HySafe Research Priorities Workshop

Washington DC, 10-11 November 2014

Correlations for venting of localized and full volume deflagrations in low strength equipment and buildings

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Vented deflagration pressure dynamics

- Introducing burning velocity

$$\frac{dn_b}{d\tau} = 3\left[\chi\,\pi^{\varepsilon+1/\gamma_u}\left(1-n_u\pi^{-1/\gamma_u}\right)^{2/3} + (1-A)R_b^{\#}W\right]$$

$$\frac{dn_u}{d\tau} = -3\left[\chi\,\pi^{\varepsilon+1/\gamma_u}\left(1-n_u\pi^{-1/\gamma_u}\right)^{2/3} + (1-A)R_u^{\#}W\right]$$

where $\tau = t\,S_{ui}/a$ - non-dimensional time,

$$R_u^{\#} = \left\{(2\gamma_u)/(\gamma_u-1)\pi_m\sigma_u\left[(1/\pi_m)^{2/\gamma_u} - (1/\pi_m)^{1+1/\gamma_u}\right]\right\}^{1/2}$$

$$R_b^{\#} = \left\{(2\gamma_b)/(\gamma_b-1)\pi_m\sigma_b\left[(1/\pi_m)^{2/\gamma_b} - (1/\pi_m)^{1+1/\gamma_b}\right]\right\}^{1/2}$$

$$Br = \frac{c_{ui}/S_{ui}}{E_i-1}\cdot\frac{F}{V^{2/3}}$$

$$W = \frac{1}{(36\pi_0)^{1/3}\sqrt{\gamma_u}}\frac{\mu F}{V^{2/3}}\frac{c_{ui}}{S_{ui}}$$

$$Br_t = \frac{\sqrt{E_i/\gamma}}{\sqrt[3]{36\pi_0}}\cdot\frac{Br}{\chi/\mu}$$

- energy equation becomes

$$\frac{d\pi}{d\tau} = \frac{\chi Z\pi^{\varepsilon+1/\gamma_u}\left(1-n_u\pi^{-1/\gamma_u}\right)^{2/3} - \gamma_b W\left[(1-A)R_u^{\#} + AR_b^{\#}\frac{\pi^{1/\gamma_u}-n_u}{n_b}\right]}{\left(\pi^{1/\gamma_u} - \frac{\gamma_u-\gamma_b}{\gamma_u}n_u\right)\frac{1}{3\pi}}$$

Deflagration–Outflow Interaction (DOI) number

The main unknown in the $\Delta\pi_m = \lambda\left(Br_t\right)^{-\sigma}$ correlation is Deflagration-Outflow Interaction (DOI) factor χ/μ.

It can be calculated as a product of flame wrinkling factors:

$$\chi/\mu = \Xi_K \, \Xi_{LP} \, \Xi_{FR} \, \Xi_{u'} \, \Xi_{AR} \, \Xi_O$$

Ξ_K - Karlowitz wrinkling factor due to the turbulence generated by the flame front itself

Ξ_{LP} - leading point wrinkling factor

Ξ_{FR} - wrinkling factor due to fractal increase of flame surface area

$\Xi_{u'}$ - wrinkling factor to account for initial turbulence

Ξ_{AR} - increase of flame area due to enclosure elongation

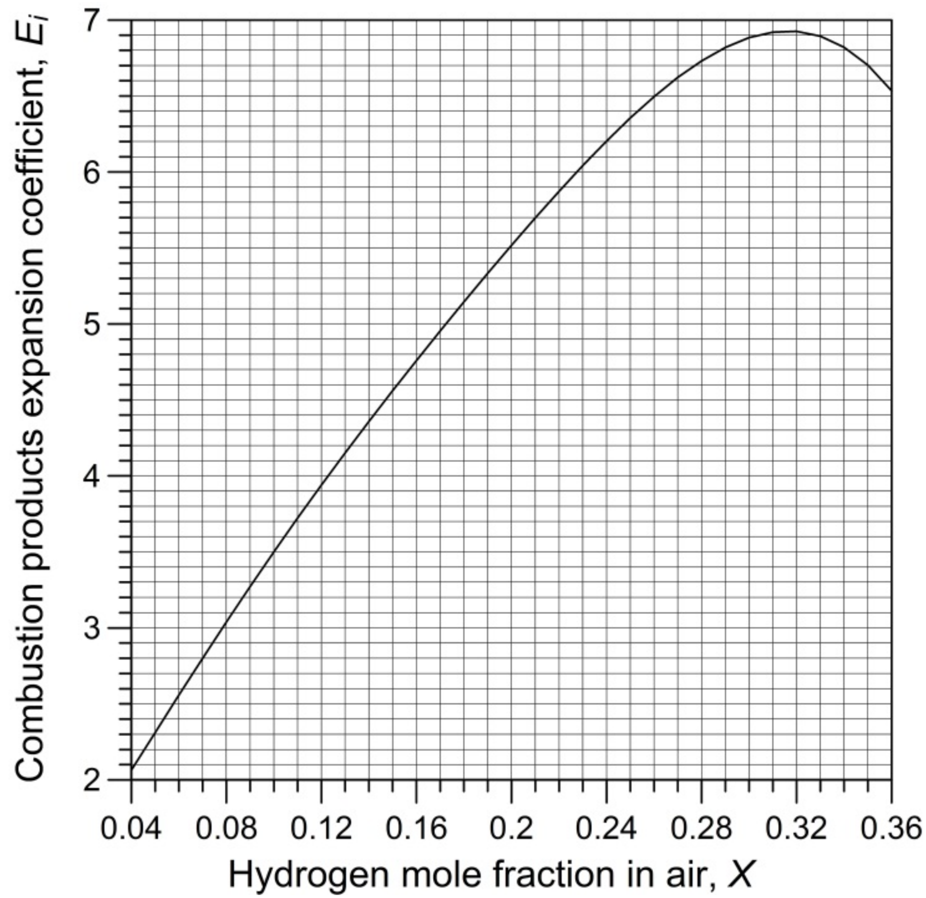
Ξ_O - factor arising due to the turbulence in presence of obstacles

Karlowitz wrinkling factor

$$\chi/\mu = \Xi_K\ \Xi_L\ \Xi_{PF}\ \Xi_{Ru'}\ \Xi_A\ \Xi_{RO}$$

Karlowitz wrinkling factor appears due to the turbulence generated by the flame front itself $\Xi_K^{max} = (E_i - 1)/\sqrt{3}$

where E_i is the combustion products expansion coefficient, dependent on the hydrogen mole fraction.



