VENTED HYDROGEN-AIR DEFLAGRATION IN A SMALL ENCLOSED VOLUME

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✓ Context

- Problem: Reduce green house gases, pollution and dependency on oil-based fuels
- Solution: Hydrogen, clean energy carrier (fuel cell)
- Risk: H_2 leak could fill a small confined volume in a part of a system and could ignite.
- Few studies at small scale: - McCann (1985), CH_4/air, $V=5.8\ dm^3$ and $54.9\ dm^3$
  - Sato (2010), C_3H_8/air, $V=4\ dm^3$

✓ Objectives of the study

- Vented deflagration in a small confined volume ($V=3.4\ dm^3$) with a stoechiometric H_2/air mixture
- Evaluate models of literature for vented deflagrations at small scale

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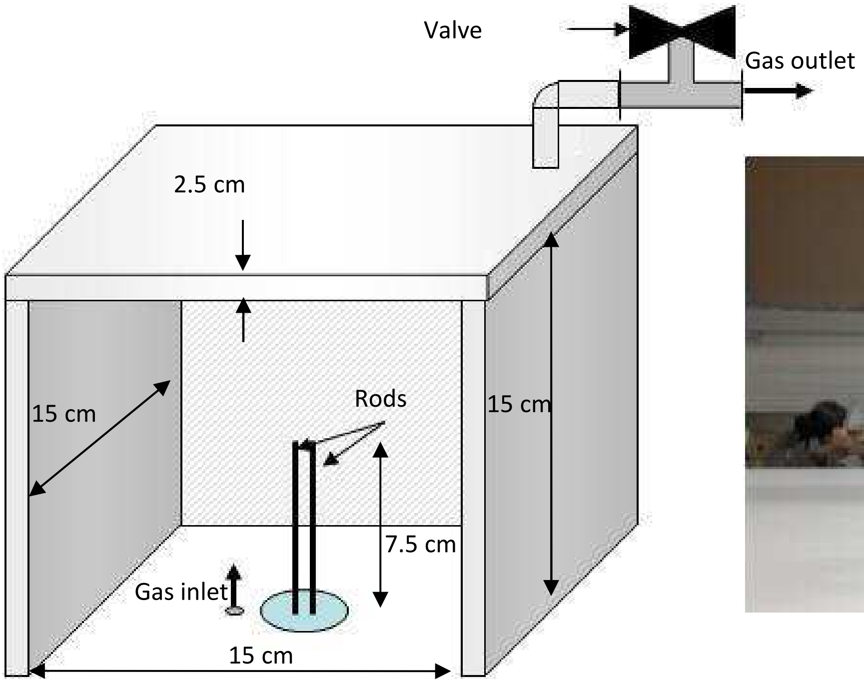
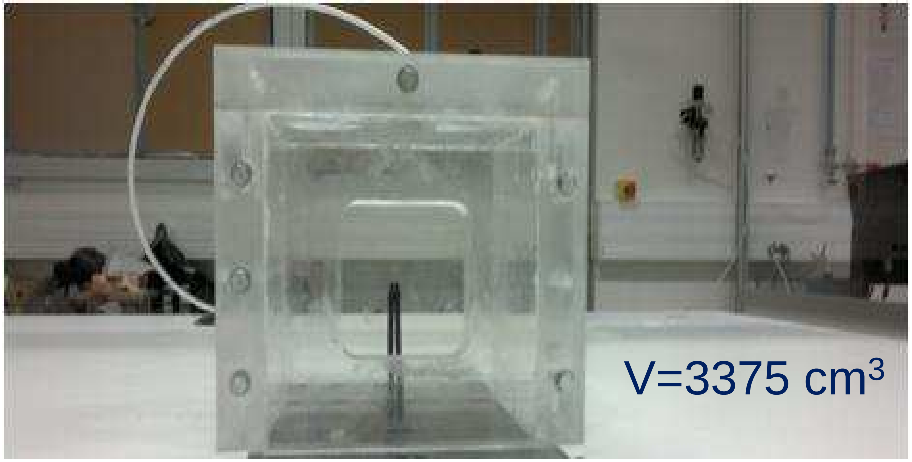
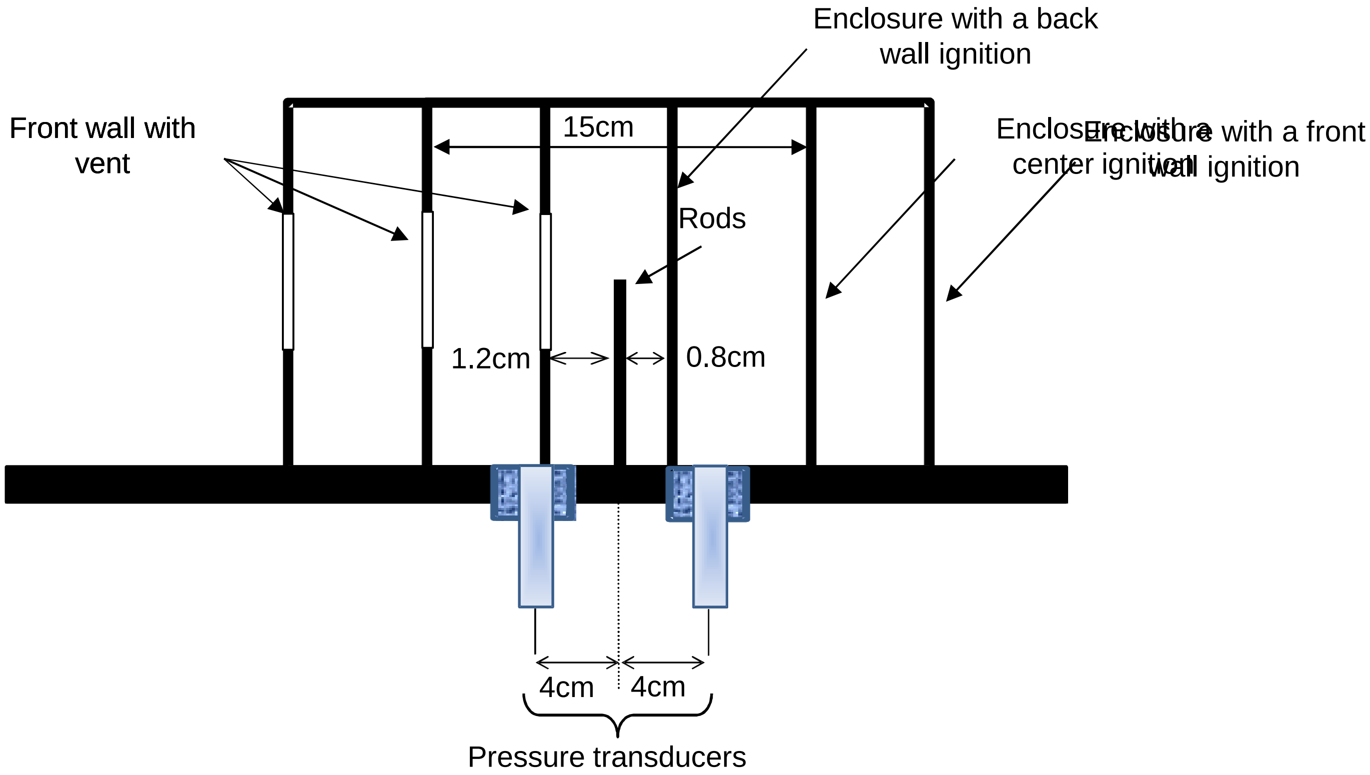
Experimental setup





