Flame propagation and deflagration to detonation transition (DDT) in obstructed channels

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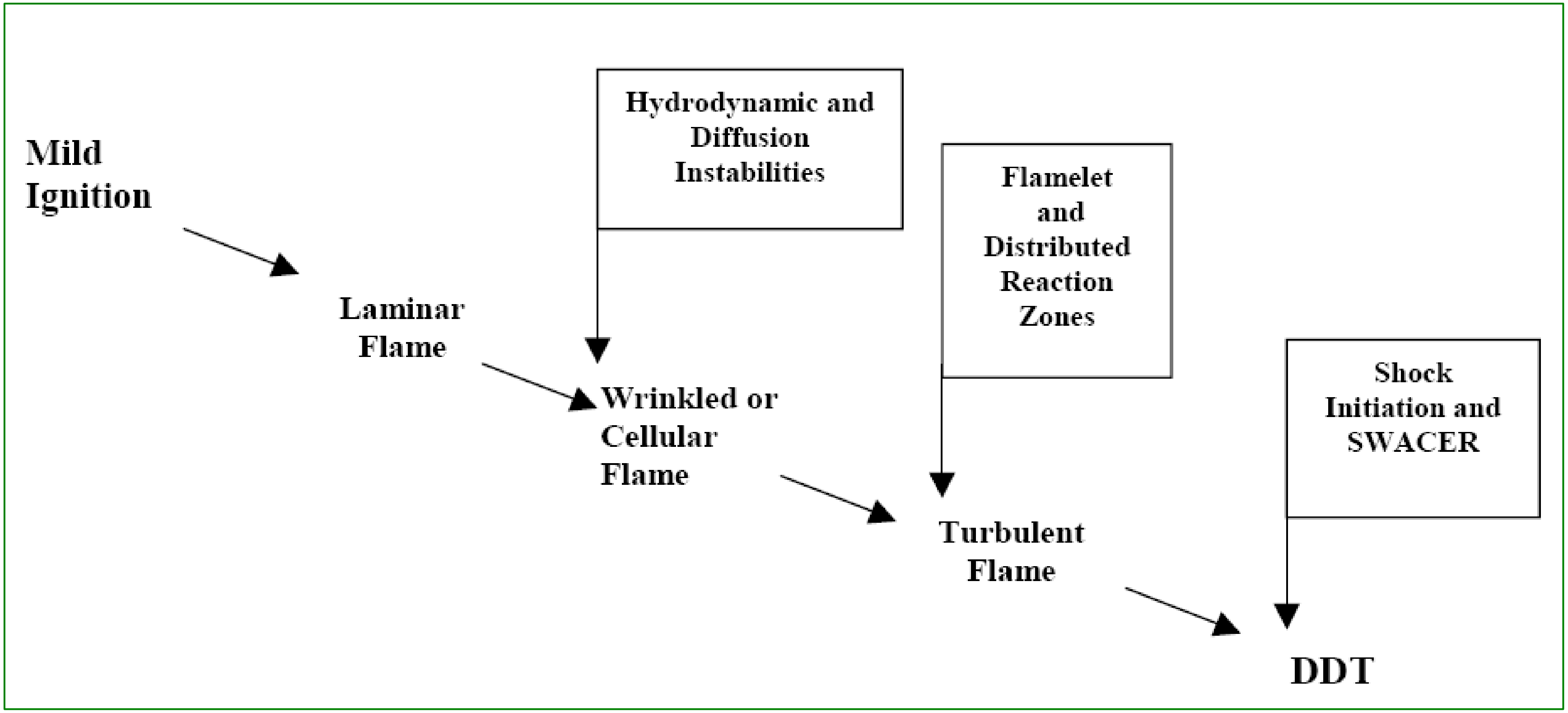
Outline

- Regimes of flame propagation in channels
- Mechanisms of flame acceleration
- Flame propagation and DDT in smooth tubes
- Flame propagation and DDT in rough tubes (with obstacles)
- Recent advanced CFD simulation of flame acceleration and DDT by Gamezo et al.
- Experimental validation of this simulation at WUT

Flame propagation in tubes

- **Lower limit** ⇒ LAMINAR FLAME (m/s)
- **Upper limit** ⇒ CJ DETONATION (km/s)
- **Between limits** ⇒ spectrum of TURBULENT FLAMES (deflagrations) depending on:
  - Initial conditions (pressure, temperature, composition)
  - Boundary conditions (geometry, size, wall roughness, obstacles, etc.)
- **Smooth tubes** ⇒ continuous flame acceleration and abrupt DDT
- **Rough (obstructed) tubes** ⇒ several distinct regimes of steady flame propagation

Regimes of flame propagation leading to DDT



Mild Ignition

Laminar Flame

Hydrodynamic and Diffusion Instabilities

Wrinkled or Cellular Flame

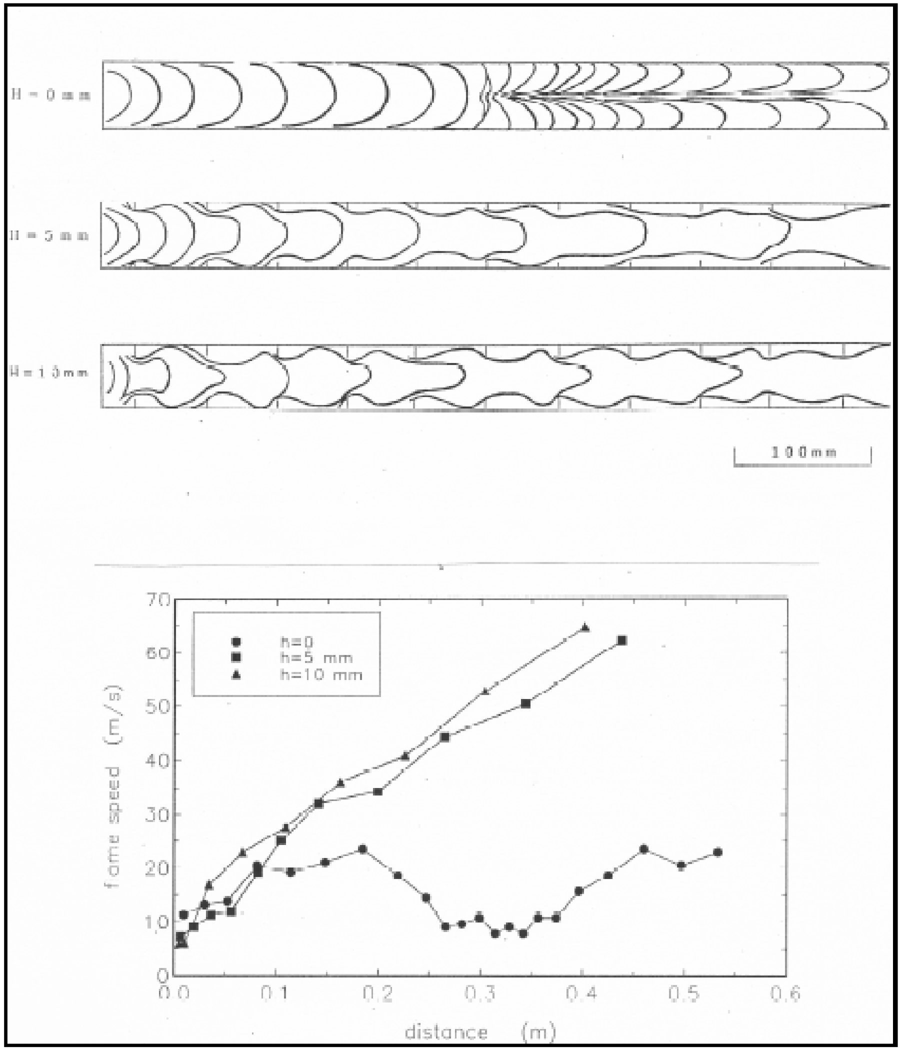
Flamelet and Distributed Reaction Zones

Turbulent Flame

Shock Initiation and SWACER

DDT

Flame acceleration in channel



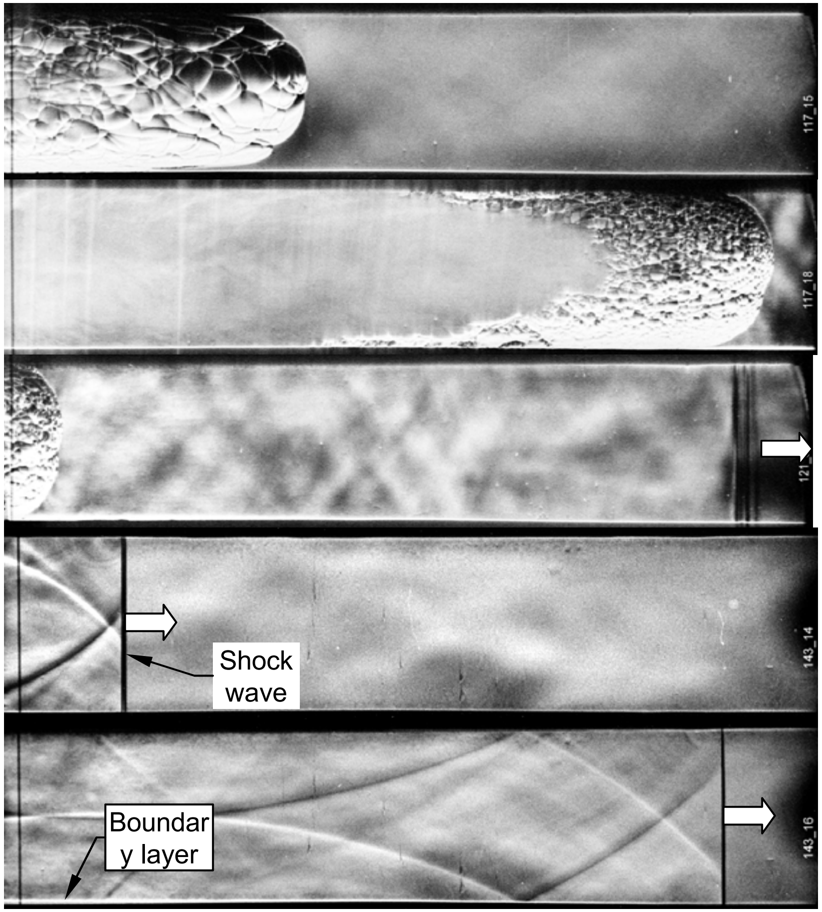
Open end 50mm channel;

Stoichiometric propane-air at 1 bar

(Teodorczyk et al., 1992)

Effect of boundary layer on the flame acceleration and DDT

Premixed flames in smooth closed tube - stoichiometric hydrogen-oxygen



Shadow photograph of early stage of flame propagation

p_0=0.75 bar

at 210-440 mm from ignition

Ignition by electric spark of 20mJ

(Kuznetsov M., Dorofeev S., 2005)

Early accelarating flame

Phil. Trans. R. Soc. Lond. A, volume 315 *Oppenheim, plate* 3

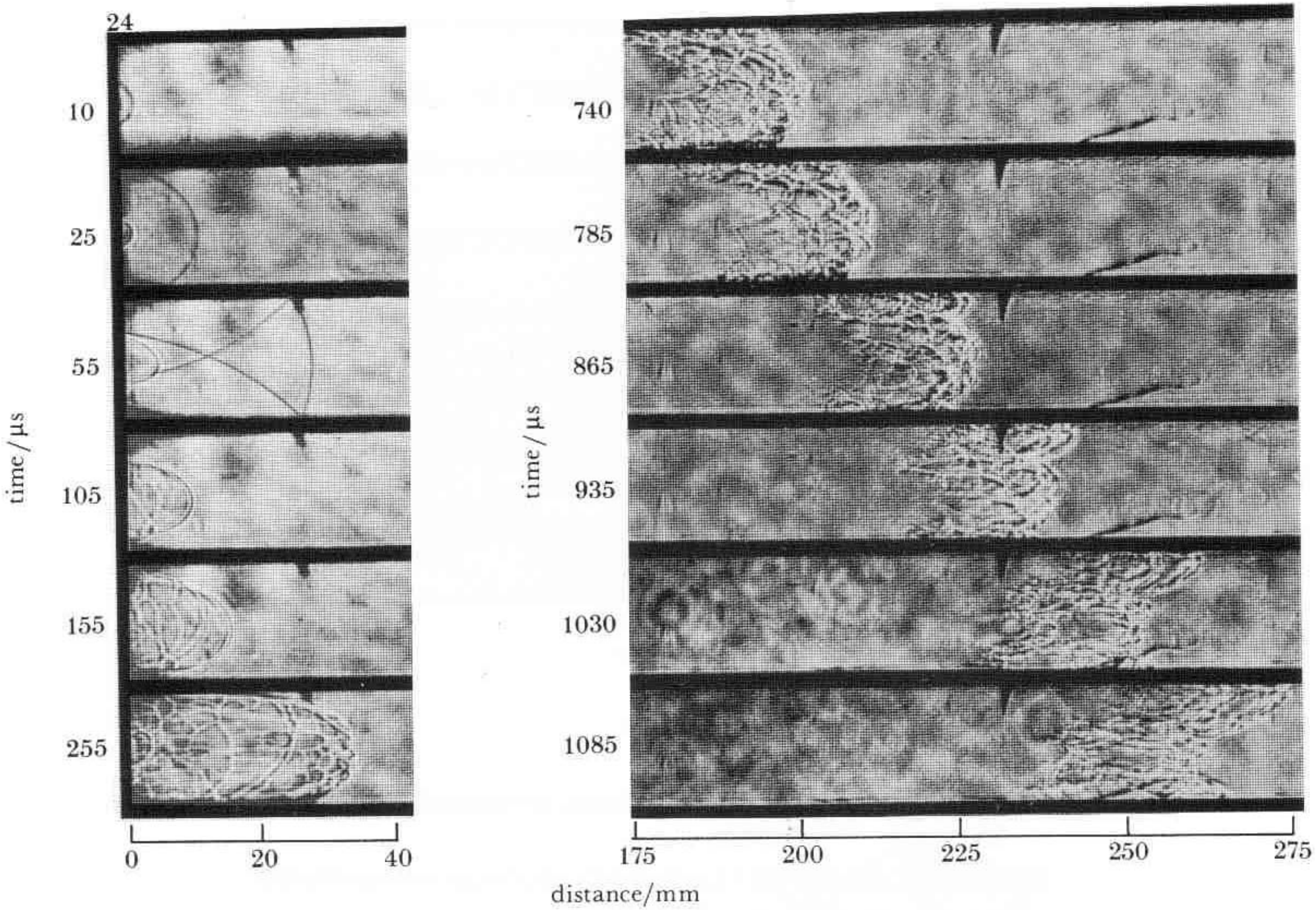


FIGURE 24. Cinematographic schlieren records of ignition, and initial stages of inflammation in a stoichiometric hydrogen–oxygen mixture.

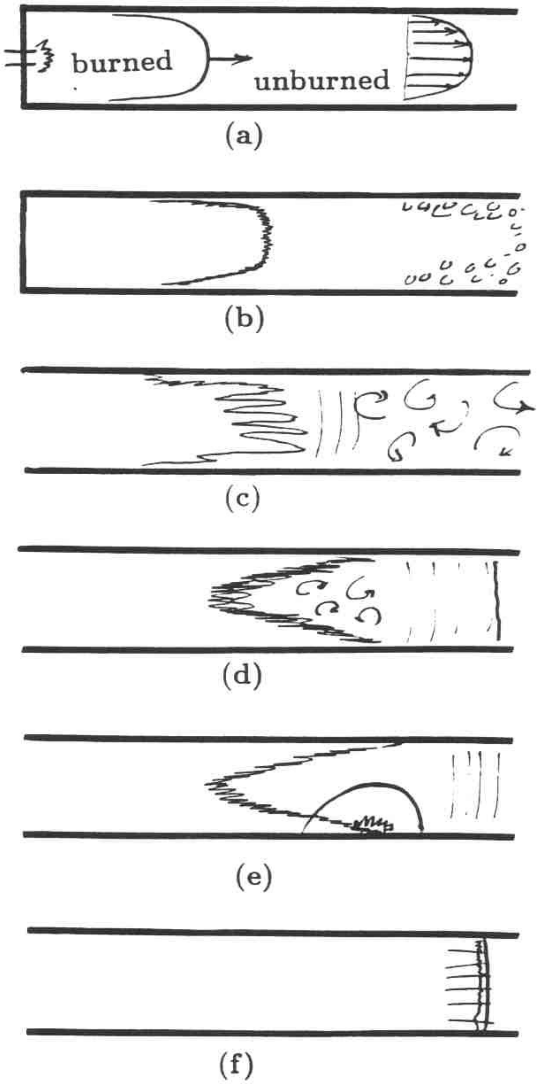
Mechanisms of flame acceleration

- Growth of flame surface area:
  - flame folding
  - velocity gradient in the flow
- Baroclinic vorticity generation
  - Density gradient normal to the pressure gradient
- Hydrodynamic instabilities
  - Rayleigh – Taylor
  - Richtmyer – Meshkov
- Microexplosions of vortices

Mechanisms of turbulence growth

- Initial gas flow turbulence in the mixture
- Gas flow turbulence generated at the shear layer near the wall
- Nonuniform concentration (temperature, pressure) distribution in the flammable mixture
- Interaction of the flame front with an accoustic or pressure wave

Progress of DDT event in a smooth tube



a) the initial configuration showing a smooth flame and the laminar flow ahead;

b) first wrinkling of flame and instability of the upstream flow;

c) breakdown into turbulent flow and a corrugated flame;

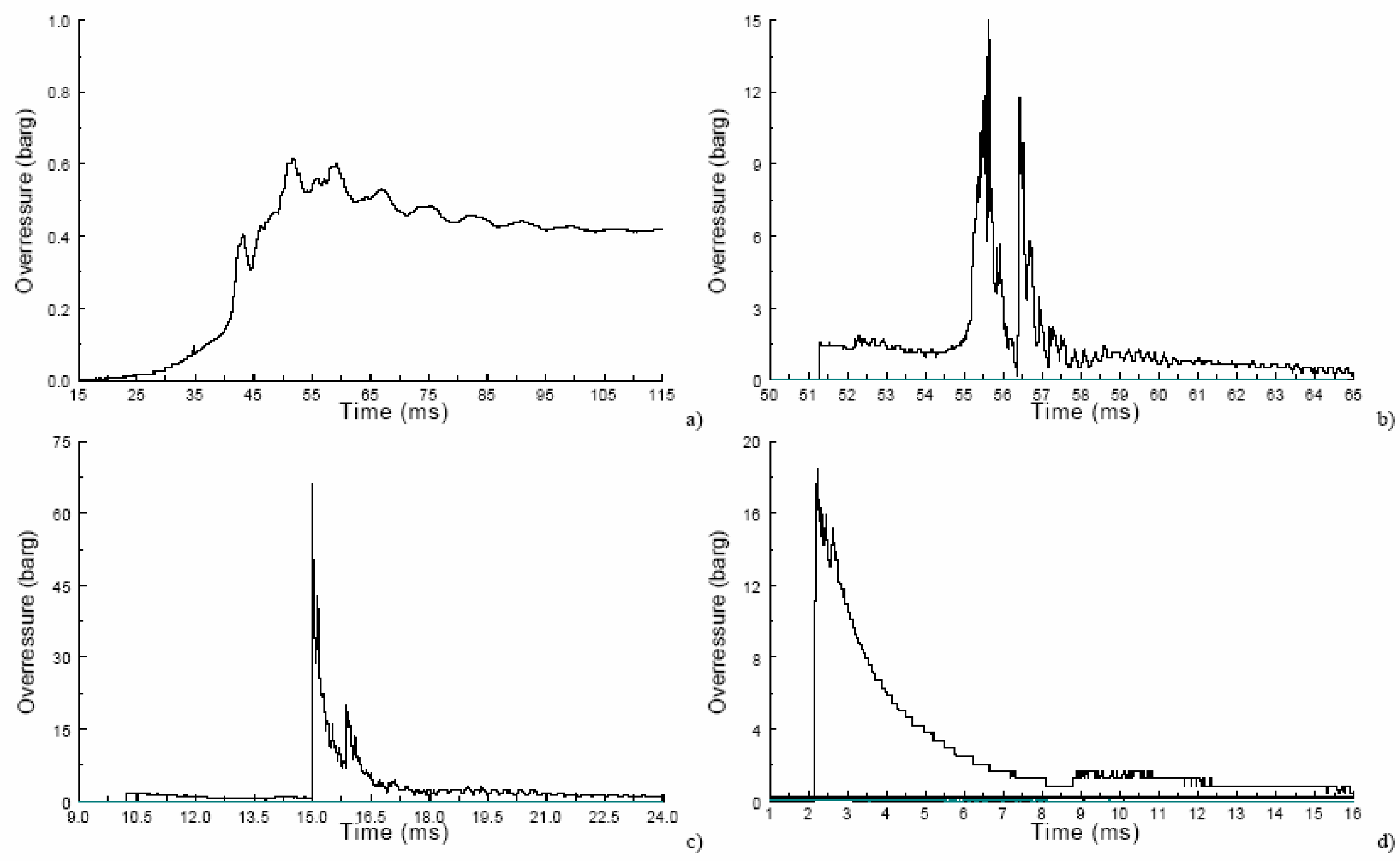
d) production of pressure waves ahead of the turbulent flame;

e) local explosion of a vertical structure within the flame;

f) transition to detonation.