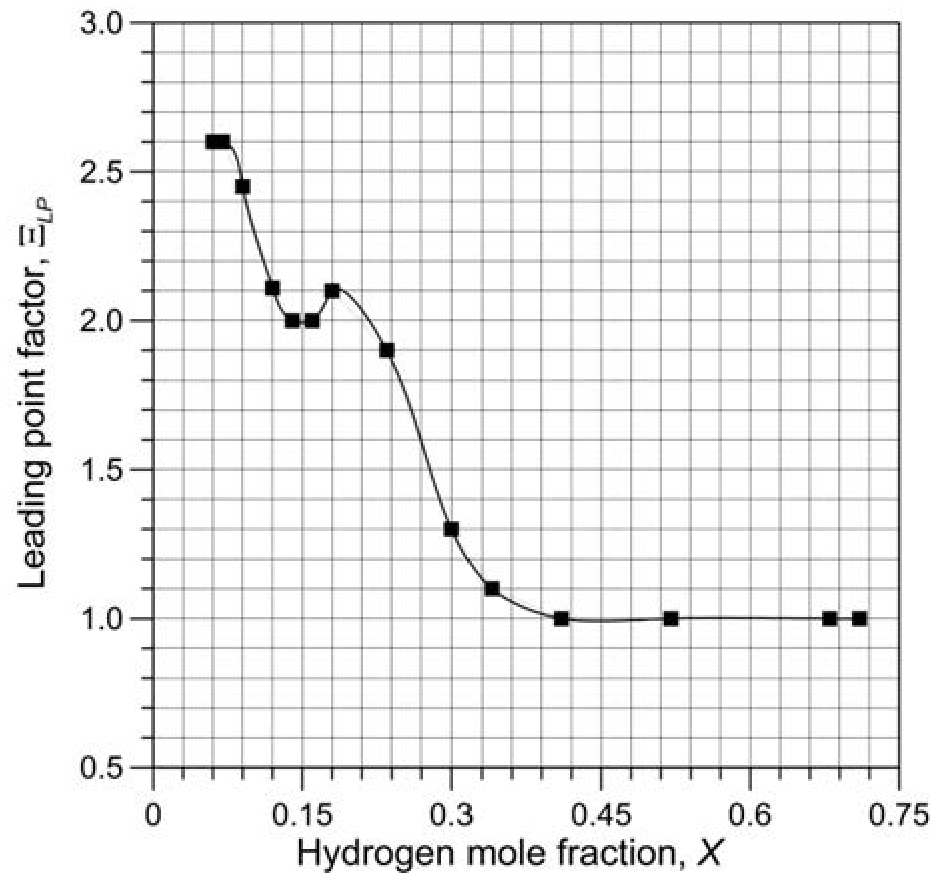
Ξ_K is calculated as $\Xi_K = \psi \cdot \Xi_K^{max}$

where empirical coefficient ψ is taken to be equal 0.75

Leading point concept wrinkling factor

$$\chi/\mu = \Xi_K \, \Xi_L \, \Xi_{PF} \, \Xi_{Ru'} \, \Xi_A \, \Xi_{RO}$$

Leading point wrinkling factor appears due to the preferential diffusion of hydrogen in the stretched turbulent flame brush. It is a function of hydrogen mole fraction in hydrogen–air mixture



Fractal flame structure wrinkling factor

$$\chi/\mu = \Xi_K \, \Xi_L \, \boxed{\Xi_{PF}} \, \Xi_{Ru'} \, \Xi_A \, \Xi_{RO}$$

Fractal wrinkling factor

$$\Xi_{FR} = \left(R / R_o\right)^{D-2}$$

appears due to the fractal

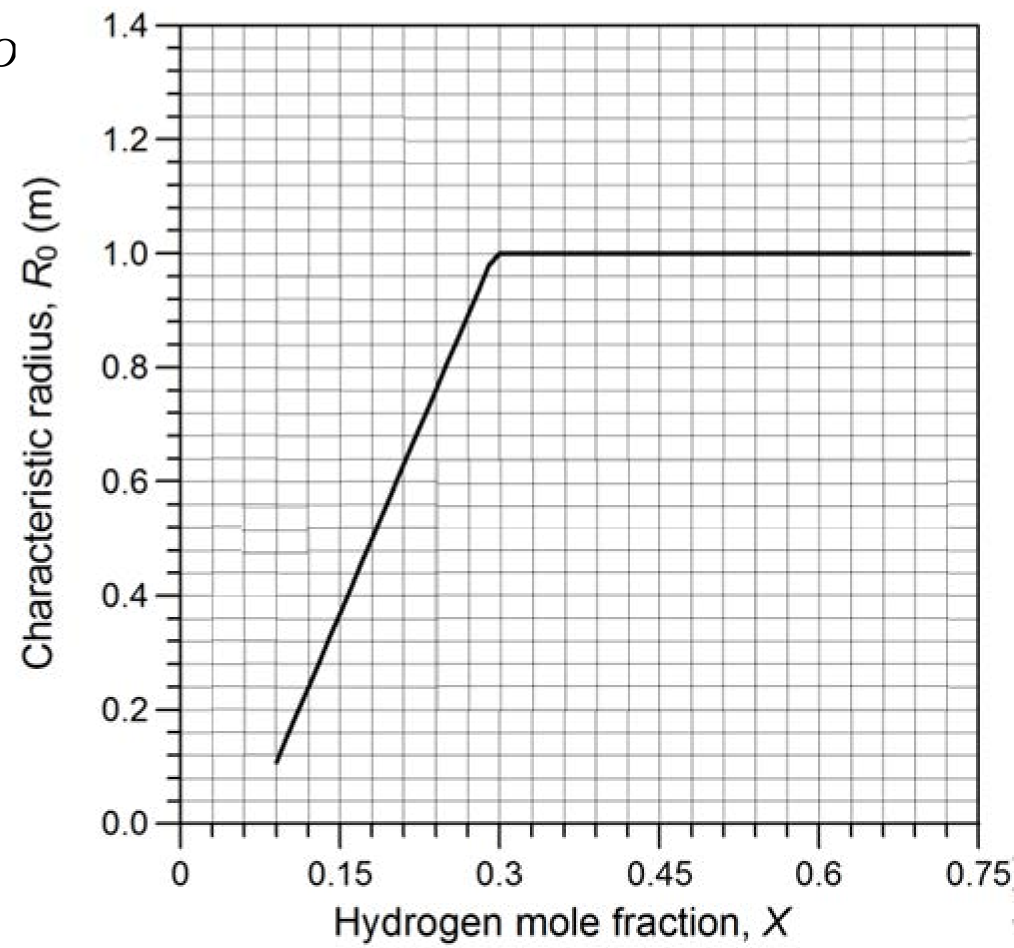
increase of flame front area

which occurs when the flame

radius exceeds characteristic

radius R_0 of transition from

Laminar to turbulent flame.