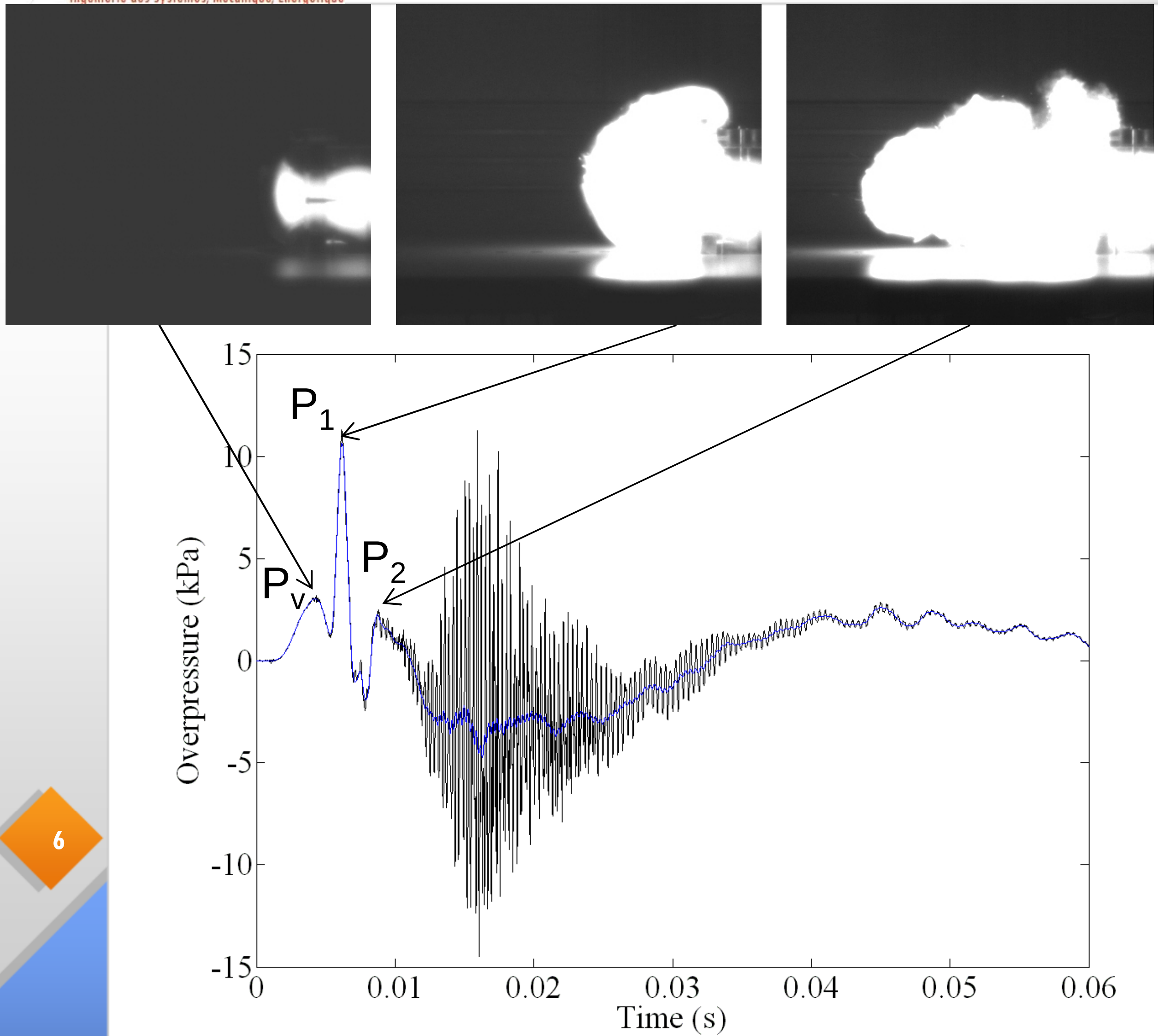
- Walls: Plexiglas
- H_2/air, ϕ=1, regulated by mass flow controllers
- Ignition by spark: E_n=122 mJ
- Pressure transducers PCB Piezotronics (±1.3%)
- High speed camera Phantom at 15000 fps

