EFFECT OF METHANE ADDITION ON TRANSITION TO DETONATION IN HYDROGEN-AIR MIXTURES DUE TO SHOCK WAVE FOCUSING IN A 90 – DEGREE WEDGE (ID 237)

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PRESENTATION PLAN

1. BACKGROUND

- Detonation (in majority of cases) is undesirable phenomenon leading to losses in infrastructure and/or casualties
- detonation has more efficient theoretical cycle (~59%) comparing to const. Volume (~54%, Humphrey) or const. Pressure (~37%, Brayton) → RDE
- Natural gas doping as possible mitigation technique (DDT, propagation in semi-confined channel, HP hydrogen self-ignition) – NATURALHY project

- **Transition criteria in tubes:**

- flame speed approaching to choked flow (speed of sound in products)
- 7λ criterion (Dorofeev et al., Shock Waves 2000)
- semi-empirical equations combining BR, obst. spacing, orifice diam…

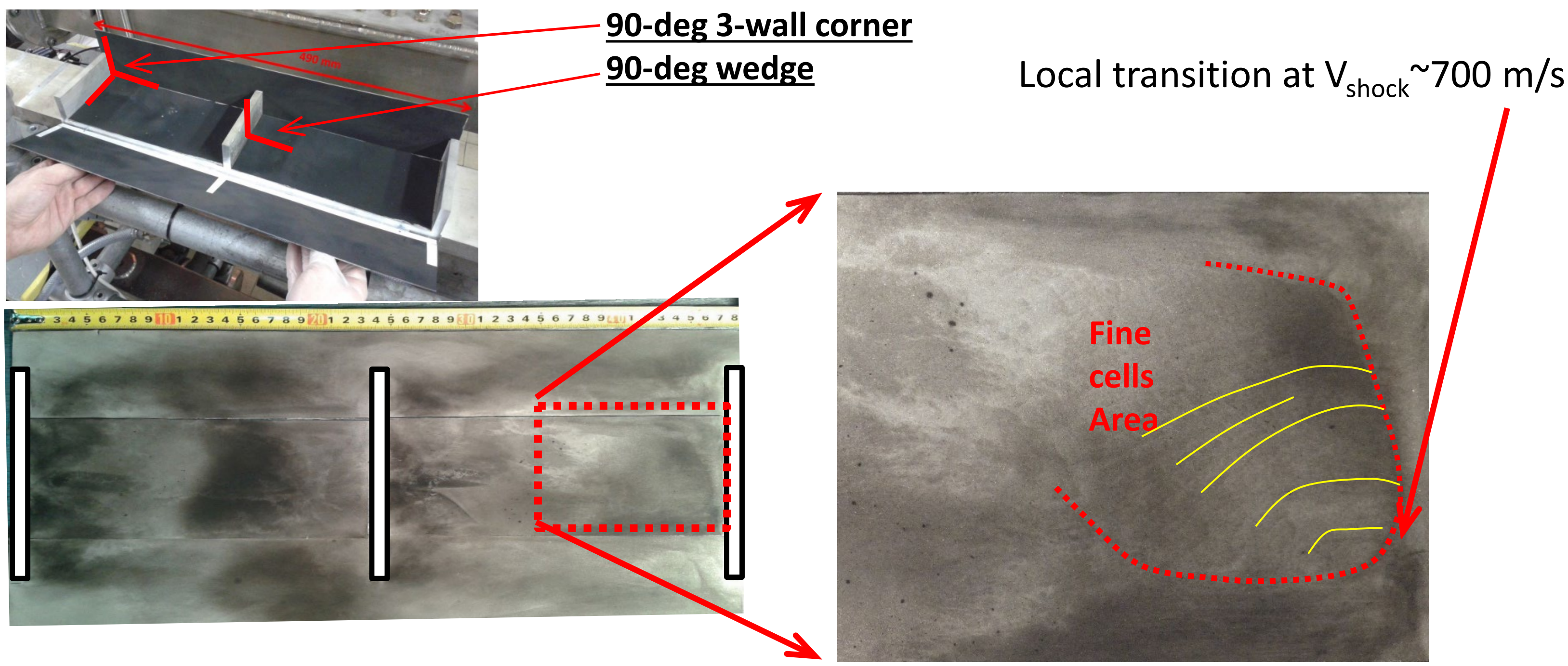
- **Transition to detonation triggers:**

- direct (high ignition energy)
- turbulent flame area
- shock interaction with walls/other shocks → reflection and/or focusing
  reflector types → flat, wedge, parabolic, semicircle, conical,…

1. Background

Detonability depends on scale:

- in ~0.1 m diam. tubes with obstacles detonability range ~18 – 58% H_2 in air (Rudy et al. 2021)
- in 0.305 m diam. tube, lower detonability limit LDL ~15% H_2 in air (*Kogarko, 1948*)
- in 0.43 m diam. tube → LDL ~13.6% H_2 in air (*Tieszen et al., 1985*)
- in 2.3 m height channel (RUT facility) → LDL ~12.5% H_2 in air *(Dorofeev, 1996)*
- in large scale open, congested cloud DDT in HC-air at ~500 - 600 m/s (*Pekalski et al. 2015*)



1. BACKGROUND

Reflectors and transition cfriteria:

- **flat wall** → shock tube

  - Meyer and Oppenheim (1972) ‚strong' and ‚weak' ignition, $-2\ \mu s/K$ criterion (H_2+O_2)

- **3-D:**

  parabolic – Buraczewski and Shepherd (2004) (H_2-air, 13-26kPa, M = 2.04),

  90-deg wedge – Rudy (IJHE, 2023), H_2-air, 1 bar; Zezhong Y. et al. (ChJA, 2023; CaF, 2023), Gelfand et al. (Arch. Comb. 1998)

  60-deg wedge – Zezhong Y. et al. (ChJA, 2023) H_2+O_2+Ar, 20-60 kPa, M = 2.2-2.3
  Zezhong Y. et al. (CaF, 2023), CH_4+O_2+Ar, 10-25 kPa, M = 2.2-2.3

  conical – Smirnov et al. (AA, 2017, 2018), H_2-air, 0.35 bara, M = 1.9

  semi-eliptical (multi) **-** Utkin (2020), H_2+O_2, 0.04 atm, M = 2.44

Recorded events: no ignition, deflagration, delayed detonation, direct detonation