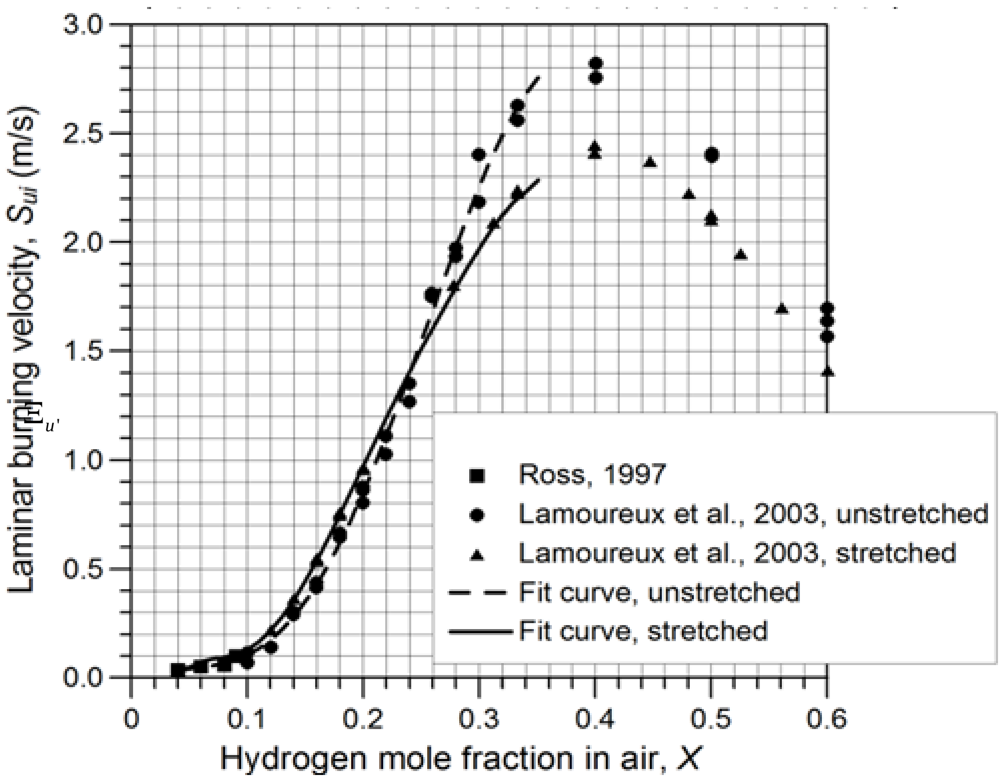
Radius *R* is considered to be limited by enclosure dimensions

$R = \sqrt[3]{3V / 4\pi_0}$, where π_0 is 3.1415… and *D* = 2.33 (Bradley, 1999)

Initial turbulence wrinkling factor 1/2

$$\chi/\mu = \Xi_K \, \Xi_L \, \Xi_{PF} \, \Xi_{Ru'} \, \Xi_A \, \Xi_{RO}$$

Wrinkling factor due to the presence of turbulence in unburned mixture can be expressed through turbulent flame velocity $\Xi_{u'} = S_t / S_W^{SGS}$



Using modified Yakhot's equation (Molkov, 2012) by substitution of laminar burning velocity with unresolved sub-grid scale wrinkled flame velocity $S_t = S_W^{SGS} \cdot \left(\frac{u'}{S_t} \right)^2$ where u' is RMS velocity in unburned mixture

Initial turbulence wrinkling factor 2/2

Maximum overpressure during deflagration is determined by the fastest burning rate, which is achieved when flame approaches enclosure walls and is affected by all wrinkling factors. S_u in Yakhot's original equation can thus be replaced by SGS wrinkled flame velocity $S_W^{SGS} = S_u \cdot \Xi_K \cdot \Xi_{LP} \cdot \Xi_{FR} \cdot \Xi_{AR} \cdot \Xi_O$

Turbulent burning velocity S_t can now be found by solving equation

$S_t = S_W^{SGS} \cdot \left(\dfrac{u'}{S_t} \right)^2$ numerically and wrinkling factor $\Xi_{u'} = S_t / S_W^{SGS}$

can be determined.

Aspect ratio & Obstacles wrinkling factors

$$\chi/\mu = \Xi_K\ \Xi_L\ \Xi_{PF}\ \Xi_{Ru'}\ \Xi_A\ \Xi_{RO}$$

Aspect ratio wrinkling factor $\Xi_{AR} = A_{EW} / A_S$ characterize the increase of the flame front surface area due to enclosure elongation, where A_{EW} is the internal surface area of the enclosure and A_S is the surface area of the sphere of the same volume with radius *R*.

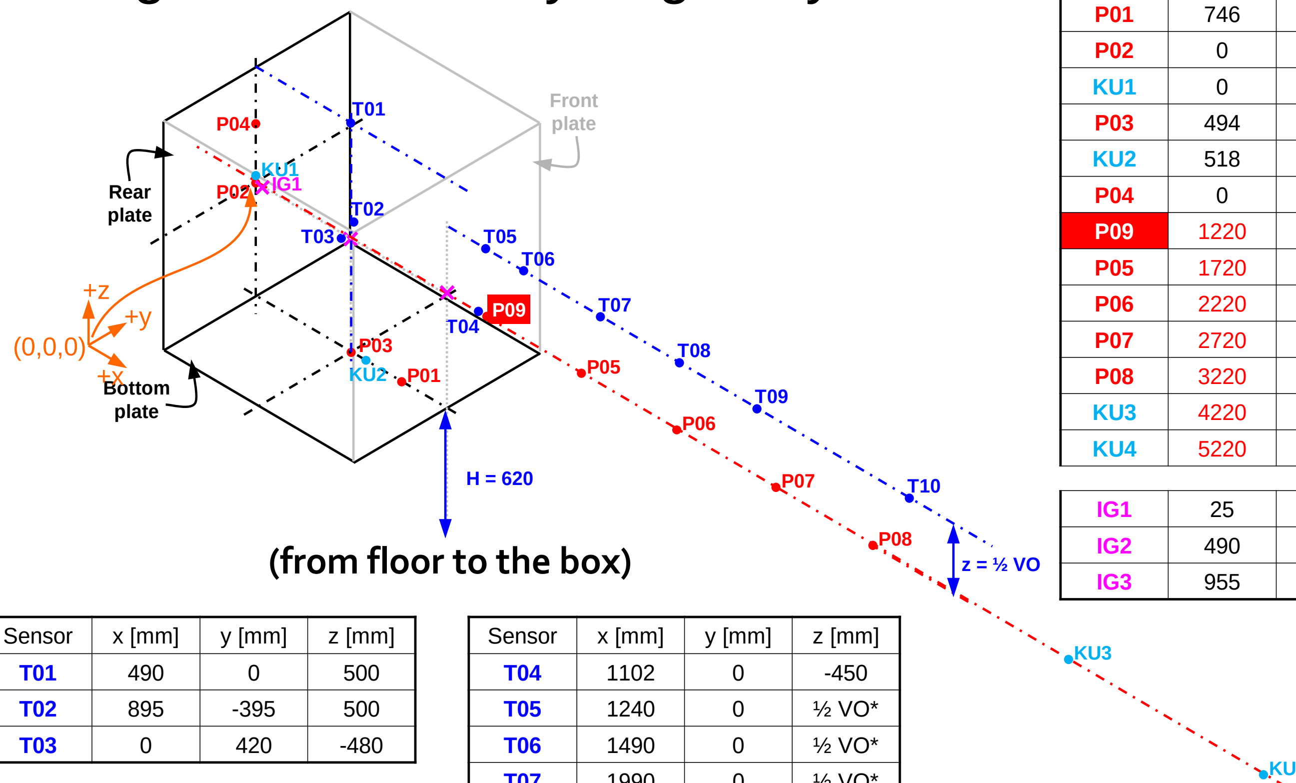
$$R = \sqrt[3]{3V / 4\pi_0}$$

Wrinkling factor due to the presence of obstacles Ξ_O is considered equal unity for the majority of the experiments involving in development of present correlation.

