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Inhibition Effectiveness of Water Mist on Ignition of Propane/Air Mixture

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Introduction

Minimum ignition energy is a good indicator of the effectiveness of an inhibiting agent to prevent explosion.

1. Determine which parameter is essential for prevention of ignition, net discharge energy, energy density or volumetric energy release rate.

2. Inhibition effectiveness of water mist for ignition of propane/air mixture.

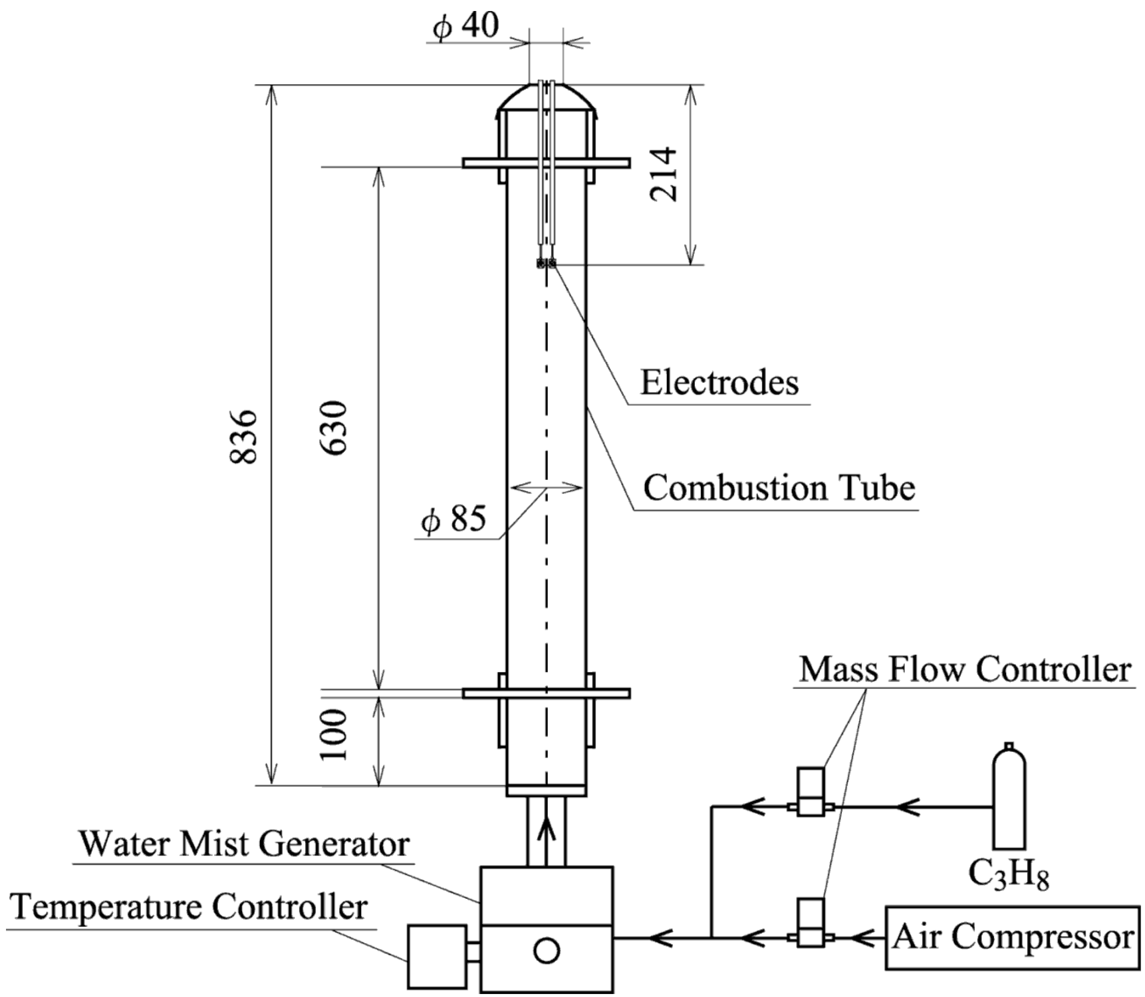
Ignition parameters

- **Net Dicharged Energy: E_i [J]**
  E_i: Net discharged energy [J]

- **Energy Density: $q_i = E_i/V_k$ [J/m^3]**
  E_i: Net discharged energy [J]
  V_k: Flame kernel volume [m^3]

- **Volumetric Energy Release Rate: $\dot{q}_i = E_i/V_k t_d$ [W/m^3]**
  E_i: Net discharged energy [J]
  V_k: Flame kernel volume [m^3]
  t_d: Discharge duration [s]