Limited data for P_0 = 1 bara H_2-air, no data for H_2-CH_4-air

2. OBJECTIVES

- Quantify 90-deg wedge reflector influence on transition to detonation due to shock focusing in H_2-air mixtures at ambient initial conditions → baseline data

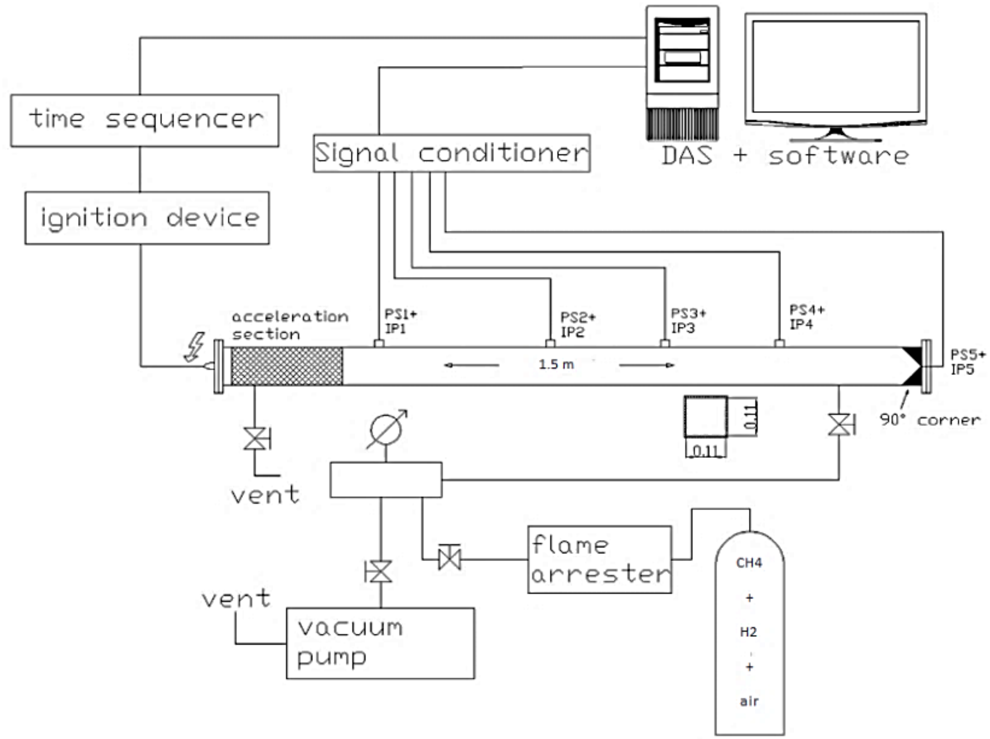
- Quantify the influence of 5% CH_4 (in fuel) in CH_4-H_2-air mixture on the critical conditions needed for transition to detonation

- Provide data of transition shock velocities and overpressures recorded at the time of transition

- Provide experimental data for CFD simulation

3. Experimental setup

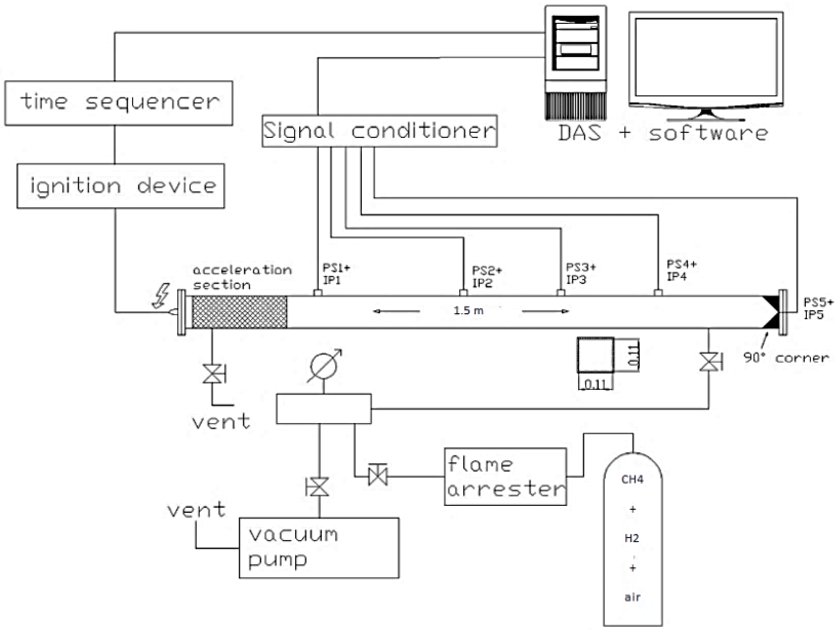
- 0.11 x 0.11 x 1.5 - 2 m detonation tube
- 0.3 - 0.5 m acceleration section filled with 6 × 6 mm mesh layers made of 1 mm dia. steel wire
- 5 pairs of PS + IP → 10 Ch
- Data sampling freq. 2 MHz
- Electric spark ignition
- Partial pressure method for mixture preparation, mixture stored for min. 24 hrs before use