New experiments used in the correlation derivation

KIT experimental facility (1/2)

- L × H × W=0.98 × 1.00 × 0.96 m
- Vent openings: from 0.10 × 0.10 m to 1.00 × 0.96 m
- Concentration range: 10 to 50% hydrogen by volume



(from floor to the box)

Sensor	x [mm]	y [mm]	z [mm]
P01	746	0	-500
P02	0	0	0
KU1	0	0	25
P03	494	0	-500
KU2	518	0	-500
P04	0	0	250
P09	1220	0	0
P05	1720	0	0
P06	2220	0	0
P07	2720	0	0
P08	3220	0	0
KU3	4220	0	0
KU4	5220	0	0

IG1	25	0	0
IG2	490	0	0
IG3	955	0	0

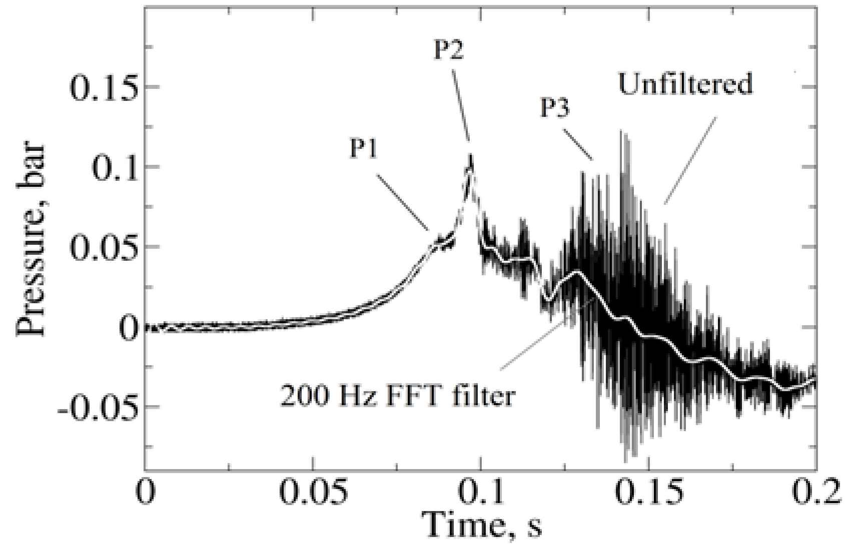
Sensor	x [mm]	y [mm]	z [mm]
T01	490	0	500
T02	895	-395	500
T03	0	420	-480

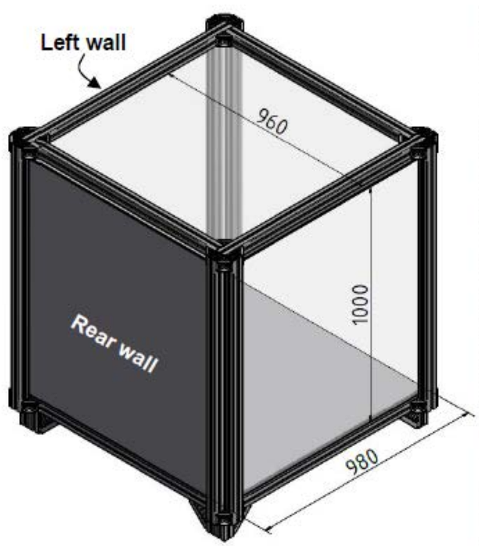
Sensor	x [mm]	y [mm]	z [mm]
T04	1102	0	-450
T05	1240	0	½ VO*
T06	1490	0	½ VO*
T07	1990	0	½ VO*
T08	2490	0	½ VO*
T09	2990	0	½ VO*
T10	3990	0	½ VO*

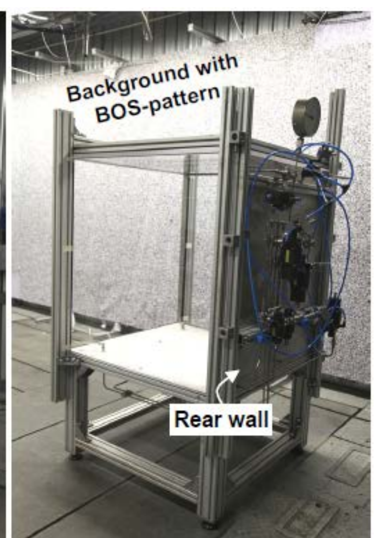
* ½ VO: Half of vent opening height
(= upper rim of opening)

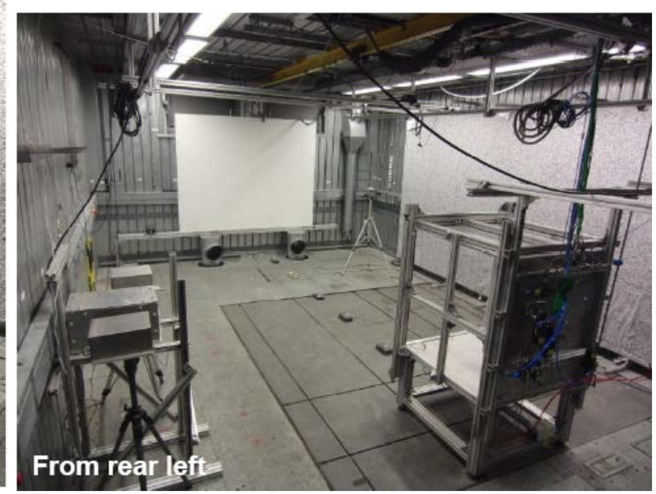
KIT experimental facility (2/2)

- Spark ignition location:
  - o Near middle of front wall;
  - o Near the centre of the enclosure;
  - o Near middle of the rear wall;
  - o At the rear wall under top plate
- 200 Hz FFT filter applied to readings



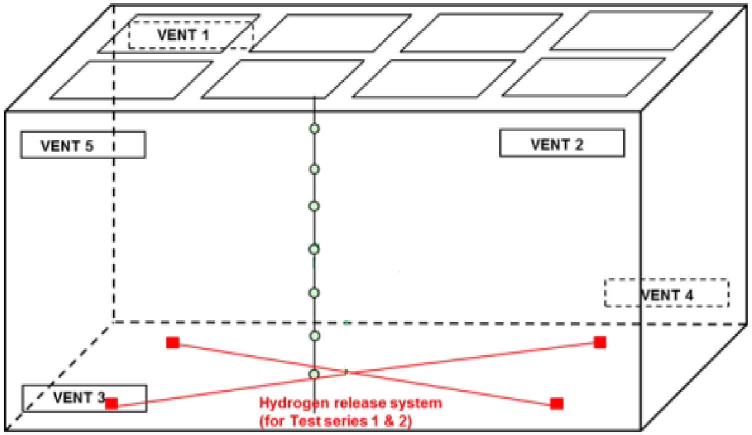


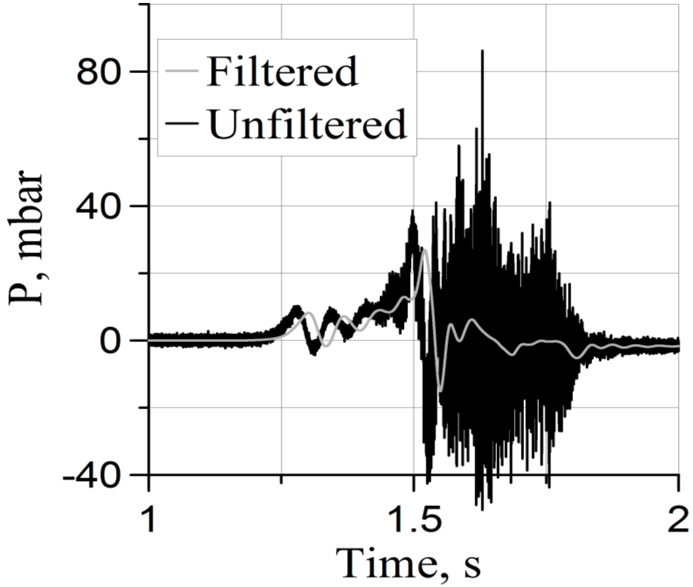




HSL experimental facility (1/2)