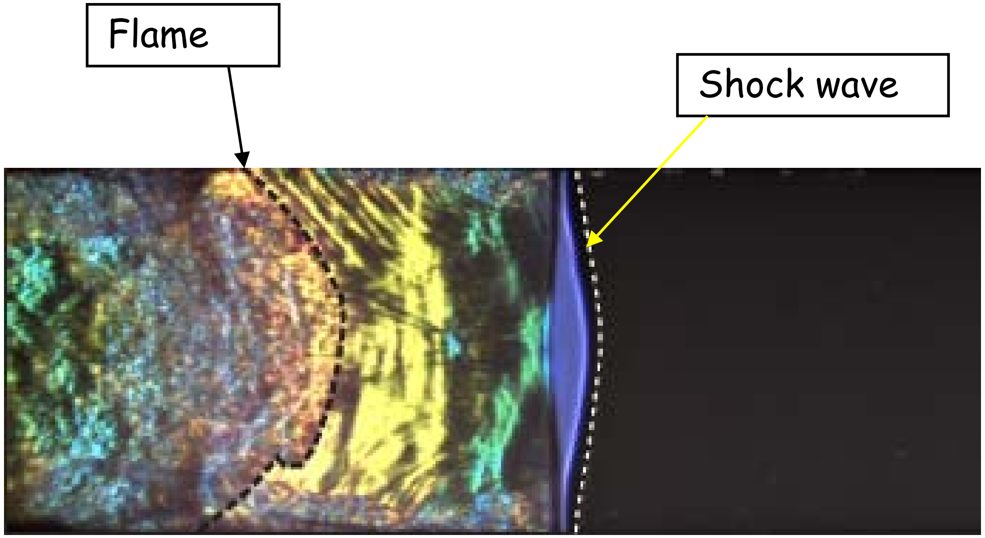
(Shepherd&Lee, 1992)

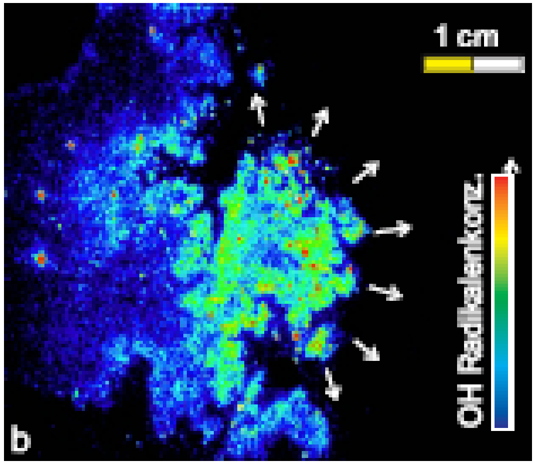
Deflagration and detonation pressure



a) Slow deflagration; b) fast deflagration; c) overdriven detonation after DDT; d) CJ detonation

Fast deflagration



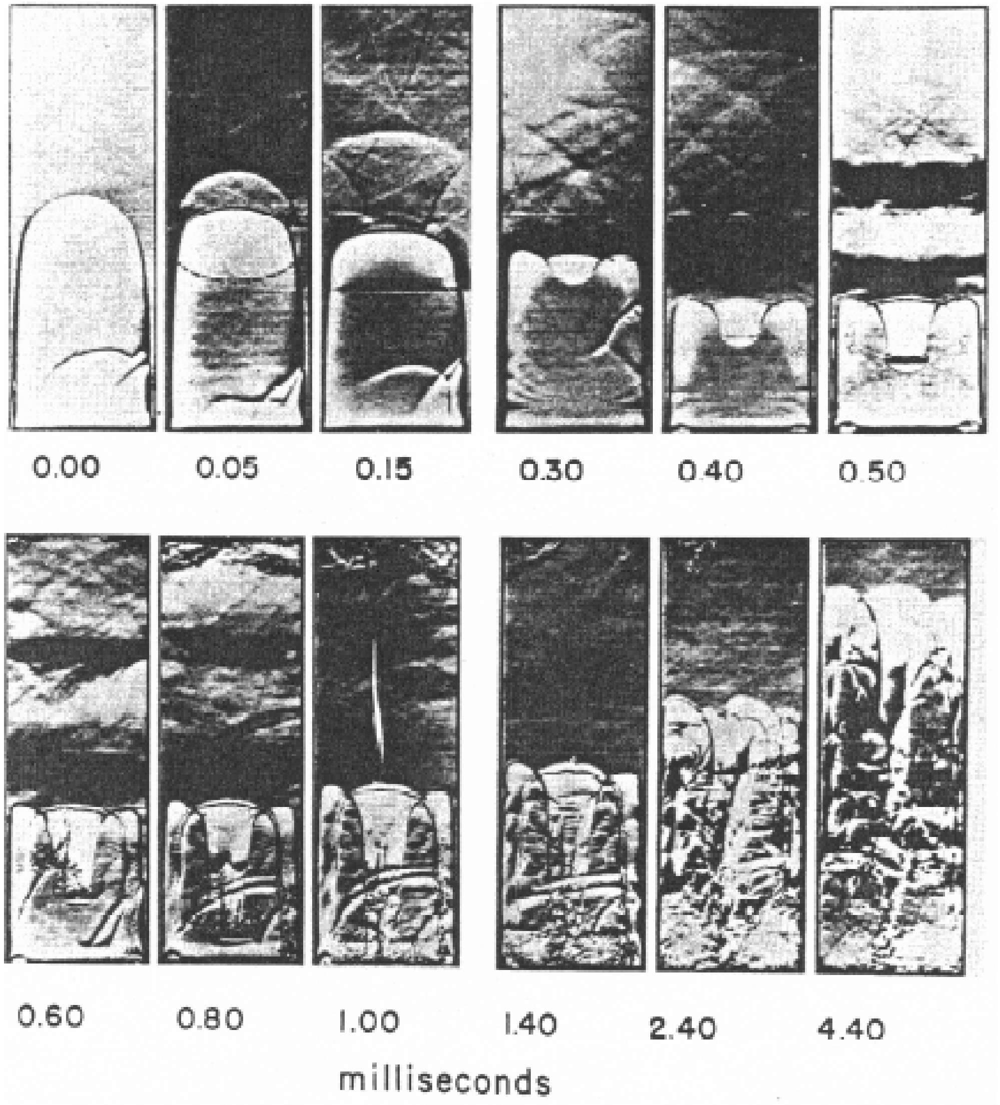


Schlieren image of a fast deflagration wave (22% H2 in air), flame velocity 1200 m/s;

OH radical distribution of a fast deflagration wave, flame velocity 850 m/s, 17,5% H2 in air;

(Eder, 2001)

Flame interaction with shock wave

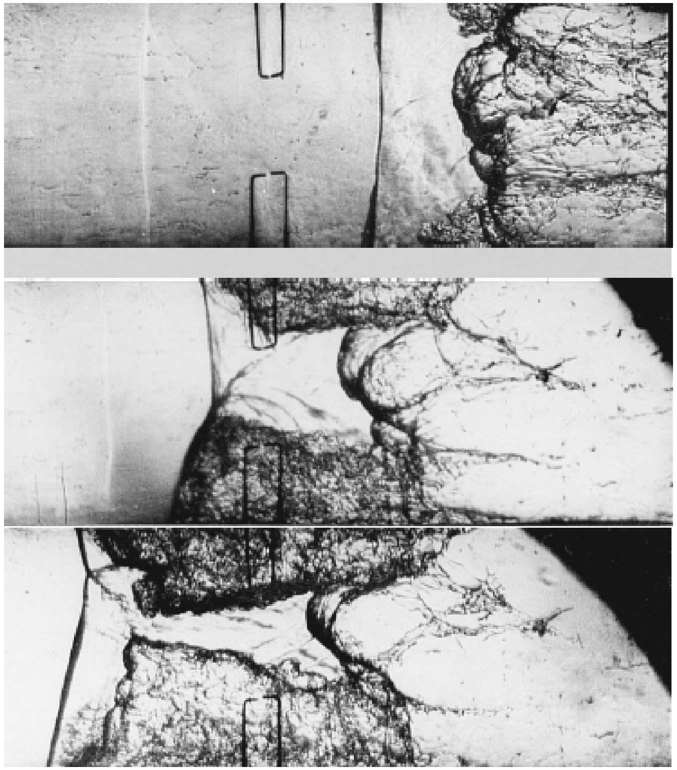


Butane-air flame;

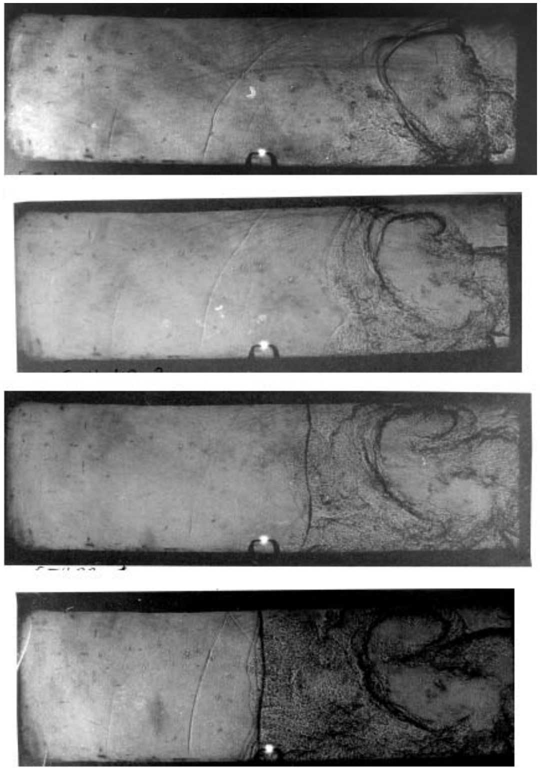
Shock wave of pressure ratio of 1.3

(Markstein, 1968)

Flame interaction with shock wave



Reflected shock (*moving right to left*) emerging following multiple-shock flame interaction. Original incident shock Mach No. 1.7 (incident not shown). Mixture C2H4 + 3O2 + 4N2, initial pressure 13.2 kPa, Δt 50 μs



DDT resulting from the interaction of a reflected shock with a flame kernel

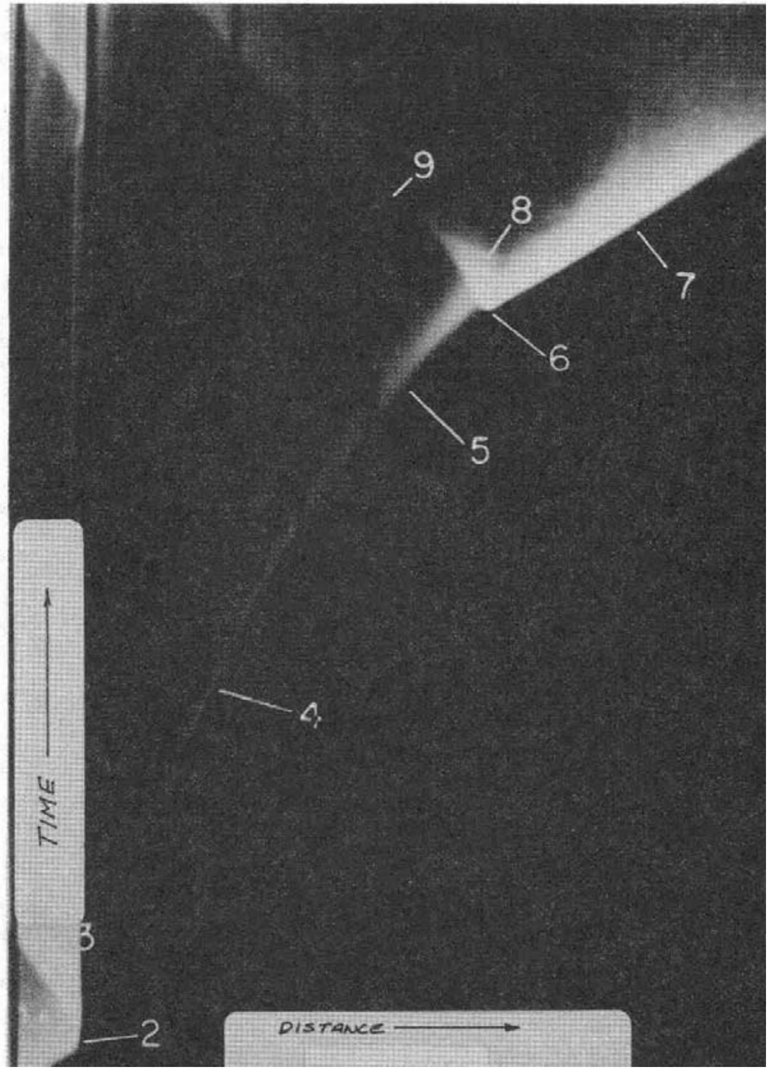
(Bombrey&Thomas, 2002)

Transition distance to DDT

Depends on:

- Combustible mixture (chemistry and thermodynamics)
- Tube diameter – for hydrogen-air in smooth tube:
  - 8 m in 50 mm tube
  - 30 m in 400 mm tube
- Ignition source
- Obstacles, wall roughness
- Initial conditions
- ???

DDT in smooth tube



Streak direct photograph

4, 5 – accelerating flame

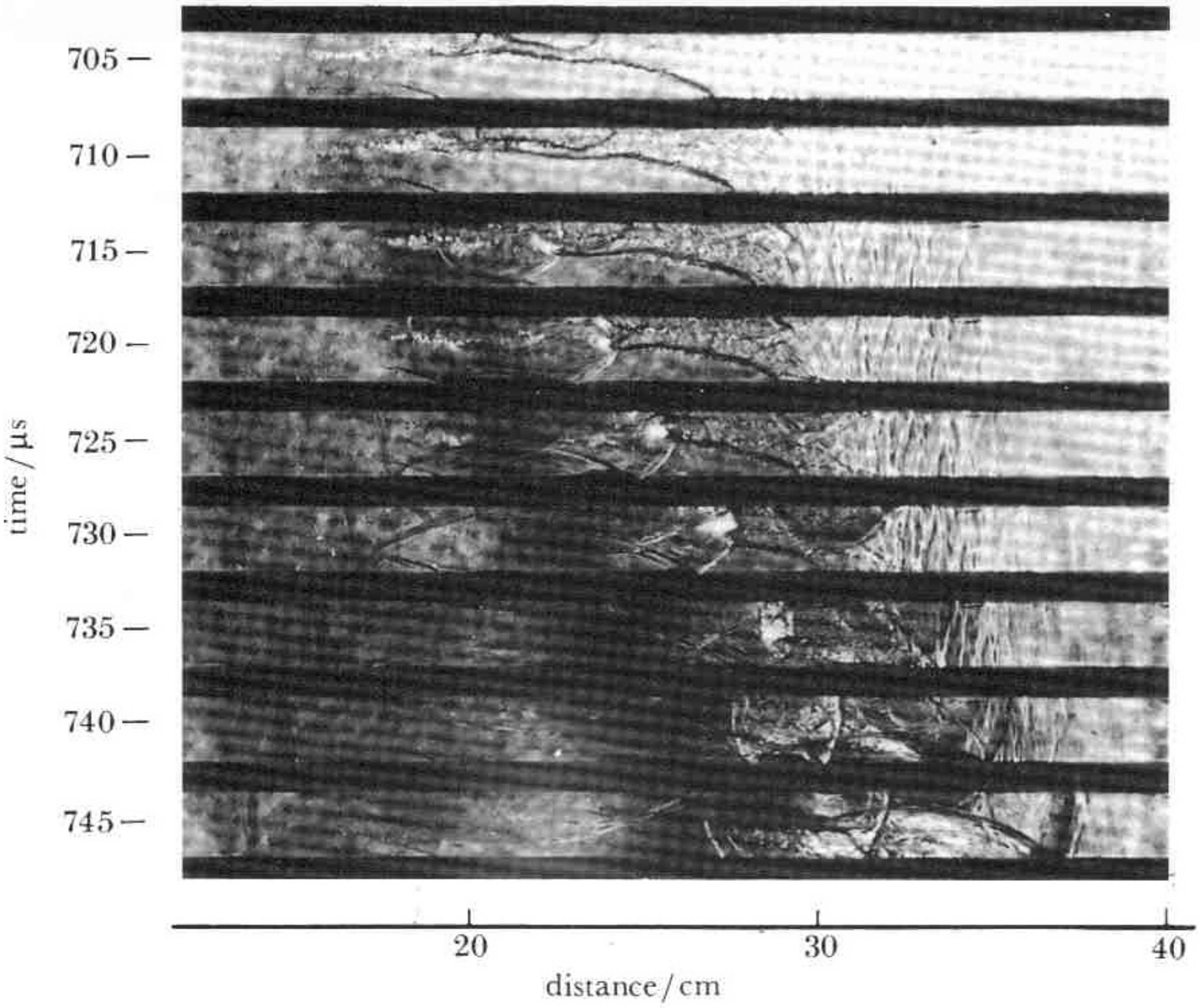
6 – explosion ahead of the flame

7 – detonation

8, 9 – retonation wave

(Lee, 1978)

