Explosion Protection of Buildings

Author: Miroslav Mynarz
Explosion Protection of Buildings

Explosion of Gas and Vapours of Combustible Liquids and Calculation of Blast Wave Parameters
Explosions on the basis of combustion

The most frequent accidents in chemical industry:
- fire
- explosion
- leak of toxic substance

The most frequent source of the explosion:
- vapours of organic solvent

Burn (explosion) of 1 kg of toluene:
- release of energy ~ 40 MJ
- it can destroy a chemical laboratory
- it can cause losses in lives
Explosions on the basis of combustion

- FUEL
- FIRE
- OXIDANT
- IGNITION SOURCE

It is burning, when all sides are connected. It is not burning, when any of sides is missing.
**Explosions on the basis of combustion**

- **Fuel and oxidant:**

<table>
<thead>
<tr>
<th>FUEL</th>
<th>OXIDANT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas:</td>
<td>Gas:</td>
</tr>
<tr>
<td>- acetylene, methane, hydrogen</td>
<td>- oxygen (air)</td>
</tr>
<tr>
<td>- liquefied petroleum gas (LPG)</td>
<td>- chlorine</td>
</tr>
<tr>
<td>Liquid:</td>
<td>Liquid:</td>
</tr>
<tr>
<td>- petrol</td>
<td>- hydrogen peroxide</td>
</tr>
<tr>
<td>- acetone, ether, hexane</td>
<td>- nitric acid</td>
</tr>
<tr>
<td>Solid:</td>
<td>- perchloric acid</td>
</tr>
<tr>
<td>- plastics</td>
<td>Solid:</td>
</tr>
<tr>
<td>- dusts of organic agents</td>
<td>- metal peroxides</td>
</tr>
</tbody>
</table>
Explosions on the basis of combustion

- Process of gas explosion:

Diagram was created thanks to participation on the 12th Conference on Structures Under Shock and Impact organized by Wessex Institute of Technology, Southampton.
Classification according to the type of energy caused by the ignition source:

- **Straight heat:**
  - sparks (fire chambers, engines);
  - flame;
  - hot surfaces.

- **Arisen by transformation of other energy to heat one:**
  - by transformation of mechanical energy (mechanical sparks, steel sparks);
  - arisen by friction or impact;
  - friction of bodies;
  - heat of compression;
  - shock wave.
Ignition

- Of electric energy:
  - short circuit;
  - electric arc;
  - contact resistance;
  - electrostatic charge;
  - static electricity;
  - lightening discharge.

- Of light energy:
  - solar radiation;
  - ionizing radiation;
  - flashlight.

- Of chemical energy:
  - exothermic reactions of agents.

Figure was created thanks to participation on the 12th Conference on Structures Under Shock and Impact organized by Wessex Institute of Technology, Southampton.
## Ignition

**Ignition sources of major fires/explosions:**

<table>
<thead>
<tr>
<th>Source: National Safety Council, Chicago</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrical (wiring of motors)</strong></td>
</tr>
<tr>
<td><strong>Smoking</strong></td>
</tr>
<tr>
<td><strong>Friction (bearing or broking parts)</strong></td>
</tr>
<tr>
<td><strong>Overheated materials (abnormally high temperatures)</strong></td>
</tr>
<tr>
<td><strong>Hot surfaces (heat from boilers, lamp, etc.)</strong></td>
</tr>
<tr>
<td><strong>Burner flames (improper use of torches, etc.)</strong></td>
</tr>
<tr>
<td><strong>Combustion sparks (sparks and embers)</strong></td>
</tr>
<tr>
<td><strong>Spontaneous ignition (rubbish, etc.)</strong></td>
</tr>
<tr>
<td><strong>Cutting and welding (sparks, arcs, heat, etc.)</strong></td>
</tr>
<tr>
<td><strong>Exposure (fires jumping into new areas)</strong></td>
</tr>
<tr>
<td><strong>Incendiaryism (fires maliciously set)</strong></td>
</tr>
<tr>
<td><strong>Mechanical sparks (grinders, crushers, etc.)</strong></td>
</tr>
<tr>
<td><strong>Molten substances (hot spills)</strong></td>
</tr>
<tr>
<td><strong>Chemical action (processes not in control)</strong></td>
</tr>
<tr>
<td><strong>Static sparks (release of accumulated energy)</strong></td>
</tr>
<tr>
<td><strong>Lightning (where lightning rods are not used)</strong></td>
</tr>
<tr>
<td><strong>Miscellaneous</strong></td>
</tr>
</tbody>
</table>
Ignition

