Mitigation of hydrogen-air detonations

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Outline

• Flame quenching, MSEG
• Deflagration arresters
• Detonation arresters
• Detonation quenching – new ideas
  • by inert gas zone
  • by foams and meshes
  • by air gaps
• Testing of arresters
Flame quenching by walls

- **Cooling** – dominant effect
- Chemical effect (destruction of radicals)
- Quenching distance:

\[
d_q \propto \delta \propto \frac{\lambda}{c_p \rho_u S_L} \propto \frac{\lambda T_u}{c_p \bar{M}} \frac{1}{p_0} \frac{1}{S_L}
\]

\(S_L\) – laminar burning velocity
\(\delta\) - flame thickness

- only about 22% of the heat generated by the flame per unit surface must be removed in order to quench the flame
Flame quenching by walls

(Yang et al., 2003)
### Maximum experimental safe gap (MESG)

**Forced flow conditions parameter – in explosions, fast deflagrations**

<table>
<thead>
<tr>
<th>Fuel in stoichiometric mixture with air</th>
<th>Pressure after explosion $p_e$ (atm)</th>
<th>MESG for a partition of 25 mm thick (mm)</th>
<th>Quenching distance at $p = 1$ atm (mm)</th>
<th>Quenching distance at $p = p_e$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexane</td>
<td>7.8</td>
<td>0.95</td>
<td>3.56</td>
<td>0.5</td>
</tr>
<tr>
<td>Benzol</td>
<td>8.7</td>
<td>0.95</td>
<td>2.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>9.3</td>
<td>0.15</td>
<td>0.2</td>
<td>0.07</td>
</tr>
<tr>
<td>Acetylene</td>
<td>6.9</td>
<td>0.02</td>
<td>0.76</td>
<td>0.05</td>
</tr>
</tbody>
</table>

**MESG – dynamic parameter (depends on the direction of the flow relative to flame)**

(Chomiak, 1990)
Deflagration arresters

• Devices to prevent the passage of flame along a pipe
• Three types:
  • Type 1 – with multiple small channels (planar sheet metal, crimped ribbon, wire gauze, perforated plate, perforated block, sintered metal, parallel plate, wire pack, packed bed);
  • Type 2 – hydraulic devices;
  • Type 3 – velocity flame stoppers.
Deflagration arresters

Type 1

• Mechanism of operation: flame quenching and heat loss

• Diameter of the aperture of an arrester should be smaller than the quenching diameter by at least 50%.

• Desirable properties
  • high free cross-sectional area available for flow
  • low resistance to flow
  • high capacity to absorb the heat of the flame
  • ability to withstand mechanical shock
Deflagration arresters

Type 2

- Contain a liquid, usually water, which serves to break up the gas stream into bubbles and so prevents passage of the flame
Deflagration arresters

Type 3 – velocity stoppers

• Used in end-of-line applications to prevent a flame passing from downstream to the upstream side
• Principle of operation: to assure that the velocity of the upstream gas passing through the arrester is sufficiently high to prevent a flame propagating through the arrester from the downstream side.
• Velocity necessary to prevent flashback through apertures larger than those which would give quenching:

\[ u_T = 0.2015 g_L D \]

D – internal pipe diameter (m)

\( g_L \) – laminar velocity gradient (s\(^{-1}\)); a function of the gas and its concentration; for hydrogen its maximum value is equal to 10 000 s\(^{-1}\)

\( u_T \) – turbulent flashback velocity (m/s)
Deflagration arresters

On the market:

**PROTEGO** - ranging in size from 10 mm to 400 mm, approved in Germany for mixtures of hydrogen and air in all ranges of concentration

**ENARDO** - arresters for hydrogen-air mixtures

**WESTECH Ltd.**

Others ………………. 
Detonation arresters
Detonation arresters

1. Same as for deflagration – just longer channels and stronger
Detonation arresters

(a) Perforated plate
(b) Wire gauze and gauze packs
(c) Sintered metal
(d) Ceramic balls
Detonation arresters
Detonation arresters

2. With a "shock absorber"
Detonation arresters

3. With a "detonation momentum attenuator"
Detonation arresters

Detonation propagating through detonation arrester with "detonation momentum attenuator,"

$2H_2 + O_2 + Ar$
Detonation arresters

Simulation of detonation propagating through detonation arrester with "detonation momentum attenuator", - DETO2D code
Detonation quenching

Active arresters for waste gas recovery processes
(Kidde Graviner Ltd.)
Detonation quenching by inert zone

2H₂+O₂ mixture

\( P_0 = 0.3 \text{MPa and 0.5MPa} \)

3.6m x 60mm x 60mm channel

Inerts: Ar, He, N₂, CO₂
Detonation quenching by inert zone

Fig. 3a–d. Streak photographs of $2\text{H}_2+\text{O}_2$ detonation interaction with Ar zone: initial mixture pressure $p_0=0.5$ bar; Ar injection pressure: a 2 bar, b 4 bar, c 6 bar, d 8 bar; A – primary retonation wave reflected from ignition end; B – shock wave after detonation reflection from channel end; C – retonation wave from reinitiated detonation; D – primary detonation wave; R – reinitiated detonation wave
Detonation quenching by inert zone