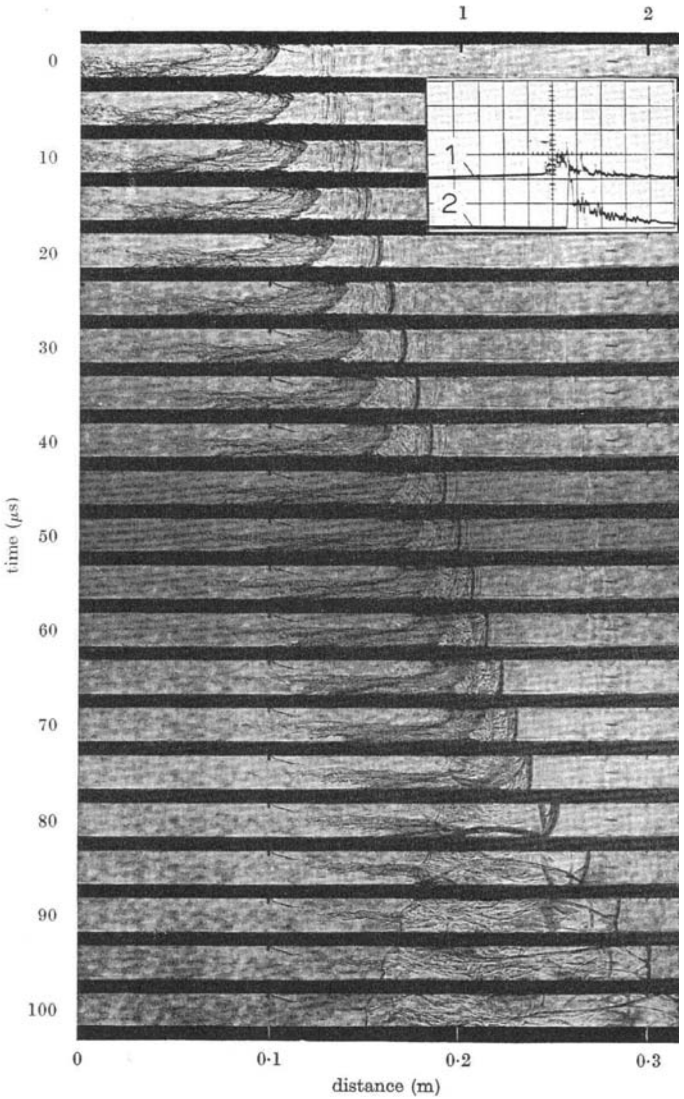
DDT in smooth tube

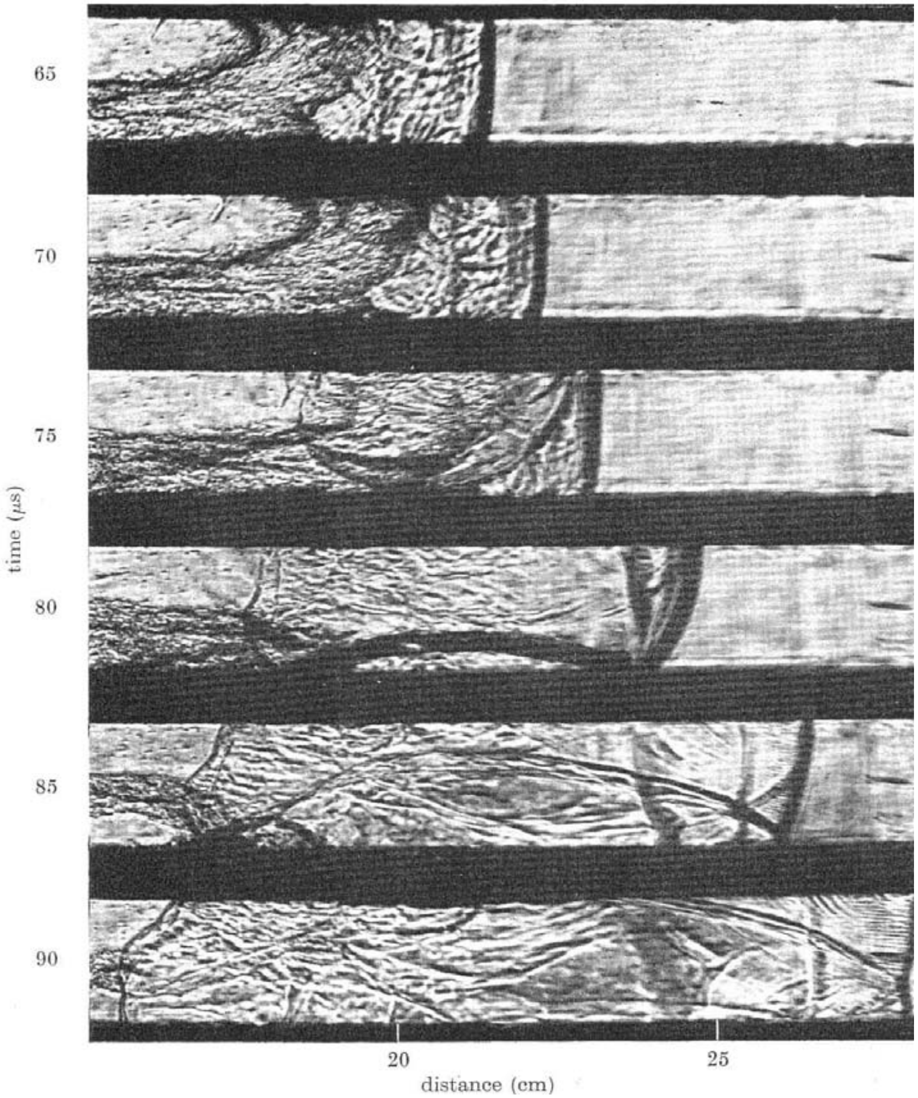


Schlieren framing photographs by rotating mirror camera

(Myer&Oppenheim, 1965)

DDT in smooth tube



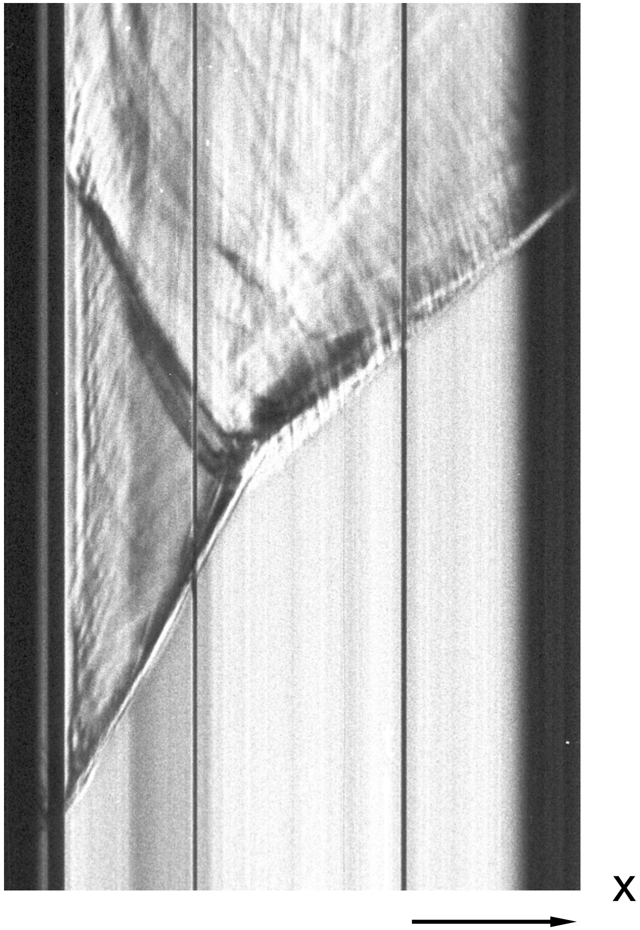


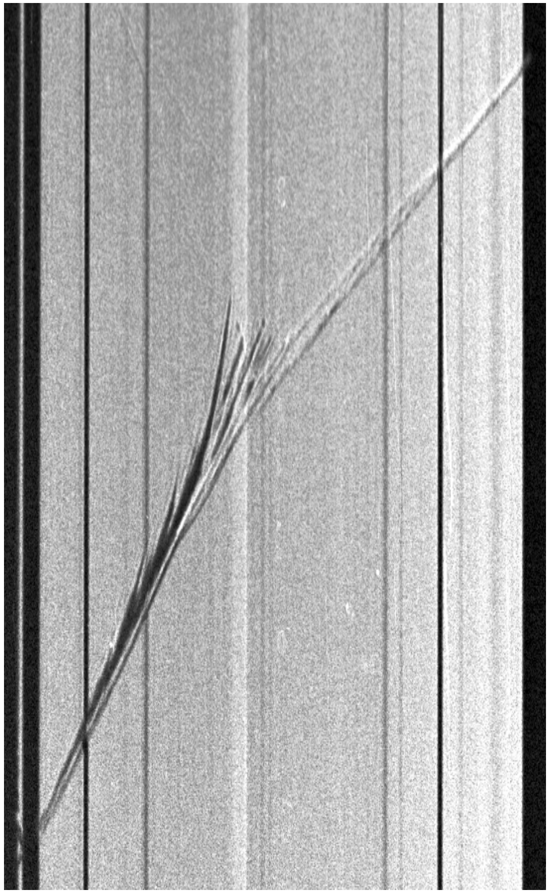
(Urtiev&Oppenheim, 1965)

Two modes of DDT

DDT via local explosion

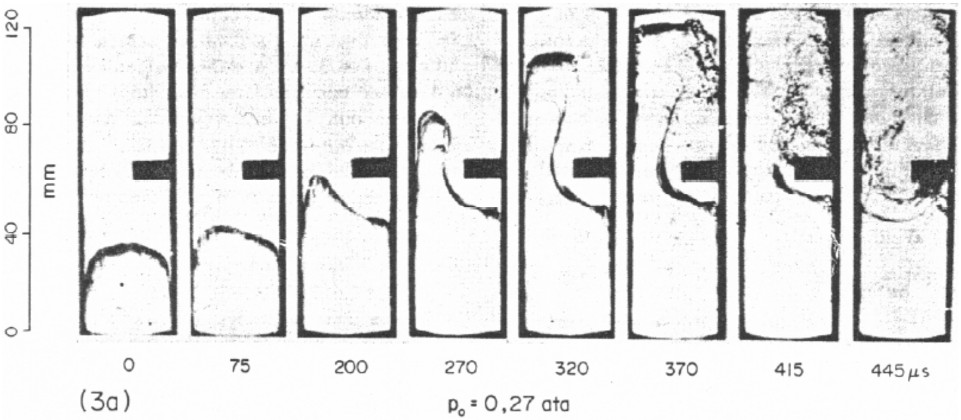
DDT via gradual amplification of transverse waves

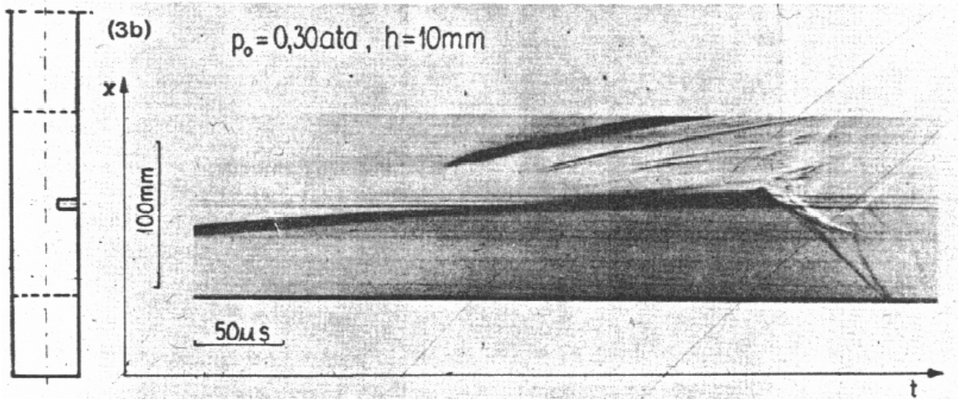


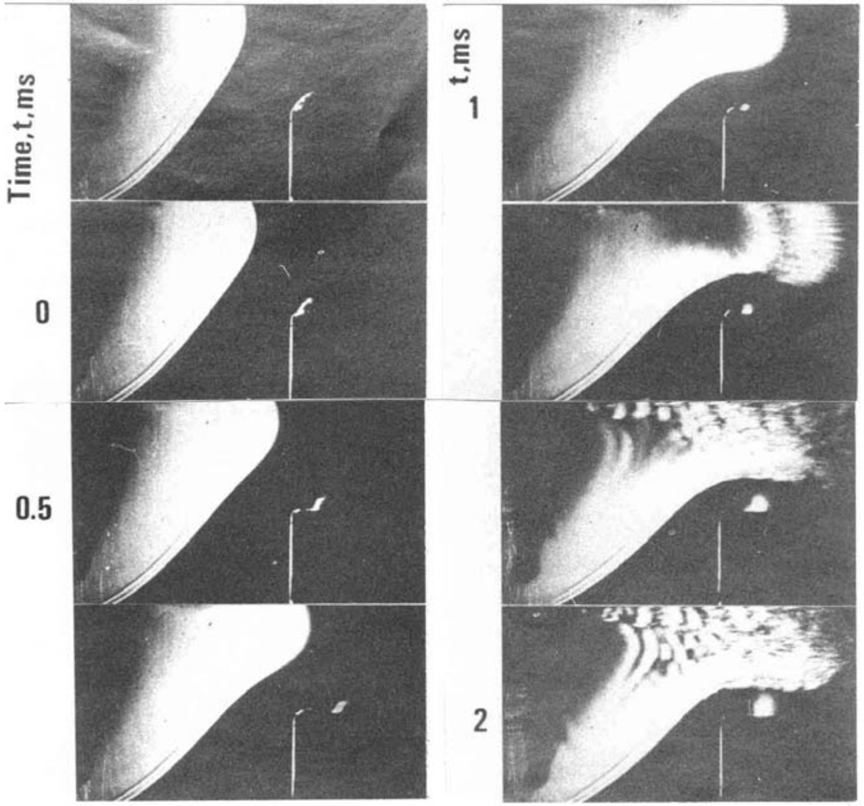


(Courtesy of J.Chao, 2006)

Flame acceleration over the obstacle



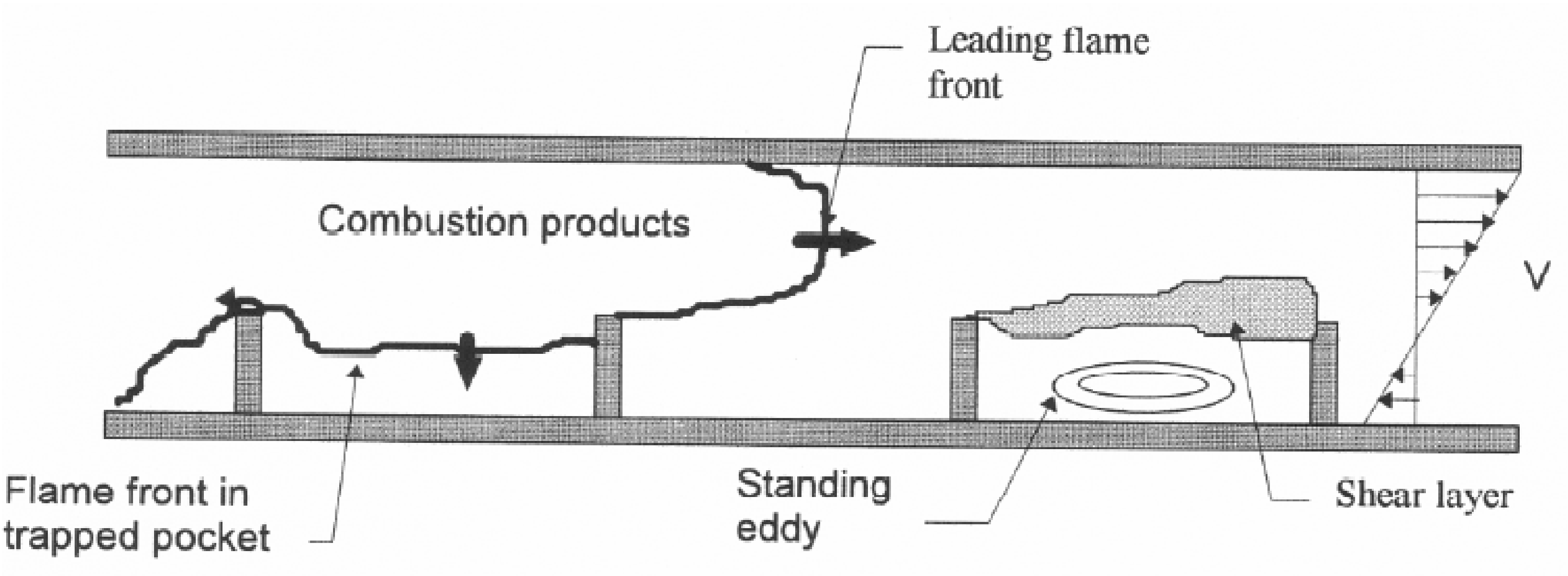




(Wolanski, 1983)

(Hirano, 1987)

Flame acceleration over the obstacle



DDT in tube with obstacles

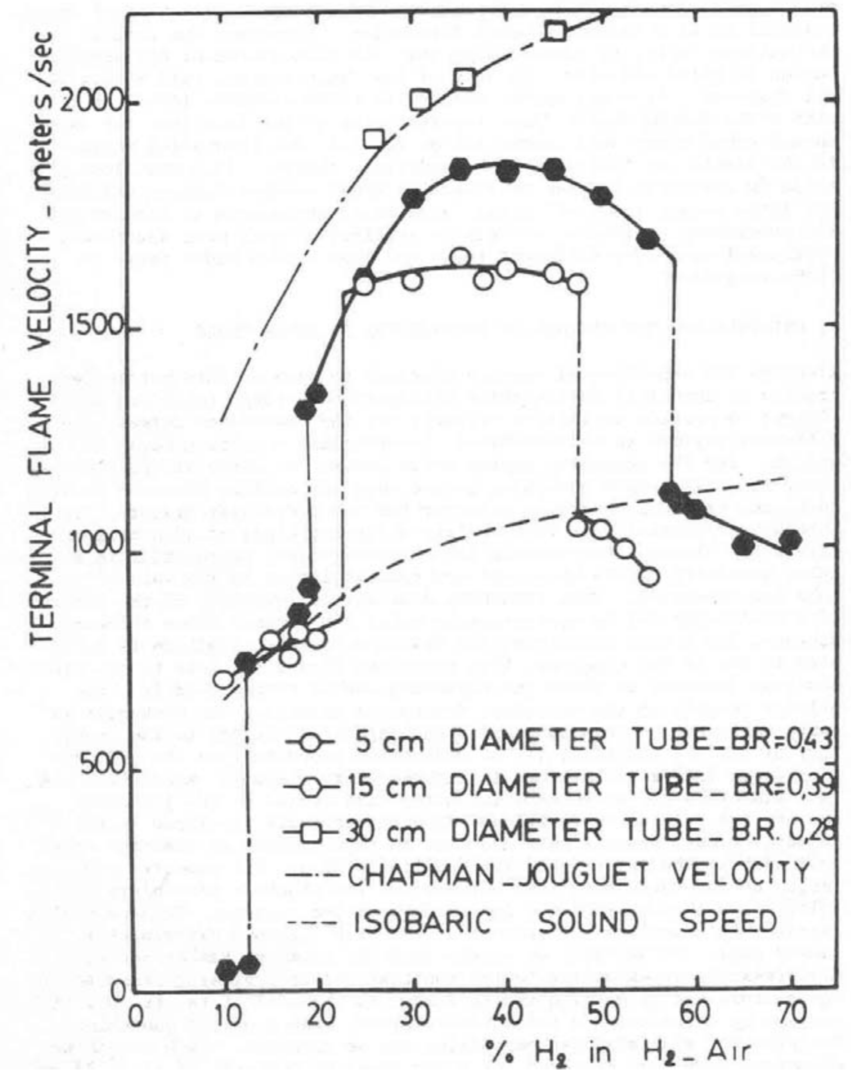
Flame velocity versus fuel concentration for H2-air mixtures

10 m long tubes of 5 cm, 15 cm and 30 cm in internal diameter with obstacles (orifice plates).