Experimental setup



- 3 ignition locations: center – back wall – front wall
- 5 centered square vent areas: 225 cm^2, 81 cm^2, 49 cm^2, 25 cm^2 and 9 cm^2
- Vent cover: thin polyethylene film

Experimental results



Several pressure peaks (Cooper et al. 1986 with a 760 dm^3 cubic vessel):

P_v: Relief pressure

P_1: Pressure generated by external explosion

P_2: Pressure generated by internal combustion (flame-accoustic coupling)

P_1 or P_2 dominates the internal pressure

H_2/air, ϕ=1, center ignition, raw signal (black) and filtered signal (1.5 kHz low pass filter - blue)

Experimental results

Vent area (cm^2)	K_v	Center ignition		Back wall ignition		Front wall ignition
		ΔP_1 (kPa)	ΔP_2 (kPa)	ΔP_1 (kPa)	ΔP_2 (kPa)	ΔP_2 (kPa)
225	1	3.1	-	5.0	-	1.3
81	2.8	11.0	2.5	25.0	-	2.5
49	4.6	13.0	10.0	27.8	-	6.6
25	9	-	78.9	-	61.5	40.0
9	25	-	278.4	-	180.8	196.4

- P_1 was included in P_2 which dominates for $K_v \geq 9$
- For $K_v \leq 4.6$ maximal overpressure generated by external combustion (center and back wall ignition) and back wall ignition
- P_2 was not noticed for center ignition (K_v=1) and back wall ignition ($K_v \leq 4.6$)
- For $K_v \geq 9$:
- Front wall ignition: no pressure peak P_1
- maximal overpressure generated by internal combustion and by center ignition
- Maximal overpressure ↑ with K_v

$$K_v = \frac{V^{\frac{2}{3}}}{A_v}$$

V – Volume (m^3)
A_v – Vent area (m^2)

Actuel standard to predict internal overpressure during venting explosion:

NFPA 68 and EN 14994 (2007) based on Bartknecht's equation (1993).

Limitations:

- 10 kPa < ΔP_{max} < 200 kPa
- initial pressure < 20 kPa
- static vent activation pressure < 50 kPa
- deflagration index K_G < 55 MPa.m/s

Models of the literature

Models to answer these limitations:

Correlation

Molkov (1995)

Vent area
Enclosure volume
Sound velocity
Burning velocity
Specific heat
Products expansion ratio
Bradley number
Empirical coefficients

→ Turbulent Bradley number
Deflagration Outflow Interaction

→ ΔP_{max}

Physic based model

Bauwens (2010)

Vent area
Enclosure lenghts
Discharge coefficient
Sound velocity
Burning velocity
Lewis number
Specific heat
Products expansion ratio
Universal gas constant
Gases temperature
Molar mass
Flame wrinkling coefficient

→ External cloud radius
Flame area=f(ignition location)
Flame acceleration at the exit
External Δp_{max}

→ ΔP_1, ΔP_2

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Molkov 1999

Correlation of Molkov proposed in 1995, and updated several times 1999, 2001, 2008, 2013

➢ Correlations applied with our experimental setup configurations

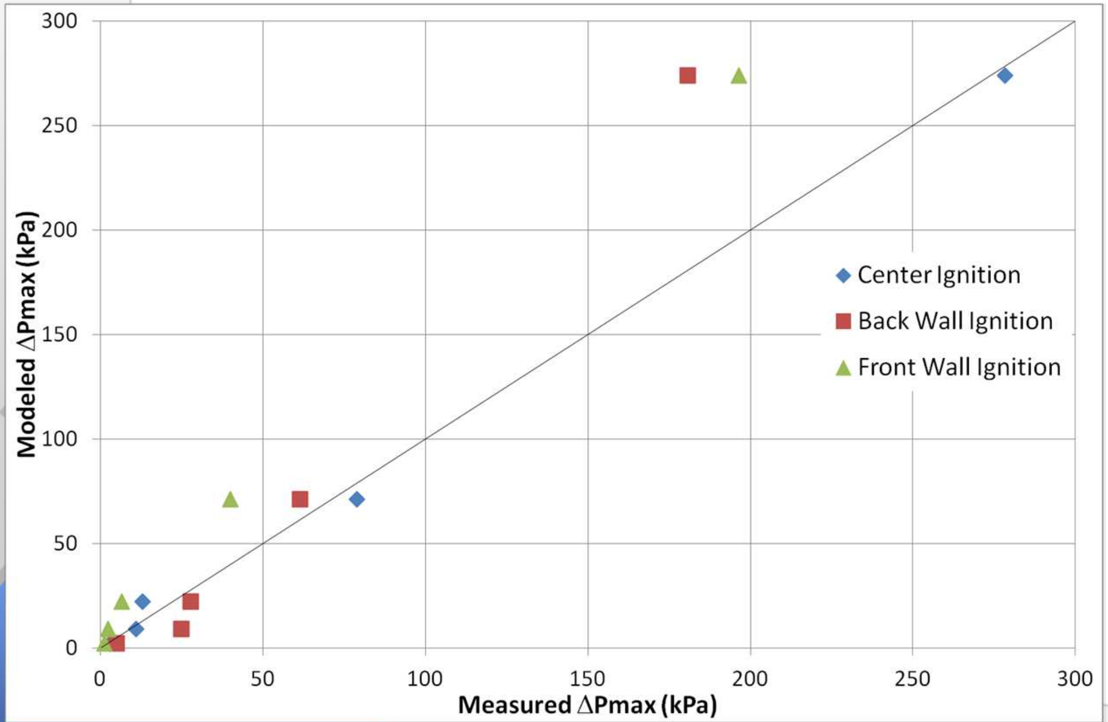
Ignition Location	Absolute average deviations for all vent areas (%)			
	Molkov 1999	Molkov 2001	Molkov 2008	Molkov 2013
Center	27	60	93	142
Back wall	42	92	66	70
Front Wall	133	185	361	434