- L × H × W=5.00 × 2.50 × 2.50 m
- Two series of experiments:
  - Series 1: 1, 2 and 4 roof vents 0.8 m^2 each;
  - Series 2: 2 and 4 0.83 x 0.27 m side vents.
- Hydrogen is supplied through 4 nozzles in the floor
- 25 Hz filter is applied to pressure data





HSL experimental facility (2/2)

Spark ignition location:

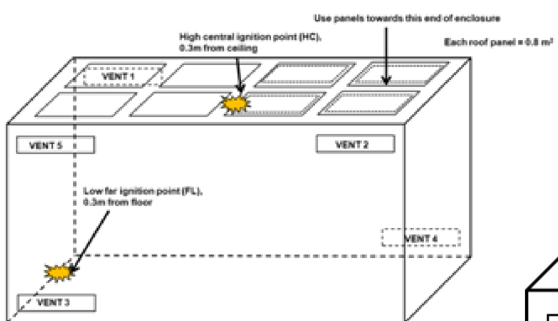
Series 1 (figure a):

- ❑ Low at far end from relief vents
- ❑ Central top

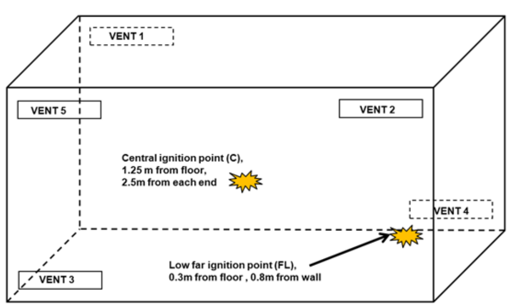
Series 2 (figure b):

- ❑ Low at far end from relief vents
- ❑ Geometric centre of enclosure

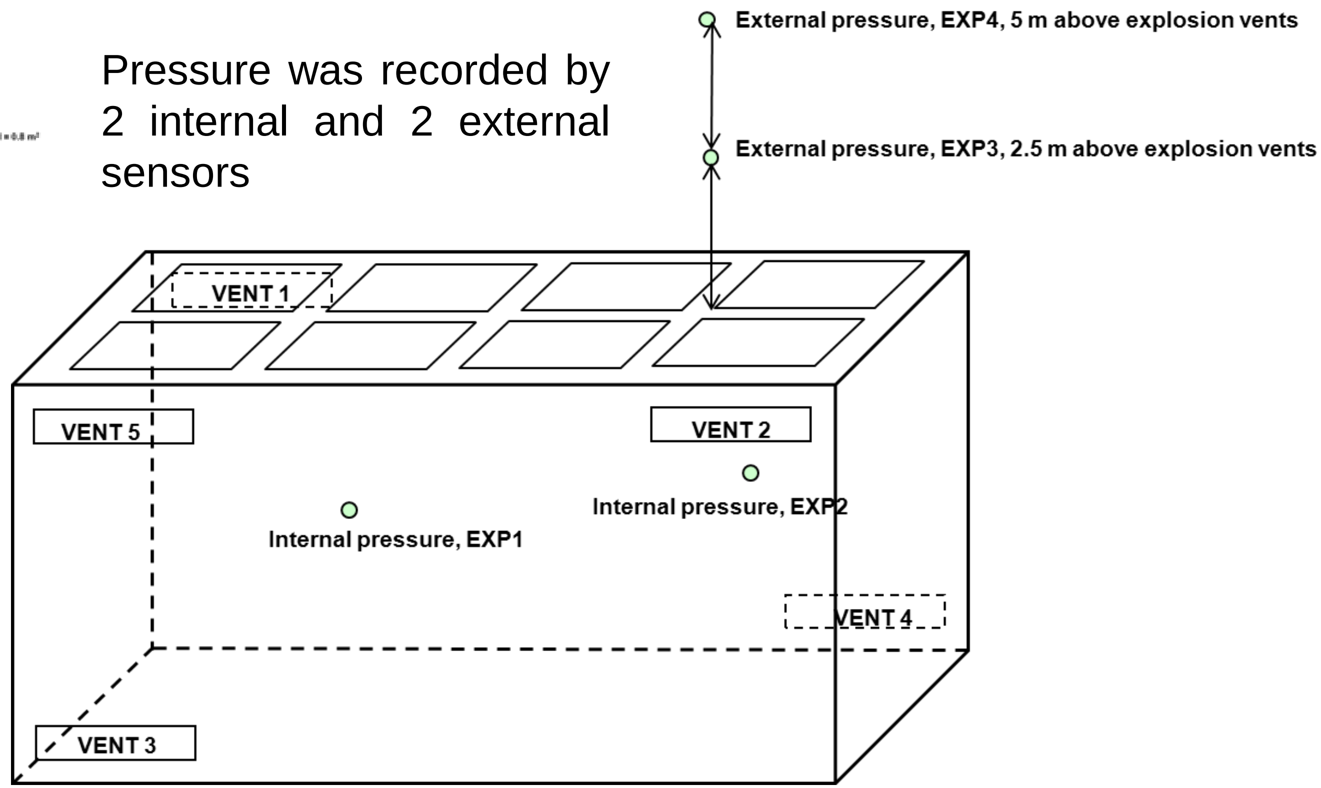
Pressure was recorded by 2 internal and 2 external sensors



a)

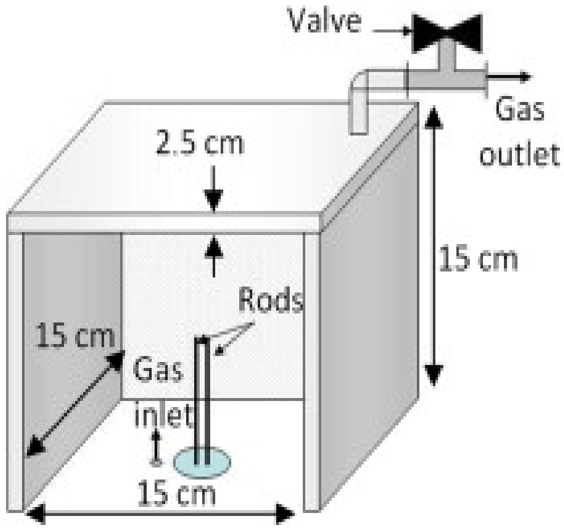


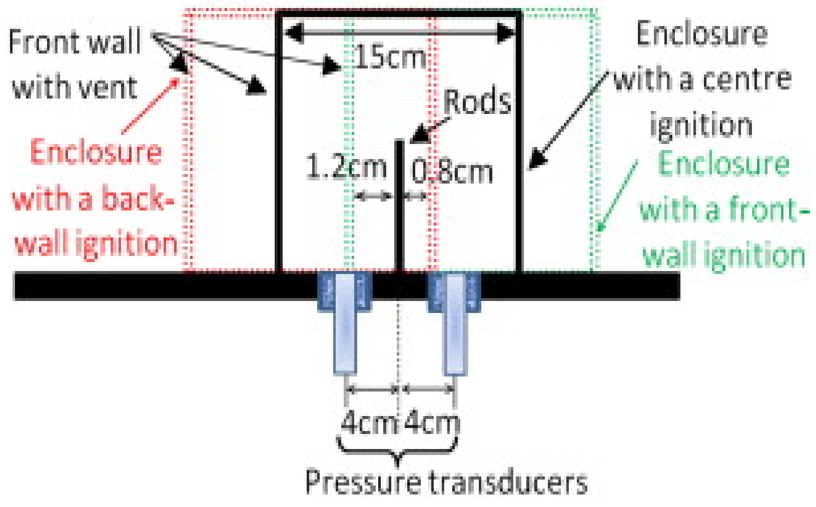
b)