Experimental Apparatus



Ignition System and Electrodes

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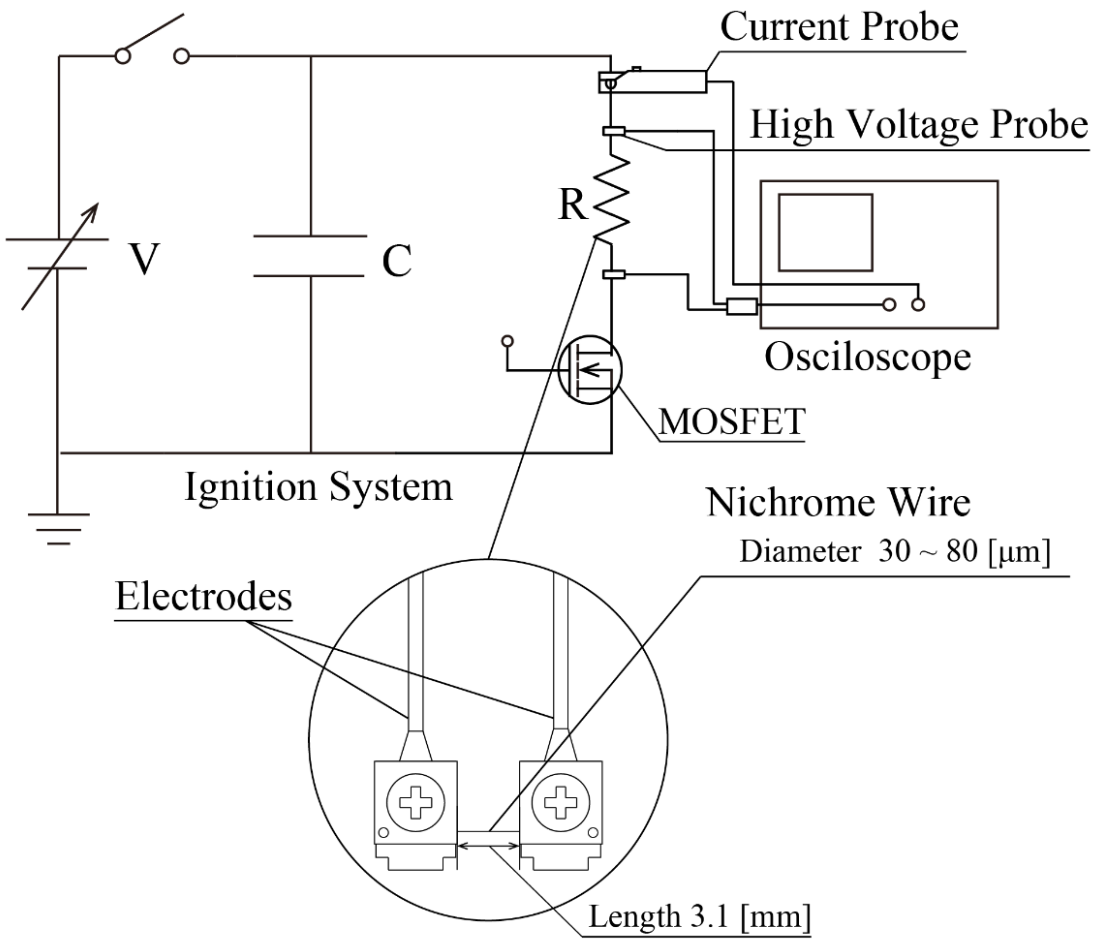
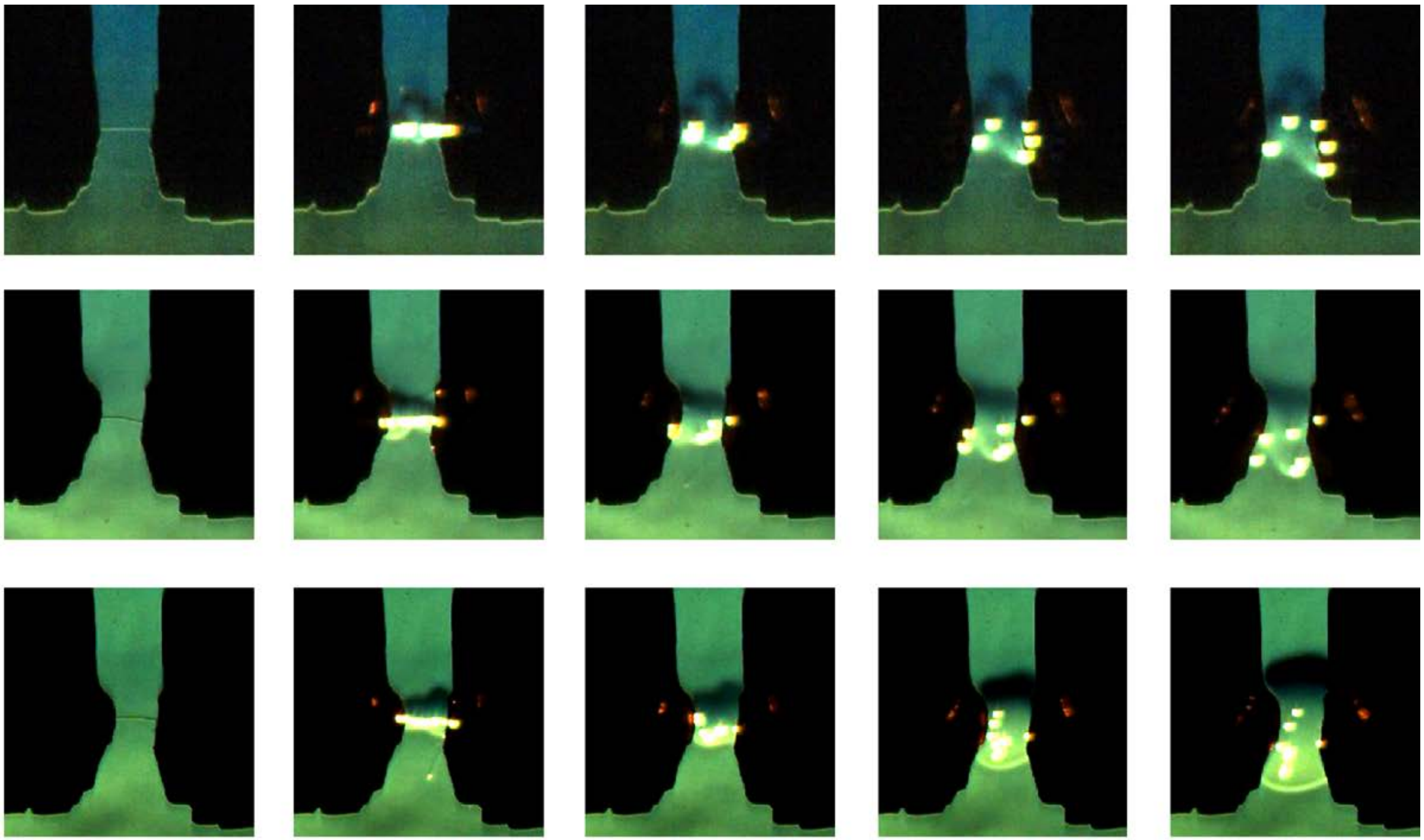


Details of Electrodes

Schlieren Images

(a) air, (b) φ = 1.3 no ignition, (c) φ = 1.3 ignition

(a)
(b)
(c)



0 [ms]　1 [ms]　2 [ms]　3 [ms]　4 [ms]

Net Discharged Energy

When a fine resistance wire was fused electrically, net discharged energy E_i is expressed by

$$\boldsymbol{\Delta E = E_c - E_r = E_i + E_h + E_m + E_{loss}}$$

$$\boldsymbol{\therefore E_i = \Delta E - (E_h + E_m + E_{loss})}$$

ΔE : Discharge energy
E_c : Charge energy
E_r : Residual energy
E_h : Sensible enthalpy to heat up the wire to the melting point
E_m : Latent heat of fusion
E_{loss} : Additional heat loss by heat transfer to terminals and radiation

Ignition probability

Ignition probability $P_i(x_i)$ can be expressed by the logistic function and is given by

$$P_i(x_i) = \frac{1}{1 + exp(-\beta_0 - \beta_1 x_i)}$$

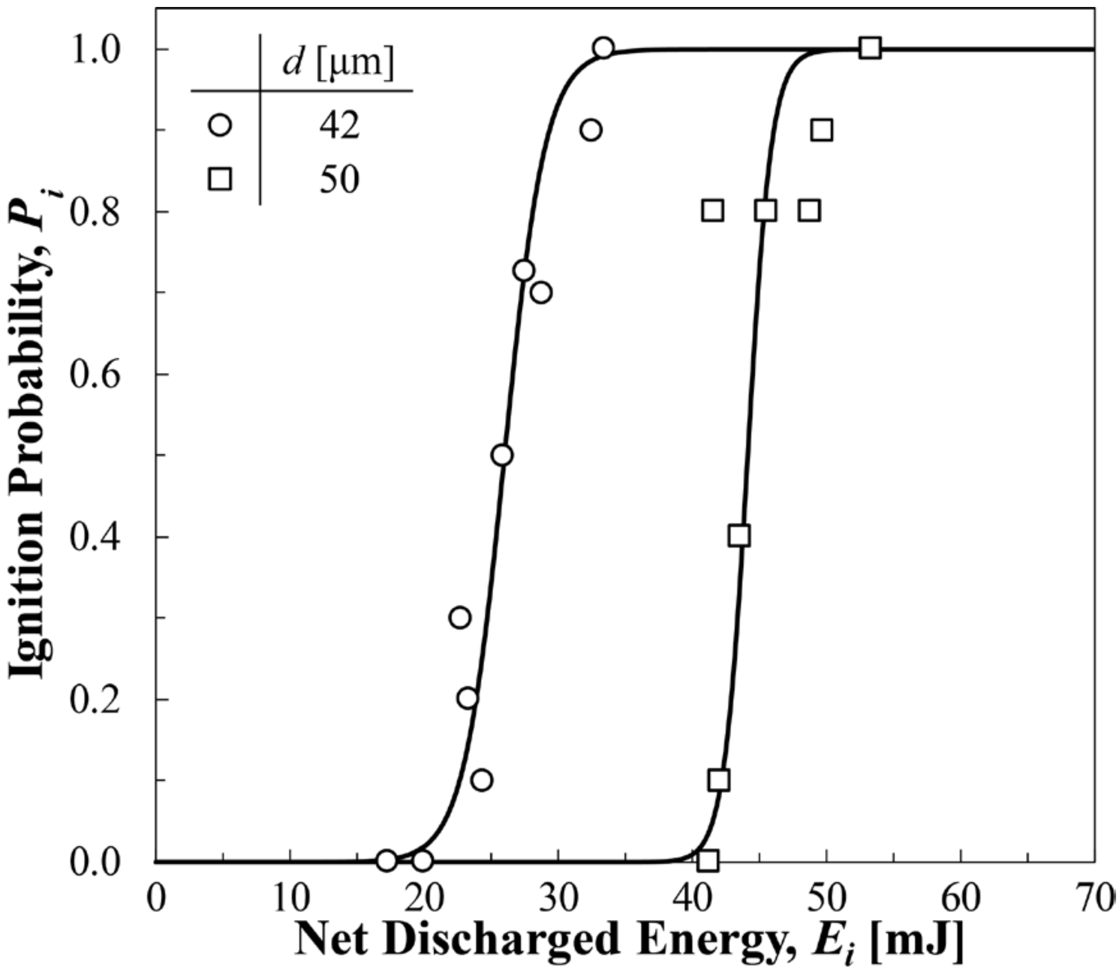
β_0 and β_1 are coefficients estimated by maximizing the likelihood function. The likelihood function is given by

$$L = \prod_{i=1}^{n} P_i(x_i)^{y_i}(1 - P_i(x_i))^{1-y_i}$$

x_i : Net discharged energy [J], Energy density [J/m^3], Volumetric energy release rate [W/m^3]

y_i : Ignition probability for i^{th} test

Effect of wire diameter



Net discharged energy
$E_i = \Delta E - (E_h + E_m)$

- Minimum net discharged energy $E_{i,min}$ for ignition

  d = 42 [μm] → $E_{i,min}$ = 19 [mJ]

  d = 50 [μm] → $E_{i,min}$ = 40 [mJ]

- Ignition probability changes with wire diameter, when the ignition probability is expressed as a function of net discharged energy.