BR = 1 - d^2/D^2 – blockage ratio

d - orifice diameter

D - tube diameter

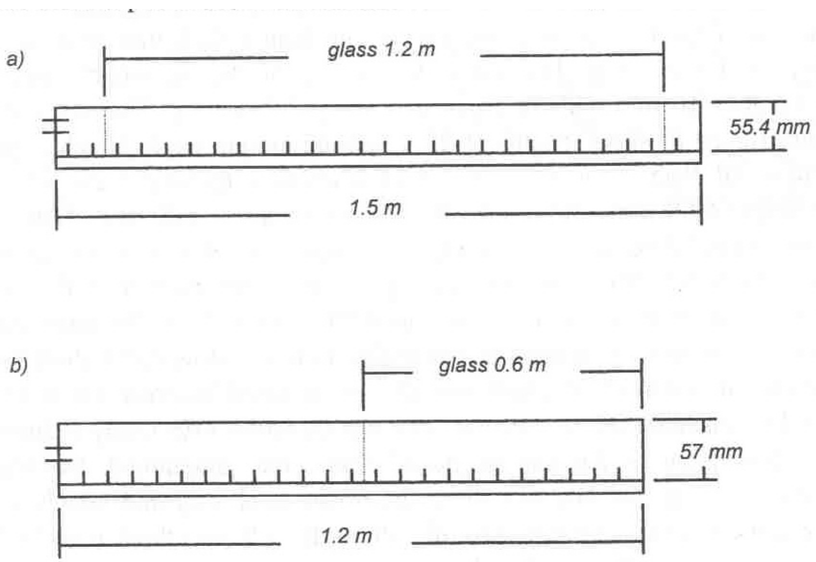


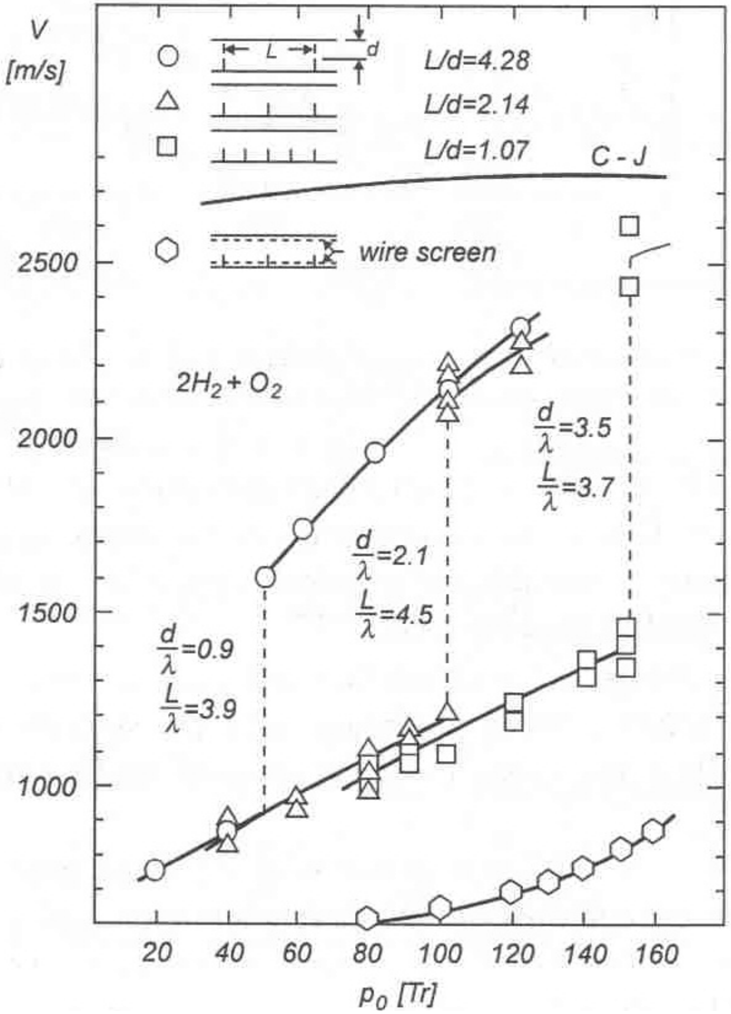
(Lee, 1986)

Regimes of flame propagation in tubes with obstacles

- **quenching regime** - flame fails to propagate,
- **subsonic regime** - flame is traveling at a speed that is slower than the sound speed of the combustion products,
- **choked regime (CJ Deflagration)** - flame speed is comparable with the sound speed of the combustion products,
- **quasi-detonation regime** - velocity between the sonic and Chapman-Jouguet (CJ) velocity,
- **CJ detonation regime** - velocity is equal to the CJ detonation velocity

DDT in channel with obstacles





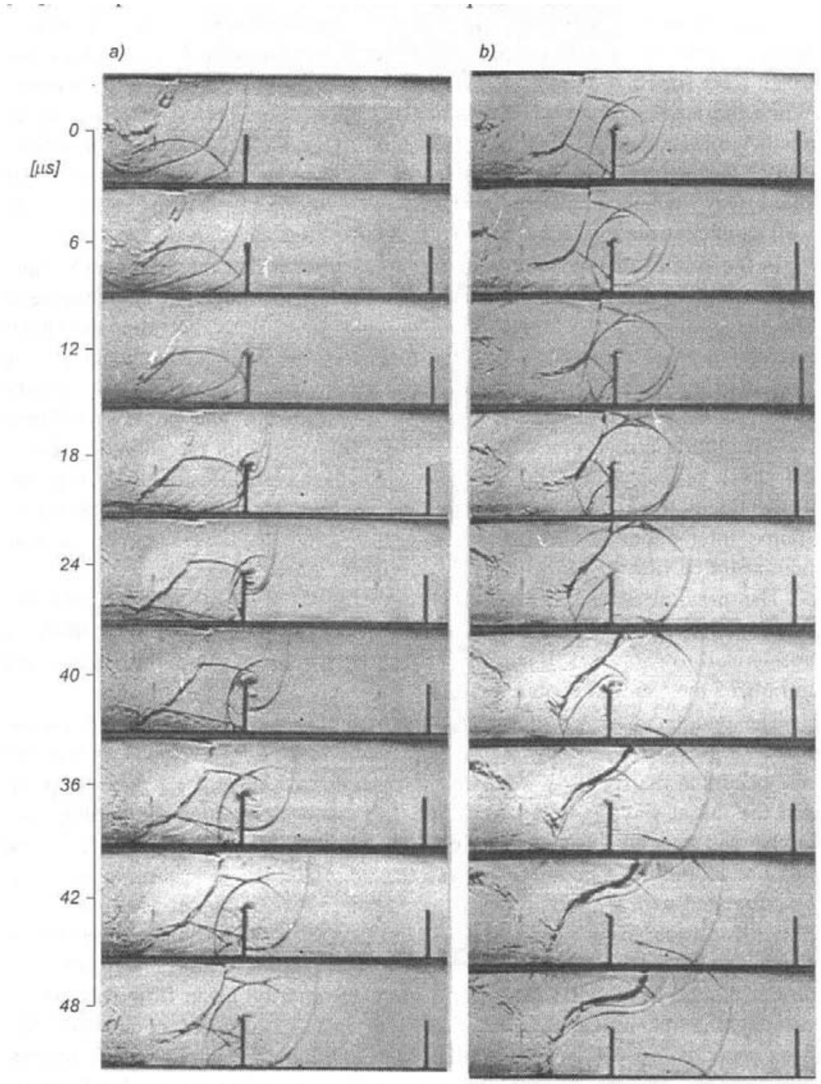
Stoichiometric hydrogen-oxygen

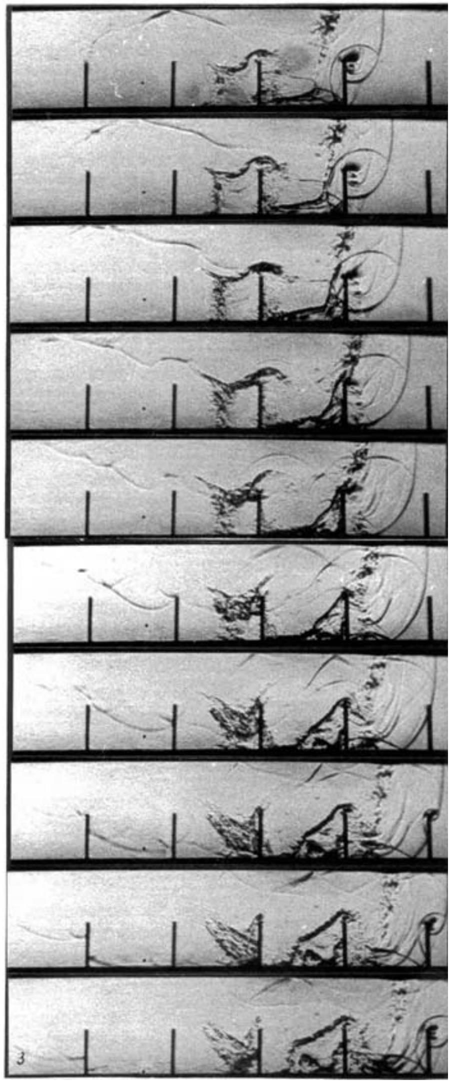
Pressure 20-150 torr

Ignition by exploding wire

(Teodorczyk, et al..1988)

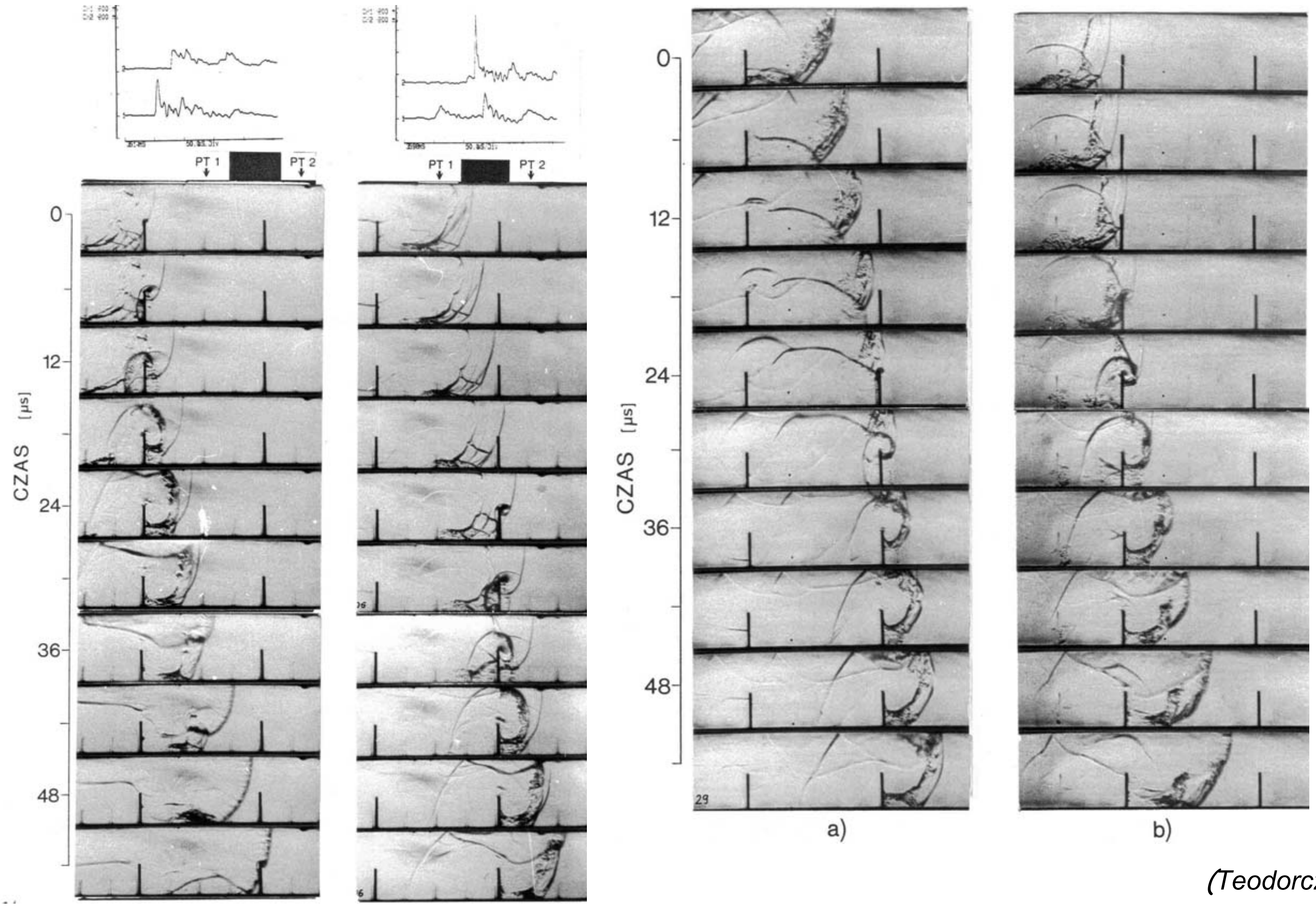
Fast deflagration in a channel with obstacles





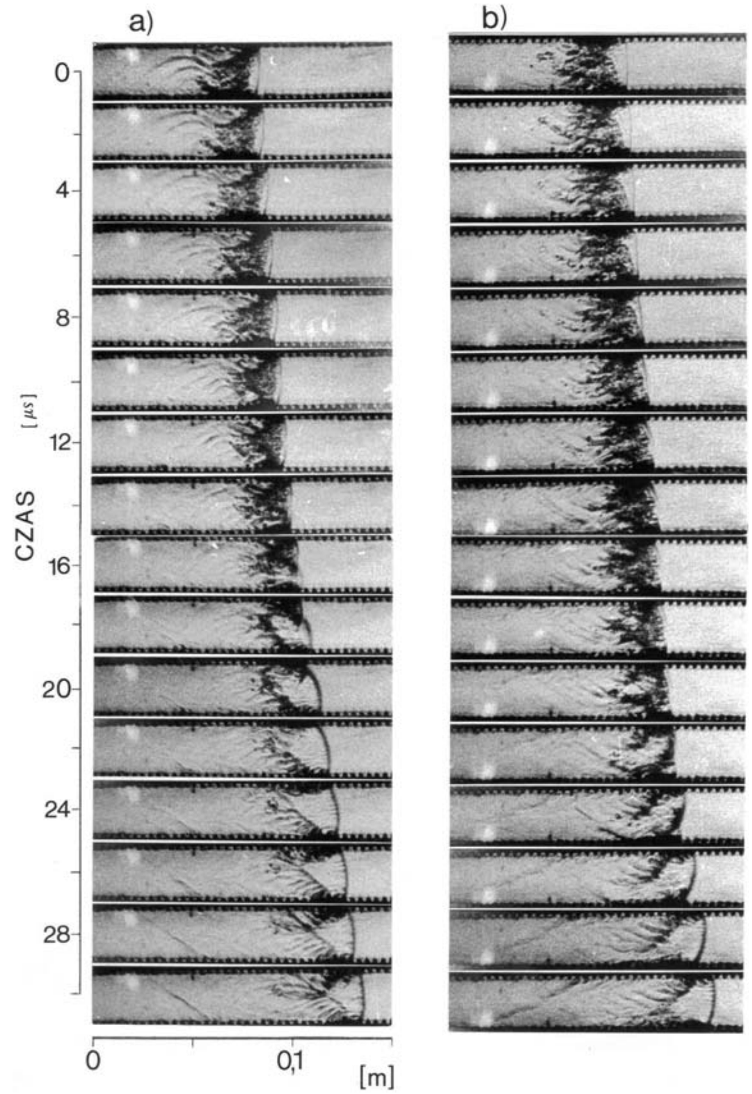
(Teodorczyk, et al..1988)