MIE = Minimum Ignition energy
inversely proportional to pressure;
addition of inert increases MIE;
dust clouds can have
comparable MIE as vapours.

Sources of ignition energy
- car plug – 25 mJ;
cleaning of shoes at doormat – static electricity 22 mJ.
## Ignition

<table>
<thead>
<tr>
<th>Combustible agent</th>
<th>Minimum energy (mJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GASES</strong></td>
<td></td>
</tr>
<tr>
<td>Methane</td>
<td>0.29</td>
</tr>
<tr>
<td>Ethane</td>
<td>0.24</td>
</tr>
<tr>
<td>Propane</td>
<td>0.26</td>
</tr>
<tr>
<td>Heptane</td>
<td>0.25</td>
</tr>
<tr>
<td>Ethylene</td>
<td>0.07</td>
</tr>
<tr>
<td>Acetylene</td>
<td>0.017</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.017</td>
</tr>
</tbody>
</table>

| **Minimum ignition energies (MIE)** |

<table>
<thead>
<tr>
<th>Combustible agent</th>
<th>Minimum energy (mJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LIQUIDS</strong></td>
<td></td>
</tr>
<tr>
<td>Acetone</td>
<td>1.15</td>
</tr>
<tr>
<td>Methanol</td>
<td>0.14</td>
</tr>
<tr>
<td>Benzene</td>
<td>0.20</td>
</tr>
<tr>
<td>Toluene</td>
<td>0.24</td>
</tr>
<tr>
<td><strong>DUSTS</strong></td>
<td></td>
</tr>
<tr>
<td>Cornstarch dust</td>
<td>0.30</td>
</tr>
<tr>
<td>Iron dust</td>
<td>0.12</td>
</tr>
</tbody>
</table>
Zones for combustible gases and vapours of liquids

- Hazardous areas classification:

**Zone 0**
area in which an explosive atmosphere of a mixture is present continuously, for long periods or often (e. g. silos, pipes).

**Zone 1**
area in which probability of occurrence of an explosive atmosphere of a mixture is occasional in normal operation (e. g. neighbourhood of supply, filling and discharging openings).

**Zone 2**
area in which an explosive atmosphere is not likely to occur in normal operation and if this atmosphere occurs then it exists only for very short time of a mixture (e. g. areas surrounding zones 0 or 1).
Region with explosive atmosphere

- Classification of hazardous areas
Region with explosive atmosphere

- Marking of equipment with explosion hazards

CE marking: CE 0081 \(\mathbb{D}\) II 2 G EEx d IIB T4

Identification of the testing laboratory in EU

Specific marking of explosive protection

Equipment group:
I – mines
II – industry

Equipment category:
2 – zone 1
3 – zone 2

Surrounding atmosphere:
G – explosive gases

Additional marks to specify the type and prevention forms of the equipment
Combustible liquids

- Classification according to the flash point:

**Combustible**

substances with flash point between 21 – 55 °C, releasing high combustible gases when in contact with moisture.

**High combustible**

liquids with flash point up to 21 °C, substances at which warming or auto ignition can occur under normal conditions; solids that can ignite and burn further after short contact with ignition source; substances releasing high combustible gases when in contact with moisture.