Effect of wire diameter

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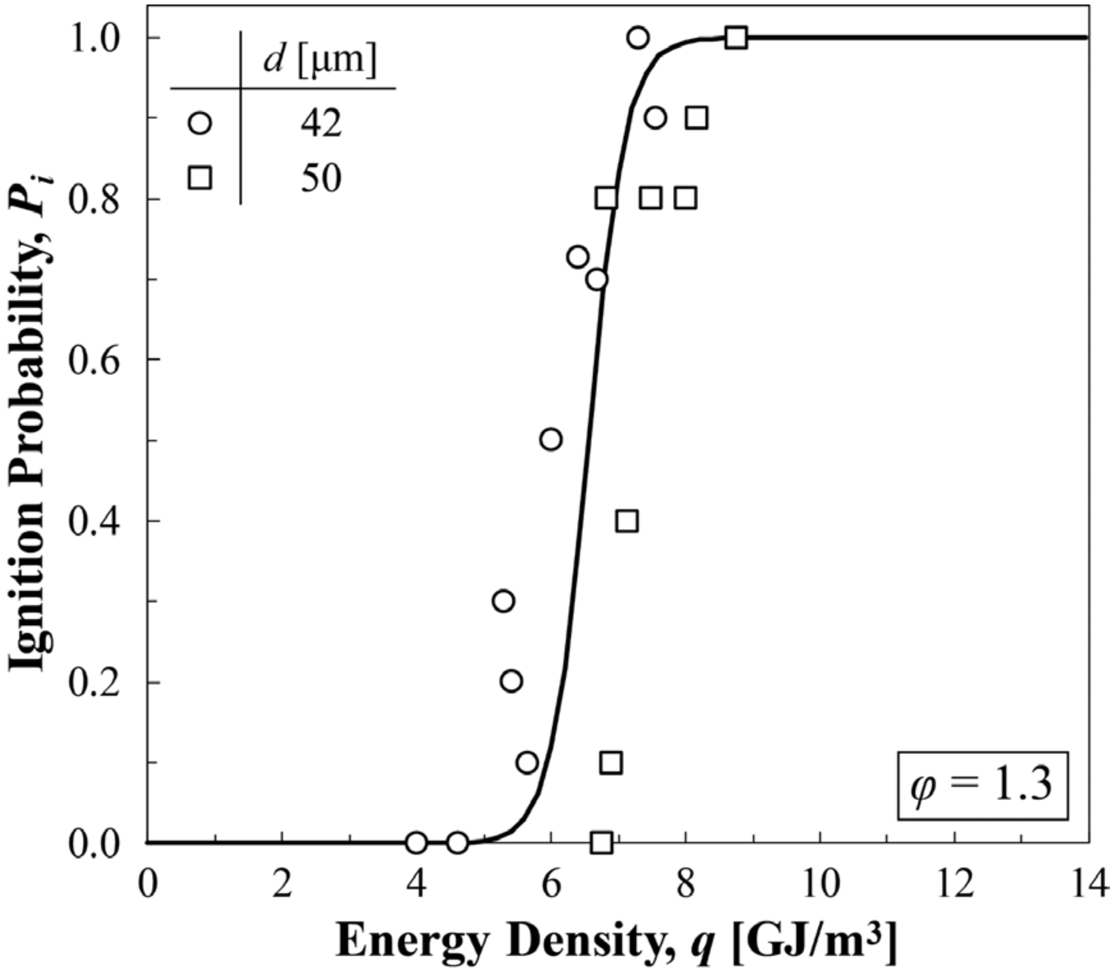

Energy density
$q = E_i / V_k$

- Ignition probability is shown as a function of the energy density, and the ignition probability for 42 μm corresponds to that for 50 μm.
- If the discharge duration is constant, the ignition probability can be expressed uniquely by the energy density.

Effect of discharge duration

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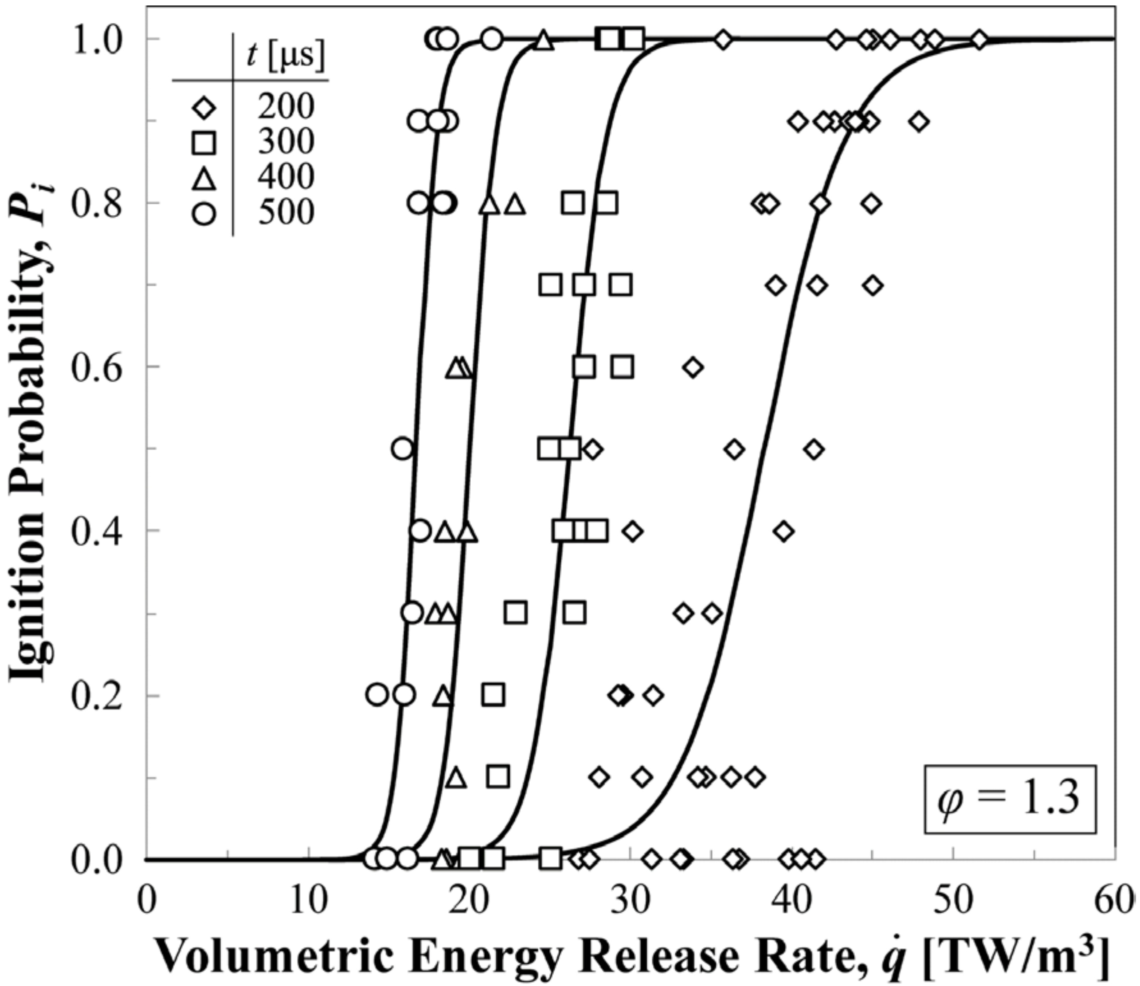

Volumetric energy release rate
$\dot{q} = E_i/V_k\tau_d$

- Ignition probability decreases with decrease of the discharge duration.
- When the ignition probability is expressed by volumetric energy release rate, ignition probability depends on the discharge duration.

