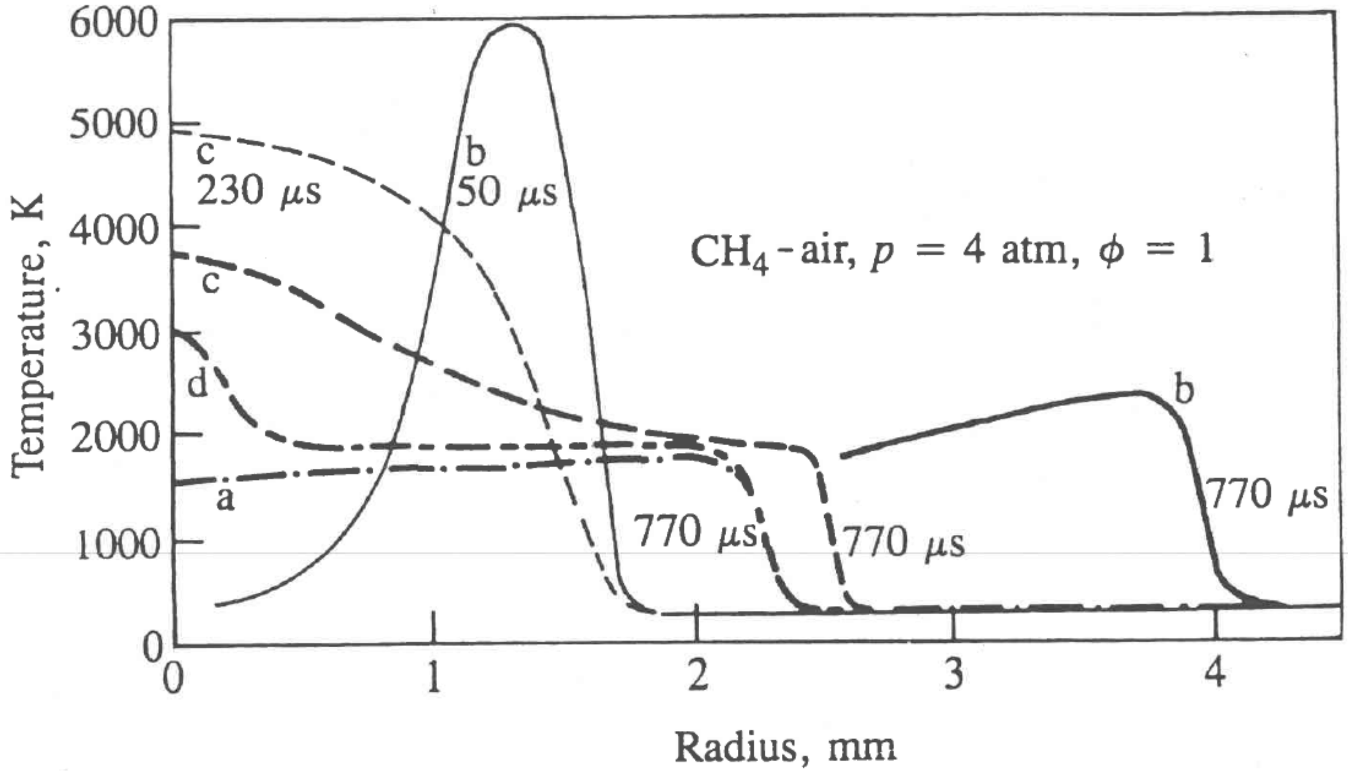


Fig.9-43 (b) Temperature profiles for different discharge modes at different times in stoichiometric methane –air mixture at 300K, 4tatm. a: CDI, 3mJ energy, 100 µs duration; b: breakdown discharge, 20mJ energy, 80ns duration; c: CDI, 3mJ energy, 100 µs duration plus 2A, 30mJ energy, 230 µs duration arc; d: CDI , 3mJ energy, 100 µs duration , plus 60mA, 30mJ energy 770 µs duration glow discharge.

Heywood, J.B., “Internal Combustion Engine Fundamentals”, MaGraw-Hill, INC.