**Extremely combustible**

liquids with flash point up to 0 °C or substances ignited when they contact air under normal conditions.
Liquids aerosols

Aerosols of liquids and mist are composed of droplets smaller than 1 mm. In practice, mists and aerosols with droplets size of 0.001 mm and 0.1 mm occur very often. Dispersion of small droplets of combustible liquid in air (e.g. oil droplets at machine run) creates the explosive system (e.g. in crankcases of engines or compressors). Explosive characteristics of liquids aerosols and mists are assessed analogous to parameters of aerosols of solid dust particles.
Explosion parameters – Explosion limits

Illustration of concentration axis, explosion range of gas and vapours of combustible liquids.

Illustration of explosion range depending on time and MIE.
All combustible agents in air-mixture are able to be ignited only within the explosion range. For concentration below the lower explosive limit, this mixture is neither explosive nor combustible. For concentration above the upper explosive limit, the mixture is combustible only in aerobic conditions but it can turn into explosive mixture after appropriate dilution with air.

<table>
<thead>
<tr>
<th>Combustible Agent</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
<th>Combustible Agent</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>acetylene</td>
<td>2.5 – 82.0 %</td>
<td>5.8 – 63.0 %</td>
<td>ammonia</td>
<td>15.5 – 31.0 %</td>
<td>4.3 – 15.0 %</td>
</tr>
<tr>
<td>coal gas</td>
<td></td>
<td></td>
<td>natural gas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>carbon monoxide</td>
<td>12.5 – 75.0 %</td>
<td>4.3 – 45.5 %</td>
<td>hydrogen sulphide</td>
<td></td>
<td></td>
</tr>
<tr>
<td>methane</td>
<td>4.0 – 15.0 %</td>
<td></td>
<td>hydrogen</td>
<td></td>
<td>4.0 – 75.6 %</td>
</tr>
<tr>
<td>petrol</td>
<td>1.1 – 6.0 %</td>
<td></td>
<td>acetone</td>
<td></td>
<td>1.6 – 15.3 %</td>
</tr>
<tr>
<td>butane</td>
<td>1.6 – 8.5 %</td>
<td></td>
<td>carbon disulphide</td>
<td></td>
<td>1.3 – 50.0 %</td>
</tr>
<tr>
<td>propane</td>
<td>2.1 – 9.5 %</td>
<td></td>
<td>gas</td>
<td></td>
<td>21.0 – 74.0 %</td>
</tr>
</tbody>
</table>
Affection of explosion limits

- Explosion limits are influenced by many effects:
  - quantity of ignition energy $E_i$;
  - initial pressure at the moment of ignition $p_i$;
  - initial temperature $T_i$;
  - moisture;
  - oxygen content.

*Explosion characteristic of methane-air mixture.*
Explosion parameters

- **Time-pressure curve:**
  
  Important points:
  
  A – ignition point
  B – point of pressure rise
  C – inflex point of a curve
  D – maximum point of a curve

Concentration of CH₄ in O₂: 66 %
Ignition energy: 10 J
Initial overpressure: 0.1 MPa
Explosion parameters

With changes of explosive mixture concentration, the time-pressure curve is markedly changed, thereby the values of explosion pressure $p_{\text{exp}}$ and rate of explosion pressure rise $(dp/dt)_{\text{exp}}$ are changed as well. The highest values of explosion pressure and rate of explosion pressure rise are reached at optimal concentration $c_{\text{opt}}$. These values are called maximum explosion pressure $p_{\text{max}}$ and maximum rate of explosion pressure rise $(dp/dt)_{\text{max}}$. For gases and vapours, optimal concentration is just slightly higher them stoichiometric.