Effect of discharge duration

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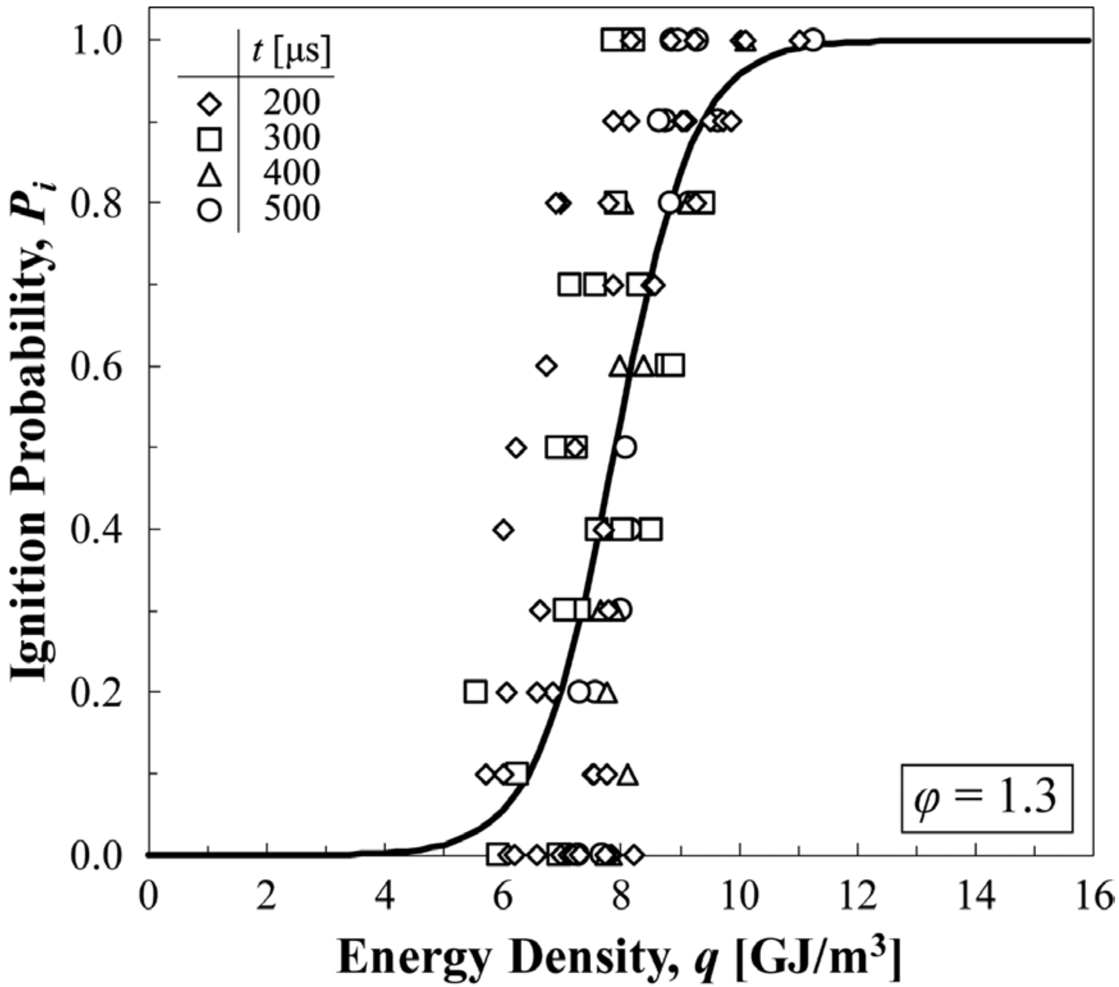


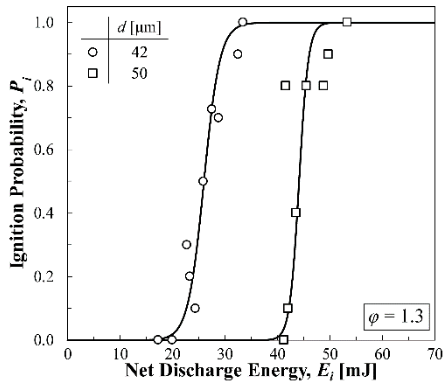
Energy density

$q = E_i / V_k$

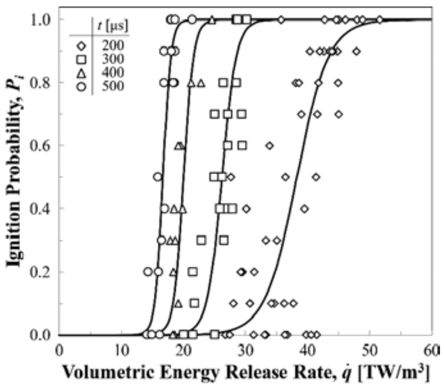
- Ignition probability collapses on one curve independently of the discharge duration.
- Ignition probability as a function of energy density is not affected by discharge duration.