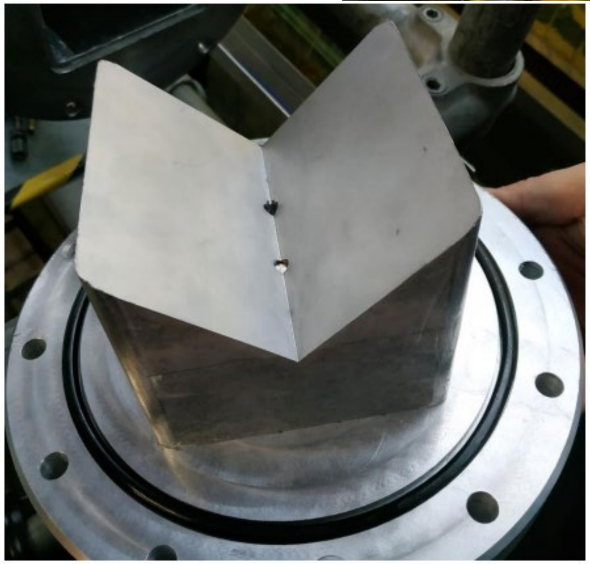


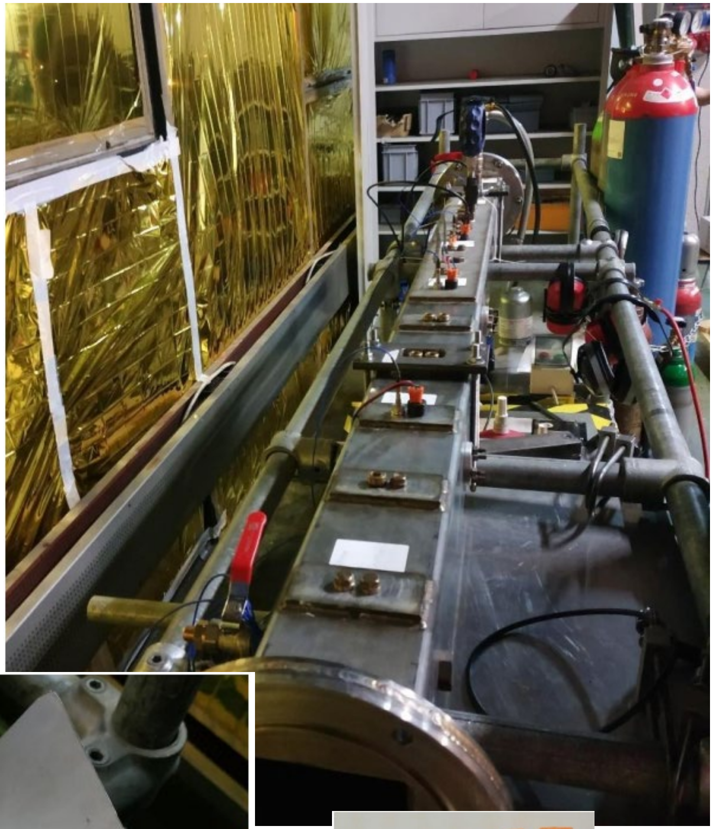
$$\phi[xCH_4 + (1-x)H_2] + [2x + (1-x)*0.5]*(O_2+3.76N_2) \rightarrow ....$$

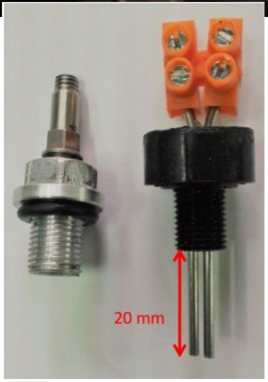
$x = 0.0, 0.05$

3. EXPERIMENTAL SETUP





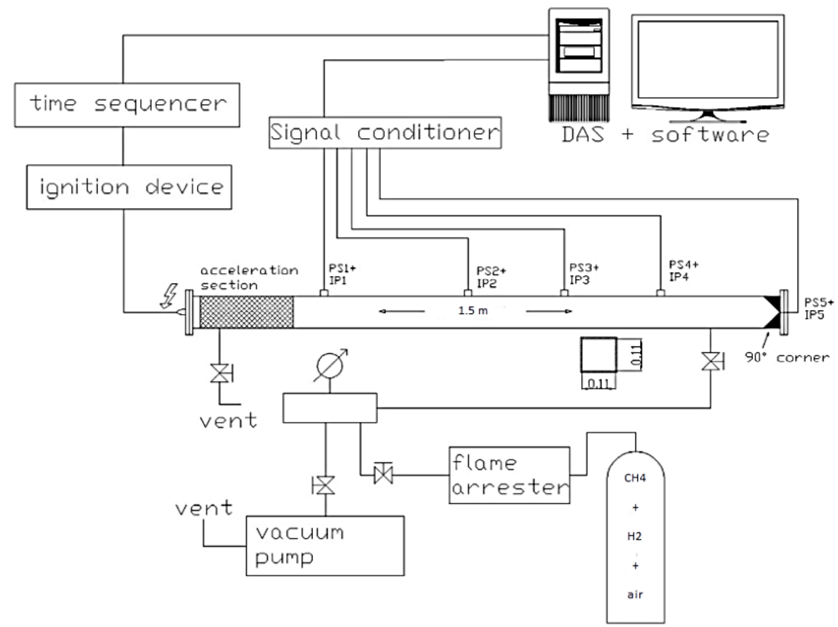




3. EXPERIMENTAL SETUP CONT.

Experimental procedure:

1. Gas evacuation
2. Pressure control
3. Filling the tube with mixture
4. Closing all the valves
5. DAS file prepration and system arming
6. Ignition
7. Evacuate the combustion products
8. Cool down the tube walls
9. Check V_S → Change acc. Section arrangment?



Initial conditions

- P_0 = 0.1 MPa
- T_0 = 298± 3K

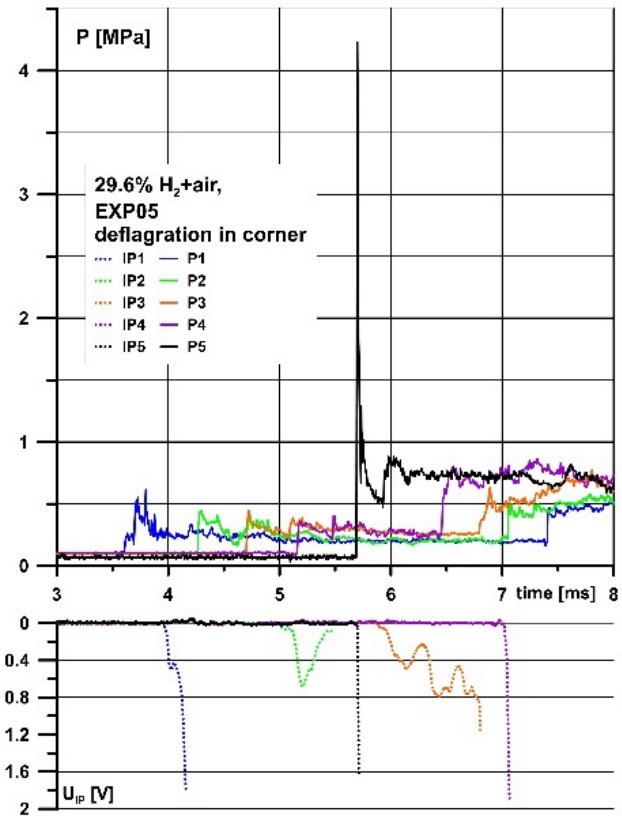
70 tests at ϕ = 0.8 – 1.6 in 5%CH_4 + 95%H_2 + air

241 tests in range 20 – 55% H_2 + air → 155 tests ϕ = 0.8 - 1.6 (25 – 40% H_2) as baseline