DDT in tube with obstacles



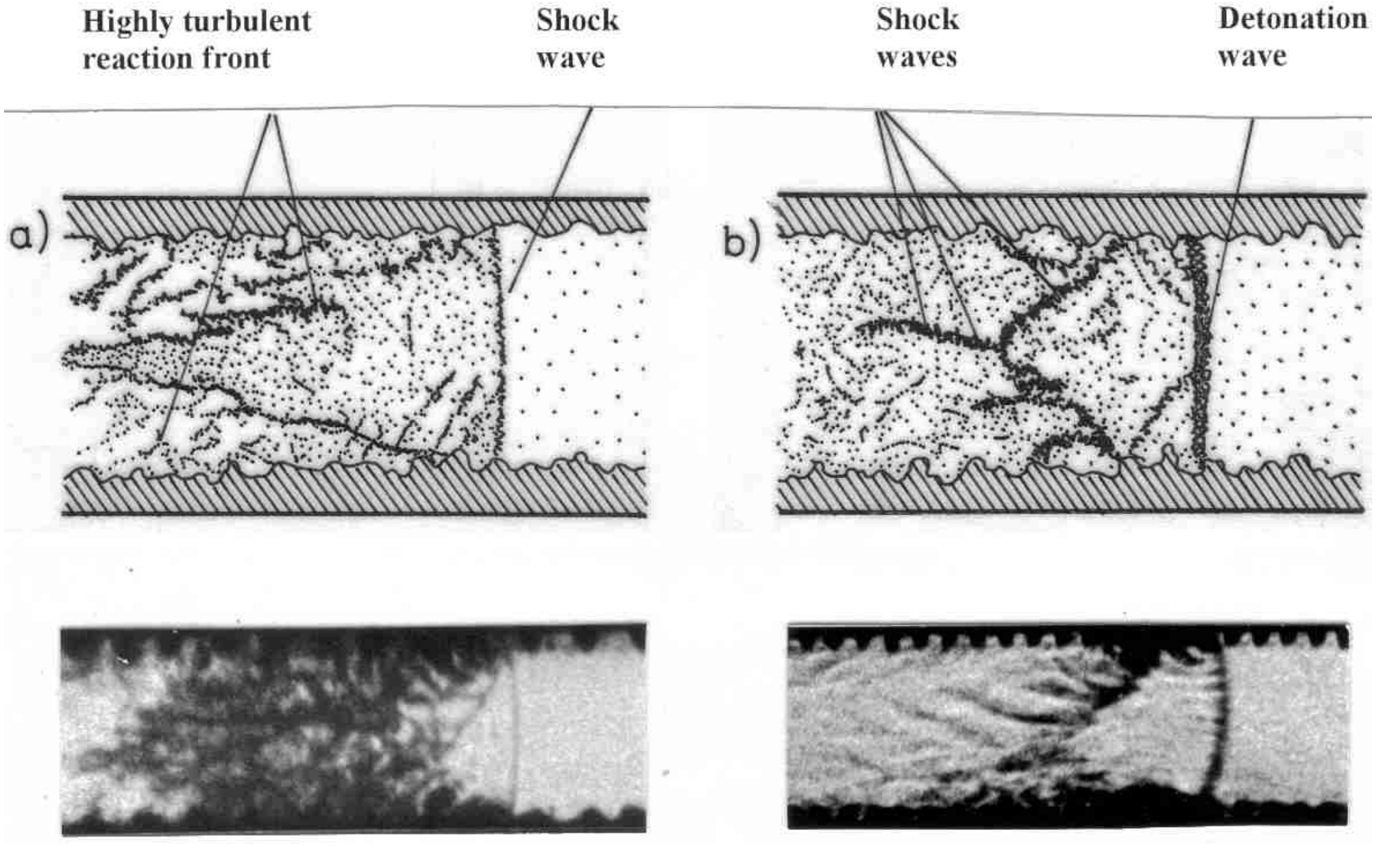
(Teodorczyk, et al..1988)

DDT in rough channel



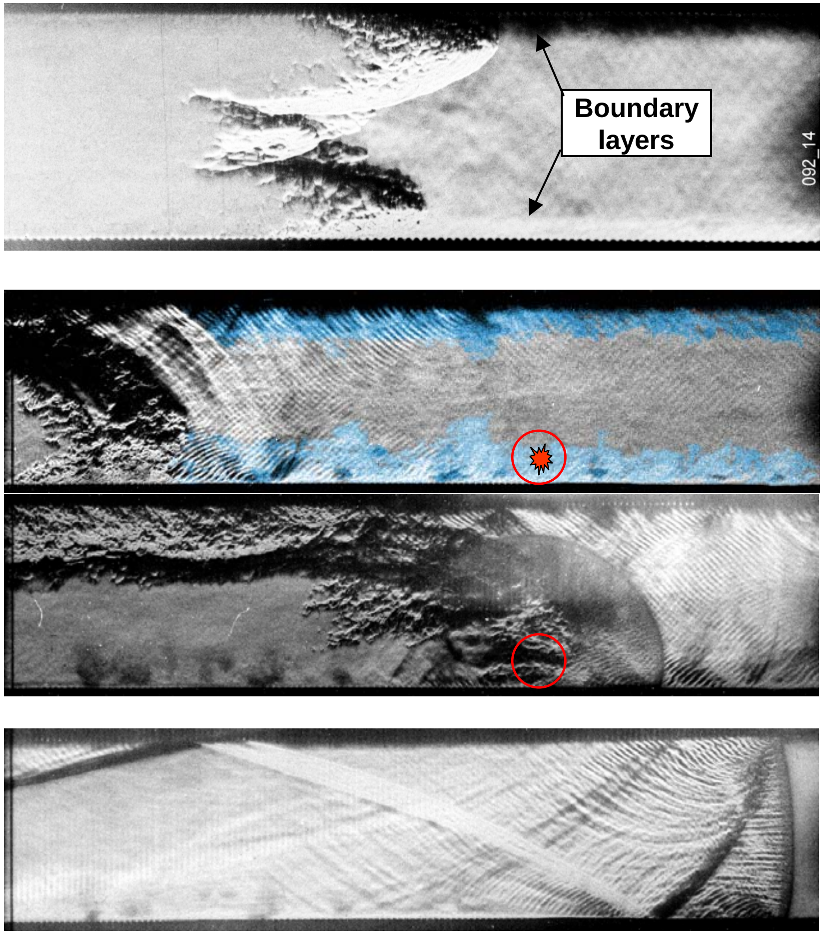
(Teodorczyk, 1990)

Fast deflagration vs detonation in a very rough channel



(Teodorczyk, 1990)

DDT in rough channel

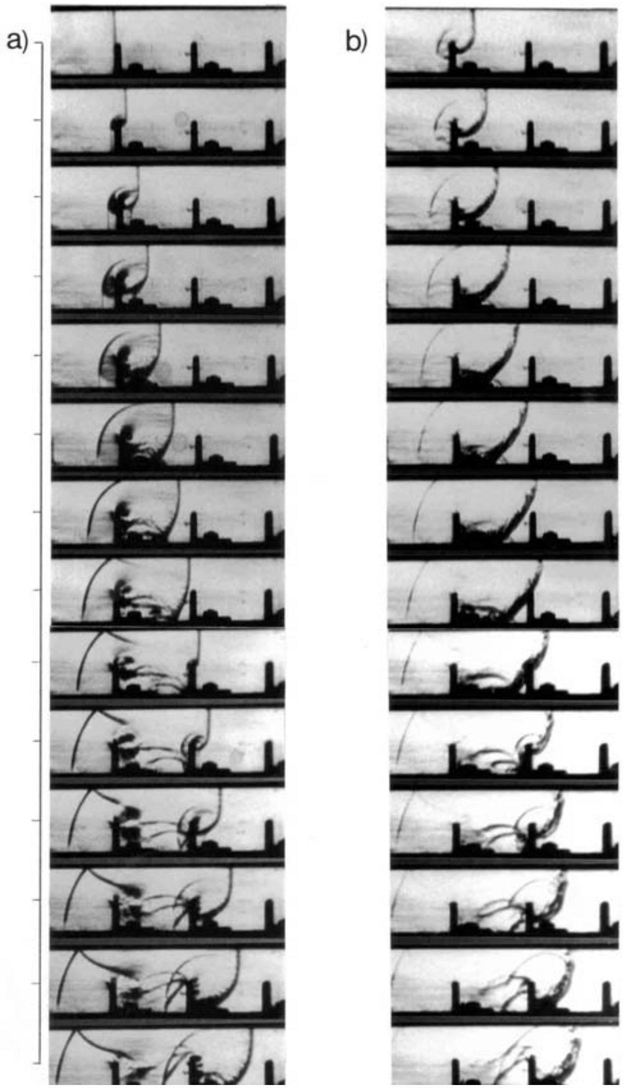


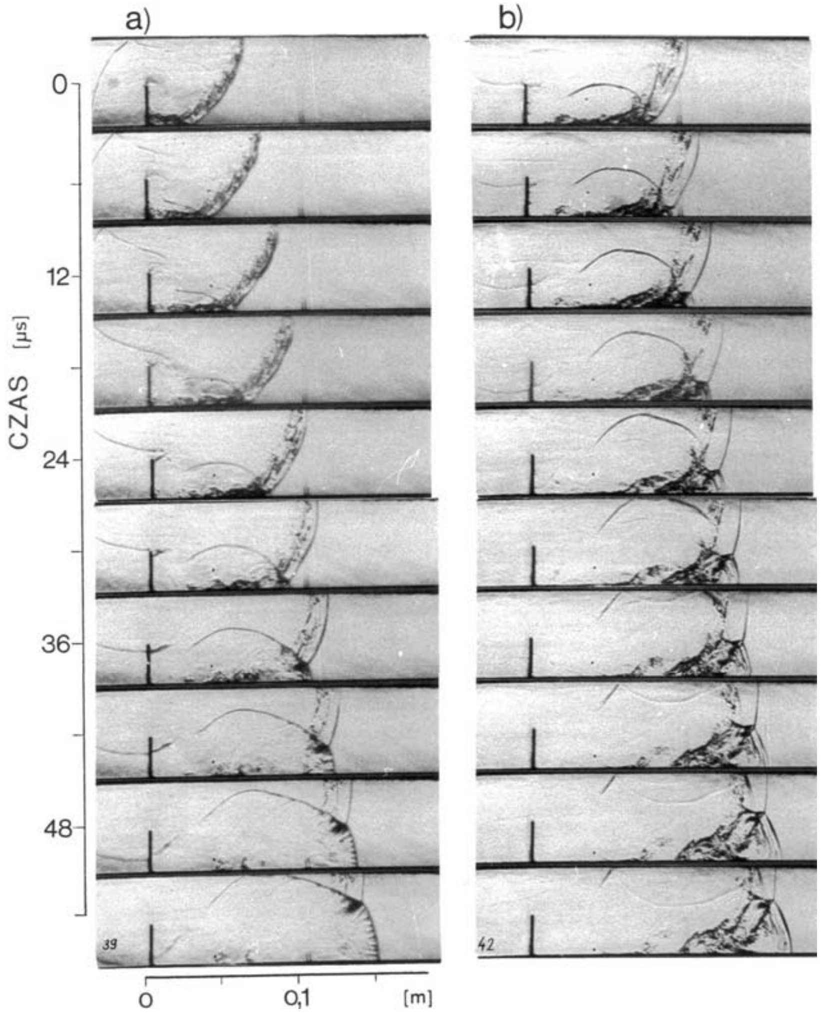
Flame speed 320 m/s

p_0=0.55 bar, 1090-1320 mm from ignition

(Kuznetsov M., Dorofeev S., 2005)

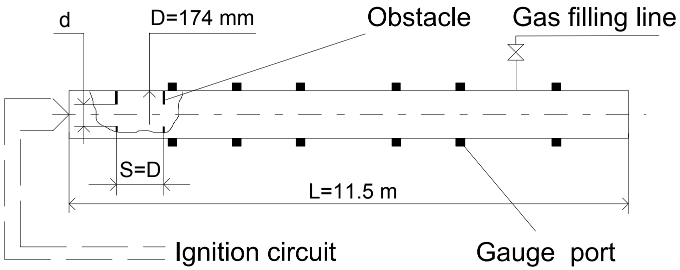
Detonation in a channel with obstacles

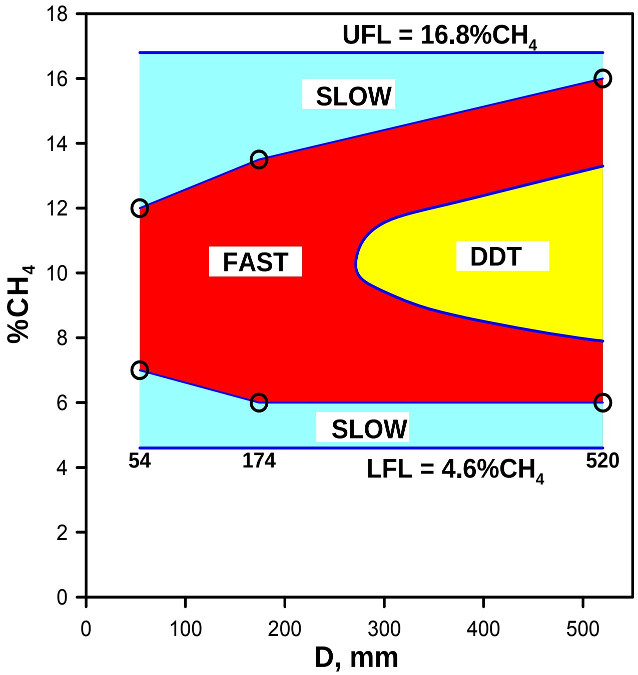


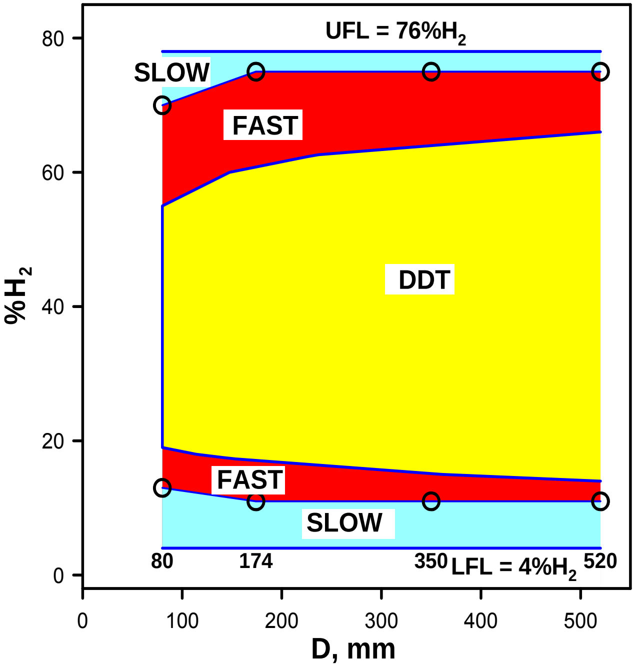


(Teodorczyk, et al..1988)

Flame acceleration and DDT in obstructed channels



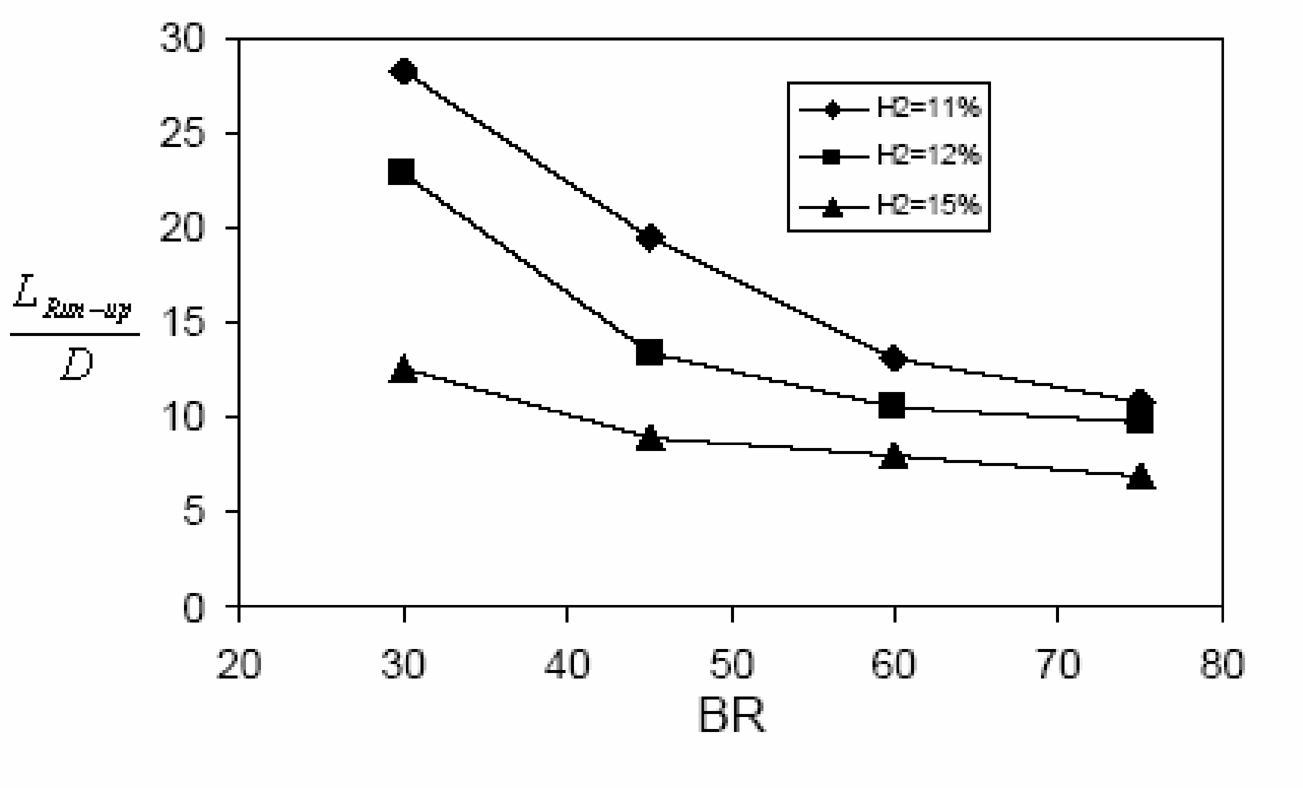




(Courtesy of M.Kuznetzov)