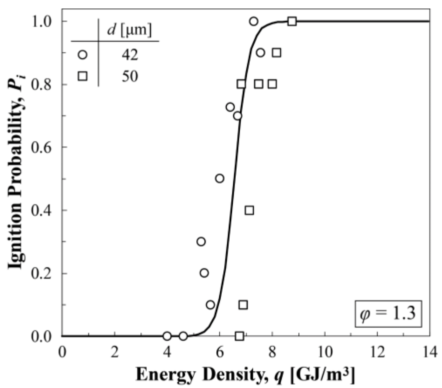
Function of ignition probability

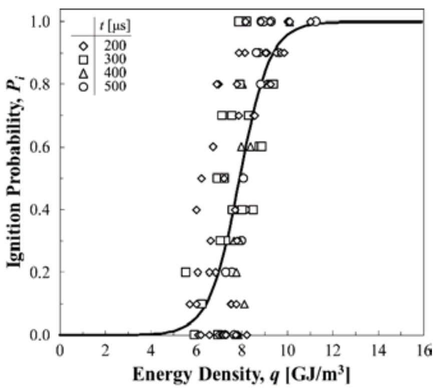
Net discharged energy



Volumetric energy release rate







Energy density

Effect of Water Mist on Ignition φ=1.3

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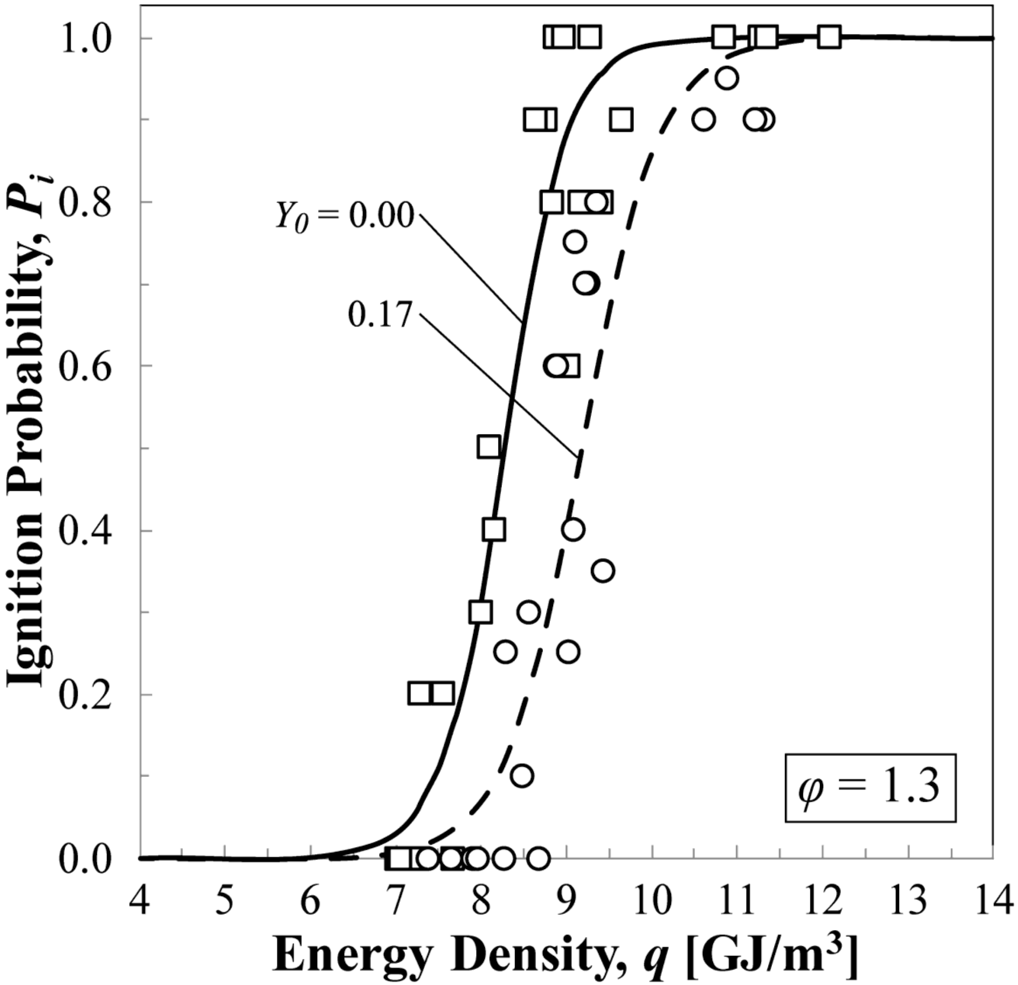
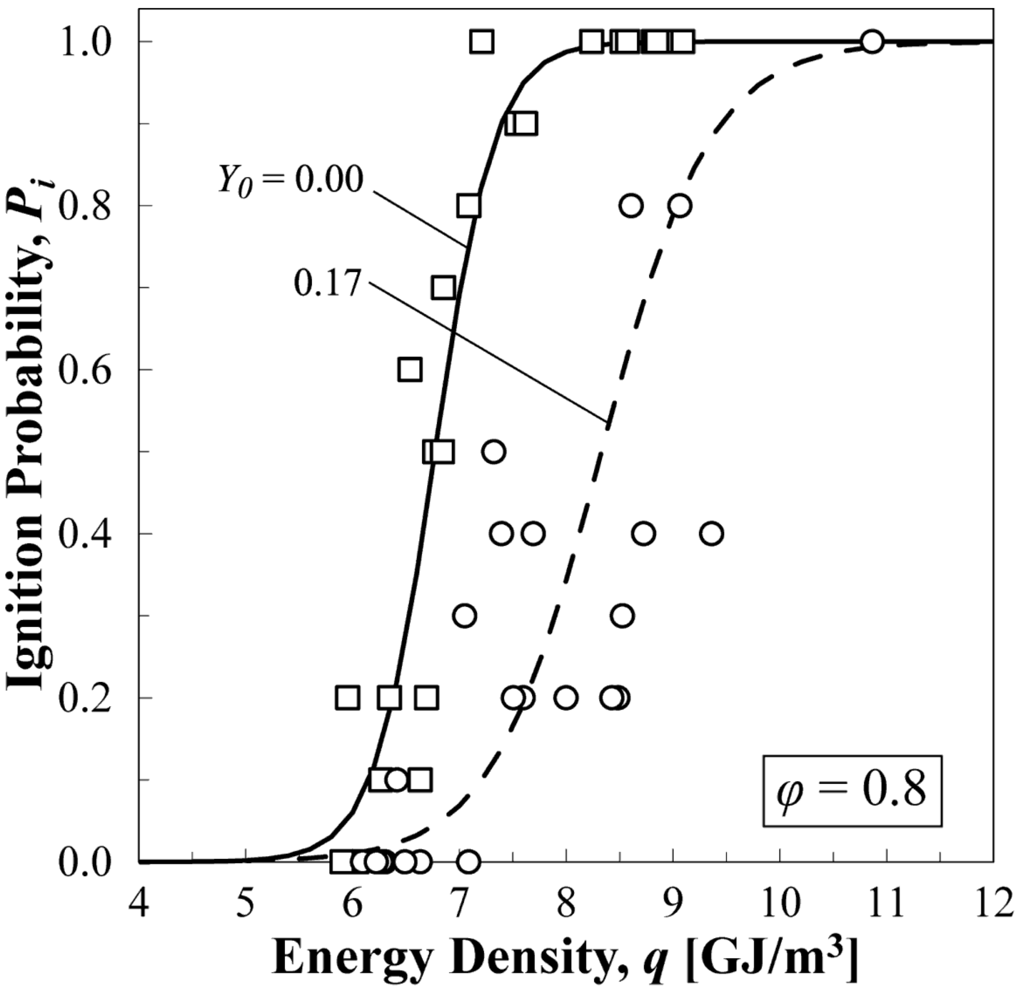


- When water mist is added to the mixture, ignition probability decreases with water mist addition and minimum ignition energy density increases.
- Water mist absorbs thermal energy delivered from the heated wire.

Effect of Water Mist on Ignition φ=0.8



- When water mist is added to the mixture, ignition probability decreases with water mist addition and minimum ignition energy density increases.
- Inhibition effectiveness of water mist on ignition is greater for lean side than for rich side.

Conclusions

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Inhibition effectiveness of water mist on ignition of propane/air mixture was investigated experimentally.

