Hyindoor

Pre normative research
on the indoor use of fuel cells and hydrogen systems

Vent sizing correlation for low strength equipment and buildings

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General strategies

- ☐ Minimize hydrogen inventory to exclude formation of flammable mixture even in confined enclosure after complete release and dispersion of hydrogen

- ☐ Utilize vent covers sized to reduce deflagration overpressure below structural limits of the enclosure

- ☐ Minimization of hydrogen inventory below amount which will produce structural damage in low strength equipment and buildings in case of deflagration)

Motivation

- Hydrogen leak in an enclosure can lead to accumulation of the hydrogen in concentrations exceeding Low Flammability Limit. Subsequent ignition of hydrogen – air mixture lead to a deflagration producing overpressure which can result in structural damage or collapse of equipment or buildings
- Provision of vent opening(s) is a common way to relief overpressure produced by deflagration in a closed environment. Oversizing venting openings is undesirable due to the practical (environmental, structural, etc.) considerations
- Calculation of the appropriate vent sizing ensuring that a specified maximum overpressure will not be exceeded requires development of venting correlation technique relating deflagration overpressure with parameters such as vent area, hydrogen concentration levels, enclosure geometry, etc.

Development history

- A theory of a vented deflagration in a low strength equipment and structures had been under development since 1996 (Molkov, 1996)
- Engineering correlation for calculation of vent sizing required to ensure that overpressure will not exceed specified values has been developed for the case of uniform mixture filling an entire enclosure (Molkov et al., 1999)
- Correlation relating deflagration overpressure to a product of a number of flame wrinkling factors arising due to various combustion mechanisms and instabilities, which affect turbulent burning velocity, was developed at University of Ulster (Molkov and Bragin, 2013)
- Present version incorporates additional experiments by KIT, HSL and INSA and simplify calculation of several wrinkling factors (Chernyavsky et al., 2014, in preparation)

Deflagration correlation

❑ Correlation for uniform mixture filling the entire enclosure

Maximum overpressure for relatively small pressures can be expressed as $\Delta\pi_m = \left(\frac{\mu}{\chi} \frac{\left(E_i/\gamma\right)^{1/2}}{\left(36\pi\right)^{1/3}} \frac{c_{ui}/S_{ui}}{E_i - 1} \frac{F}{V^{2/3}} \right)^{-2}$

In general form this correlation can be expressed in the form $\Delta\pi_m = \lambda\left(Br_t\right)^{-\sigma}$

Here $Br_t = \frac{\sqrt{E_i/\gamma}}{\sqrt[3]{36\pi_0}} \cdot \frac{Br}{\chi/\mu}$ is the of turbulent Bradley number, $Br = \frac{c_{ui}/S_{ui}}{E_i - 1} \cdot \frac{F}{V^{2/3}}$

is the Bradley number, E_i is the combustion products expansion coefficient, γ is the specific heat ratio of unburned mixture, χ/μ is the Deflagration-Outflow Interaction (DOI) number, *F* is the vent area, *V* is the enclosure volume, S_{ui} is the initial laminar burning velocity, and c_{ui} is the speed of sound in the initial unburned mixture.

DOI number

The main unknown in the correlation $\Delta\pi_m = \lambda\left(Br_t\right)^{-\sigma}$ 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 accounting for the initial turbulence

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

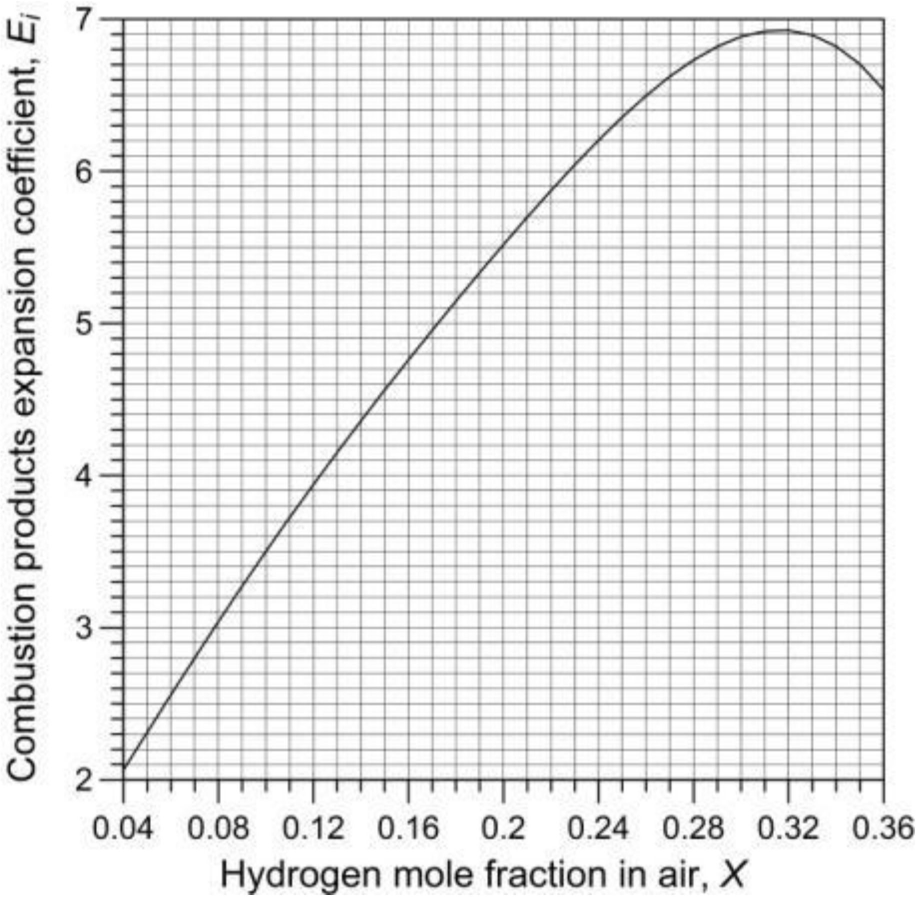
Ξ_O - factor arising due to the turbulence in presence of obstacles