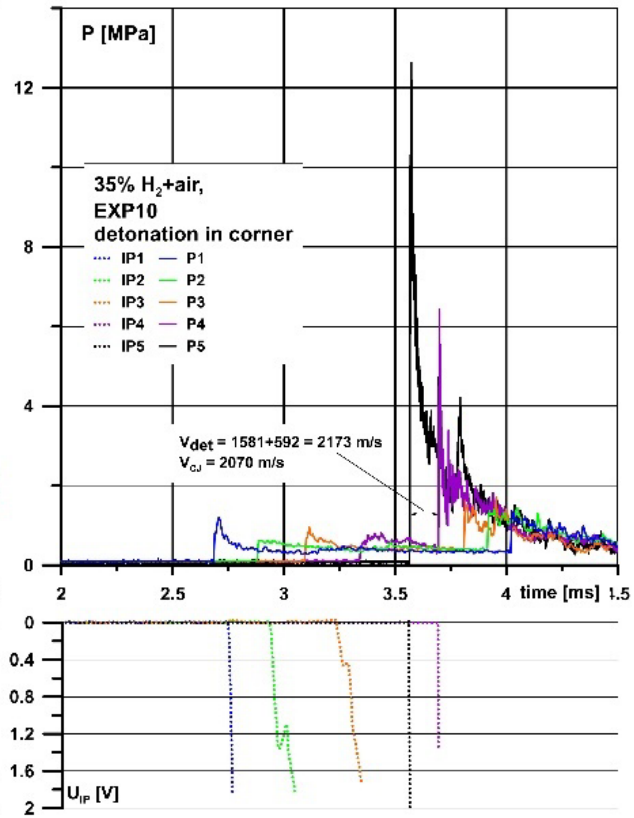
4. DATA PROCESSING

3 ignition types recorded: deflagration, detonation and delayed detonation

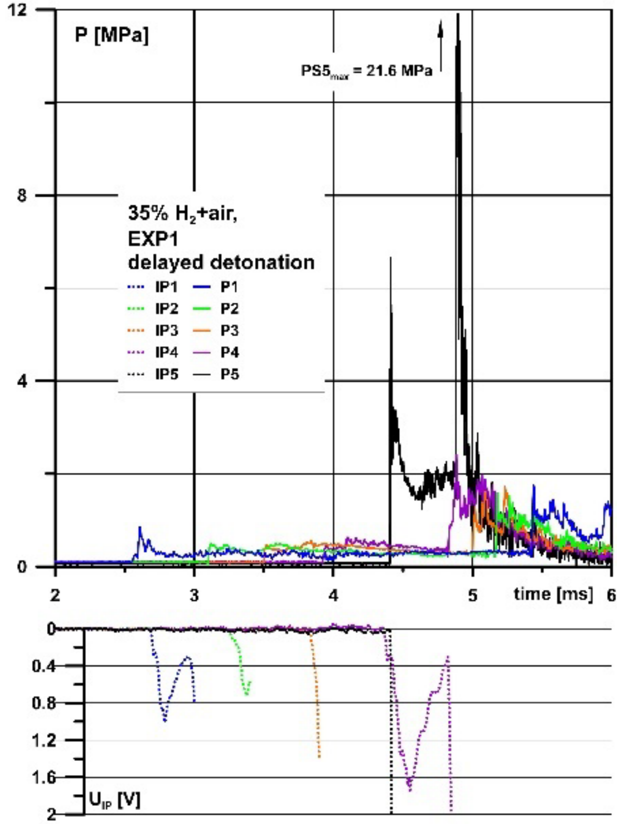
+ early detonation (undesirable) ~10% of all tests