Institute National des Sciences Appliques (INSA) experimental facility

- L × H × W=0.15 × 0.15 × 0.15 m
- Five vent sizes: 225, 81, 49, 25 and 9 cm^2
- Vents are covered with a film with 3 kPa burst pressure
- Three ignition locations: near front wall, in the centre and near far wall
- All experiments used 30% hydrogen-air mixture by volume
- 1.5 kHz low pass filter applied for pressure data processing





Updated vented deflagration correlation

With all wrinkling factor coefficients defined, Deflagration-Outflow Interaction (DOI) number χ/μ can be found and experimental data can be put on the plot in order to determine coefficients in the equation $\pi_{red} = \lambda \cdot Br_t^{-\sigma}$

In addition to recent HSL, INSA (published as Rocourt et al., 2014) and KIT data obtained in 2013-14, the following previous experimental results had been used in producing the correlation for vented deflagration:

- Kumar (2006)
- Kumar (2009)
- Pasman et al. (1974)
- Daubech et al. (2011, 1 m^3)
- Daubech et al. (2011, 10.5 m^3)
- Bauwens et al. (2011)
- Bauwens et al. (2012)

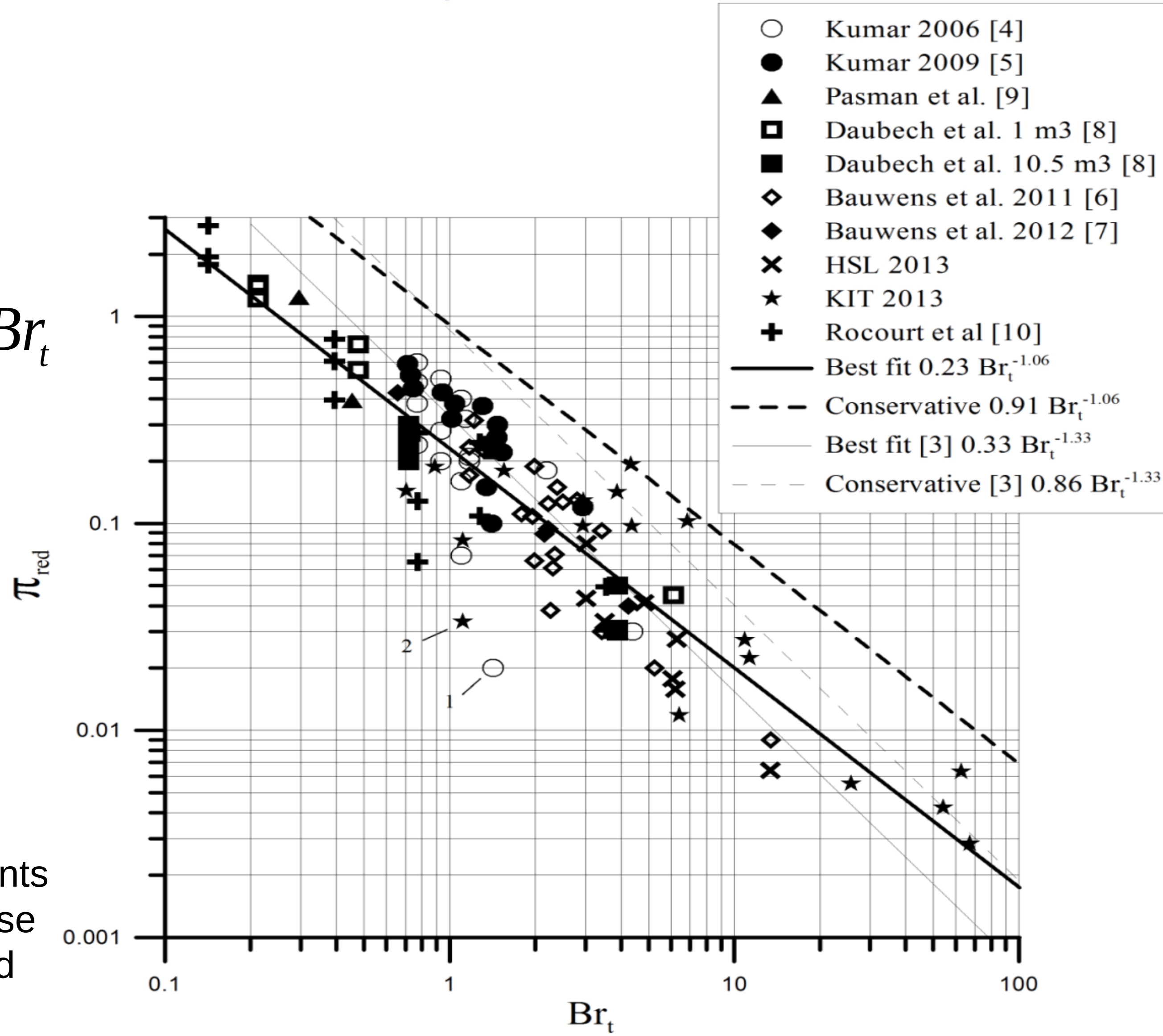
Updated vent sizing correlation

Plotting all experimental data in double logarithmic scale in π_{red} *versus* Br_t produces **best fit** correlation

$$\pi_{red} = 0.23 \cdot Br_t^{-1.06}$$

and **conservative** correlation

$$\pi_{red} = 0.91 \cdot Br_t^{-1.06}$$



Note there are two outlying points in the correlation, which increase the spread between best fir and conservative correlations.

Outlying point 1 corresponds to Kumar (2004) experiment experiencing 1 sec delay between vents opening. Outlying point 2 corresponds to KIT experiment HIWP3-39 in which there was a gas leak through the enclosure walls edge resulting in an additional pressure relief.

Vent sizing procedure (brief overview)

With the empirical coefficients in the formula $\pi_{red} = \lambda \cdot Br_t^{-\sigma}$ known it is possible to use it find vent size required to keep overpressure below specified limit .

