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

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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

- Current Probe
- High Voltage Probe
- Oscilloscope
- MOSFET
- Nichrome Wire
  - Diameter 30 ~ 80 [μm]
- Electrodes
  - Length 3.1 [mm]
Schlieren Images

(a) air, (b) $\varphi = 1.3$ no ignition, (c) $\varphi = 1.3$ ignition

(a)

(b)

(c)

0 [ms]  1 [ms]  2 [ms]  3 [ms]  4 [ms]
When a fine resistance wire was fused electrically, net discharged energy $E_i$ is expressed by

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

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

$\Delta E$ : 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 $P_i(x_i)$ can be expressed by the logistic function and is given by

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

$\beta_0$ and $\beta_1$ 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

- Minimum net discharged energy $E_{i,min}$ for ignition
  
  $d = 42$ [μm] $\rightarrow E_{i,min} = 19$ [mJ]
  
  $d = 50$ [μm] $\rightarrow E_{i,min} = 40$ [mJ]

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

Net discharged energy $E_i = \Delta E - (E_h + E_m)$
Effect of wire diameter

Energy density
\[ q = \frac{E_i}{V_k} \]

- 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

- 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.

Volumetric energy release rate

\[ \dot{q} = \frac{E_i}{V_k \tau_d} \]
Energy density
\[ q = \frac{E_i}{V_k} \]

- 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 $\varphi=1.3$

- 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.
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.
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.
Discharge duration

![Discharge duration graph](image)

- **Voltage, $V$ [V]**
- **Elapsed Time, $t$ [µs]**

- The graph shows the voltage decay over time, with the discharge duration highlighted.

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16th International Water Mist Conference (21-22/Sep/2016, Vienna)
Relation of $E_t$ and Discharge Duration

![Graph showing the relation between net discharged energy ($E_i + E_{loss}$) and discharge duration ($t$). The x-axis represents discharge duration in microseconds ($\mu s$), and the y-axis represents net discharged energy in millijoules (mJ). The scatter plot includes a trend line indicating the general trend of the data.](image-url)
Relationship of $E_i$ and $l$
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 $\dot{q}_i$ 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

$$\dot{q}_i = \frac{\Delta i}{V_k t_d}$$

$\dot{q}_i$: 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

Experimental Apparatus

<table>
<thead>
<tr>
<th></th>
<th>LED Light</th>
<th>High Speed Camera</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLG-55 (REVOX)</td>
<td>Luminous flux : 2100 [lm]</td>
<td>FASTCAM Mini AX100 (Photron)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Frame rate : 37500 [fps]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Resolution : 256 × 256 [pixel]</td>
</tr>
</tbody>
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Image of schlieren photography (side view)
Schlieren imaging condition

Nichrome diameter : $d = 70 \, [\mu m]$

Capacitance : $C = 2200 \, [\mu F]$

Charge voltage : $E_c = 20\, [V]$

Equivalence ratio : $\phi = 1.3$

Net discharge energy : $E_t \, 98.7\, [mJ]$

Frame rate : $37500 \, [fps]$
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 $E_{\text{min}}$ and Equivalence Ratio

Ignition Criterion

- **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$^3$)
  $\tau_d$: Discharge Duration (s)

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