When concentration from $c_{\text{opt}}$ is increasing or decreasing, both explosion pressure and rate of explosion pressure rise are going down to the explosion limits LEL and UEL. Independent propagation of the explosion in the mixture is not possible beyond these limits.
Explosion parameters

On the curve, the point A represents ignition of explosive mixture. After ignition, time $t_{i,ex}$ (so-called time of ignition delay) passes before pressure increase appear. It is setup time for explosive mixture to combustion. From the point B, explosion pressure is increasing on the curve. As a result of temperature increase, reaction rate is increasing up to the point C in which rate of explosion pressure rise is highest. Between points C and D, rate of explosion pressure rise is decreasing as a result of decrease of reaction components. This rate is zero in the point D. From the point D, pressure is decreasing owing to decrease of temperature of the combustion products and vapours condensation.
Calculation of walls failure of buildings or rooms

- **Boiling Liquid Expanding Vapor Explosion (BLEVE)**

At fast heating (for example as a result of surrounding fire) of silo with liquefied gas under pressure, liquid is evaporating and pressure rises further which can lead even to a rupture of silo's envelope. If such a situation occurs pressure falls very fast which causes forceful boiling of liquid without necessity of heat supply of surrounding. Forceful evaporation can overgrow to mechanical explosion. If stocked gas is combustible its ignition means more hazard.
Calculation of walls failure of buildings or rooms

- **BLEVE**

Typical scenario:
- fire in neighbourhood of a tank with combustible liquid;
- heating of tank walls and liquid inside, increasing of vapours pressure;
- overheating of tank material above the liquid level to the extent that it is not able to resist the pressure of vapours;
- rupture of a tank and explosive evaporisation of a part of its volume.
Classification of explosion according to the geometry of environment

- Unconfined areas – open space
- Confined (inside) space
- Partly confined space
- Pipes and tunnels – 1D geometry
Affection of explosion limits

- Quantity of ignition energy
  With increasing ignition energy, explosion range becomes wider whereas especially upper explosive limit reaches higher values. Explosive limits are generally determined at room temperature, atmospheric pressure and standard ignition energy that is $E_i = 10 \, \text{J}$ for gases and vapours.

- Initial temperature
  With increasing temperature, explosive range becomes wider. Lower explosive limit is decreasing and upper limit is increasing. Dependence is linear but gradient of a line is not the same for all combustible agents.
Affection of explosion limits

- Initial pressure at the moment of ignition
  
  With increasing initial pressure, upper explosive limit is increasing (lower explosive limit is decreasing only slightly).

  With decreasing pressure, explosive range is getting narrower and explosive region is getting closed at some mixtures so at particular negative phase, the explosion does not occur at all at given ignition energy.
**Affection of explosion limits**

- **Moisture**
  Relative moisture of gas-air mixture affects the explosion range only slightly. The biggest explosion range is supposed for solid mixture.

- **Oxygen content**
  With increasing oxygen content, upper explosion limit is markedly moving to higher values (at upper oxygen limit, oxygen is lacking). Lower explosion limit is not influenced by oxygen content because specific heat capacity of oxygen is similar to nitrogen.
Typical combustion properties of some chosen hydrocarbons