Karlowitz wrinkling factor

[illegible] $\Xi_K \Xi_{LP} \Xi_{FR} \Xi_{AR}$

Karlowitz wrinkling factor arises 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 $\Xi_K = \psi \cdot \Xi_K^{max}$

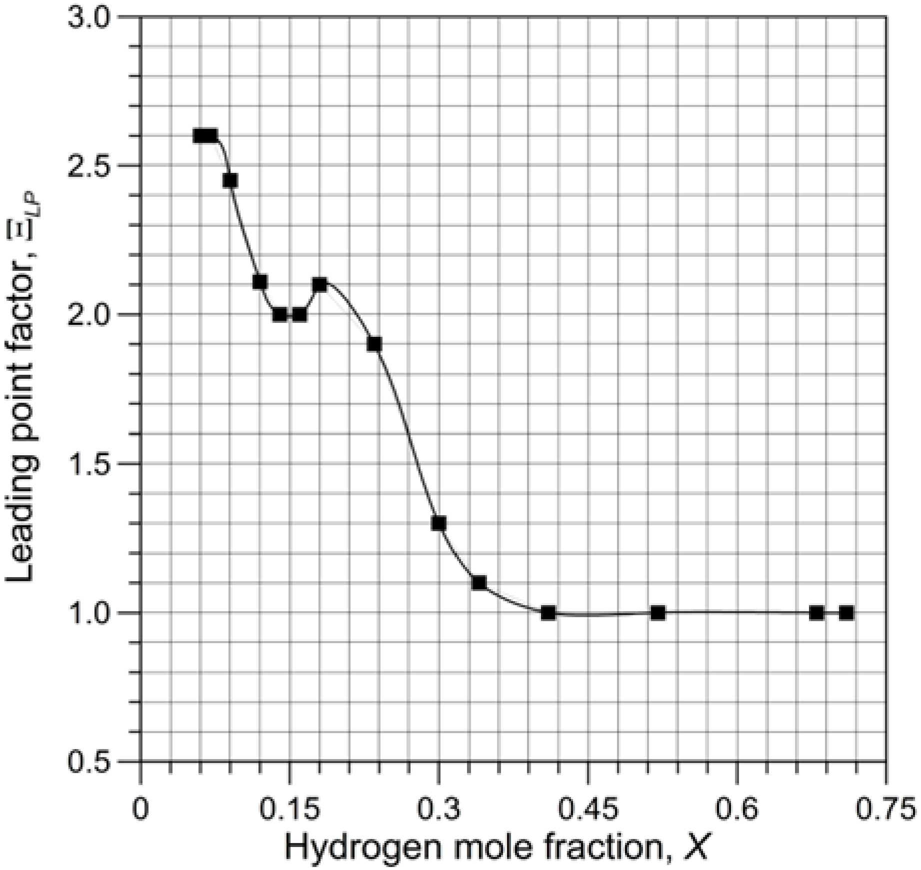
where empirical coefficient ψ is taken to be equal 0.75

Leading point wrinkling factor

[illegible]

Leading point wrinkling factor appears due to the preferential diffusion of hydrogen in the stretched turbulent flames.