1. The energy density is the most suitable to express ignition probability.

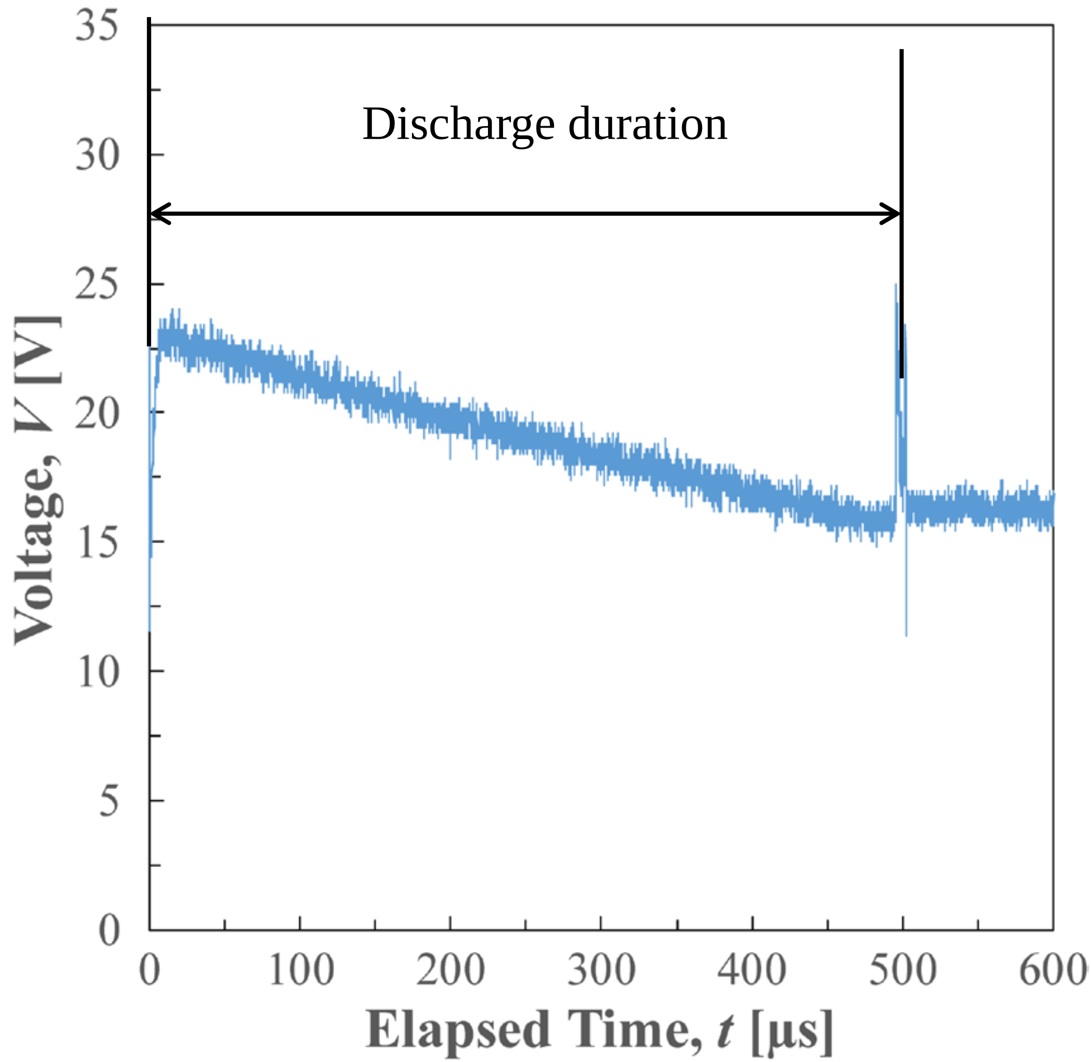
2. When water mist is added to the mixture, ignition probability decreases and minimum ignition density increases.

3. Inhibition effectiveness of water mist on ignition is greater for lean side than for rich side.

Thank you for your kind attention.

Note

Discharge duration



Relation of E_i and Discharge Duration

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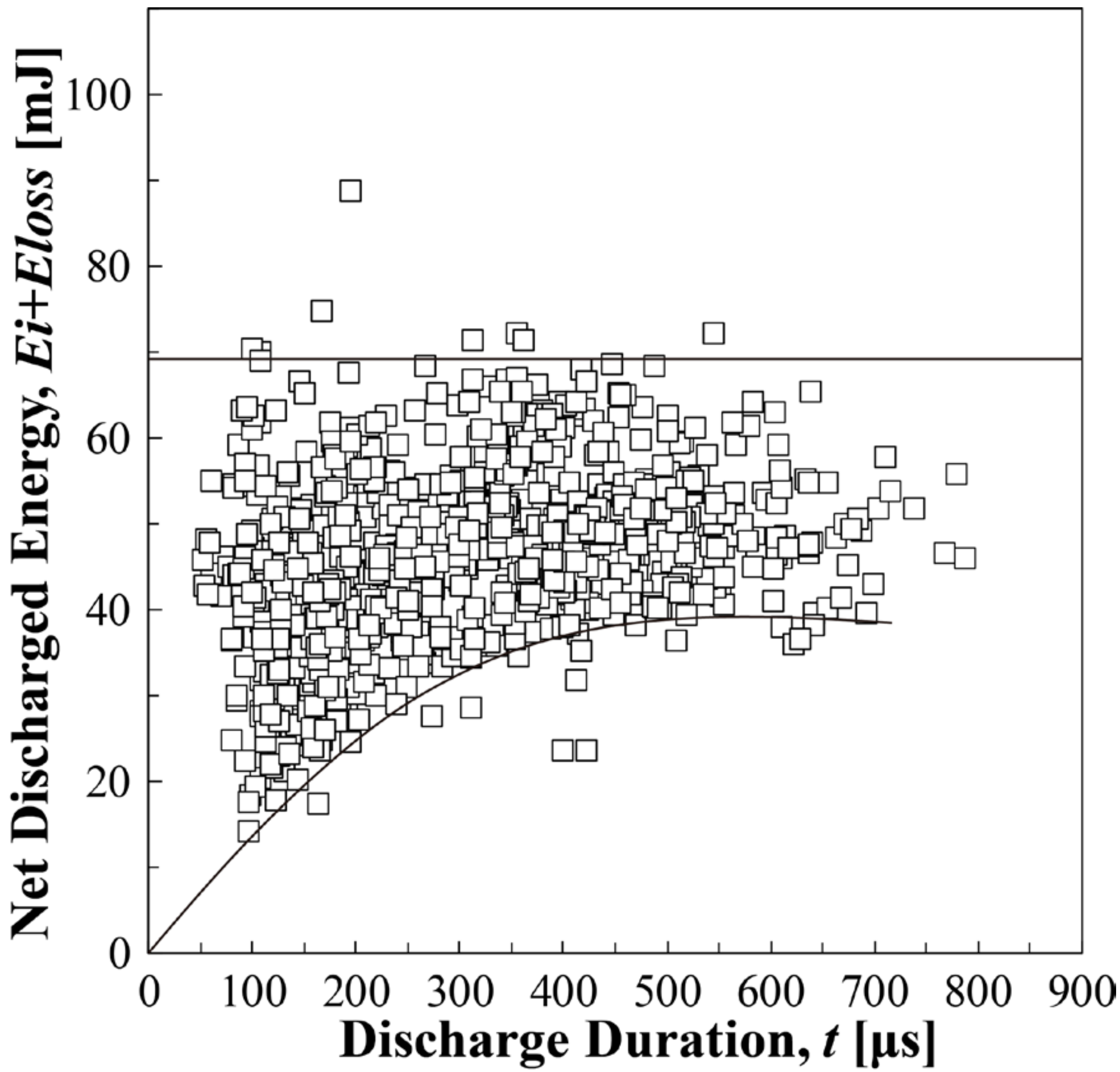