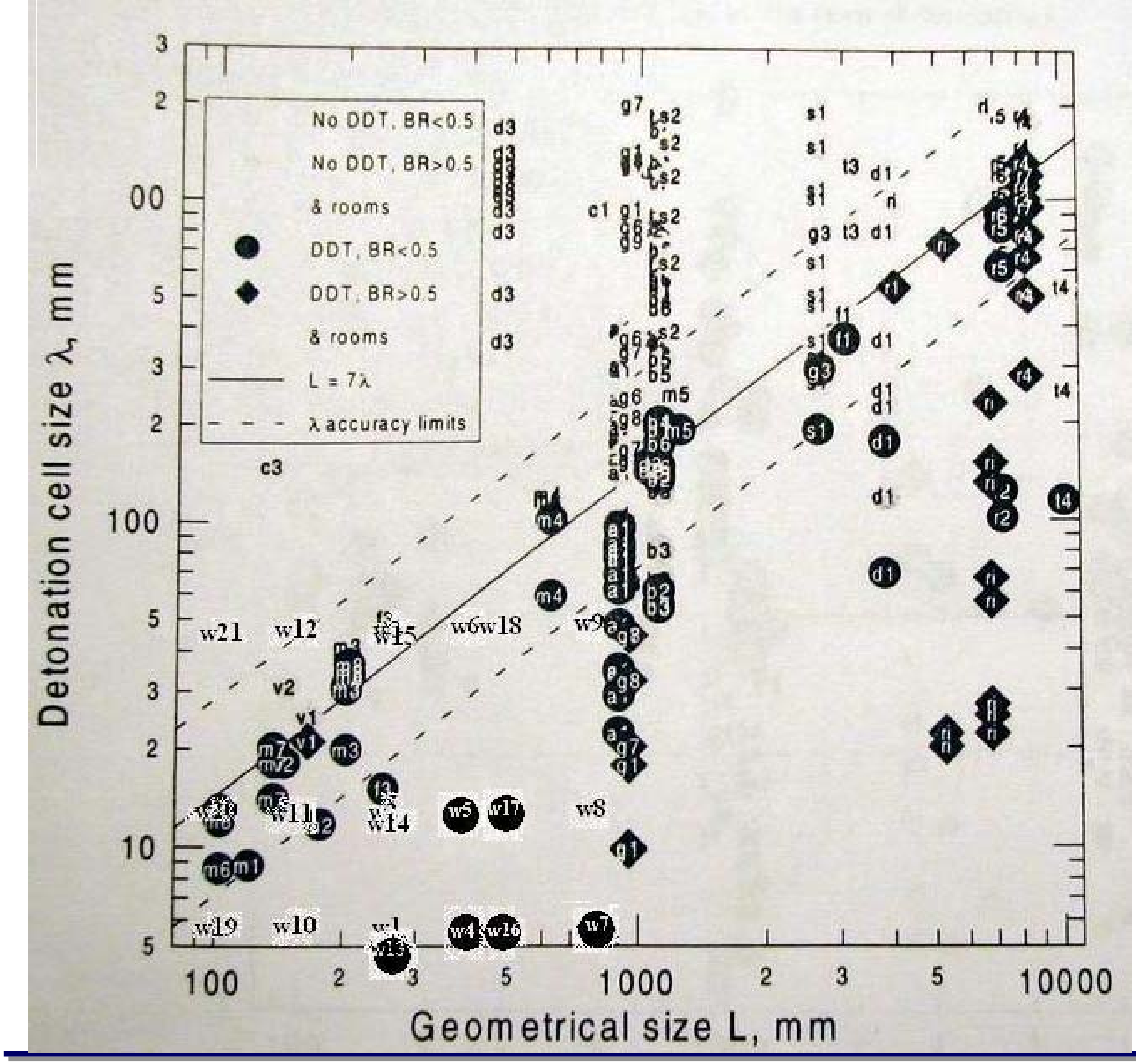
Run-up distance for DDT in obstructed channels

In tubes at 0.1 MPa, H_2-air



(Courtesy of S.Dorofeev)

DDT limits in obstructed channels (H_2-air)



Geometrical size

$$L = \frac{L_1}{1-\alpha}$$

where

$$L_1 = \frac{L+H}{2}$$

$$\alpha = \frac{1-h}{H}$$

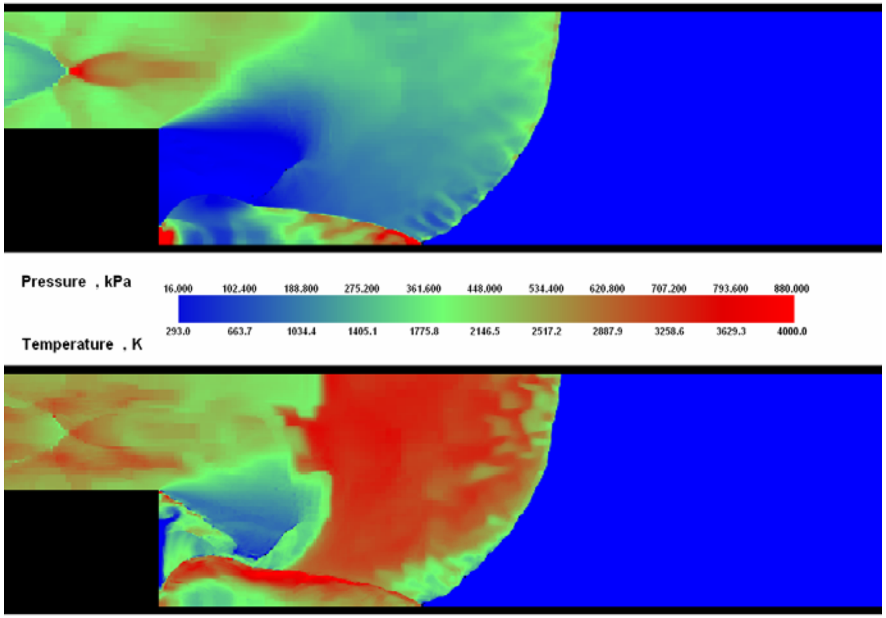
L – distance between obstacles

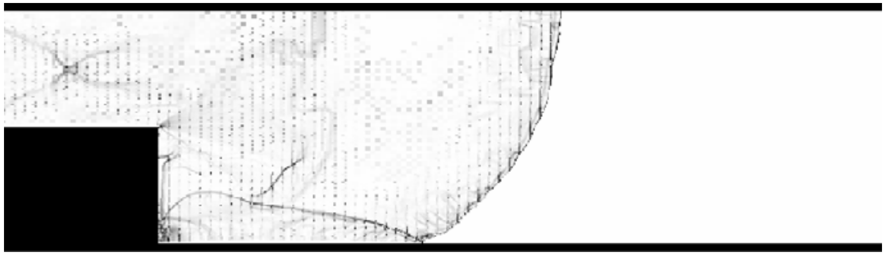
H – channel height

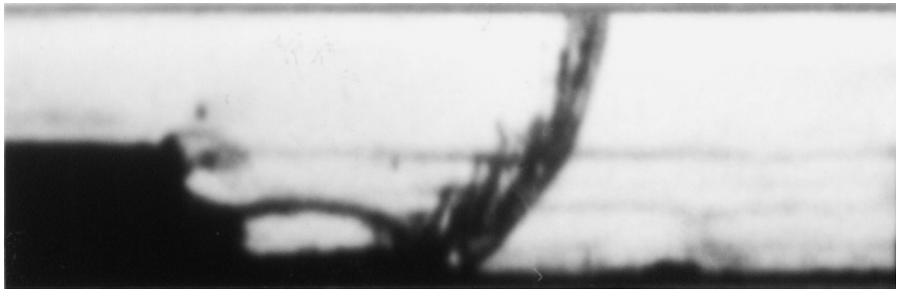
h – obstacle height

(Courtesy of S.Dorofeev)

Detonation simulation







Simulation: DETO2D

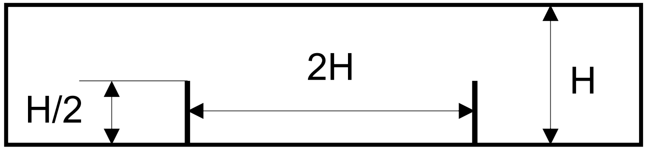
Experiment: Teodorczyk A., Lee J.H.S. and Knystautas R.: *Propagation Mechanism of Quasi-Detonations*, Twenty-Second Symposium (Int.) on Combustion, The Combustion Institute 1988, pp. 1723-1731

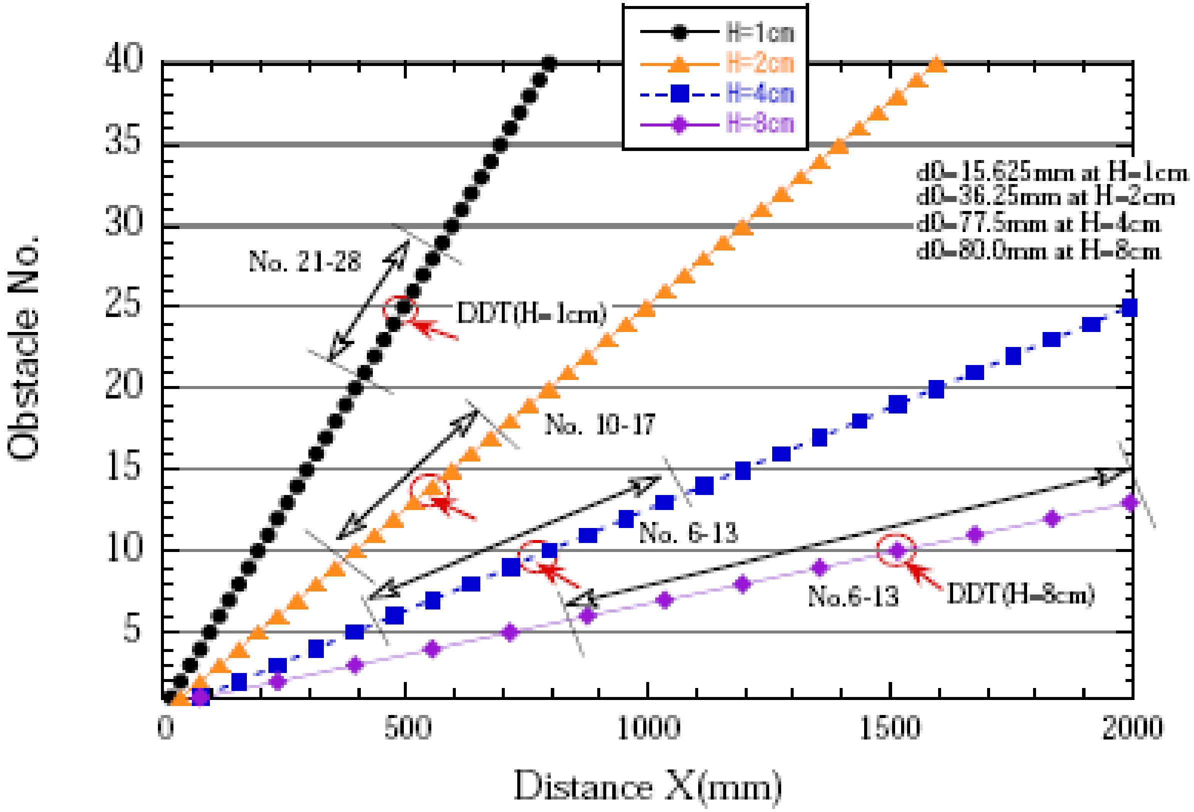
DDT simulations

V.Gamezo et al., 31st Symposium International on Combustion, Heidelberg 2006

- stoichiometric hydrogen-air mixture at 0.1 MPa
- Reactive Navier-Stokes equations with one-step Arrhenius kinetics
- 2D channel with obstacles
- Grid: 0.02 mm (min)

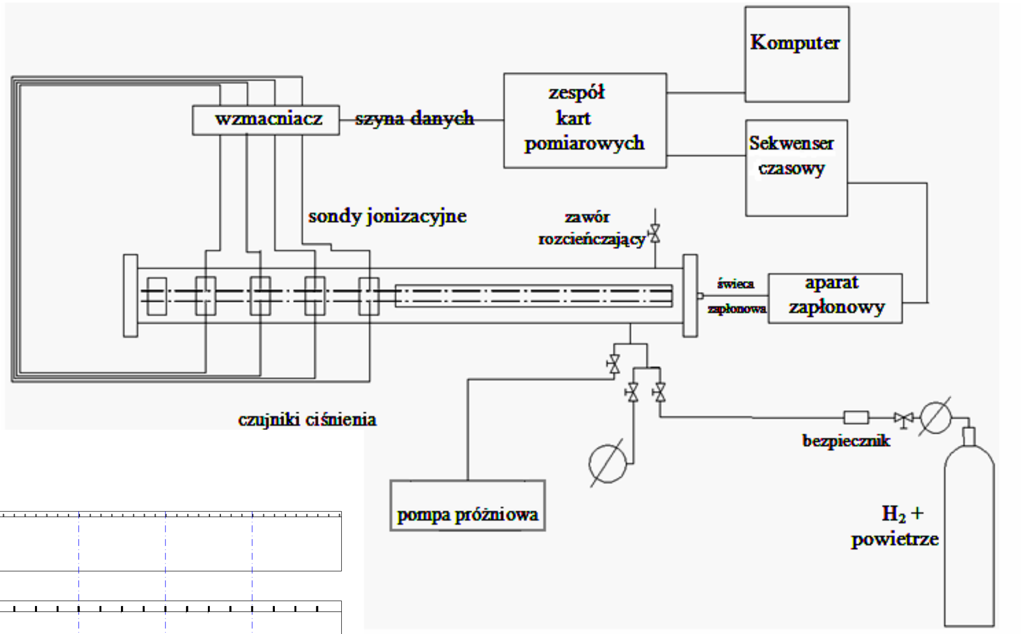
Zoom.bat

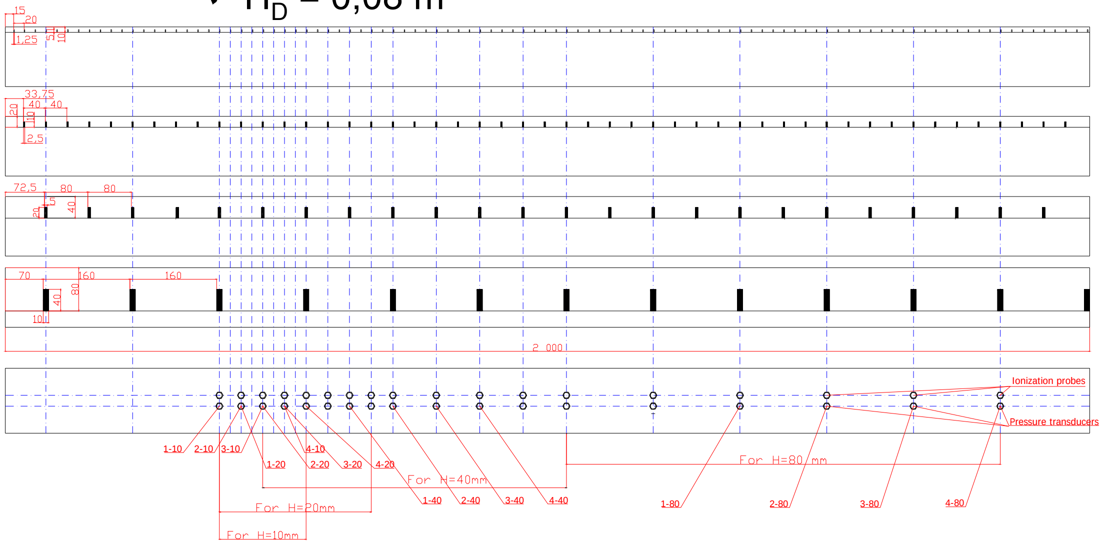




Experimental study

- Channel:
  - \- lengtht 2 m,
  - \- width   0.11 m
  - \- heigth:
    - ✓ $H_A = 0{,}01$ m
    - ✓ $H_B = 0{,}02$ m
    - ✓ $H_C = 0{,}04$ m
    - ✓ $H_D = 0{,}08$ m

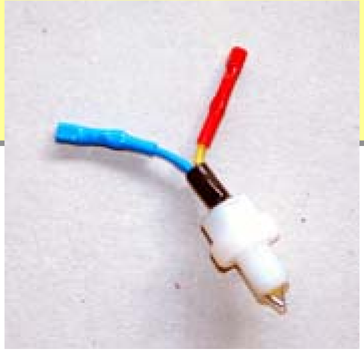


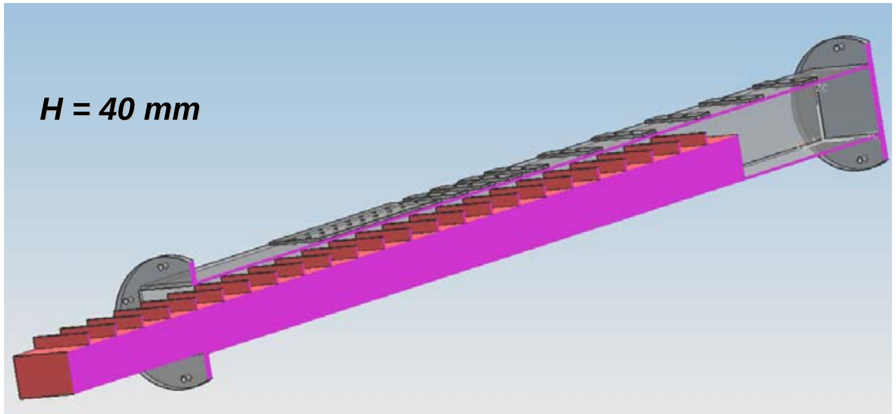


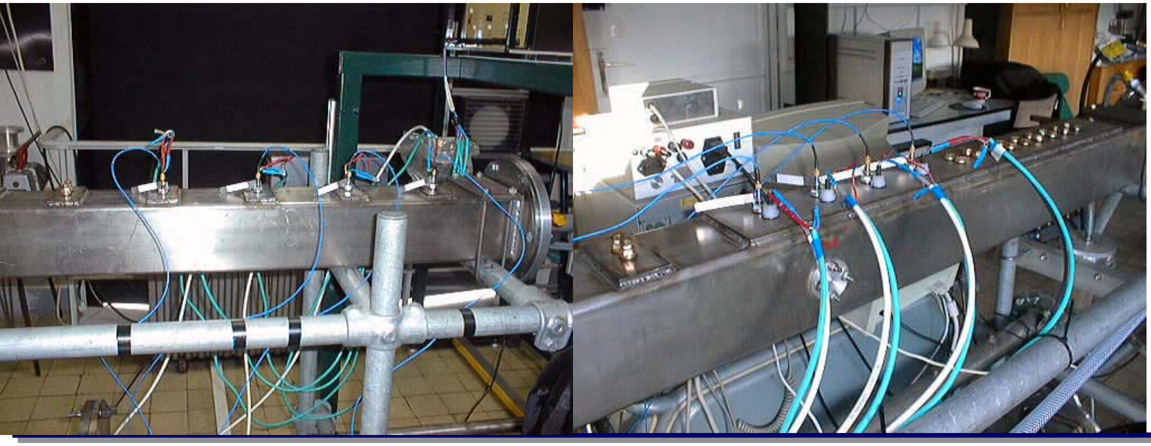
Obstacle height	h =H/2
Obstacle spacing	b = 2H