➢ Molkov 1999 correlates better than other updated versions with small scale experimental results

➢ Molkov 1999 has been chosen to be compared to Bauwens model

Molkov 1999

A_V (cm^2)	K_v	Molkov (1999) ΔP_{max} (kPa)	Center ignition		Back wall ignition		Front wall ignition	
			Measured ΔP_{max} (kPa)	Dev. (%)	Measured ΔP_{max} (kPa)	Dev. (%)	Measured ΔP_{max} (kPa)	Dev. (%)
225	**1**	2	3.1	-35.5	5	-60	1.3	53.9
81	**2.8**	9	11	-18.2	25	-64	2.5	260
49	**4.6**	22	13	69.2	27.8	-20.1	6.6	233.3
25	**9**	71	78.9	-10	61.5	15.5	40	77.5
9	**25**	274	278.4	-1.6	180.8	51.6	196.4	39.5



- Correlation rather consistent with center ignition
- Overestimation for front wall ignition
- Not conservative for center and back wall ignition

Assumptions for Bauwens model:

- ΔP_2 asymptotically approaches a constant volume explosion pressure P_{cv}= 811.7 kPa when Av → 0 m^2 (Bauwens 2012)

- Initial flame velocity=laminar flame velocity S_L=2.14 $m.s^{-1}$ (Le≈0.9 for stoechiometric H_2/air mixture – $S_{u0}=0.9L_e^{-1}S_L$)

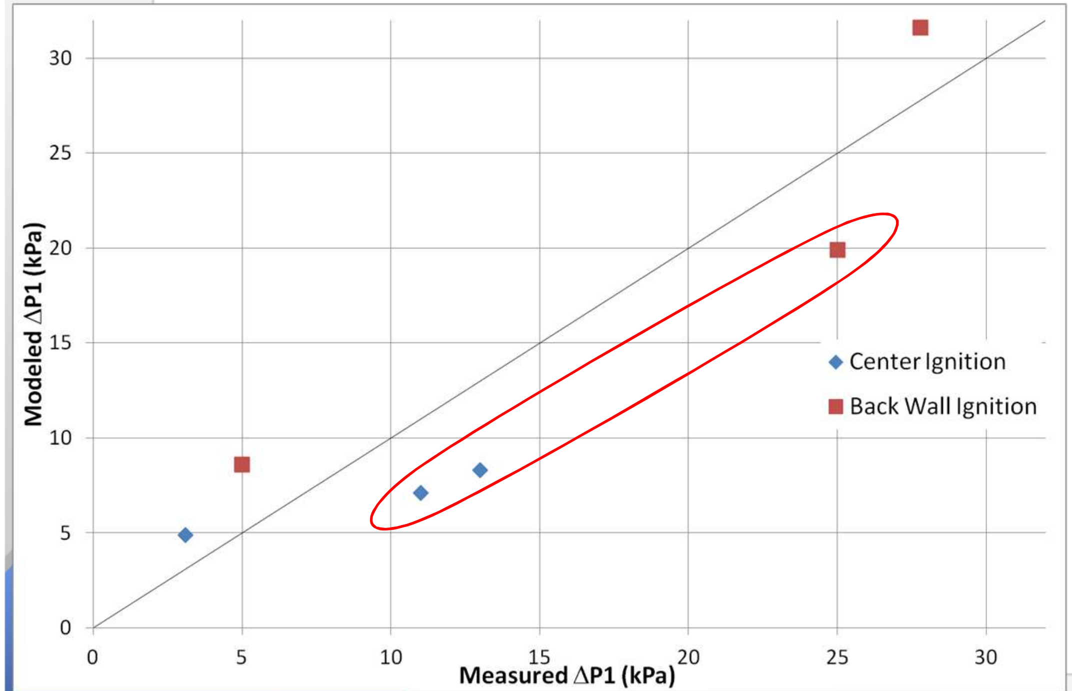
- Bauwens model: vented gas composed of 90% of products and 10% of reactants → 100% products considered in the present study