V_S = 598 m/s



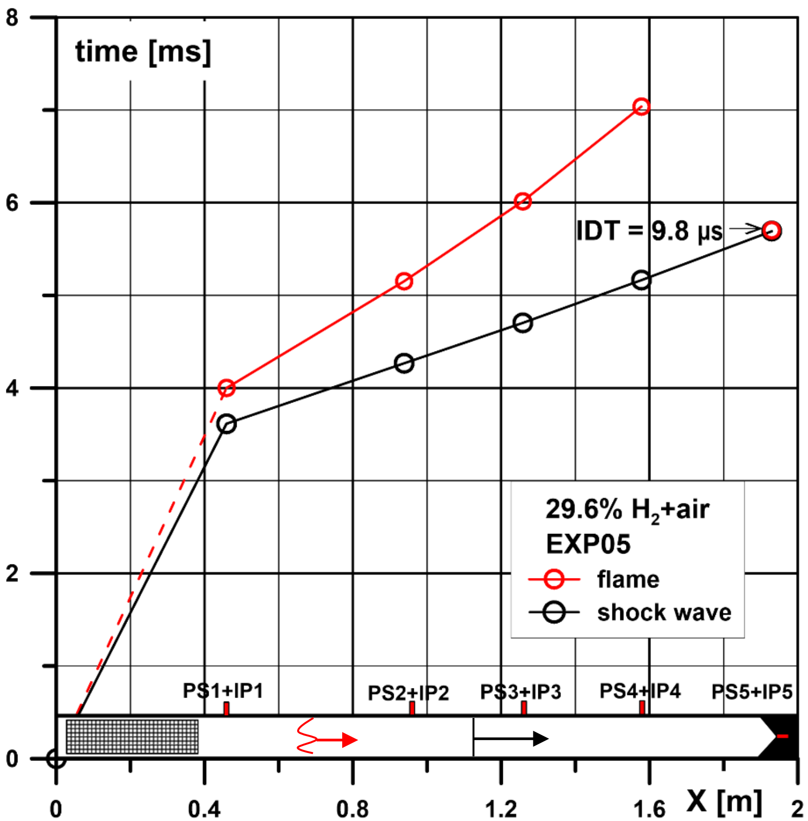
V_S = 895 m/s

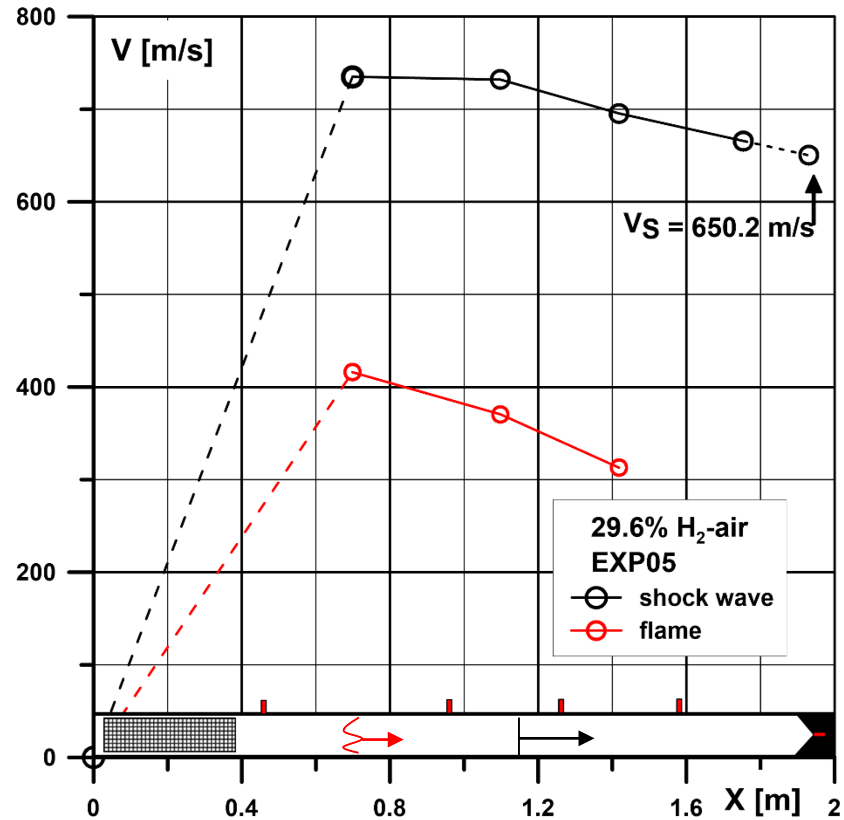


V_S = 691 m/s

4. Data processing cont.

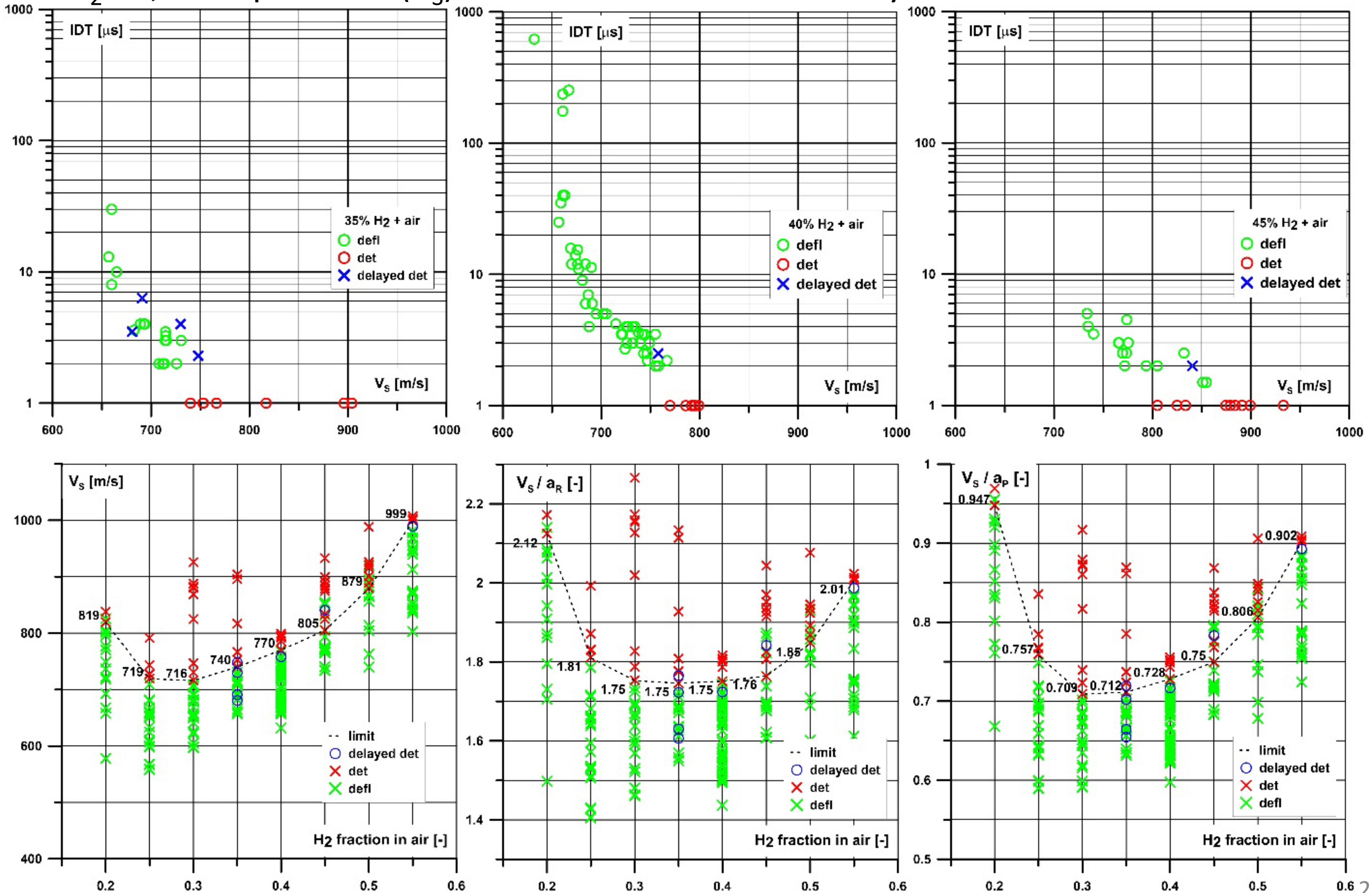
- ToA method for flame and shock wave velocity calculations
- Velocity of the shock wave at the reflection extrapolated
- Pressure in the corner obtained from max. PS5 value.
- Calculation of ignition delay time (IDT) in wedge tip