The algorithm involves:

- Selecting maximum acceptable overpressure
- Using correlation to find corresponding turbulent Bradley number Br_t
- Calculating the DOI factor by evaluating all flame wrinkling factors based on known enclosure geometry and hydrogen concentration
- Calculating Bradley number
- Finding out required vent area

Layered and gradient concentration localised mixtures

Localised mixture vented deflagrations

- MAX overpressure (for relatively small pressures) $\Rightarrow$ $\partial\pi/\partial n_u = 0$
- Fresh mixture at outflow $A=0$ $\Rightarrow$ $W = \dfrac{\chi\, Z\, \pi^{\varepsilon+1/\gamma}\omega_b^{2/3}}{\gamma_b\, R_u^{\#}}$
- For low fuel concentrations $\gamma_b = \gamma_u = \gamma$ $\Rightarrow$ $Z = \gamma\left[E_i - 1\right]\pi^{(1-\gamma)/\gamma}$
- Vol. fraction of combustion process (completed combustion, adiabatic compression) $\omega_b = \omega_{ui}\, E_i\, \pi^{1/\gamma}$ ($\omega_{ui} = \Phi$ - unburnt vol. fraction)
- Expanding in Taylor series around $\pi = 1.0$:

$$\left(1/\pi\right)^{2/\gamma} \approx 1 - 2/\gamma\left(\pi - 1\right), \quad \left(1/\pi\right)^{(\gamma+1)/\gamma} \approx 1 - \left(\left(\gamma+1\right)/\gamma\right)\left(\pi-1\right) \Rightarrow R_u^{\#} = \left\{2\pi\left(\pi-1\right)\sigma_u\right\}^{1/2}$$

$$\Rightarrow R_u^{\#} = \left\{2\pi\left(\pi-1\right)\pi^{1/\gamma}\right\}^{1/2}$$

- For adiabatic compression $\sigma_u = \pi^{1/\gamma}$
- Substituting ω_b, *Z* and $R_u^{\#}$ in equation for *W*: $W = \dfrac{\chi\left(E_i - 1\right)E_i^{2/3}\,\Phi^{2/3}}{\left[2\left(\pi-1\right)\right]^{1/2}}\,\pi^{\frac{5-9\gamma}{6\gamma}+\varepsilon}$
- Low pressures, lean mixtures $\pi^{(5-9\gamma)/6\gamma+\varepsilon} \approx 1.0$
- Eventually, expression for MAX overpressure

$$\boxed{\Delta\pi_m = \left\{\left(\frac{\mu}{\chi}\frac{\left(E_i/\gamma\right)^{1/2}}{\left(36\pi\right)^{1/3}}\frac{c_{ui}/S_{ui}}{E_i - 1}\frac{F}{V^{2/3}}\right)^{-1}\left(\frac{\left(E_i/\gamma\right)^{1/2}E_i^{2/3}}{\sqrt{2}}\right)\Phi^{2/3}\right\}^2 = \left\{Br_t^{-1}\left(\frac{\left(E_i/\gamma\right)^{1/2}E_i^{2/3}}{\sqrt{2}}\right)\Phi^{2/3}\right\}^2}$$

Different representation

- Assuming $M_m \approx M_{air} \Longrightarrow \omega_{ui} \approx n_{ui}$ and $W = \dfrac{\chi\left(E_i - 1\right) E_i^{2/3}}{\left[2\left(\pi - 1\right)\right]^{1/2}} n_m^{2/3}$
- Mass fraction of combustible fuel-air mixture $n_m = \left(m_g + m_v^{'}\right)/\left(m_g + m_v\right)$
- Mass of air in localised hydrogen-air mixture

$$m_v^{'} = \frac{pM_v}{RT}\left(1-\varphi\right)V = \ldots = \frac{M_v}{M_g}\frac{\left(1-\varphi\right)}{\varphi}m_g \Longrightarrow n_m = \frac{M_v\left(1-\varphi\right) + M_g\,\varphi}{M_g\,\varphi\left(\dfrac{m_v}{m_g}+1\right)}$$

- Expression for vol. fraction of fuel-air mixture Φ

$$\Phi = \frac{\left(V_g + V_{v'}\right)}{\left(V_g + V_v\right)} = \ldots = \frac{1}{\varphi}\frac{1}{1+\dfrac{m_v}{m_g}\dfrac{M_g}{M_v}} \Longrightarrow \frac{m_v}{m_g} = \frac{M_v}{M_g}\left(\frac{1}{\Phi\varphi} - 1\right)$$

- Vol. fraction of the local flammable fuel-air mixture $n_m = \dfrac{1+\left(\dfrac{1}{\varphi}-1\right)\dfrac{M_v}{M_g}}{1+\left(\dfrac{1}{\Phi\varphi}-1\right)\dfrac{M_v}{M_g}}$
- and:

$$\Delta\pi_m = \left\{ Br_t^{-1}\left(\frac{\left(E_i/\gamma\right)^{1/2} E_i^{2/3}}{\sqrt{2}}\right)\left(\frac{1+\left(\dfrac{1}{\varphi}-1\right)\dfrac{M_a}{M_f}}{1+\left(\dfrac{1}{\Phi\varphi}-1\right)\dfrac{M_a}{M_f}}\right)^{2/3}\right\}^2$$

Layered mixture deflagration

- Vented deflagration of the layered mixture model:

$$\Delta\pi_m = \left\{ \left(\underbrace{\frac{\mu}{\chi} \frac{(E_i/\gamma)^{1/2}}{(36\pi)^{1/3}} \frac{c_{ui}/S_{ui}}{E_i - 1} \frac{F}{V^{2/3}}}_{Br_t} \right)^{-1} \left(\frac{(E_i/\gamma)^{1/2} E_i^{2/3}}{\sqrt{2}} \right) \Phi^{2/3} \right\}^2$$

- Correlation will be sought in the form similar to the uniform mixture deflagration:

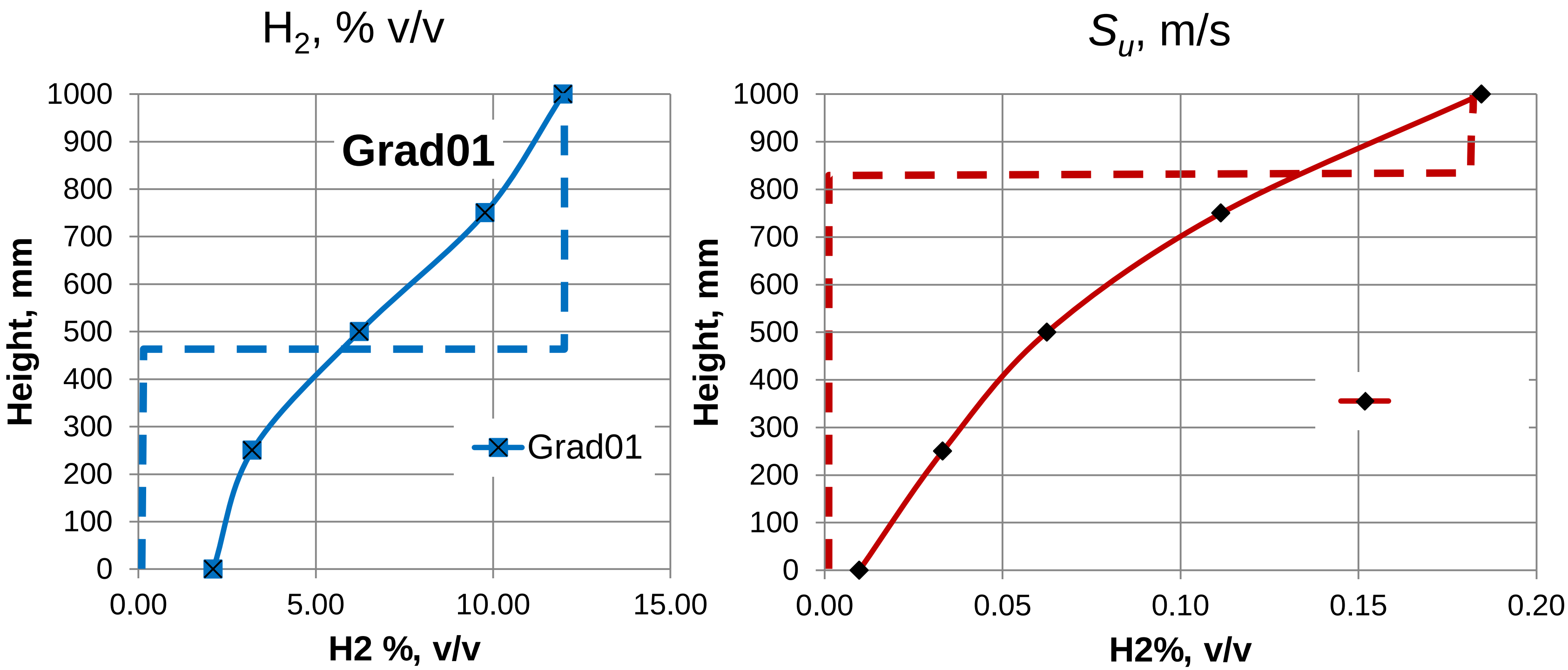
$$\Delta\pi_m = A\left(Br_t\right)^{-B} \left\{ \left(\frac{(E_i/\gamma)^{1/2} E_i^{2/3}}{\sqrt{2}} \right) \Phi^{2/3} \right\}^B$$