It is a function of hydrogen mole fraction in hydrogen – air mixture



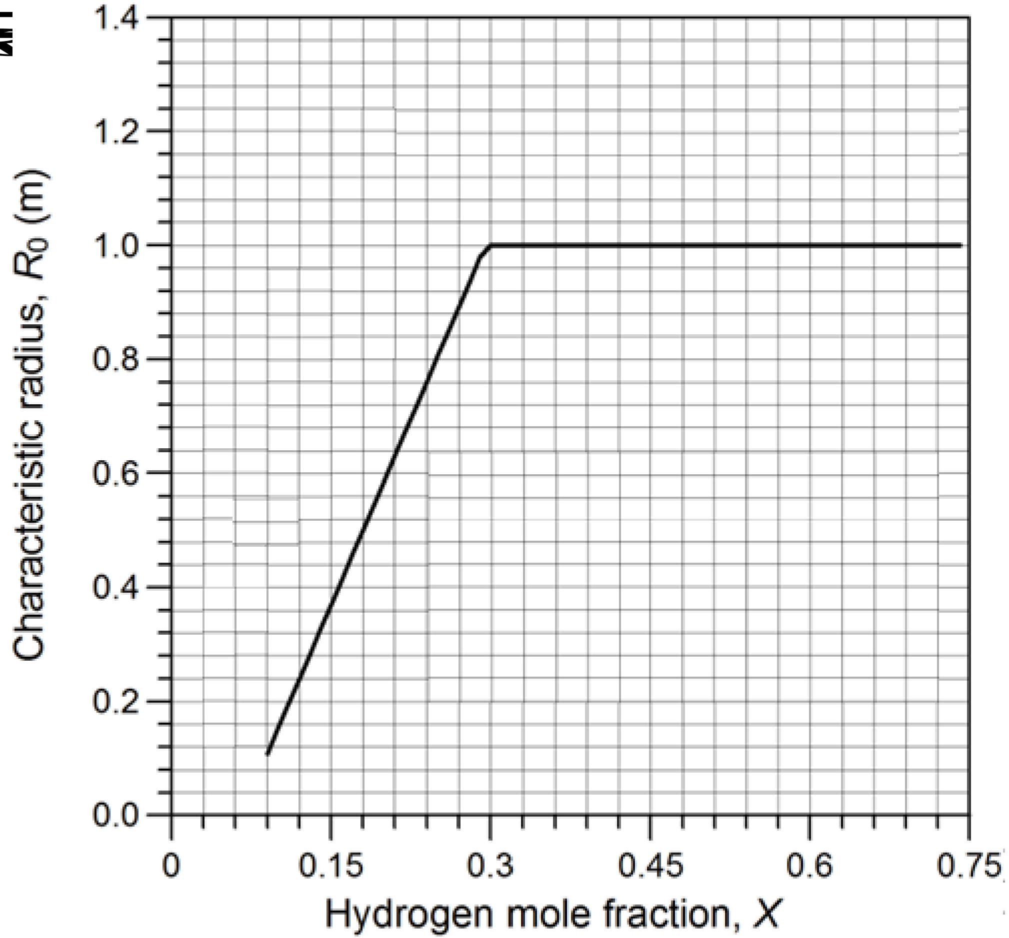
Fractal wrinkling factor

$$\mu = \Xi_K \Xi_{LP} \Xi_{FR} \Xi_{AR}$$

Fractal wrinkling factor

$$\Xi_{FR} = (R/R_0)^{D-2}$$

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.



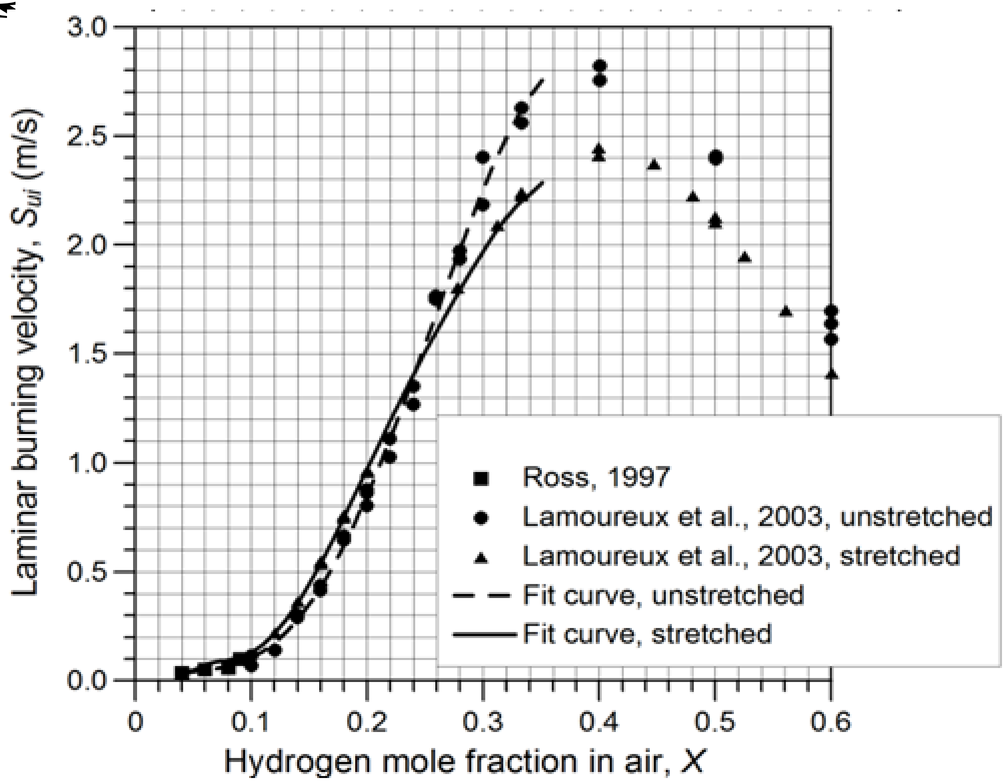
Radius *R* is considered to be limited by enclosure dimensions $R = \sqrt[3]{3V/4\pi_0}$, where π_0 is 3.1415… and *D* = 2.33 (Bradley, 1999)