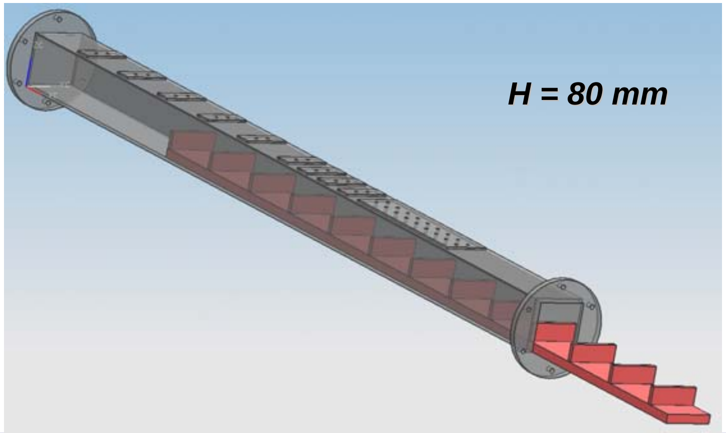
Experimental

- **Diagnostics** (pairs):
  - 4 piezoquartz pressure transducers
  - 4 ion probes
- **Ignition:**
  - weak spark plug
- **Data acquisition:**
  - amplifier
  - 8 cards (10MHz each)
  - computer



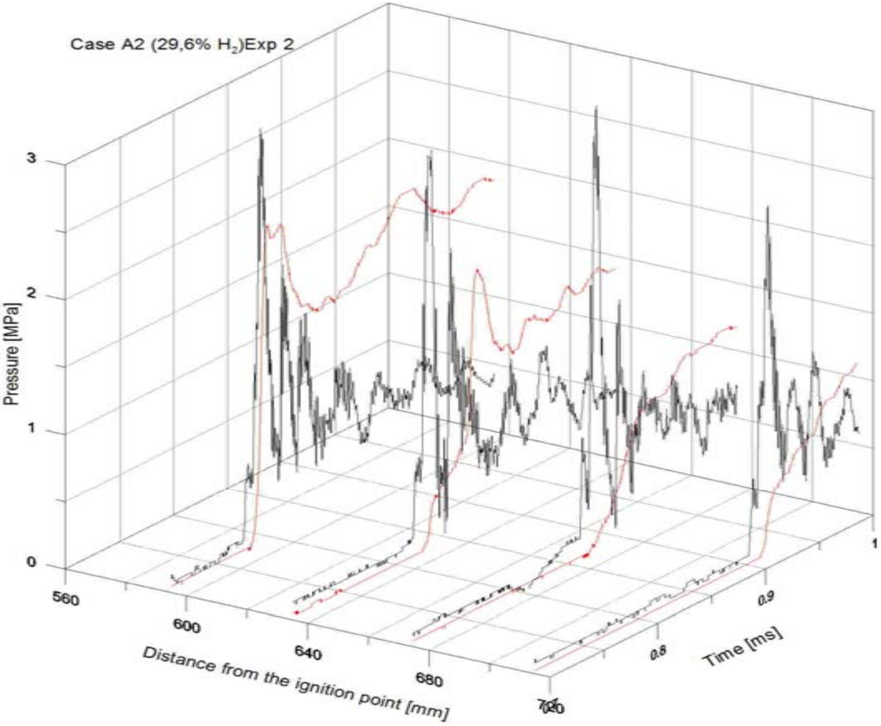


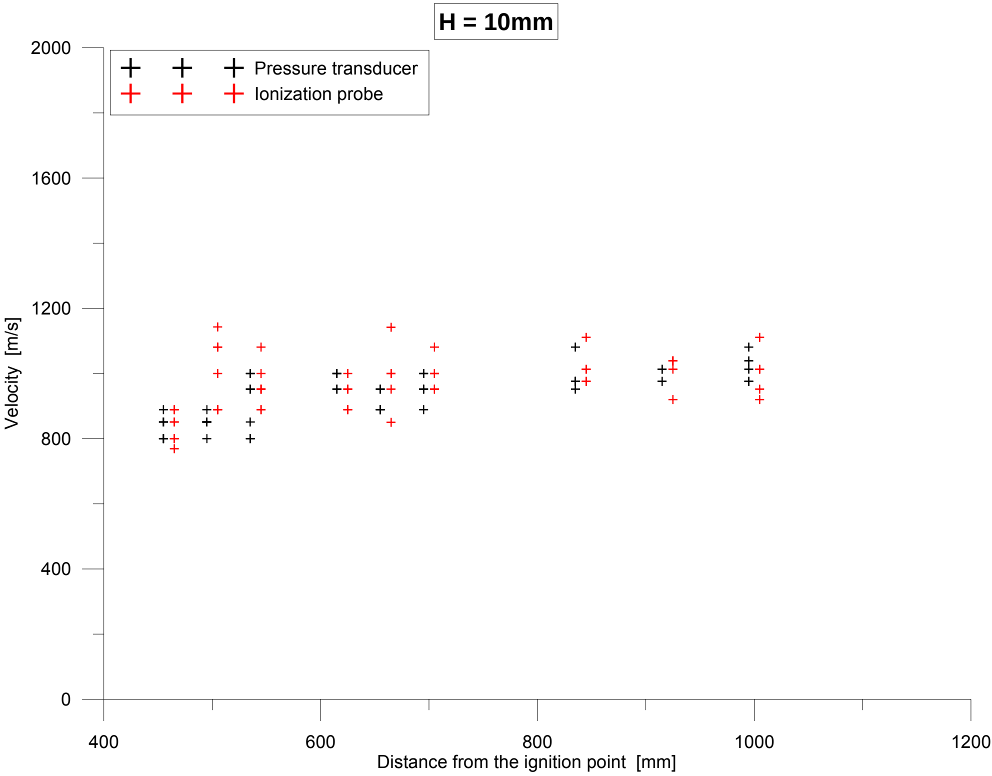




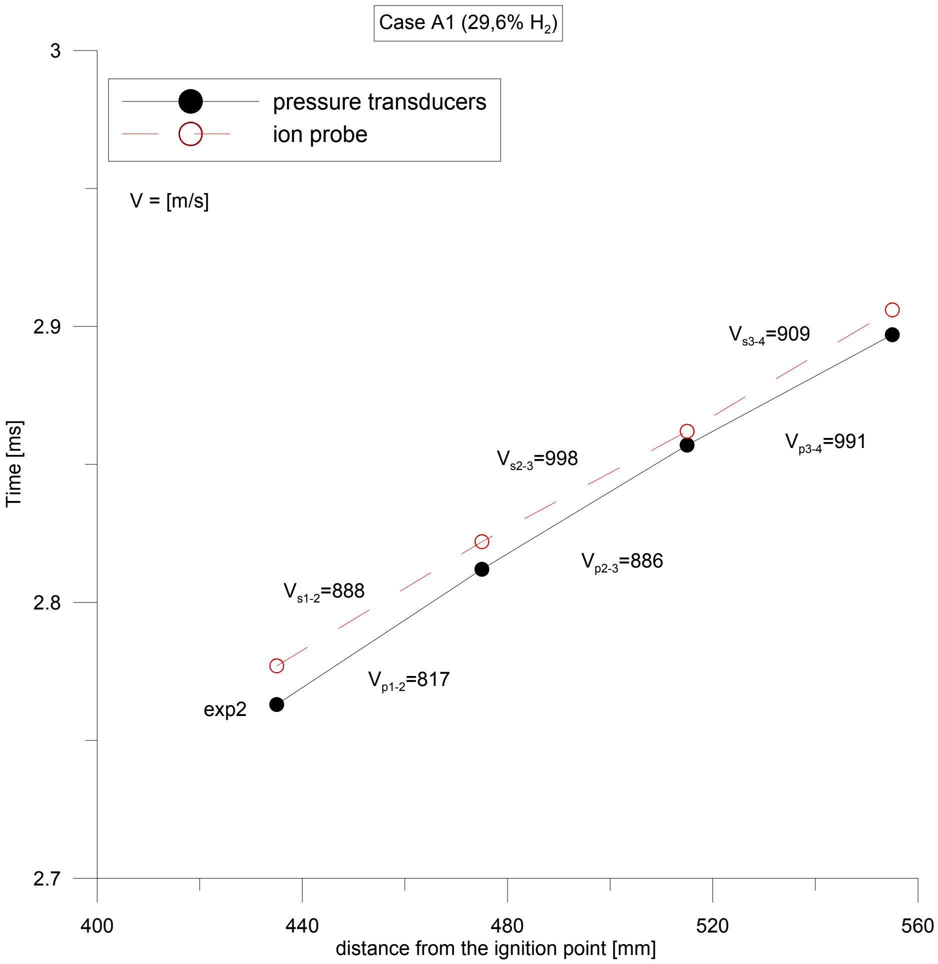
Results – case A (H = 1 cm)

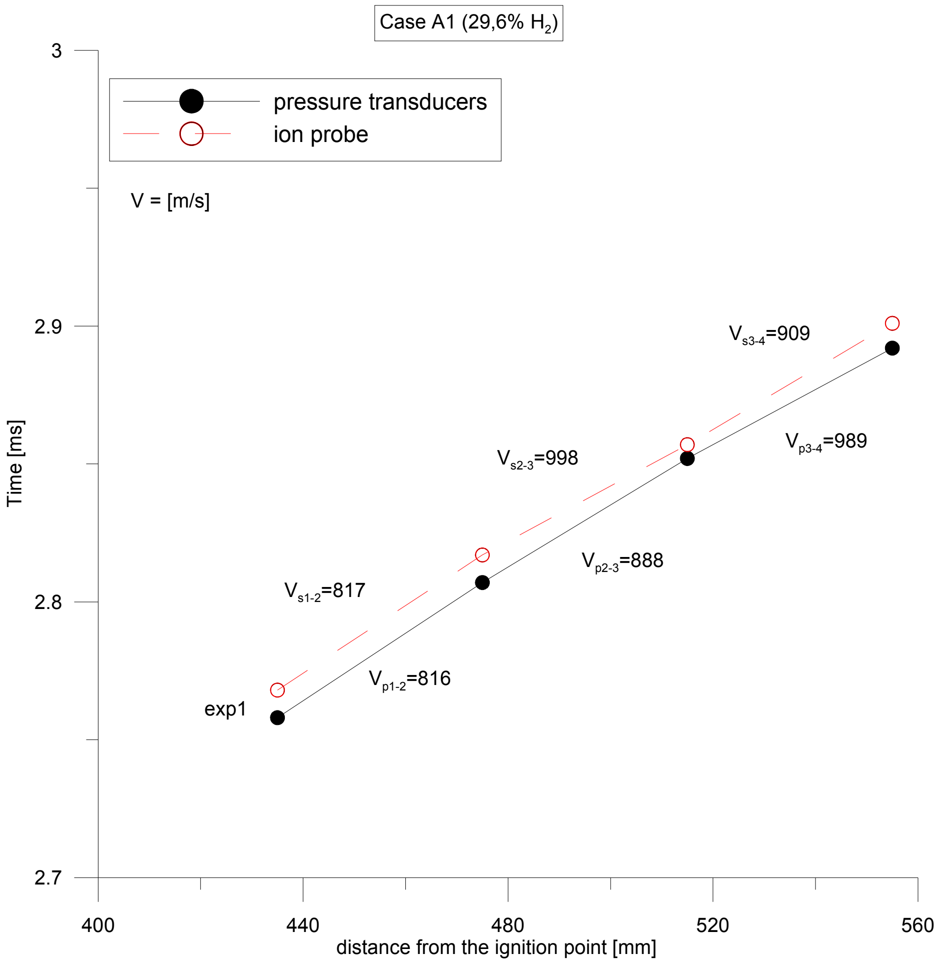
- ✓ Fast deflagration, 900 -1050 m/s, no DDT
- ✓ Maximum pressure 3 MPa





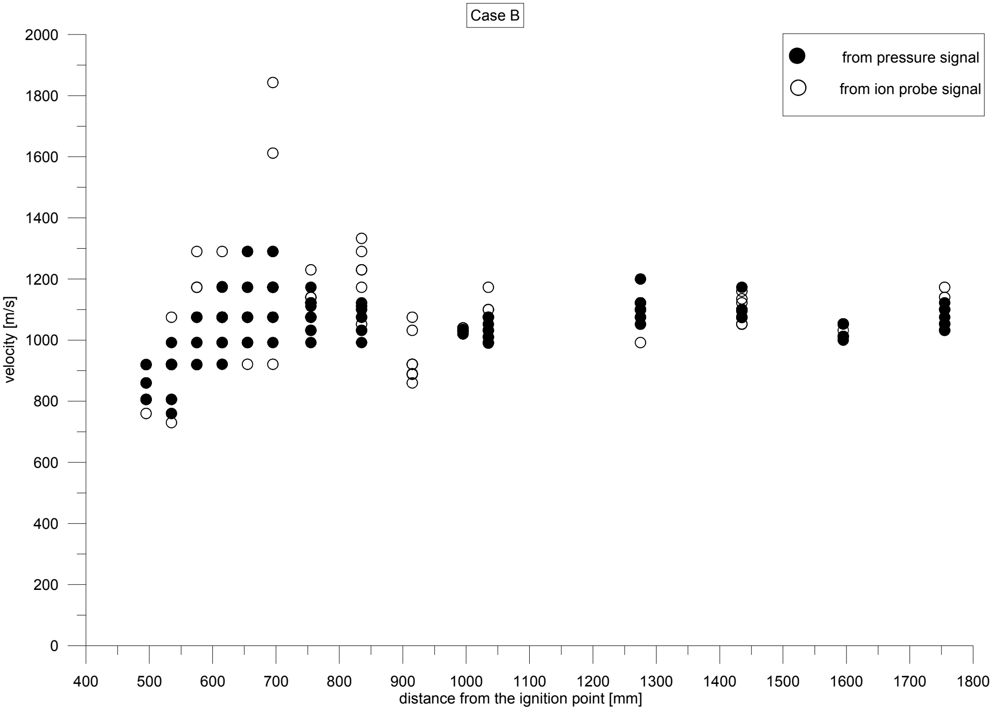
Results – case A (H = 1 cm)

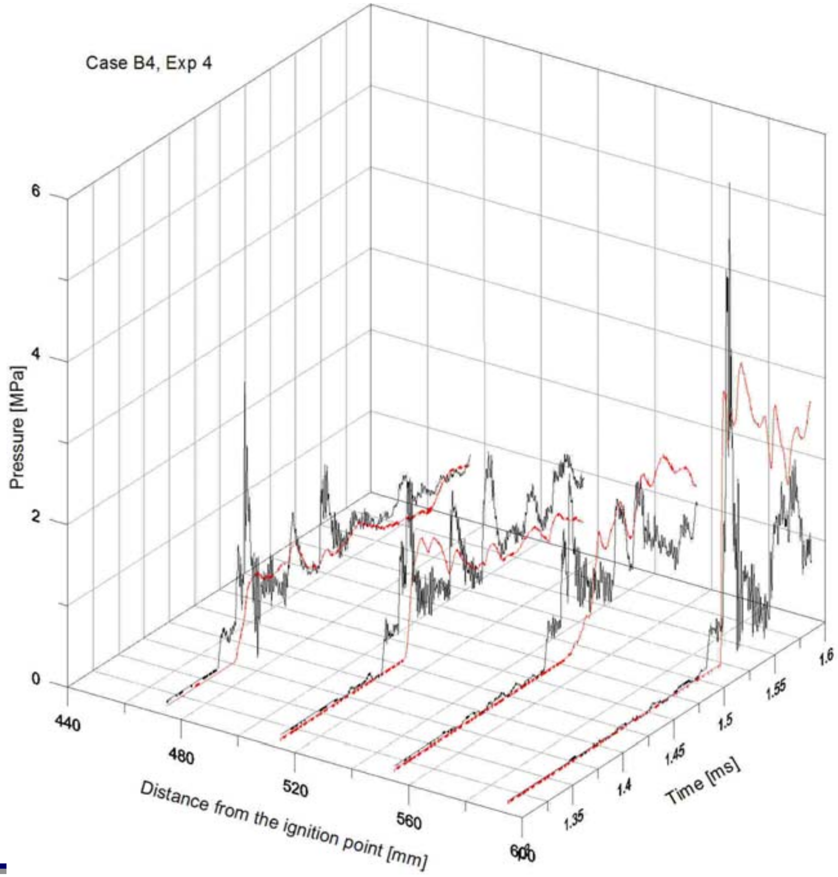




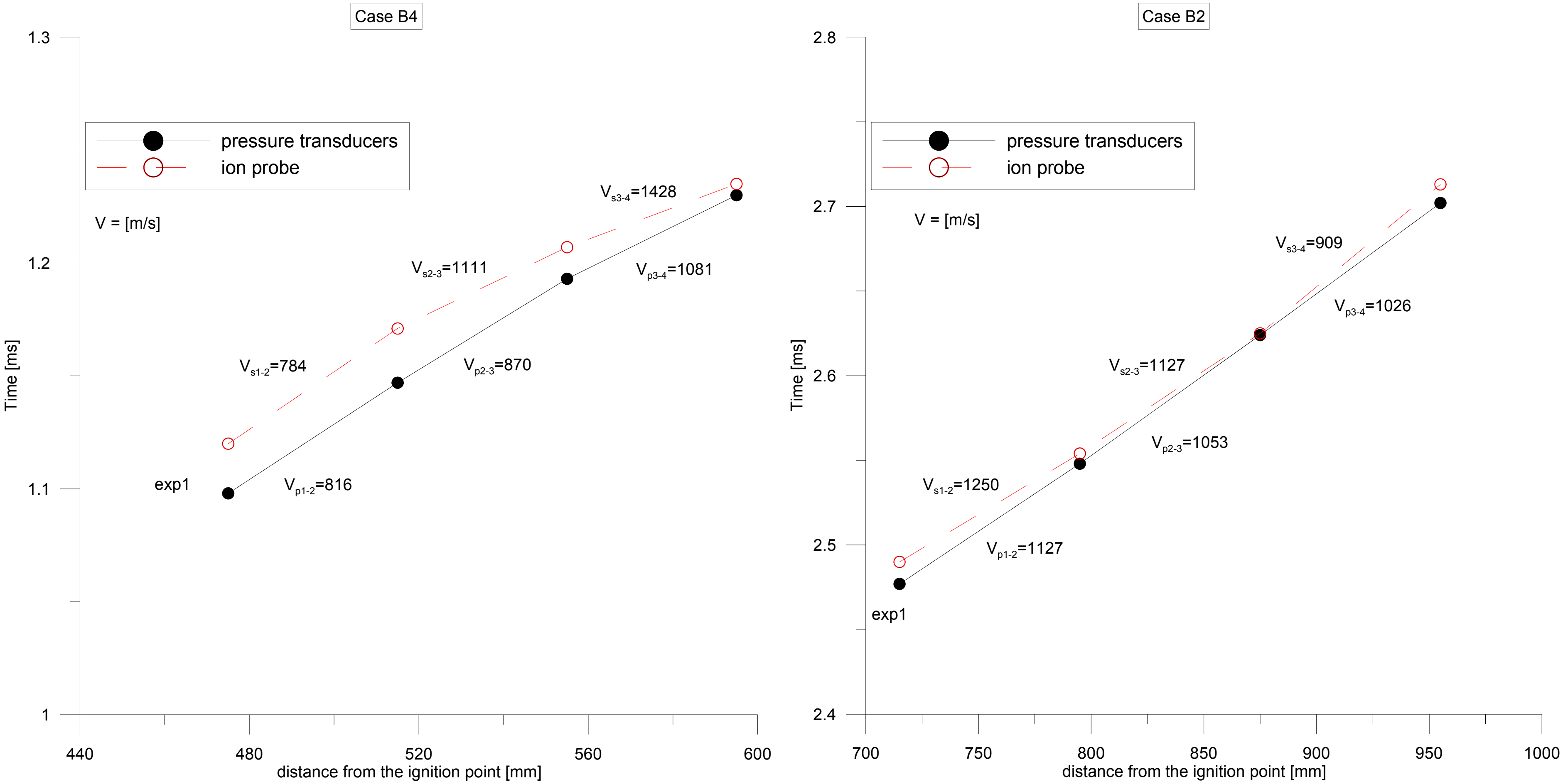
Results – case B (H = 2 cm)