(a), (f) Steady detonation
(b)–(c) Shock wave
(d) Shock wave & reaction
(e) Overdriven detonation
Detonation quenching by inert zone

Fig. 6a–f. Streak photographs of $2\text{H}_2+\text{O}_2$ detonation interaction with Ar zone; $p_0=0.3$ bar; Ar injection pressure: a 0.5 bar, b 3 bar, c 5 bar, d 5.9 bar, e 6.6 bar, f 7 bar; C - retonation wave from strong DDT
Detonation quenching by inert zone

**Fig. 14.** Flame velocity vs. distance in $2H_2 + O_2$ at $p_0=0.3$ bar for different He injection pressures.

**Fig. 13a-c.** Streak photographs of $2H_2 + O_2$ detonation interaction with He zone; $p_0=0.3$ bar; He injection pressures: a 0.5 bar, b 1 bar, c 6.5 bar
Detonation quenching by inert zone

1D numerical simulation – DL code
Detonation quenching by meshes

Detonation interaction with
the mesh lining the wall

First European Summer School on Hydrogen Safety, Belfast, 15-24 August 2006
by Andrzej Teodorczyk
Detonation quenching by meshes

Detonation interaction with the wire mesh lining the wall
Detonation quenching by meshes

No meshes
Detonation quenching by fiberglass

Detonation propagation over the fiberglass section
Detonation quenching by fiberglass

Detonation propagation over the fiberglass section
Detonation quenching by perforated plate

(Courtesy of J. Chao, McGill University)
Detonation quenching by perforated plate

![Diagram showing the setup for detonation quenching with a perforated plate, pressure transducers, and a parabolic mirror.](image-url)

(Courtesy of J. Chao, McGill University)
Detonation quenching by perforated plate

(Courtesy of J. Chao, McGill University)
Detonation quenching by perforated plate

(Courtesy of J. Chao, McGill University)
Detonation quenching by perforated plate

Theoretical CJ Pressure

incident

CJ detonation

(Courtesy of J. Chao, McGill University)
Detonation quenching by diffraction

1. Enlarged cross-section tube
2. Perforated tube
3/4. Perforated tube and wire mesh /steel wool
5. Air gap

\[ d > 13 \lambda \]
\[ h > 10 \lambda \]
\[ h > 3 \lambda \text{ for } w > 3h \]
Detonation quenching by air gap

**Objective**: controlled DDT for testing arresters
Detonation quenching by air gap

Experimental setup

- 50 mm tube
- 0.1MPa initial pressure
Detonation quenching by air gap

Quenching and DDT

No quenching
Detonation quenching by air gap
Testing of arresters

Flame arresters — Performance requirements, test methods and limits for use

1. Mixture inlet
2. Explosion proof container or pipe end
3. Ignition source
4. Unprotected pipe (length L_1, diameter D)
5. Flame detectors for flame velocity measurement
6. Pressure transducer
7. Detonation flame arrester
8. Flame detector
9. Protected pipe (length L_2, diameter D_2)
10. Pipe end
11. Mixture outlet
Testing of arresters

8 - arrester
9 – pressure transducer
10 – photodiode

Flame transmitted
Testing of arresters

**Problems:**
- existing protocols for testing arresters differ from country to country
- unsteady detonations – DDT, overdriven
- fast deflagration vs CJ detonation
- tests are subject to misinterpretation

![Graph 1: CJ detonation](image1)

![Graph 2: Overdriven detonation](image2)
Testing of arresters

50 mm TUBE

Scaling effect

150 mm TUBE

PARAMETERS: S/D = 1; 2; 4; 6
M/D = 0; 20; 40; 60
FUEL/AIR: PROPANE; ETHYLENE; HYDROGEN

PARAMETERS: S/D = 1; 2; 4; 6
M/D = 0; 20
FUEL/AIR: PROPANE; ETHYLENE; HYDROGEN
Summary of the tests for 50 mm and 150 mm tubes showing arrester response: (+) succeful, flame stopped; (-) failure, flame passed; and the type of combustion wave achieved at the end of flame tube: DF - deflagration, DT - detonation, QDT - quasidetonation, DDT - deflagration to detonation transition, ODT - overdriven detonation

<table>
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<tr>
<th>S/D</th>
<th>Mixture</th>
<th>50 mm</th>
<th>150 mm</th>
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<td></td>
<td></td>
<td>M/D</td>
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<tr>
<td></td>
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<td>0</td>
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<tr>
<td>1</td>
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<td>(+)</td>
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<tr>
<td></td>
<td></td>
<td>DF</td>
<td>DF</td>
</tr>
<tr>
<td></td>
<td>Ethylene-air</td>
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<td>DF</td>
<td>DF</td>
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<tr>
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<td>DF</td>
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<tr>
<td></td>
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<td>DDT, DT</td>
<td>DT</td>
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</tbody>
</table>
Pressure histories without obstacles

Propane-air

Ethylene-air

Hydrogen-air

50 mm tube

150 mm tube
Pressure histories with obstacles

150 mm tube