- New fitting value of k_T=9.26 m^{-1} (for ΔP_1) based on Bauwens (2010, 2011) and Chao (2011) experiments with a linear law.

- Flame wrinkling factor Ξ_A=1 (for ΔP_2) to avoid higher overpressures generated at large scale ($S_u=\Xi_A S_L$)

Bauwens model – ΔP_1

A_V (cm^2)	K_v	Center ignition ΔP_1 (kPa)			Back wall ignition ΔP_1 (kPa)		
		Measured	Bauwens	Deviation (%)	Measured	Bauwens	Deviation (%)
225	**1**	3.1	4.9	58.1	5.0	8.6	72.0
81	**2.8**	11.0	7.1	-35.5	25.0	19.9	-20.4
49	**4.6**	13.0	8.3	-36.1	27.8	31.6	13.7
25	**9**	-	10.1	-	-	66.3	-
9	**25**	-	13.6	-	-	269.3	-



- Deviations varying from -36% to 58% for center ignition
- Deviations varying from -20% to 72% for back wall ignition
- Not conservative for some configurations

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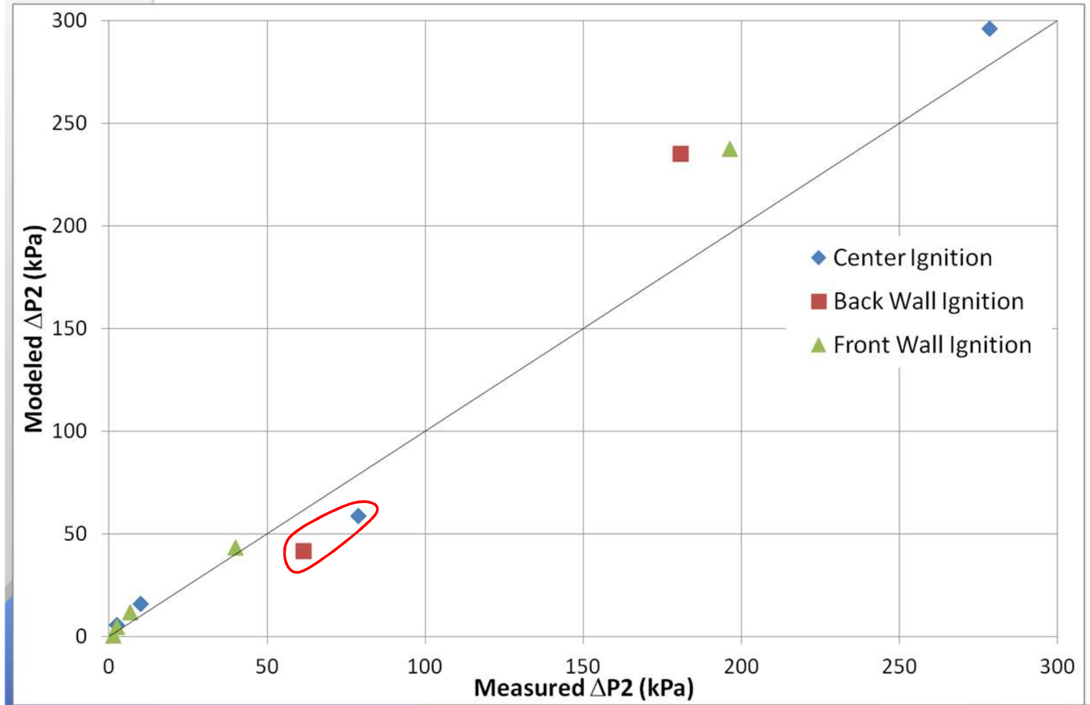
Bauwens model – ΔP_2