Wrinkling factor due to initial turbulence 1/2

[illegible]

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 subgrid 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

Wrinkling factor due to initial turbulence 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

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

can be determined.

Aspect ratio and obstacles wrinkling factors

$$\chi/\mu = \Xi_K \Xi_{LP} \Xi_{FR} \Xi_{AR} \Xi$$

Aspect ratio wrinkling factor $\Xi_{AR} = A_{EW} / A_S$ characterizes 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*:

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

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

Experiments used in correlation derivation

Vented deflagration correlation

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With all wrinkling factor coefficients defined, Deflagration-Outflow Interaction (DOI) number χ/μ can now be calculated. In order to determine coefficients in the equation $\pi_{red} = \lambda \cdot Br_t^{-\sigma}$ the experimental data can be plotted in π_{red} versus Br_t coordinate system.

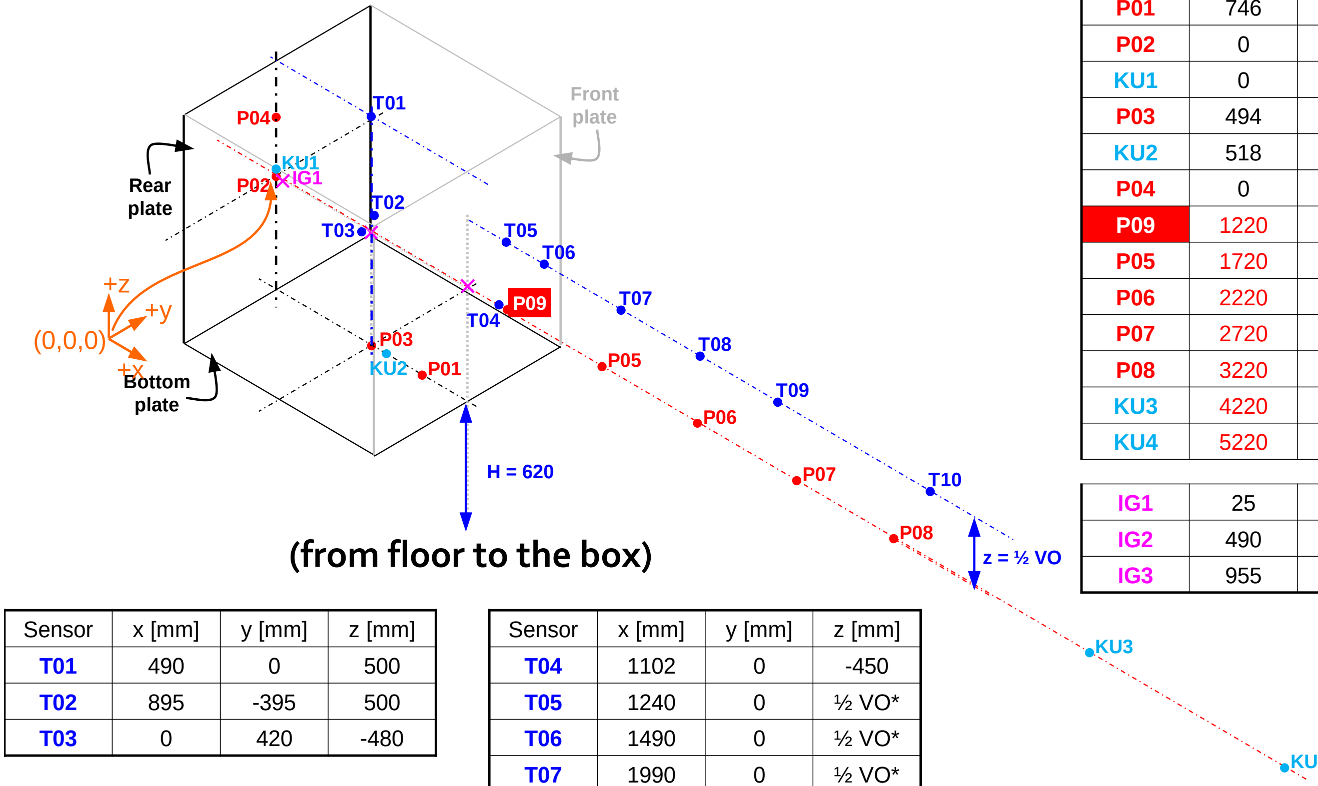
Previous version of correlation (presented at ICHS'05) used experimental results from:

- 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)

Current correlation used additional new results, obtained at KIT and HSL within Hyindoor project in 2013-2014 and results by Rocourt et al., published in 2014.