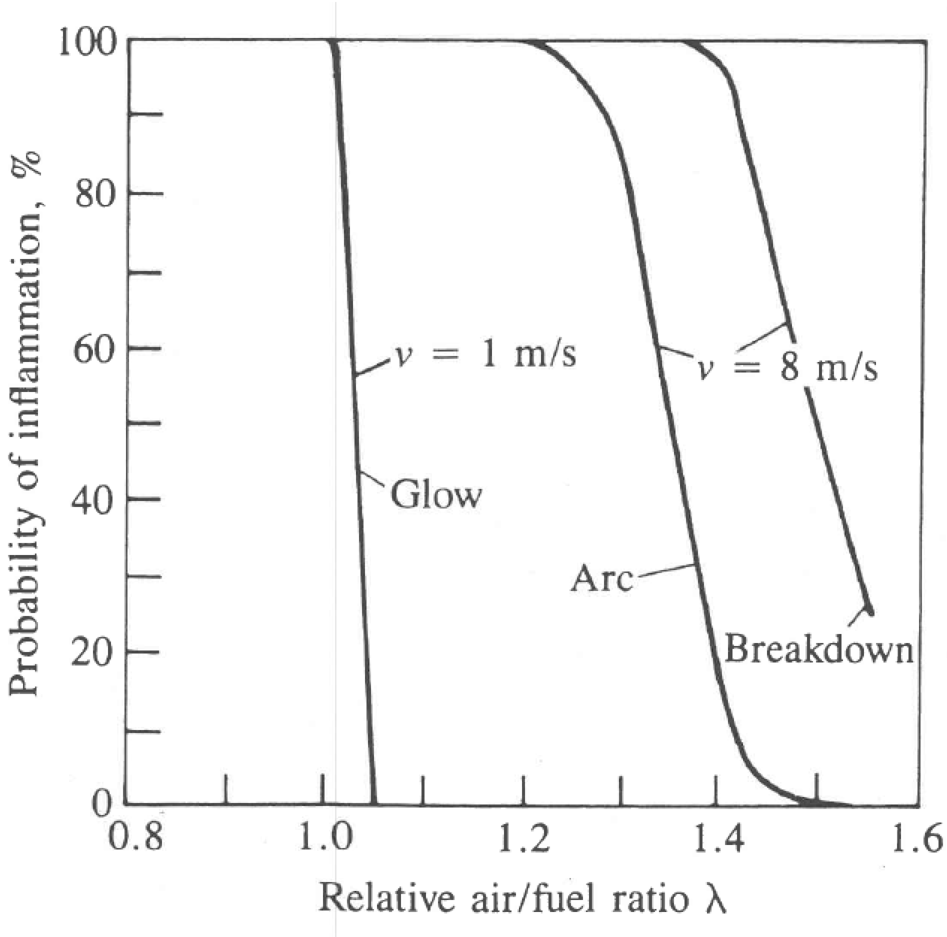


Fig.9-44 Probability of inflammation of stoichiometric methane-air mixture, at 300K, 4atm, as function of relative air/fuel ratio for different ignition discharges with equal total electrical energy (30-33mJ). Breakdown: 30mJ, 60ns duration. Arc: CDI, 3mJ, 100µs duration; plus 2A, 30mJ, 230µs duration arc. Glow: CDI, 3mJ, 100µs duration; plus 60mA, 30mJ, 770µs duration glow discharge. *v*=mixture velocity.

Heywood, J.B., “Internal Combustion Engine Fundamentals”, MaGraw-Hill, INC.