<table>
<thead>
<tr>
<th>Matter</th>
<th>Explosion limits (vol. %)</th>
<th>Stoichiometric ratio</th>
<th>Amount of gas at max. burning velocity</th>
<th>Max. laminar burning velocity</th>
<th>Adiabatic flame temperature</th>
<th>Expansion ratio $T_f / T_1$</th>
<th>Max. laminar flame speed</th>
<th>Autoignition temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>4.0</td>
<td>75</td>
<td>30</td>
<td>54</td>
<td>3.5</td>
<td>2318</td>
<td>8.0</td>
<td>28.0</td>
</tr>
<tr>
<td>Methane</td>
<td>5.0</td>
<td>15</td>
<td>9.5</td>
<td>10</td>
<td>0.45</td>
<td>2148</td>
<td>7.4</td>
<td>3.5</td>
</tr>
<tr>
<td>Ethane</td>
<td>3.0</td>
<td>12.5</td>
<td>5.6</td>
<td>6.3</td>
<td>0.53</td>
<td>2168</td>
<td>7.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Propane</td>
<td>2.2</td>
<td>9.5</td>
<td>4.0</td>
<td>4.5</td>
<td>0.52</td>
<td>2198</td>
<td>7.6</td>
<td>4.0</td>
</tr>
<tr>
<td>Butane</td>
<td>1.9</td>
<td>8.5</td>
<td>3.1</td>
<td>3.5</td>
<td>0.5é</td>
<td>2168</td>
<td>7.5</td>
<td>3.7</td>
</tr>
<tr>
<td>Pentane</td>
<td>1.5</td>
<td>7.8</td>
<td>2.6</td>
<td>2.9</td>
<td>0.52</td>
<td>2232</td>
<td>7.7</td>
<td>4.0</td>
</tr>
<tr>
<td>Hexane</td>
<td>1.2</td>
<td>7.5</td>
<td>2.2</td>
<td>2.5</td>
<td>0.52</td>
<td>2221</td>
<td>7.7</td>
<td>4.0</td>
</tr>
<tr>
<td>Heptane</td>
<td>1.2</td>
<td>6.7</td>
<td>1.9</td>
<td>2.3</td>
<td>0.52</td>
<td>2196</td>
<td>7.6</td>
<td>4.0</td>
</tr>
<tr>
<td>Acetylene</td>
<td>2.5</td>
<td>80</td>
<td>7.7</td>
<td>9.3</td>
<td>1.58</td>
<td>2598</td>
<td>9.0</td>
<td>14.2</td>
</tr>
<tr>
<td>Ethylene</td>
<td>3.1</td>
<td>32</td>
<td>6.5</td>
<td>7.4</td>
<td>0.83</td>
<td>2248</td>
<td>7.8</td>
<td>6.5</td>
</tr>
<tr>
<td>Propylene</td>
<td>2.4</td>
<td>10.3</td>
<td>4.4</td>
<td>5.0</td>
<td>0.66</td>
<td>2208</td>
<td>7.7</td>
<td>5.1</td>
</tr>
<tr>
<td>Butylene</td>
<td>1.7</td>
<td>9.5</td>
<td>3.4</td>
<td>3.9</td>
<td>0.57</td>
<td>2203</td>
<td>7.6</td>
<td>4.3</td>
</tr>
<tr>
<td>Benzene</td>
<td>1.4</td>
<td>7.1</td>
<td>2.7</td>
<td>3.3</td>
<td>0.62</td>
<td>2287</td>
<td>7.9</td>
<td>4.9</td>
</tr>
<tr>
<td>Cyklohexane</td>
<td>1.3</td>
<td>8.0</td>
<td>2.3</td>
<td>2.7</td>
<td>0.52</td>
<td>2232</td>
<td>7.8</td>
<td>4.1</td>
</tr>
</tbody>
</table>
Gas and vapours explosion theory

- TNT equivalence method:

\[ W_{TNT} = \alpha_e \cdot \frac{W_f \cdot H_f}{H_{TNT}} = \alpha_m \cdot W_f \]

where \( W_{TNT} \) is a TNT-equivalent weight of the explosive (in kg of TNT), \( W_f \) is a weight of available (real) explosive (in kg), \( H_f \) is a heat of combustion of considered explosive (in J.kg\(^{-1}\)), \( H_{TNT} \) is the explosion energy of TNT (in J.kg\(^{-1}\)), \( \alpha_e \) is a TNT equivalent based on energy (-) and \( \alpha_m \) is a TNT equivalent based on mass (-).
### TNT equivalents of some gases and vapours