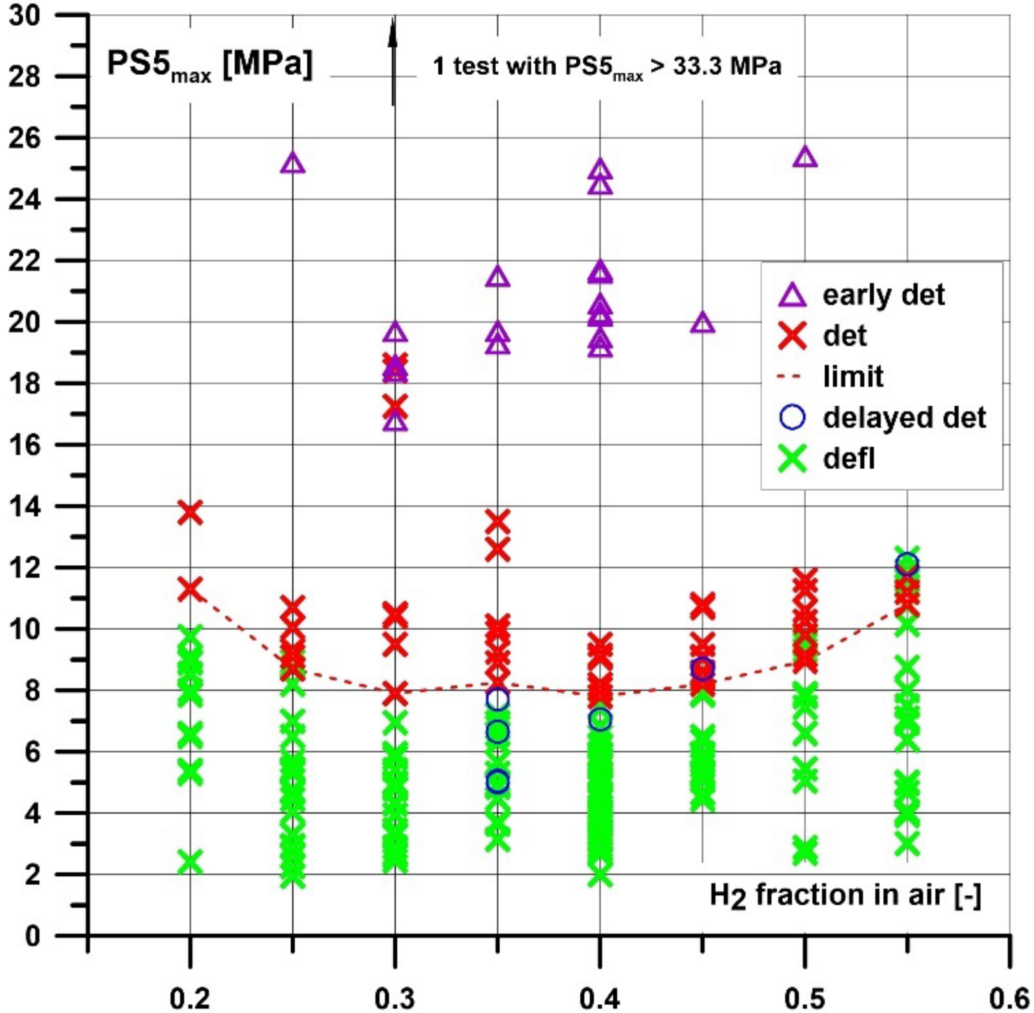
5. RESULTS.

- H_2-air, example IDT= f(V_S) and transition shock velocity



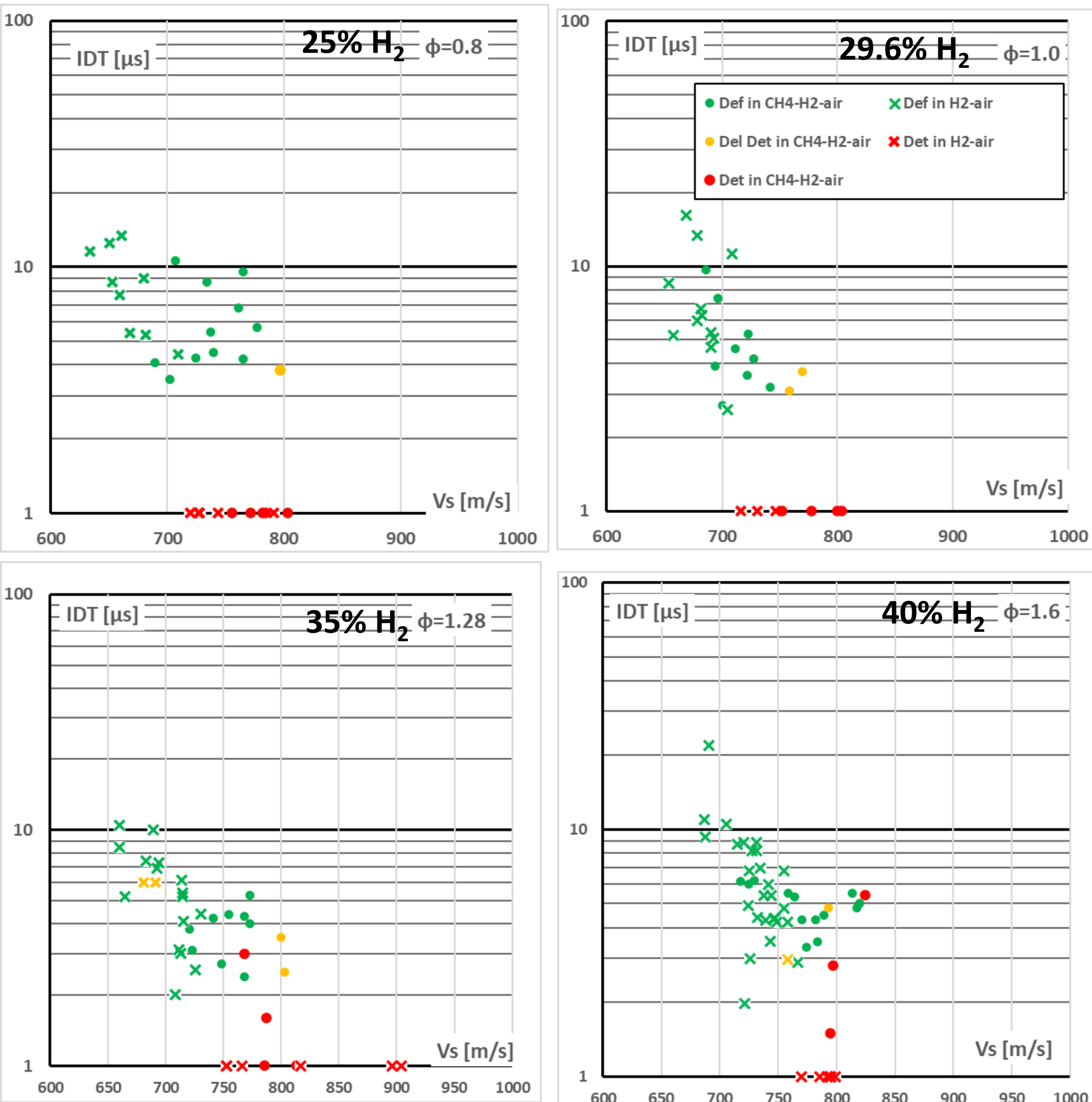
5. RESULTS.