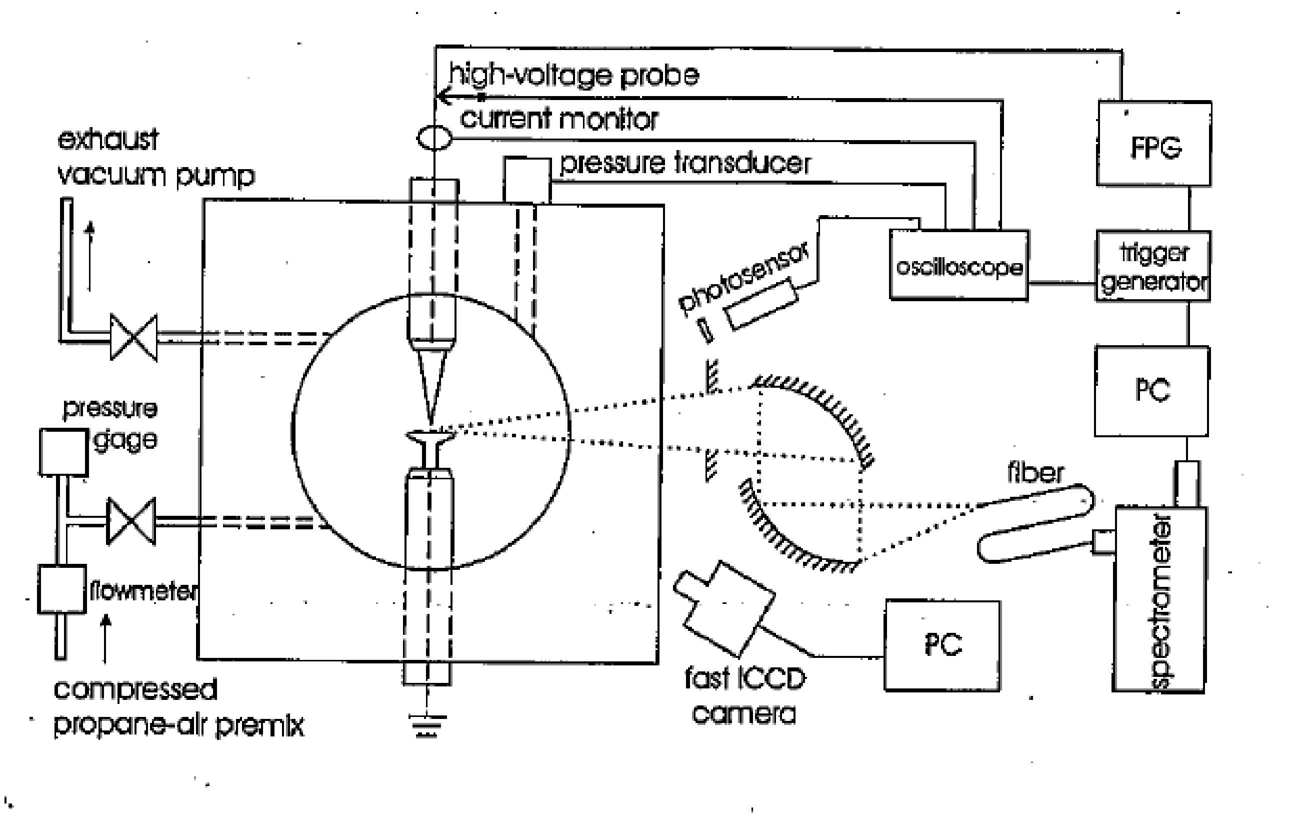


Fig.1 Experimental setup

Pancheshnyi, S.V., Lacoste, D.A., Bourdon, A., Laux, C.O., "Ignition of Propane-Air Mixtures by a Repetitively Pulsed Nanosecond Discharge", IEEE Transactions on Plasma Science, Vol.34, pp.2478-2487, (2006).