<table>
<thead>
<tr>
<th>No.</th>
<th>Explosive</th>
<th>Heat of combustion $H_f$ (kJ/kg)</th>
<th>Pressure TNT equivalent $k_{TNT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Acetylene</td>
<td>50 120</td>
<td>11.933</td>
</tr>
<tr>
<td>2</td>
<td>Butane</td>
<td>49 600</td>
<td>11.810</td>
</tr>
<tr>
<td>3</td>
<td>Methane</td>
<td>55 560</td>
<td>13.229</td>
</tr>
<tr>
<td>4</td>
<td>Propane</td>
<td>50 360</td>
<td>11.990</td>
</tr>
<tr>
<td>5</td>
<td>Coalgas</td>
<td>39 800</td>
<td>9.476</td>
</tr>
<tr>
<td>6</td>
<td>Hydrogen</td>
<td>143 000</td>
<td>34.048</td>
</tr>
<tr>
<td>7</td>
<td>Ammonia</td>
<td>22 357</td>
<td>5.323</td>
</tr>
<tr>
<td>8</td>
<td>Butylene</td>
<td>48 692</td>
<td>11.593</td>
</tr>
<tr>
<td>9</td>
<td>Benzene (vapours)</td>
<td>41 993</td>
<td>9.998</td>
</tr>
<tr>
<td>10</td>
<td>Ethylene</td>
<td>50 785</td>
<td>12.092</td>
</tr>
<tr>
<td>11</td>
<td>Ethane</td>
<td>51 690</td>
<td>12.307</td>
</tr>
</tbody>
</table>
Outer explosion of gas and vapours

- **Multi-Energy methods:**
  - defines the explosion of vapours cloud as amount of sub-explosions corresponding to various sources in the cloud.

At application of this method, determination of initial blast strength (initial overpressure) is a basic problem. It can be carried out on the basis of simulation, experimental data or estimation (conservative).

2 – 20 % of energy is concern in the blast wave!
Outer explosion of gas and vapours

The idealized p-t course of venting deflagration is given by:

\[
P_1 = S_0 \cdot \frac{(4,3 \cdot K \cdot W + 28)}{V^{\frac{1}{3}}} \quad P_2 = 58 \cdot S_0 \cdot K
\]

where \( P_1 \) is reaction pressure of exhaust areas (mbar), \( P_2 \) is maximum explosion pressure in given space (mbar), \( S_0 \) is laminar burning velocity (m.s\(^{-1}\)), \( V \) is volume of vented area (m\(^3\)), \( W \) is a weight of 1 m\(^2\) of vent area (kg.m\(^{-2}\)), \( K \) is venting coefficient (-), \( A_s \) is an area of wall with venting opening (m\(^2\)), \( A_v \) is vent area (m\(^2\)).
Outer explosion of gas and vapours

The course of blast curve in the chamber with vent areas

\[ p_{\text{red}} = 1,804 \cdot 10^{-5} \cdot \left[ D^2 \cdot S_{fl} \cdot (E_0 - 1) \right]^2 \cdot A_v^{-2} \]

where \( p_{\text{red}} \) is reduced pressure (MPa), \( D \) is diameter or dimension (m), \( S_{fl} \) is the rate of flame (m.s\(^{-1}\)), \( E_0 \) is expansion ratio (-), \( A_v \) is a size of vent area (m\(^2\)).
Outer explosion of gas and vapours

(according to ČSN EN 1991-1-7)

\[ p_d = 3 + p_{stat} \]

or

\[ p_d = 3 + \frac{p_{stat}}{2} + 0.04 \left( \frac{A_v}{V} \right)^2 \]

\( p_d \) is equivalent static pressure (kN/m\(^2\)), \( p_{stat} \) is uniformly distributed static pressure at which the structure is damaged (kN/m\(^2\)); \( A_v \) is an area of exhausted elements (m\(^2\)), \( V \) is a volume of right-angle space (m\(^3\)).

higher value is considered
Outer explosion of gas and vapours

(according to NFPA 68)

\[ P_{\text{red}} = \left( C \cdot A_S \right)^2 \cdot A_v^{-2} \]

where \( P_{\text{red}} \) is maximum pressure developed in a vented enclosure during a vented deflagration (bars), \( C \) is venting equation constant (bars\(^{1/2}\)), \( A_S \) is internal surface area of enclosure (m\(^2\)), \( A_v \) is vent area (m\(^2\)).

**Limitation:** valid only for \( p_{\text{stat}} < 0.1 \text{ bar g.} \)
Pipe

Explosion course in the pipe (the length is much greater than the diameter of the pipe) is different from its course in cubic or elongated enclosure.