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



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

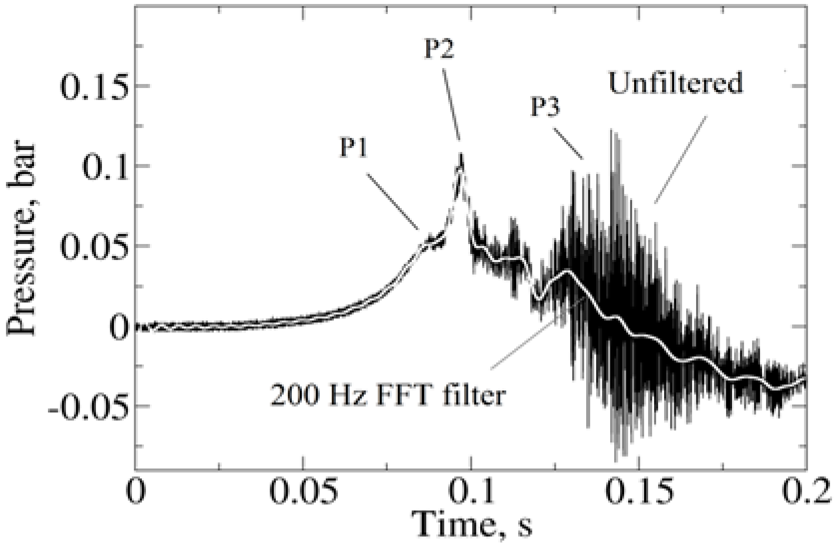
Sensor	x [mm]	y [mm]	z [mm]
T01	490	0	500
T02	895	-395	500
T03	0	420	-480

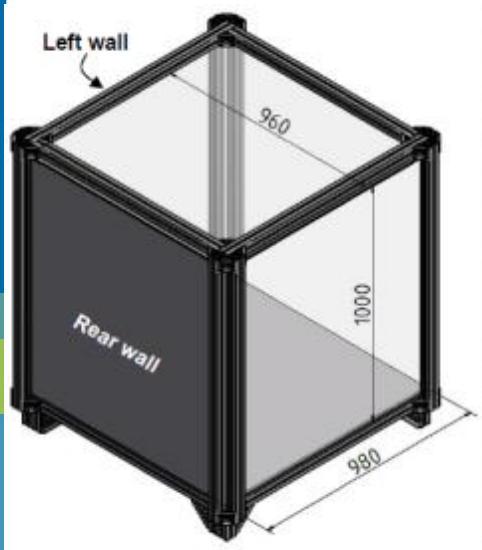
Sensor	x [mm]	y [mm]	z [mm]
T04	1102	0	-450
T05	1240	0	½ VO*
T06	1490	0	½ VO*
T07	1990	0	½ VO*
T08	2490	0	½ VO*
T09	2990	0	½ VO*
T10	3990	0	½ VO*

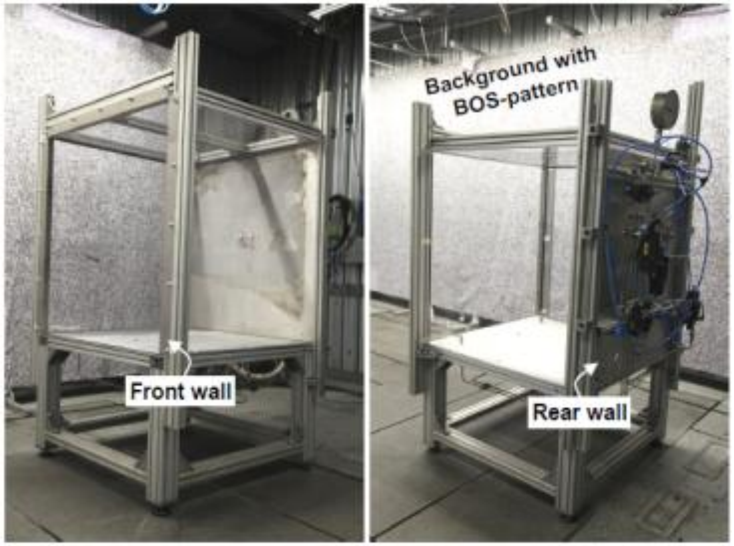
* ½ VO: Half of vent opening height
(= upper rim of opening)