A_V (cm^2)	K_v	Center ignition ΔP_2 (kPa)			Back wall ignition ΔP_2 (kPa)			Front wall ignition ΔP_2 (kPa)		
		Measured	Bauwens	Dev. (%)	Measured	Bauwens	Dev. (%)	Measured	Bauwens	Dev. (%)
225	**1**	-	0.6	-	-	0.4	-	1.3	0.6	-53.9
81	**2.8**	2.5	5.6	124	-	3.8	-	2.5	4.4	76
49	**4.6**	10	15.7	57	-	10.8	-	6.6	11.8	78.8
25	**9**	78.9	58.8	-26	61.5	41.6	-32.4	40	43.4	8.5
9	**25**	278.4	295.9	6	180.8	235	30	196.4	237.5	20.9

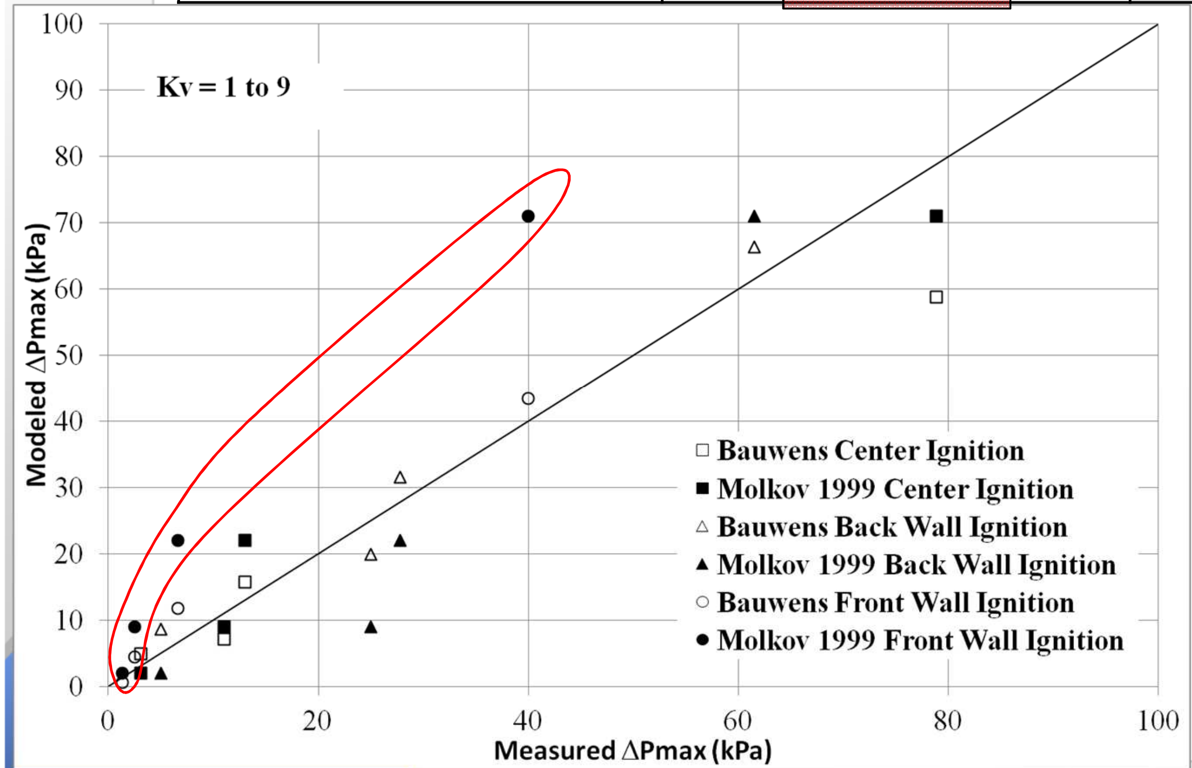


- Model more accurate for small vent areas $K_v \geq 9$
- Not conservative for some configurations

Comparison between models - ΔP_{max}

ΔP_{max} modeled is compared to ΔP_{max} measured (ΔP_1 or ΔP_2)

Ignition Location	Absolute average deviations for all vent areas (%)	
	Molkov 1999	ΔP_{max} Bauwens
Center	27	26
Back wall	42	33
Front Wall	133	48