Hydrogen gradient mixtures (1/2)

- Analytical expression for overpressure is function of unburnt mixture volume fraction Φ
- Previous studies conclusion:
  maximum overpressure depends mainly on fraction of mixture with largest burning velocity (mixtures with hydrogen concentration about 20-50% by volume in air)
- Φ is calculated taking into account only a fraction of total hydrogen volume in enclosure (within a range of high burning velocities)

Hydrogen gradient mixtures (2/2)

Two ways of the gradient layer processing

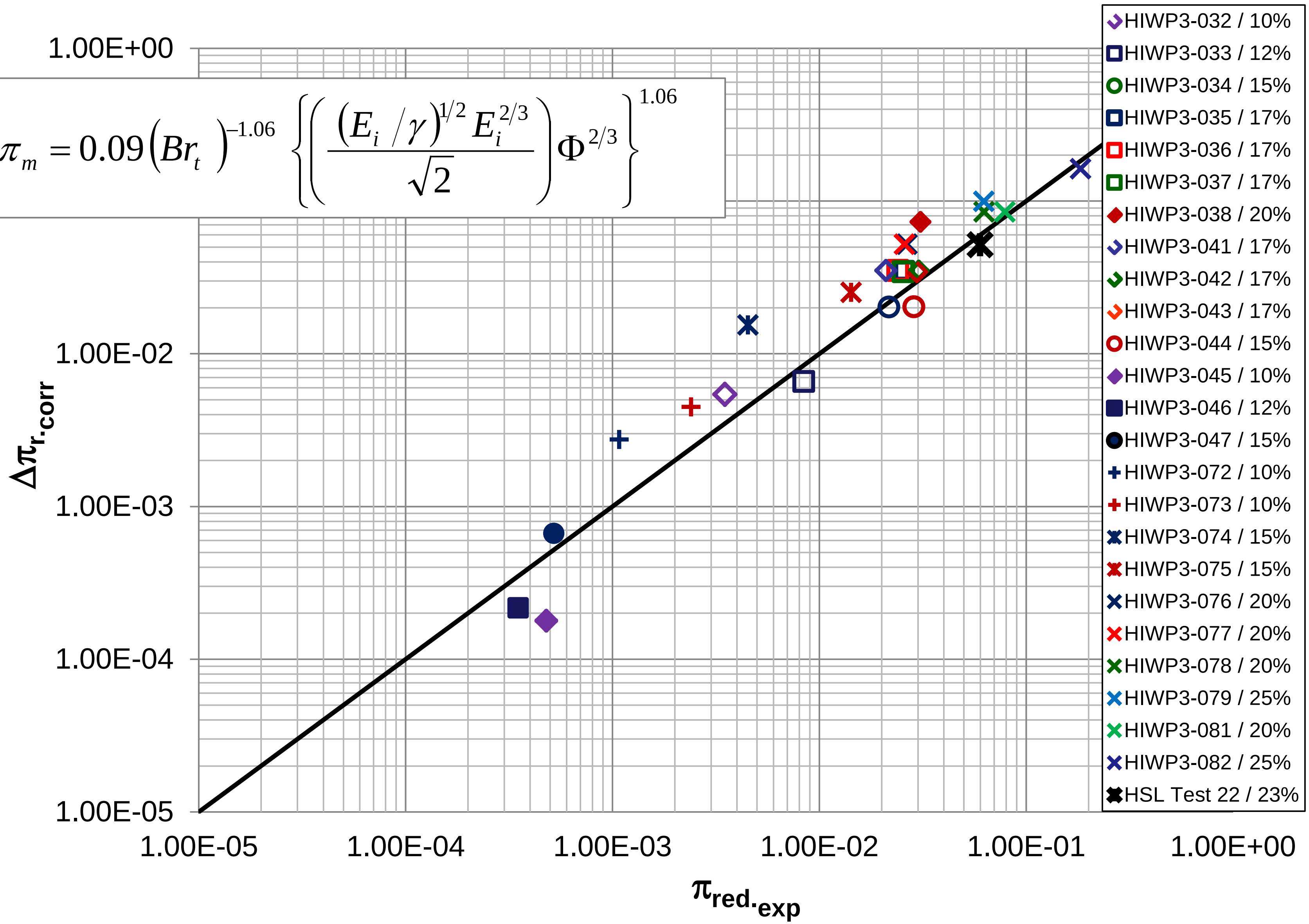


Calculations based on H_2 mass conservation (Φ=0.55)

Calculations based on the (0.7 – 1.0)· S_u (Φ=0.19)

Best fit correlation (localised)

$$\Delta\pi_m = 0.09\left(Br_t\right)^{-1.06}\left\{\left(\frac{\left(E_i/\gamma\right)^{1/2}E_i^{2/3}}{\sqrt{2}}\right)\Phi^{2/3}\right\}^{1.06}$$



Concluding remarks

- This study:
  - Development of analytical model for maximum overpressure in a vented deflagration of layered fuel-air mixture is demonstrated
  - The theory-based correlation was developed based on the experimental data obtained at KIT and HSL, best fit correlation was achieved with coefficients A=0.09, B=1.06
  - Correlation is conservative on the given set of experimental data with coefficients A=0.25, B=1.06
  - Validation on a wider range of experimental data (vessel volume, vent size, mixture parameter) is required
- Outstanding issues:
  - Delayed ignition
  - Effect of obstacles
  - Inertial vent covers
  - More experimental data on localised mixture vented deflagrations

THANK YOU

Learn more!

Acknowlegements: authors are grateful to FCH JU for funding through the HyIndoor project (www.hyindoor.eu)