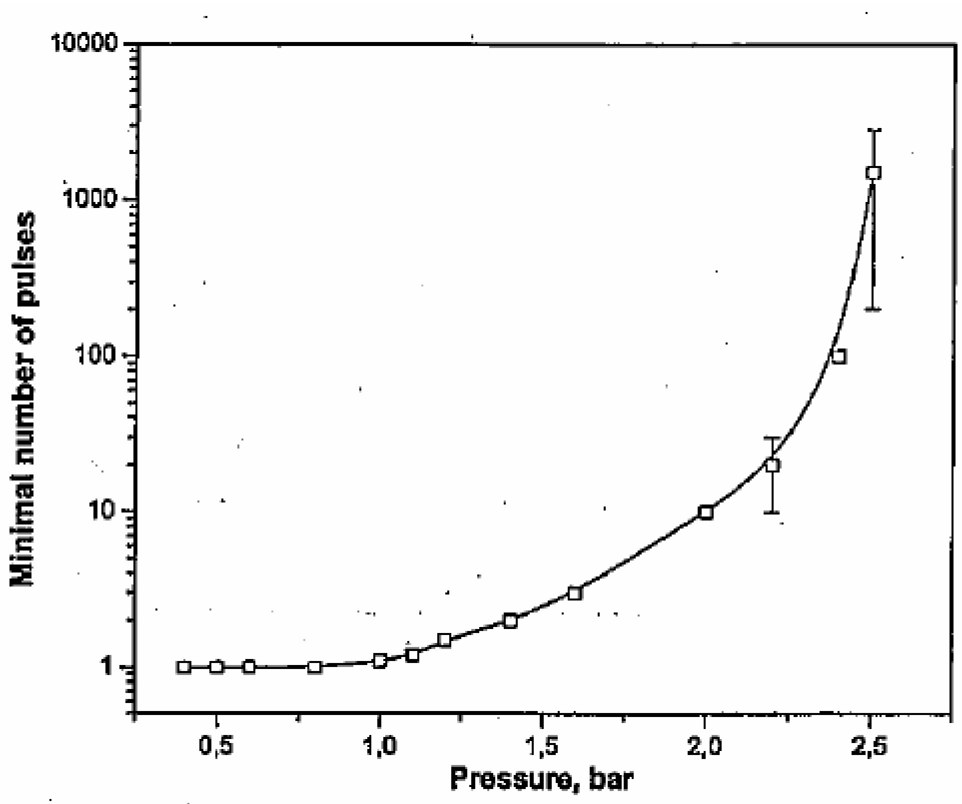


Fig.10 Minimal number of pulses in a train of 10ns pulses of 5kV amplitude at 30kHz required to cause breakdown in the gap, as a function of pressure. Air, 1.5mm

Pancheshnyi, S.V., Lacoste, D.A., Bourdon, A., Laux, C.O., "Ignition of Propane-Air Mixtures by a Repetitively Pulsed Nanosecond Discharge", IEEE Transactions on Plasma Science, Vol.34, pp.2478-2487, (2006).

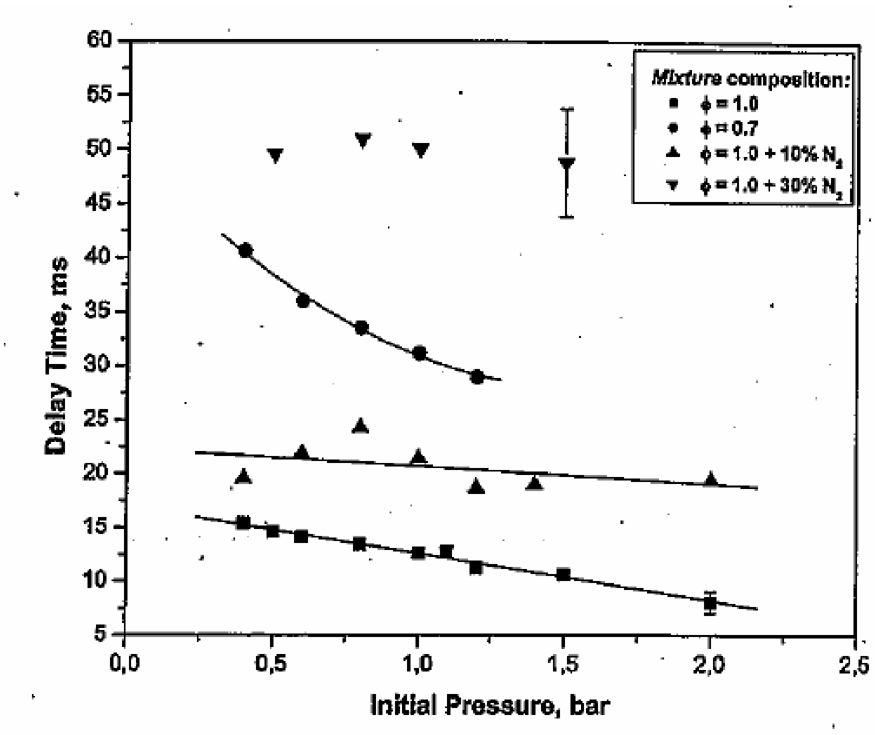


Fig.13 Combustion delay time for different combustible mixtures.