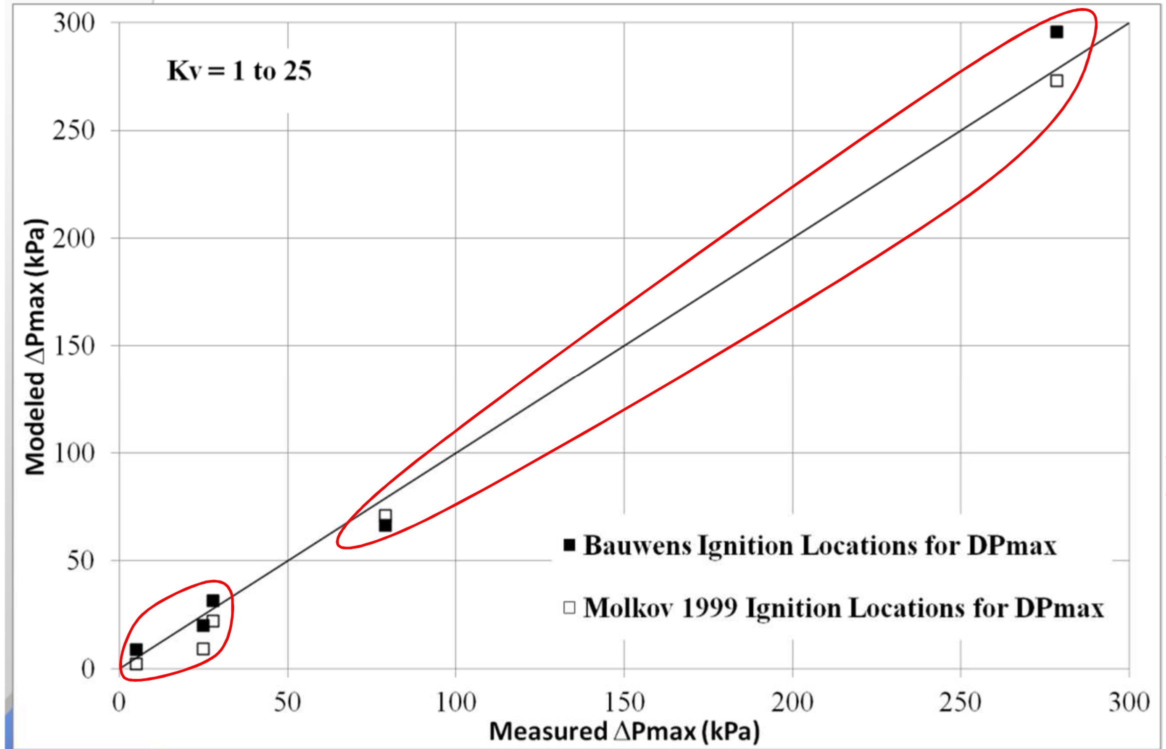


- Bauwens model is globaly more accurate than Molkov 1999
- Results of both models are close for center and back wall ignition
- Molkov 1999 overpredicts pressure for front wall ignition but is conservative for this location

Comparison between models - ΔP_{max}

Consideration of ignition location given ΔP_{max} for each vent areas

Ignition Location	Absolute average deviations for all vent areas (%)	
	Molkov 1999	ΔP_{max} Bauwens
Locations for ΔP_{max}	31	26



- The critical case is only considered for each vent area
- Both models give ≈ similars results
- Bauwens model for $K_v \leq 4.6$
- Molkov model for $K_v > 4.6$

Conclusions

✓ Experimental results

- Influence of the vent area and the ignition location on the internal overpressure for a small confined volume (H_2/air, Φ= 1, V = 3375 cm^3)
- 3 pressures peaks: vent failure pressure, external combustion, internal combustion with flame-acoustic interaction
- ΔP_{max} obtained with center ignition for $K_v \geq 9$ and back wall ignition for $K_v \leq 4.6$
- P_2 is dominant for small vent areas ($K_v \geq 9$)

✓ Molkov 1999 correlation and Bauwens model

- Approximately similar results when comparing with experimental maximal overpressures (either P_1 or P_2) for center and back wall ignition
- Models results close to experimental data (Bauwens 26%, Molkov 31%) for a safe approach.

Thanks for your attention

Any questions ?