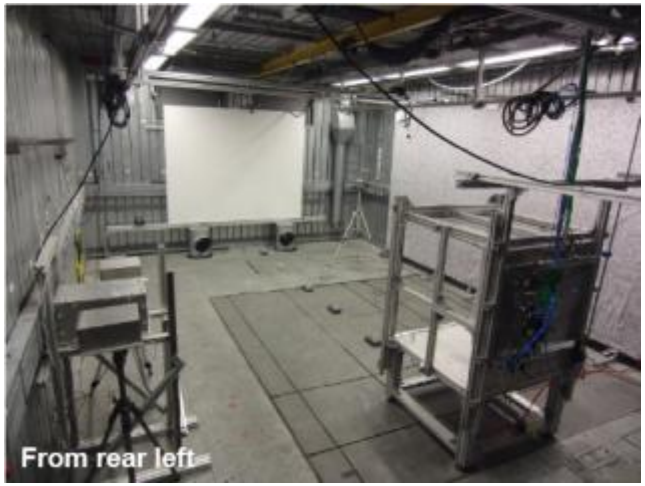
KIT experimental facility 2/2

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



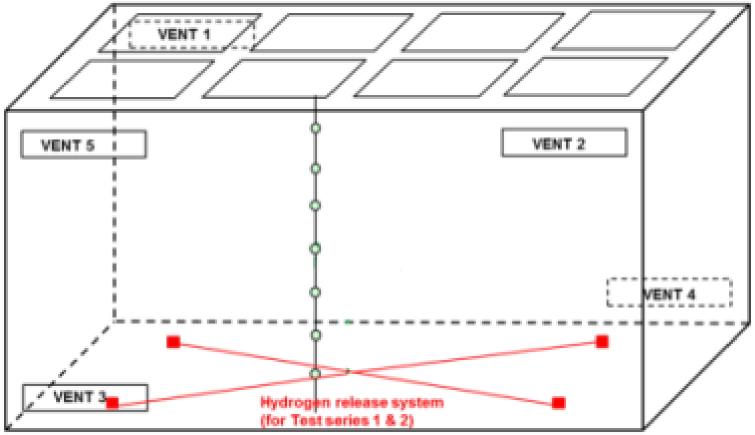


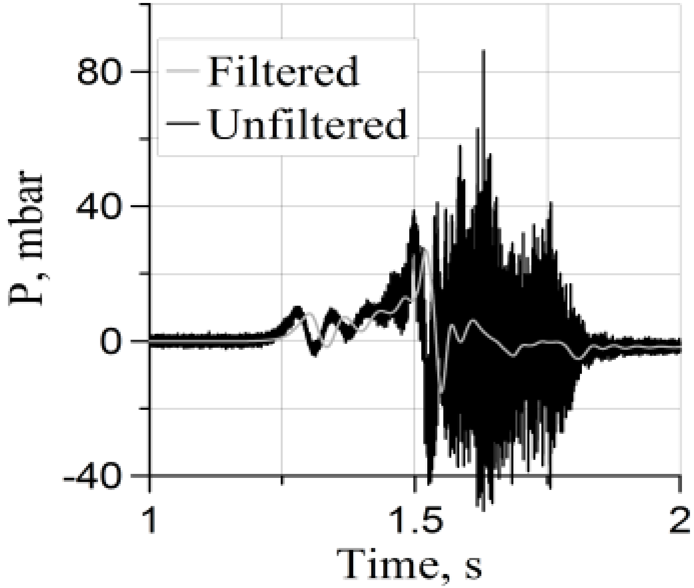




HSL experimental facility 1/2

- 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

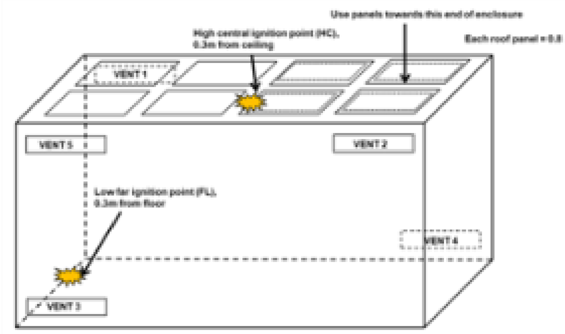
Spark ignition location:

Series 1 (figure a):

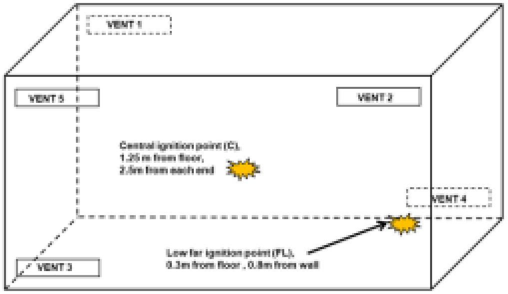
- ☐ Low at far end from relief vents
- ☐ Central top

Series 2 (figure b):