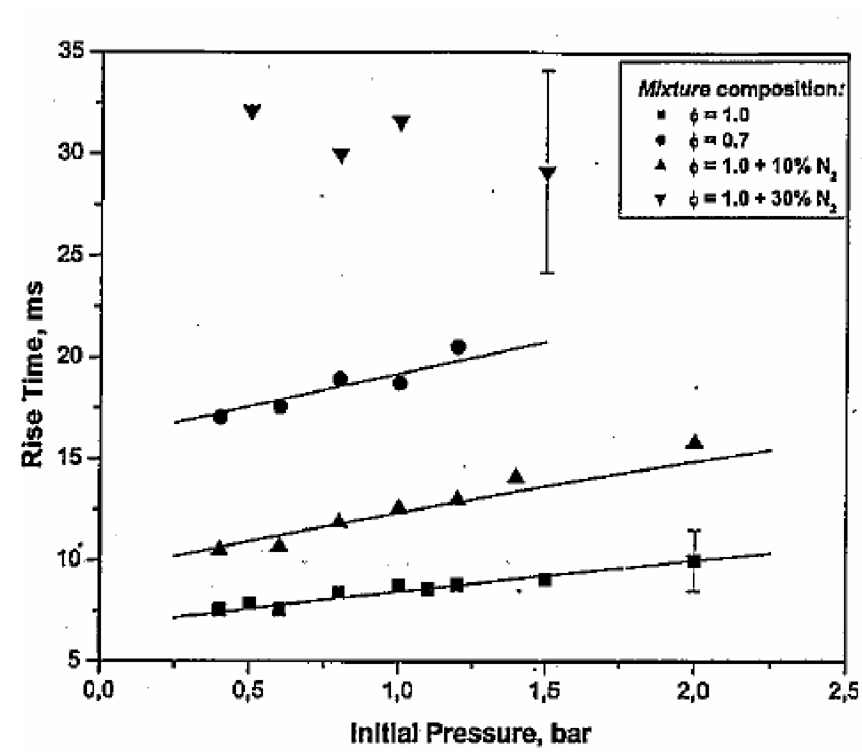


Fig.14 Pressure rise time for different combustible mixtures.

Pancheshnyi, S.V., Lacoste, D.A., Bourdon, A., Laux, C.O., “Ignition of Propane-Air Mixtures by a Repetitively Pulsed Nanosecond Discharge”, IEEE Transactions on Plasma Science, Vol.34, pp.2478-2487, (2006).

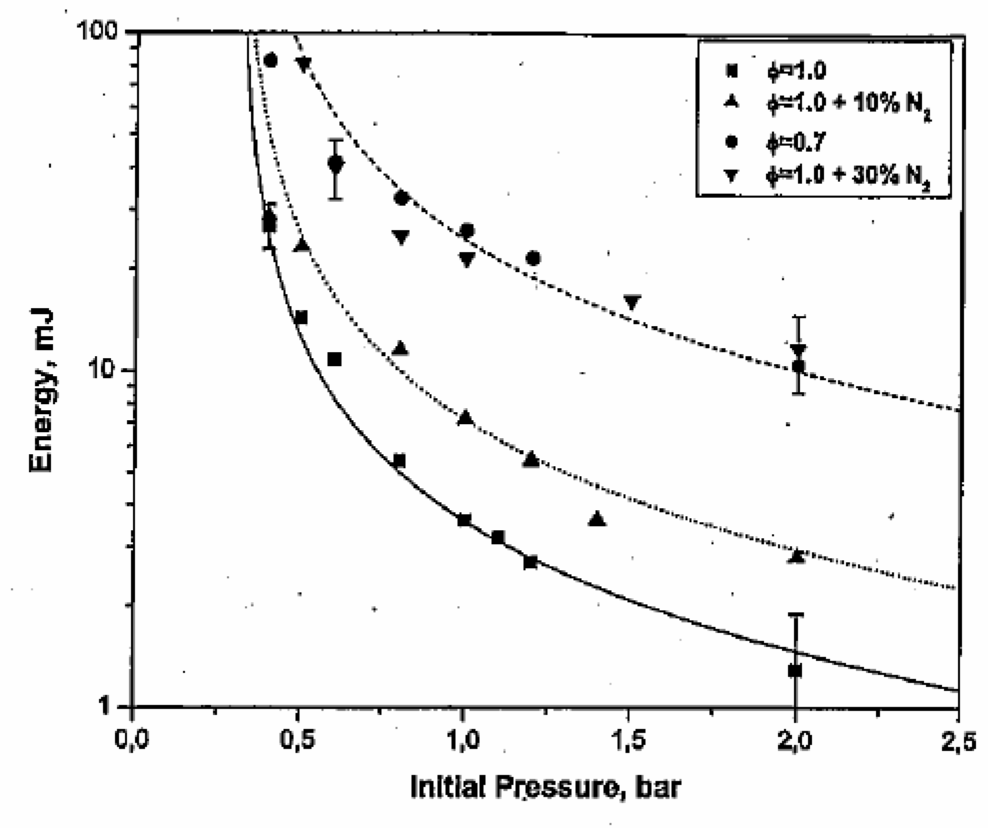


Fig.15 Minimal energy deposition into the plasma required to achieve ignition of various propane-air mixtures. Interelectrode length is 1.5mm

Pancheshnyi, S.V., Lacoste, D.A., Bourdon, A., Laux, C.O., "Ignition of Propane-Air Mixtures by a Repetitively Pulsed Nanosecond Discharge", IEEE Transactions on Plasma Science, Vol.34, pp.2478-2487, (2006).