Relationship of E_i and l

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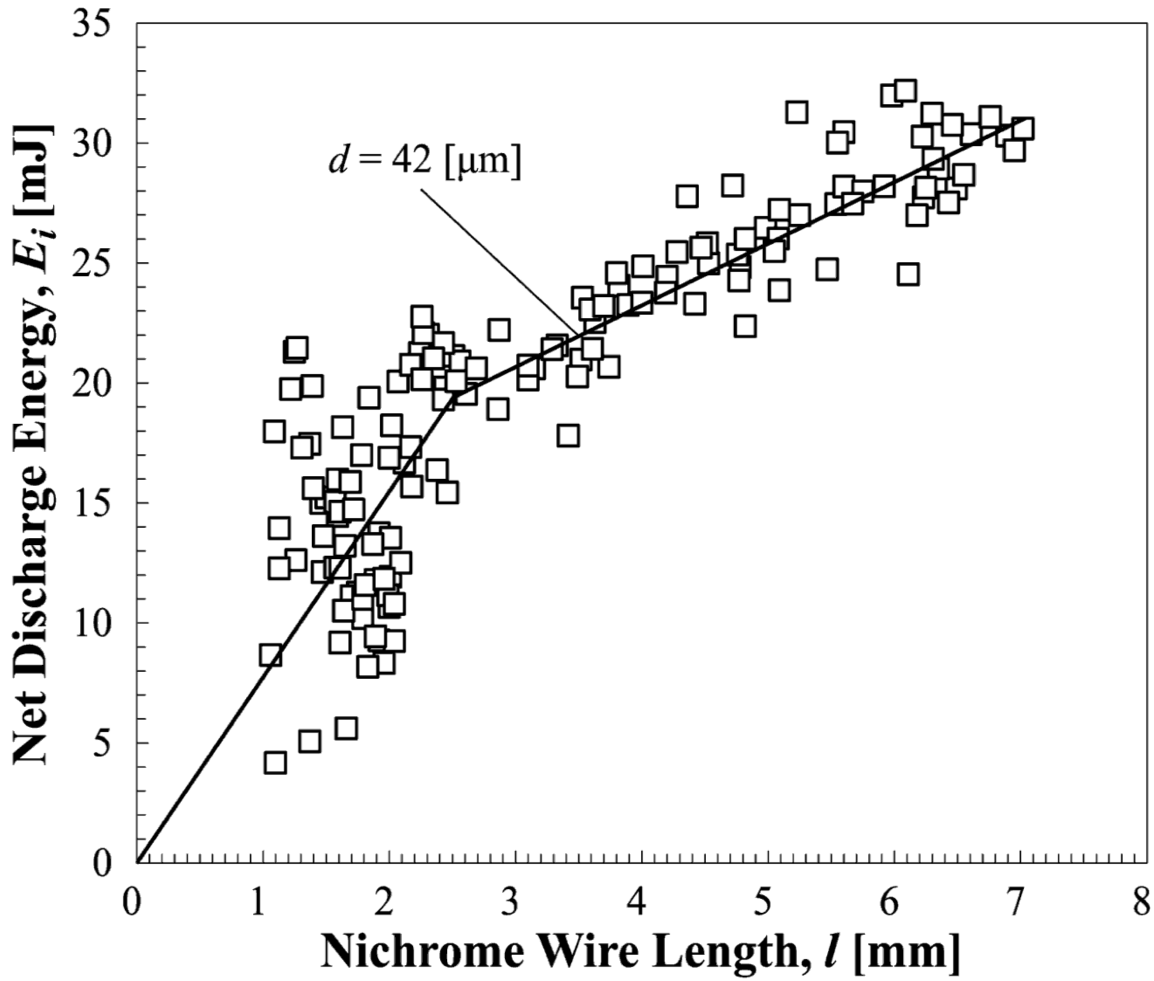

Energy density

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Energy density q_i is the total energy per unit volume to be supplied to the heat wire. Energy density q_i is expressed by

$$E_i = V_k q_i$$

$$\therefore q_i = E_i / V_k$$

q_i : Energy density [J/m^3]
E_i : Net discharge energy [J]
V_w : Flame kernel volume [m^3]

Volumetric energy release rate

Volumetric energy release rate $\dot{q}_i$ is the total energy per unit volume and unit time to be supplied to the heat wire. Volumetric energy release rate $\dot{q}_i$ is expressed by

$$\dot{q}_i = E_i / V_k t_d$$

$\dot{q}_i$: Volumetric energy release rate [W/m^3]

E_i : Net discharge energy [J]

V_k : Flame kernel volume [m^3]

t_d : discharge duration [s]

Characteristics of water mist

— Three extinguish effect —

- Cooling effect of the sensible heat and latent heat
- Dilution effect by reduction in oxygen and fuel concentrations
- Chemical effects owing to the reactivity of water vapor that may alter some reaction paths

Schlieren Optical System

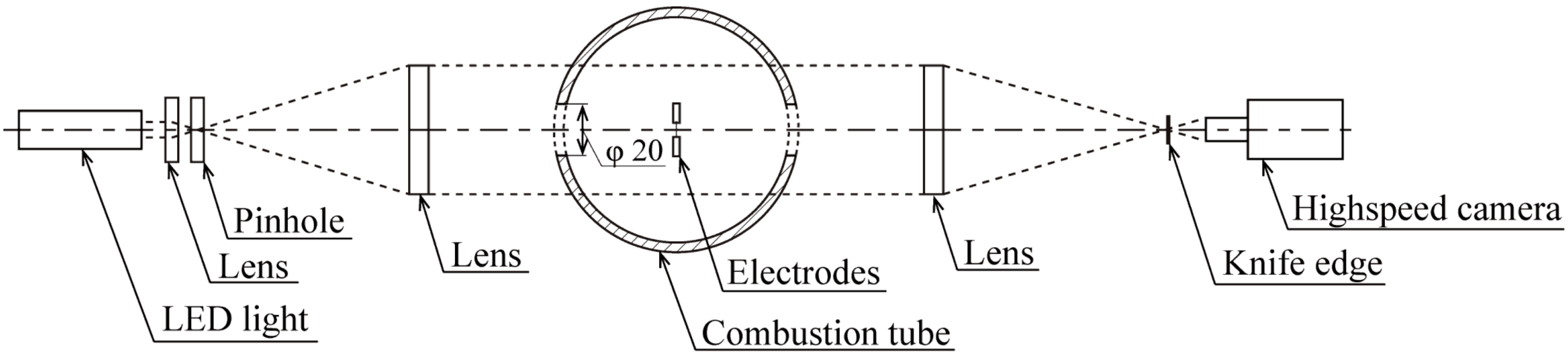
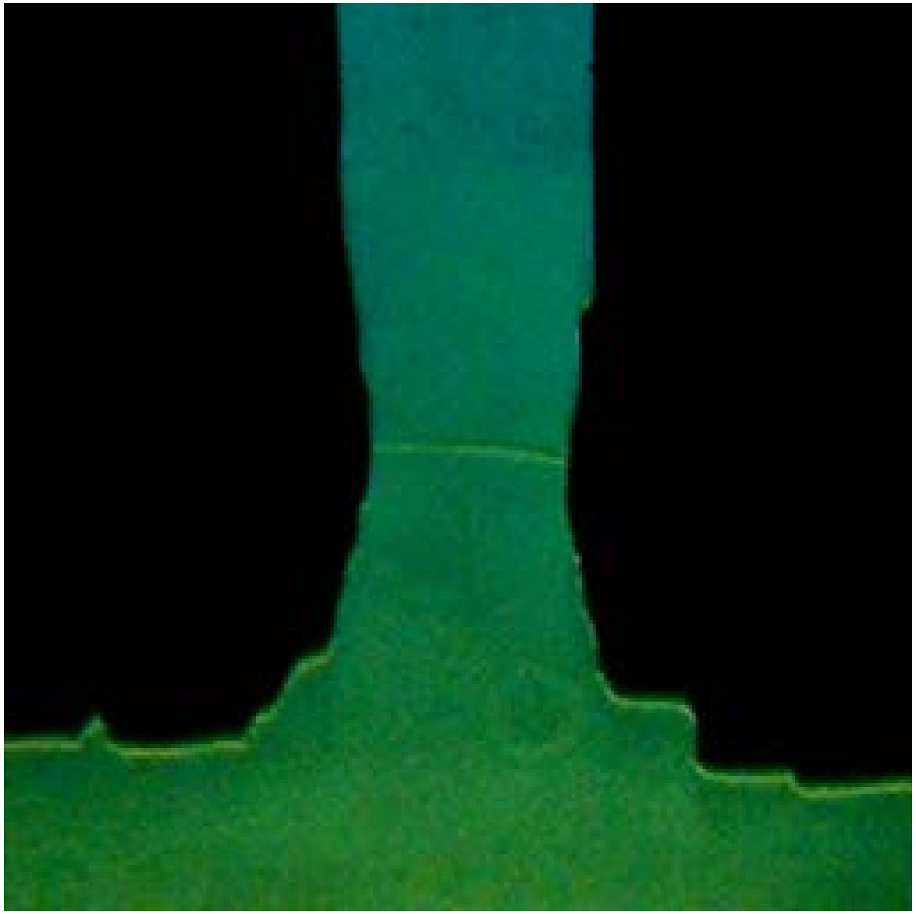


Image of schlieren photography
(side view)

Experimental Apparatus

LED Light	SLG-55 (REVOX) Luminous flux : 2100 [lm]
High Speed Camera	FASTCAM Mini AX100 (Photron) Frame rate : 37500 [fps] Resolution : 256×256 [pixel]

Schlieren Video



Schlieren imaging condition

Nichrome diameter : d = 70 [μm]

Capacitance : C = 2200 [μF]