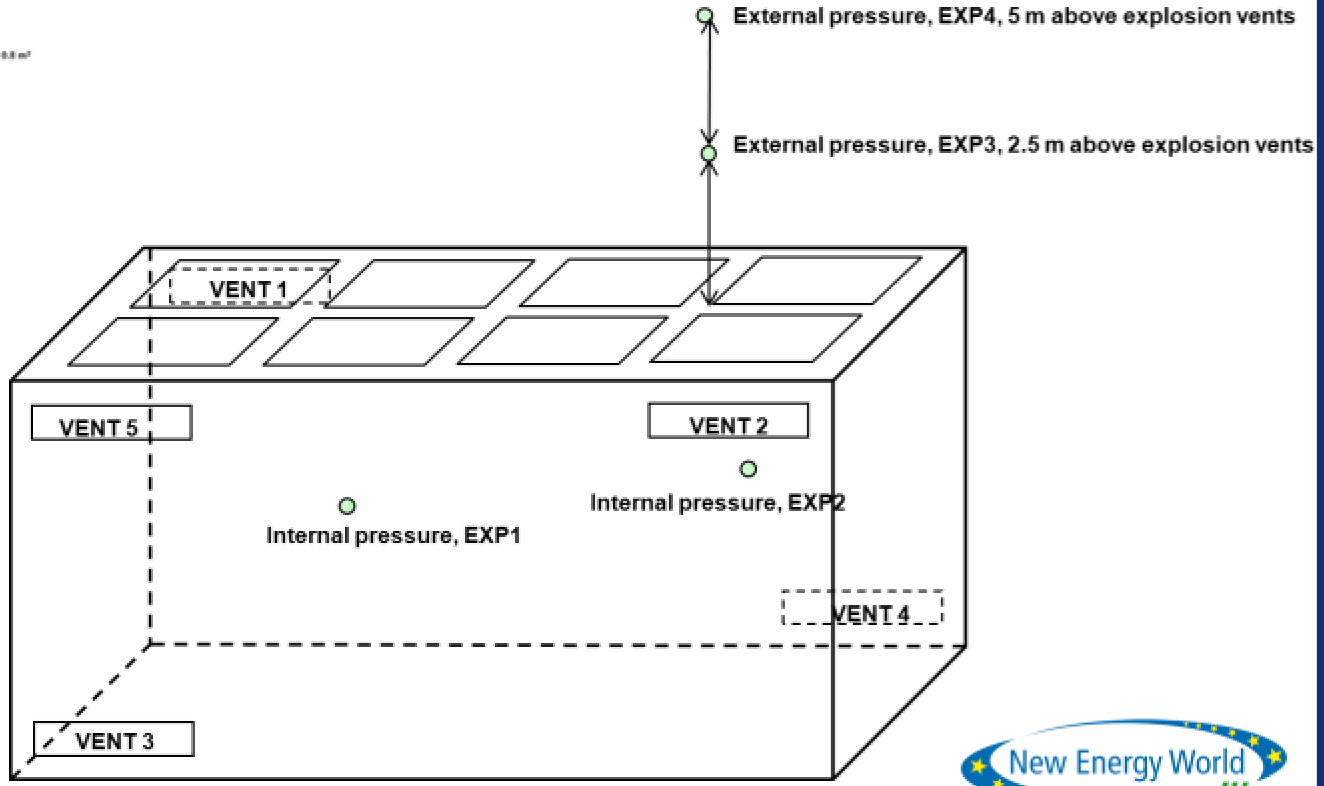
- ☐ Low at far end from relief vents
- ☐ Geometric centre of enclosure



a)



b)