The rate of expansion of the flame front is influenced by a number of factors:
- length and diameter of the pipe,
- location of ignition source,
- status of mixture movement (flow velocity),
- type of a mixture,
- obstructers in the pipe,
- closing of the pipe.
Pipe

Mechanism of propagation of the flame front depends on following cases:

- mixture ignited at the open end of the pipe,
- mixture ignited at the closed end of the pipe,
- mixture ignited in the pipe closed on both sides.
Pipe

- Mixture ignited at the open end of the pipe:

The flame is propagating in the direction to the fresh mixture by rather small velocity corresponding to normal burning velocity of given mixture; whole mixture burns inside the pipe. Combustion products are able to leak free from the pipe at the same time.

While at the beginning the flame moves in hemispherical shape into the pipe, subsequently a mixture begins to vibrate in the pipe; to expel the combustion products out of the pipe, more and more energy is needed so the fresh mixture ahead of the flame front is compressed which results in the increasing of the flame speed.
Pipe

- Mixture ignited at the closed end of the pipe:

The flame front is propagating to the open end. Arising combustion products, whose volume represents circa septuple of volume of the fresh mixture, are expelling the fresh mixture ahead of the flame front out of the pipe. The rate of movement of the flame front is then given by sum of burning velocity of the mixture and expelling velocity (80 – 90 %). Only part of the mixture (circa 1/7) burns in the pipe. The rate of the flame front is increasing so much that it exceeds the value of the Reynolds number for laminar flow (Re < 2100). Turbulent flow means that a surface of the flame front grows essentially larger and thus the burning velocity of the mixture increases intensely.
Pipe

- Mixture ignited in the pipe closed on both sides:

The rate of expansion of the flame front is lower and it does not reach maximum values at the end of the pipe. The velocity is not influenced by closing of the pipe only for gas with high Brisance (hydrogen). However, brake effect of the closed end is not forceful – in distance of 30 m, the explosion develops into detonation at all three testing gases (methane, propane, hydrogen). Starting distances are longer than in one-side open pipe. In the close pipe, leak of the fresh unreacted mixture ahead of the flame front is not possible therefore whole mixture reacts so at the same explosion velocity, the explosion pressures are higher than in one-side open pipe.
Pipe – explosion of gas and vapours of liquids

- Gas and fuel / air explosions in road and rail tunnels, in case of detonation:

\[
p(x,t) = p_0 \cdot \exp \left[ - \left( \frac{t - \frac{|x|}{c_1}}{t_0} \right) \right] \quad \text{for} \quad \frac{|x|}{c_1} \leq t \leq \frac{|x|}{c_2} - \frac{|x|}{c_1}
\]

\[
p(x,t) = p_0 \cdot \exp \left[ - \left( \frac{|x| - 2|x|}{c_2} - \frac{|x|}{c_1} \right) \right] \quad \text{for} \quad \frac{|x|}{c_2} - \frac{|x|}{c_1} \leq t \leq \frac{|x|}{c_2}
\]
Pipe – explosion of gas and vapours of liquids

- Gas and fuel / air explosions in road and rail tunnels, in case of detonation:

\[ p(x,t) = 0 \]

for all other conditions.

where \( p_0 \) is peak pressure (kN/m\(^2\)), \( c_1 \) is propagation velocity of the shock wave (m/s), \( c_2 \) is acoustic propagation velocity in hot gasses (m/s), \( t_0 \) is time constant (s), \( |x| \) is a distance to the heart of the explosion (m) and \( t \) is time (s).
Pipe – explosion of gas and vapours of liquids

- Gas and fuel / air explosions in road and rail tunnels, in case of deflagration:

\[ p(t) = 4p_0 \left( \frac{t}{t_0} \right) \left( 1 - \frac{t}{t_0} \right) \]

\[ 0 \leq t \leq t_0 \]

where \( p_0 \) is peak pressure (kN/m\(^2\)), \( t_0 \) is time constant (s) and \( t \) is time (s).
Thank you for your attention.