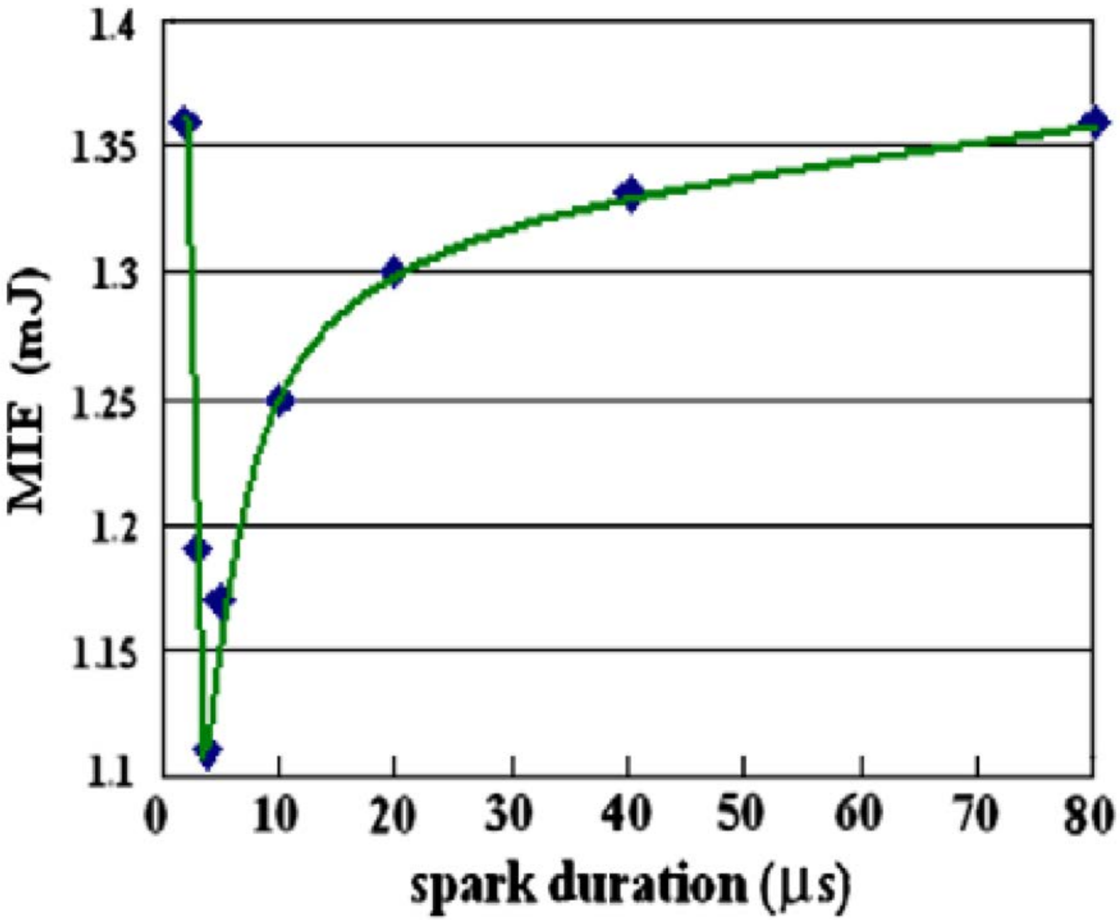
Charge voltage : E_c= 20[V]

Equivalence ratio : φ = 1.3

Net discharge energy : E_i 98.7[mJ]

Frame rate : 37500 [fps]

Relation of MIE and Spark duration



Minimum ignition energy strongly depends on the discharge duration

Ref : Jilin Han, Hiroshi Yamashita, Naoki Hayashi, Combustion and Flame 157 (2010) 1414-1421

Relation of E_{min} and Equivalence Ratio

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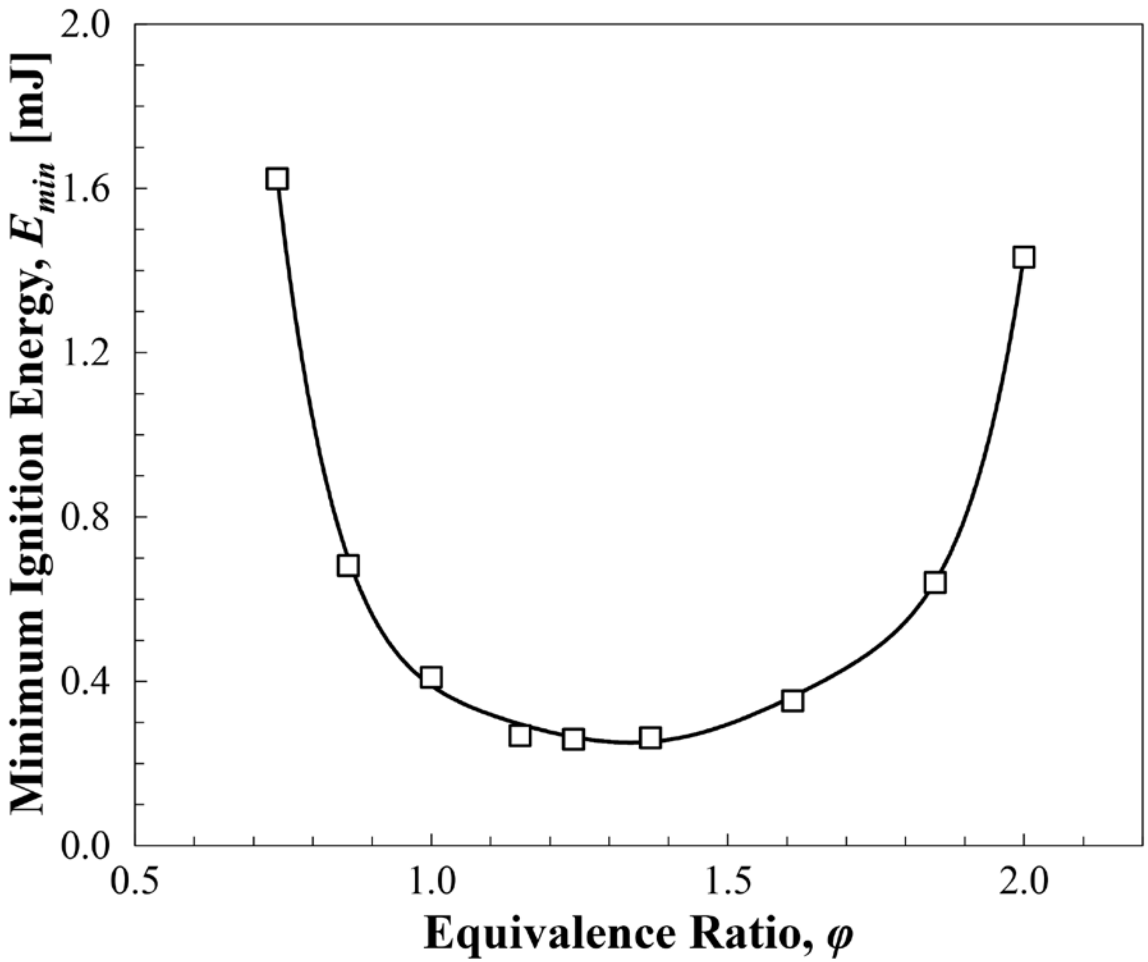

Ref : Lewis, B. and von Elbe, G., Combustion, Flames and Explosion of Gases (Second Ed.), Academic Press Inc. (1961).

Ignition Criterion

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- **Minimum Ignition Energy: E_i (J)**
  E_i: Discharge Energy (J)

- **Minimum Volumetric Energy Release Rate: $E_i/V_k\tau_d$ (W/m^3)**
  E_i: Discharge Energy (J)
  V_k: Flame Kernel Volume (m^3)
  τ_d: Discharge Duration (s)

- **Minimum Energy Density: E_i/V_k (J/m^3)**
  E_i: Discharge Energy (J)
  V_k: Flame Kernel Volume (m^3)