- H_2-air, PS5 $_{max}$ = f(H_2 fraction)



- U-shape transition curve
- Transition pressure ~8-9MPa for 25 – 50% H_2

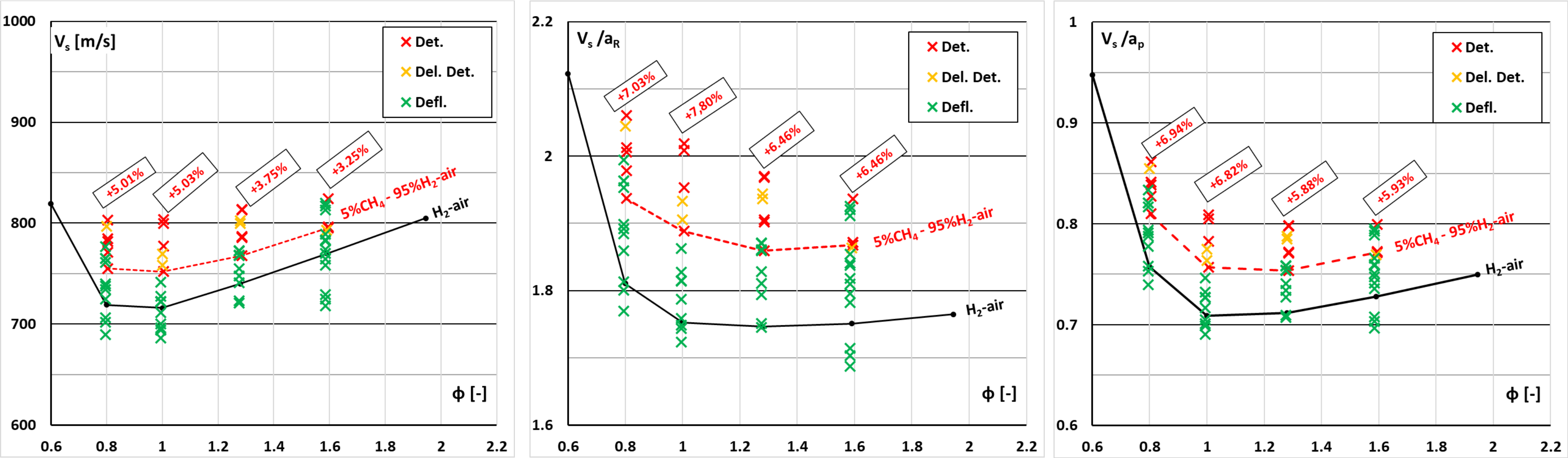
5. Results



5%CH_4-H_2-air data shifted towards higher transition velocities V_S comparing to H_2-air data

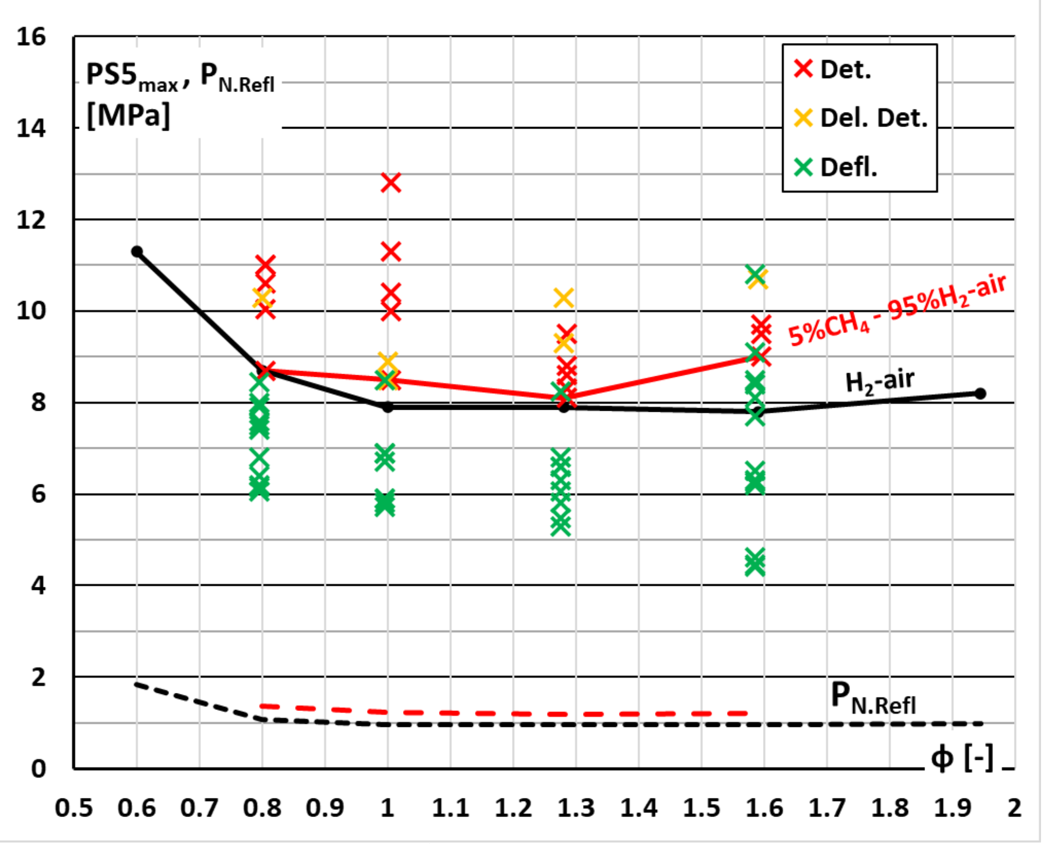
5. Results cont.