Vent sizing correlation

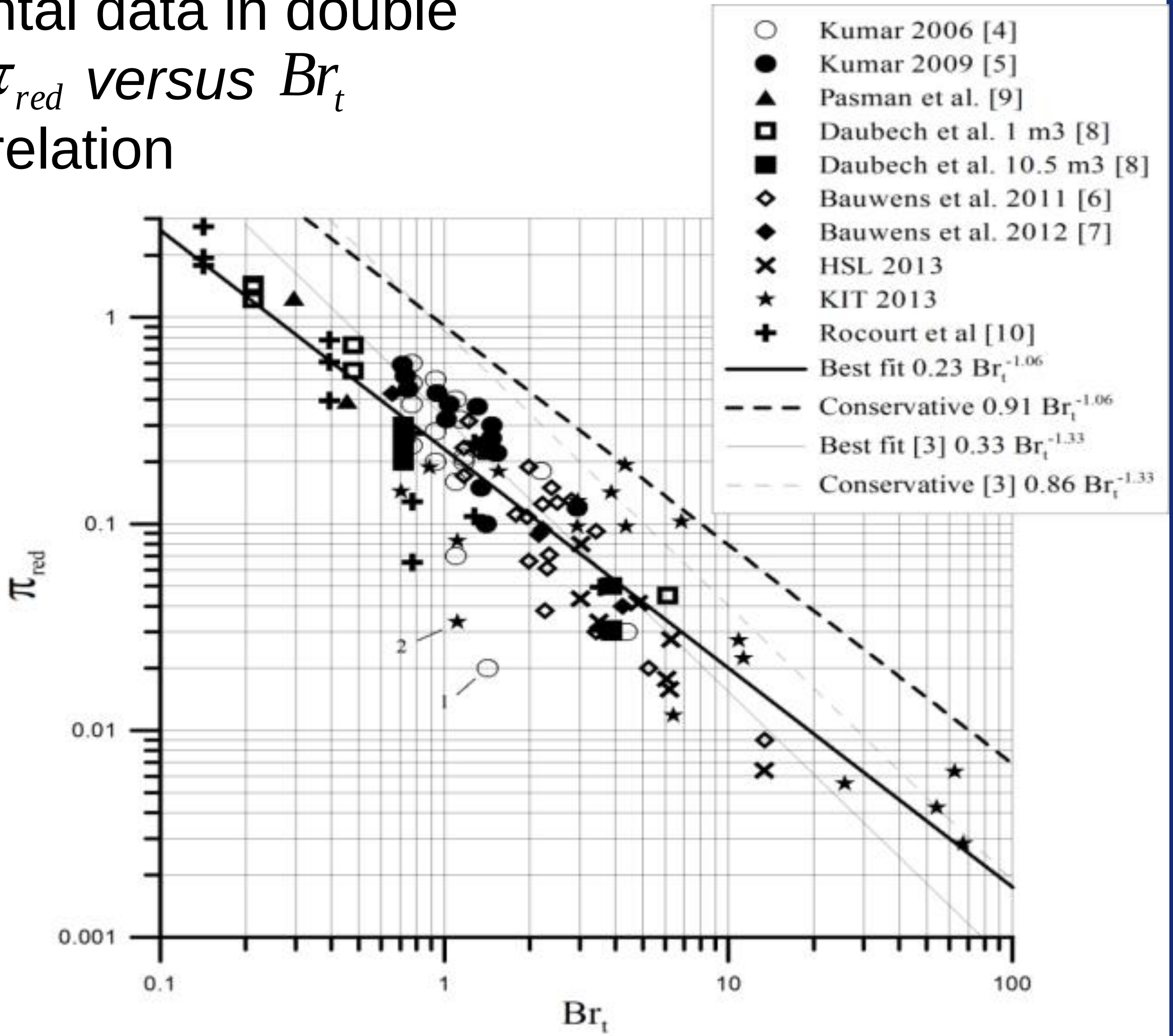
Plotting all experimental data in double logarithmic scale in π_{red} *versus* Br_t provides **best fit** correlation

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

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 methodology

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 methodology is as follows:

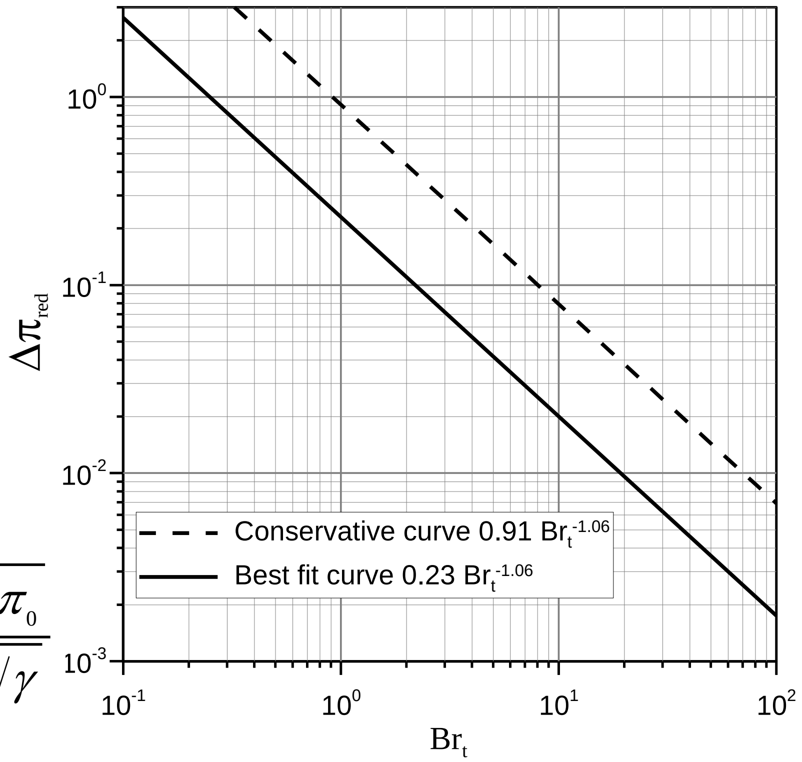
☐ Select maximum acceptable overpressure

☐ Use correlation to find corresponding turbulent Bradley number Br_t

☐ Calculate DOI factor χ / μ by evaluating all flame wrinkling factors based on known enclosure geometry and hydrogen concentration

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

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



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