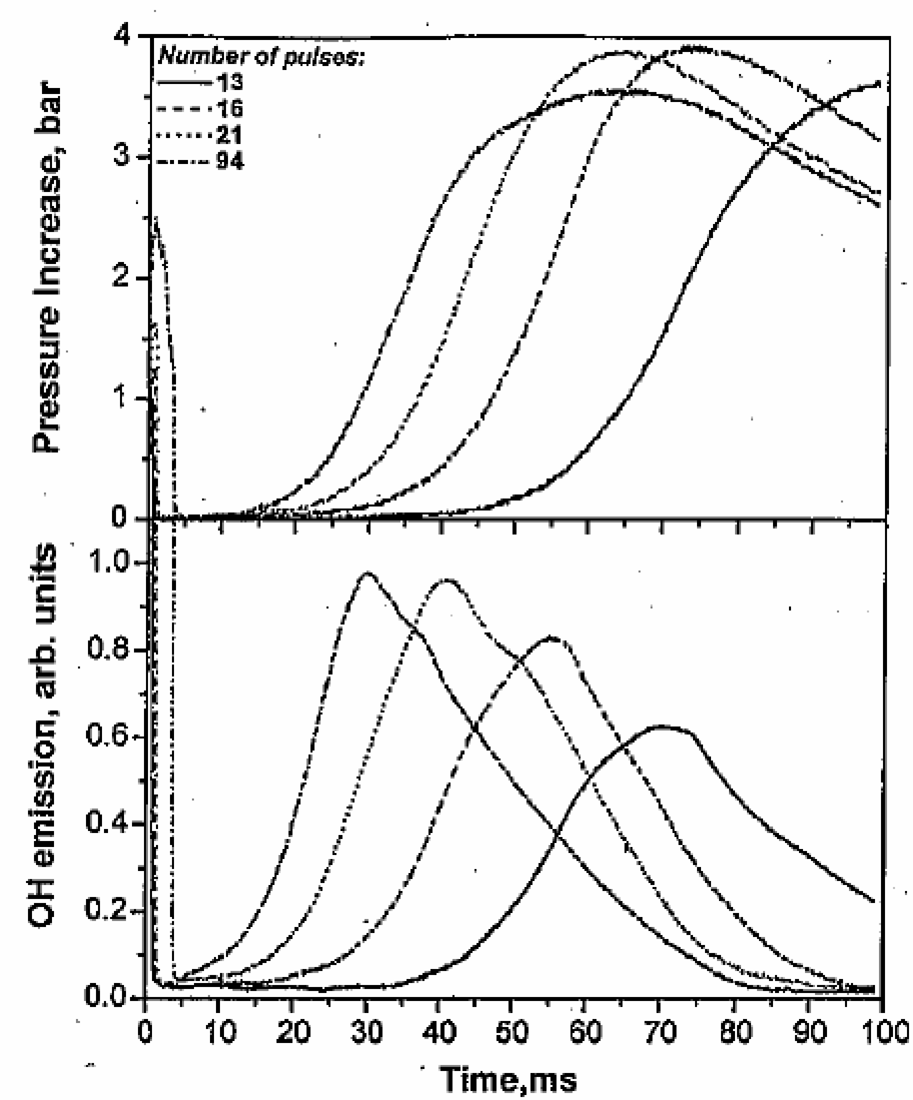


Fig.16 Profiles of pressure increase and OH emission for 30%N2 dilute propane-air mixture for an initial pressure of 1bar. The various curves correspond to different numbers of high-voltage pulses of 5kV, 10ns, 30kHz, and 1.5m. Each pulse deposits an energy of about 1.9mJ

Pancheshnyi, S.V., Lacoste, D.A., Bourdon, A., Laux, C.O., “Ignition of Propane-Air Mixtures by a Repetitively Pulsed Nanosecond Discharge”, IEEE Transactions on Plasma Science, Vol.34, pp.2478-2487, (2006).