- CH_4 addition increases the transition shock wave velocity V_S
- Transition V_S increase is of 25 - 36 m/s which corresponds to 6.5 - 7% increase in M number



5. Results cont.

- 5% CH_4 addition increases in $PS5_{max}$ recorder for transition to detonation
- $PS5_{max}$ increase does not exceed 0.5 MPa for $\phi = 0.8 – 1.28$
- $PS5_{max}$ Increase seems to increase faster for rich mixtures ~1 MPa for $\phi = 1.6$
- $PS5_{max}$ is approx. ~8 - 8.3 times higher than normal post-reflection press. in H_2-air
- $PS5_{max}$ is approx. ~6.4 – 7.45 times higher than normal post-reflection press. in 5%CH_4-H_2-air



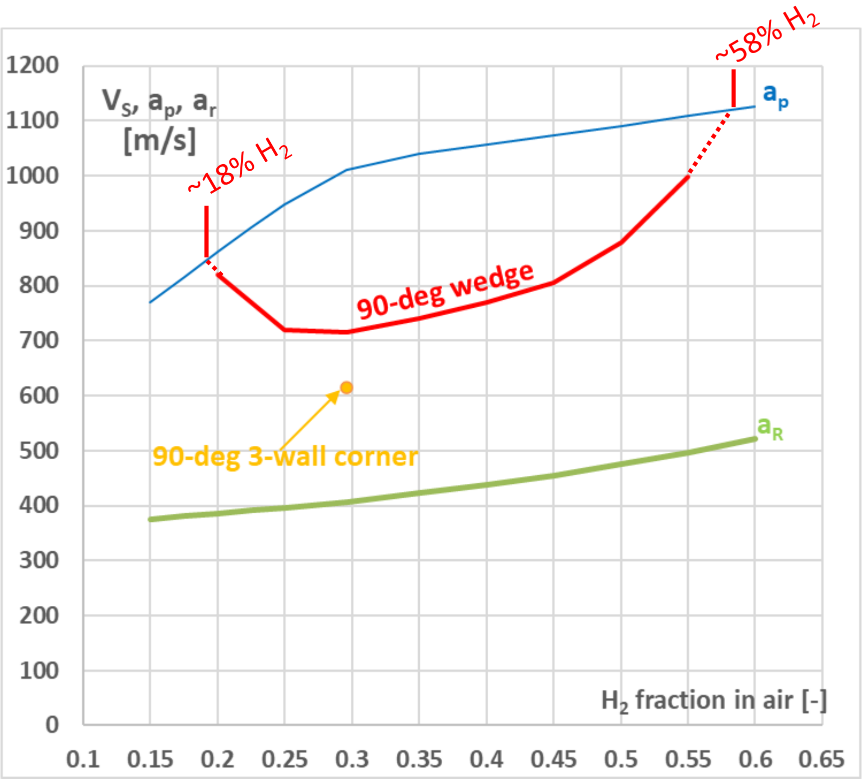
6. Conclusions

- Shock focusing in 90-deg wedge may result in ignition in deflagrative, detonative or delayed detonation mode
- IDT due to focusing highly depends on V_S: 100 m/s drop → ~1000-fold increase in IDT
- Shock focusing in 90-deg wedge causes approx. 8-fold or 6.4-7.45-fold increase in max pressure recorded comparing to normal post-reflection pressure in H_2-air mixture and 5%CH_4-H_2-air, respectively
- For H_2-air mixtures the critical V_S velocity approaches speed of sound in products for ~18 % and ~58% H_2 in air → does focusing mechanism defines the det. limits in tubes?
- 5% CH_4 addition to H_2-air mixtures shifts transition velocity up to 37 m/s or 6.5 - 7% of M numer comparing to stoichiometric H_2-air mxiture
- 5% CH_4 addition to H_2-air mixtures increases the minimum transition pressures recorded up to 1 MPa for $\phi = 1.6$; for near stoichiometric mixtures increase in pressure is approx. ≤0.5 MPa

7. Further research

Continue research by:

- Extend the investigated mixtures to HC-air mixtures – work in progress
- Extend the investigated mixtures to oxygen enriched mixtures – work in progress
- Change the reflector geometry to 90-deg 3-wall corner – work in progress



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Thank you for your attention!

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App

Detonation

Why to use detonation?
Ideal cycle efficiency analysis

Brayton
Const. pressure

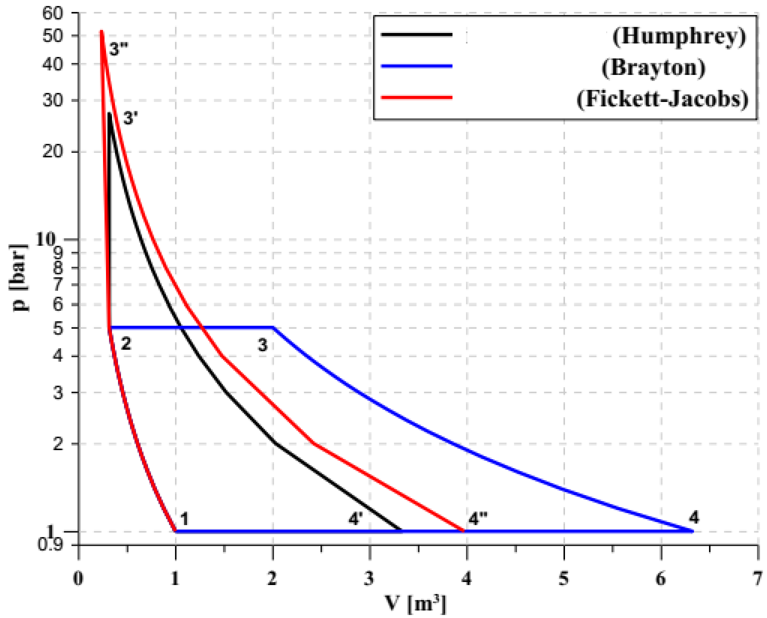
$$\eta = 1 - \frac{1}{\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}}$$

Humphrey
Const. volume

$$\eta = 1 - k \cdot \frac{T_1}{T_2} \cdot \frac{\left(\frac{T_{3'}}{T_2}\right)^{\frac{1}{k}} - 1}{\left(\frac{T_{3'}}{T_2}\right) - 1}$$

Fickett-Jacobs
detonation

$$\eta_t = 1 - k \frac{1}{\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}} \frac{\left(\frac{T_{3"}}{T_2}\right)^{\frac{1}{k}} - 1}{\left(\frac{T_{3"}}{T_2}\right) - 1}$$



Fuel	Brayton	Humphrey	Fickett-Jacobs
hydrogen – H_2	*36,86%*	*54,35%*	*59,26%*
methane – CH_4	*31,42%*	*50,49%*	*53,22%*
acetylene – C_2H_2	*36,86%*	*54,07%*	*61,37%*