- Fast deflagration, 1100 m/s
- Cases of quasi-detonations, quickly attenuated
- Maximum pressures for fast deflagrations up to 6 MPa and over 7.5 MPa for quasi-detonations



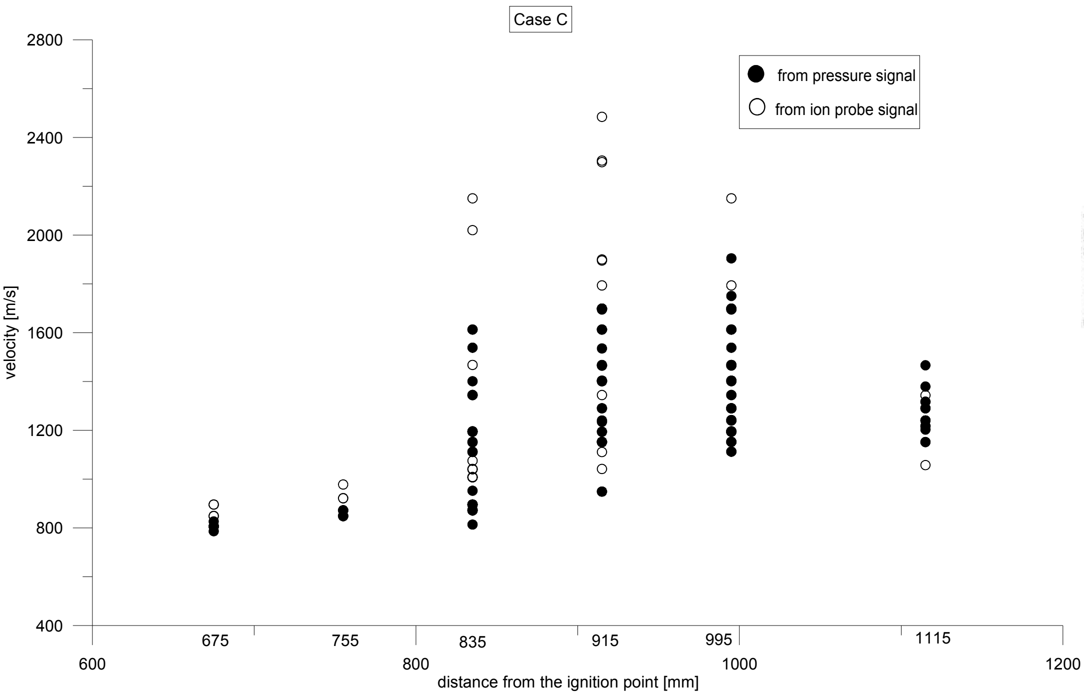


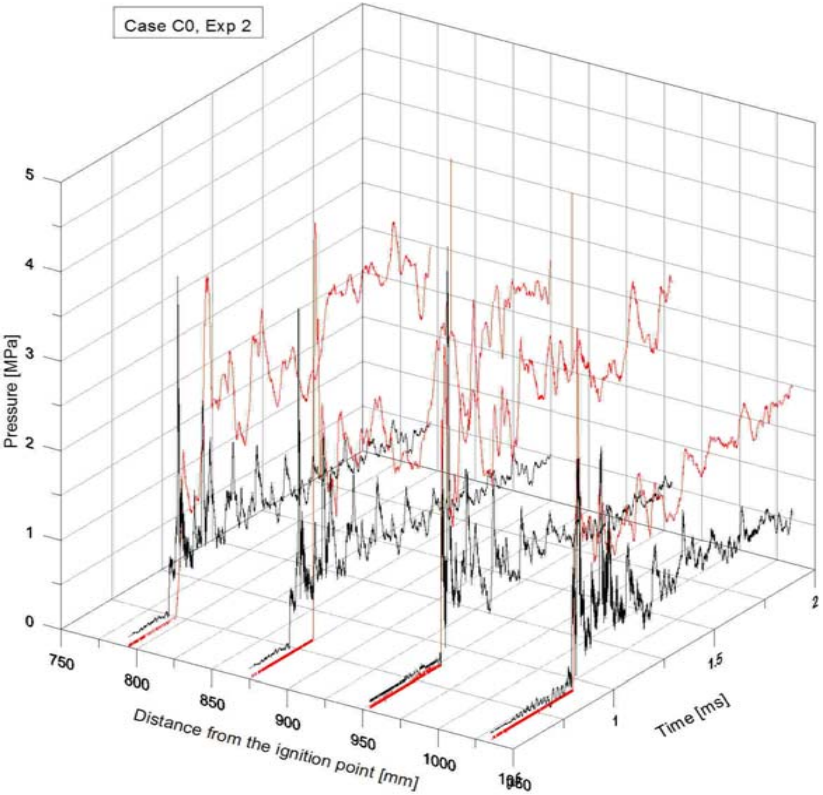
Results – case B (H = 2 cm)



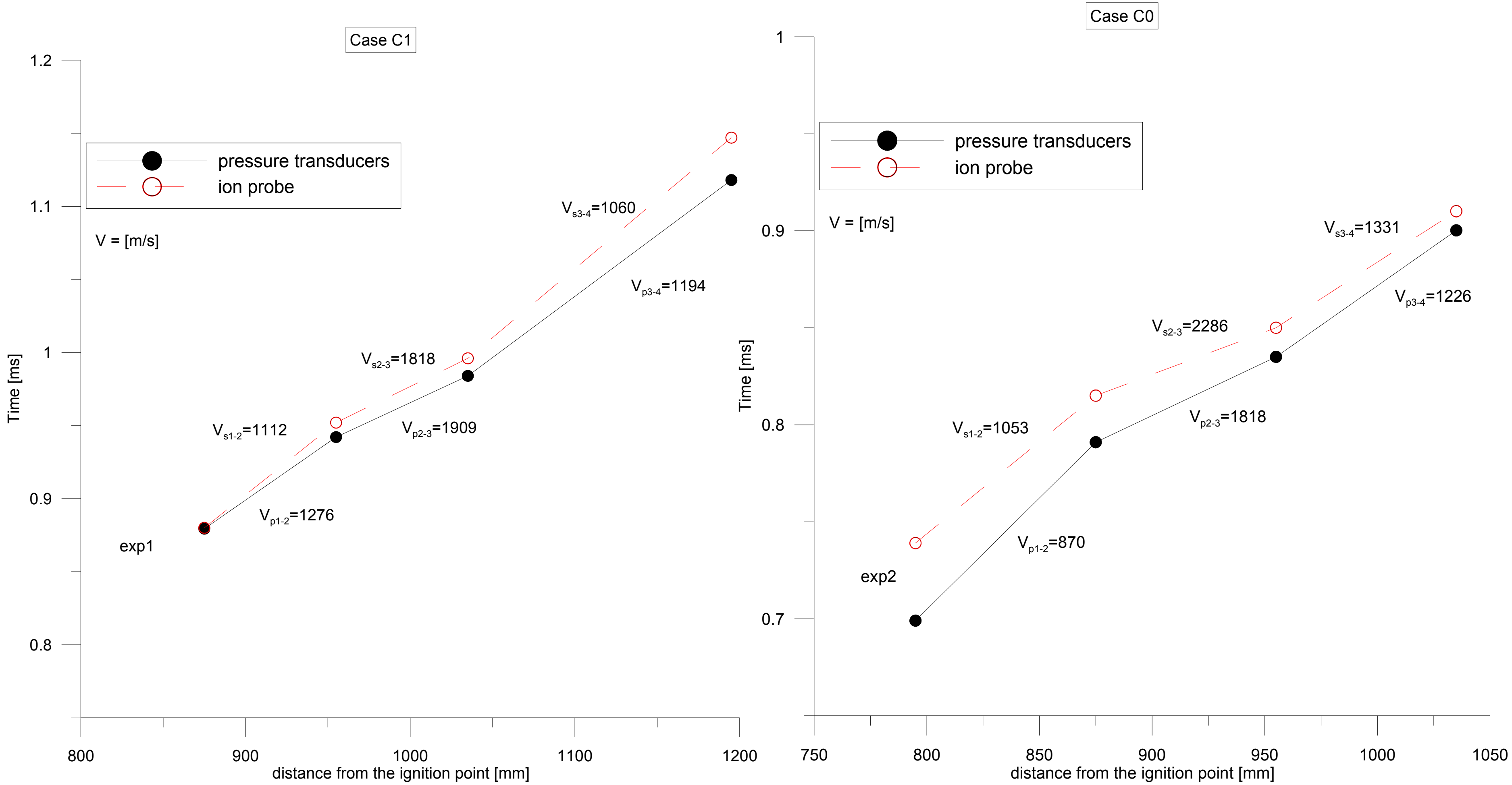
Results – case C (H = 4 cm)

- Three sub-cases:
  - ✓ Steady fast deflagration,
  - ✓ DDT followed by fast deflagration,
  - ✓ Quasi-detonation.
- Maximum pressures for fast deflagrations up to 4 MPa. In case of DDT over 8 MPa.



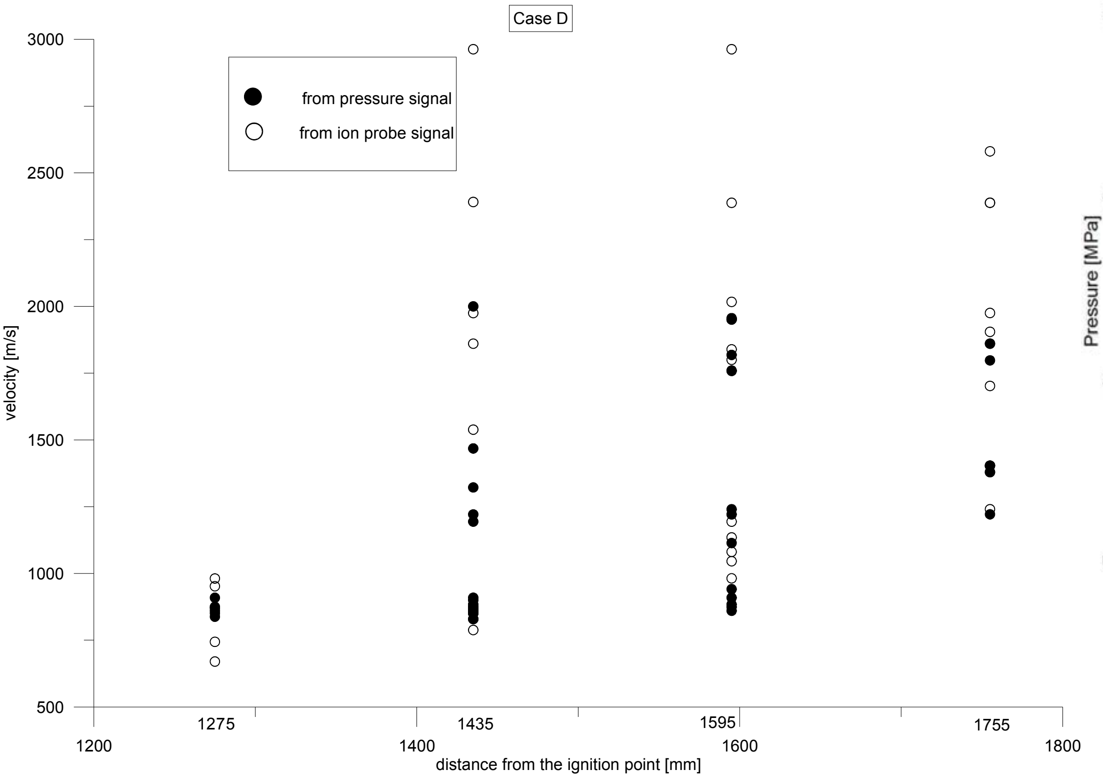


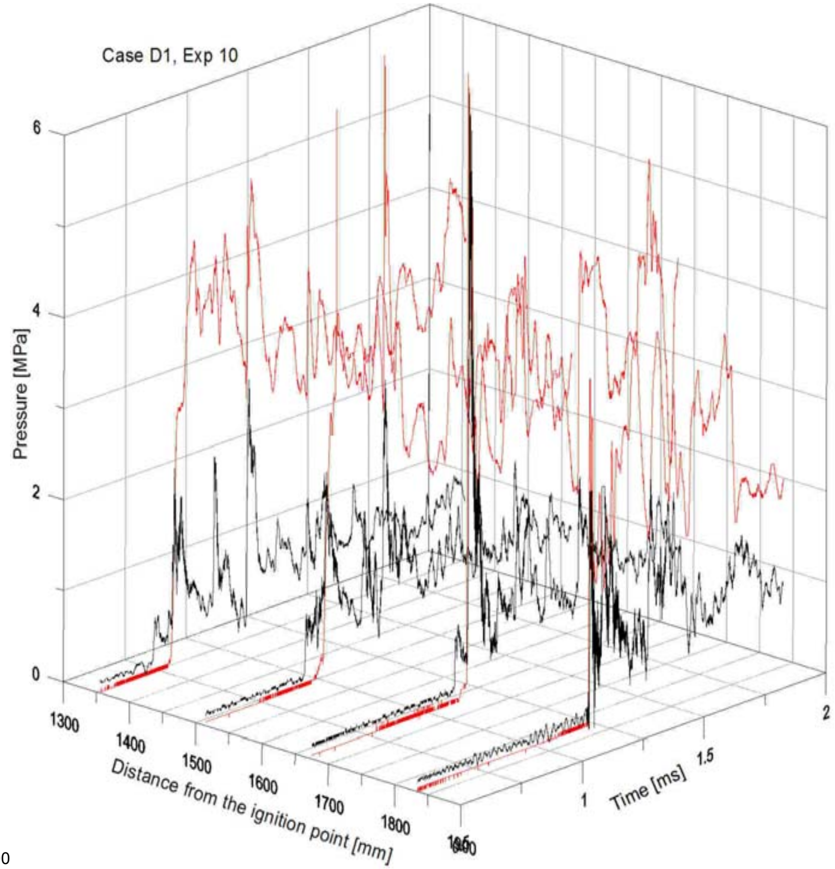
Results – case C (H = 4 cm)



Results – case D (H = 8 cm)

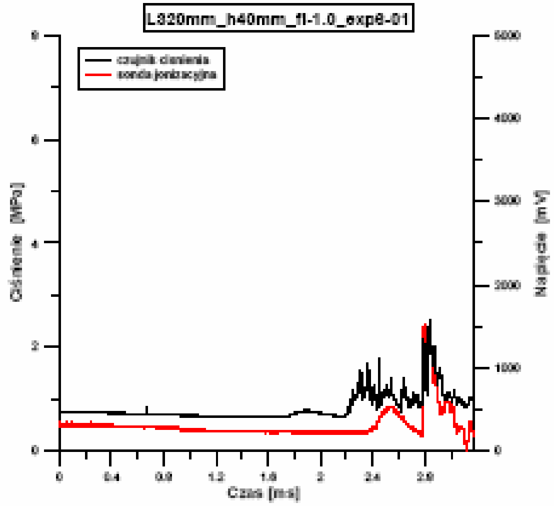
- DDT followed by steady detonation, quasi-detonation or fast deflagration

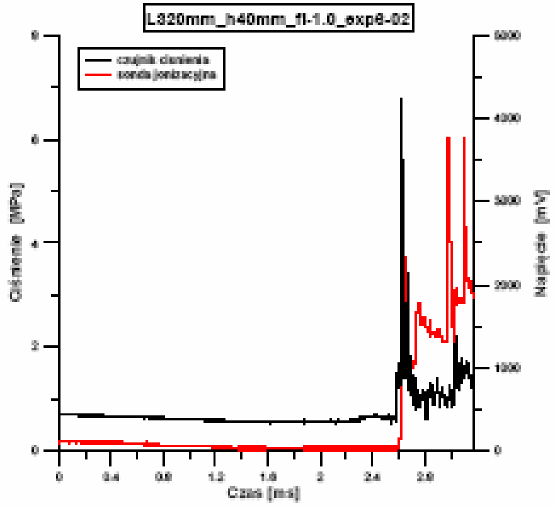


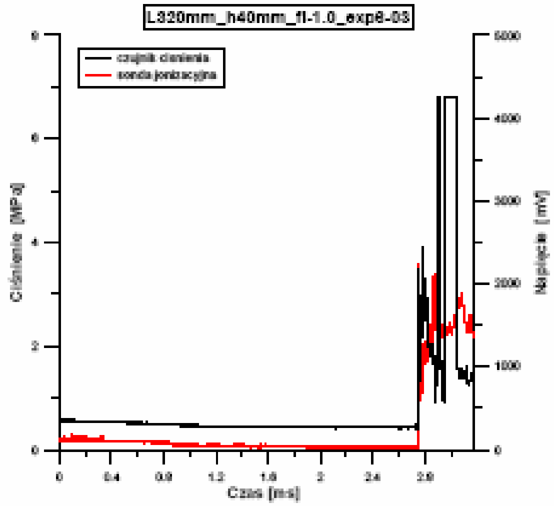


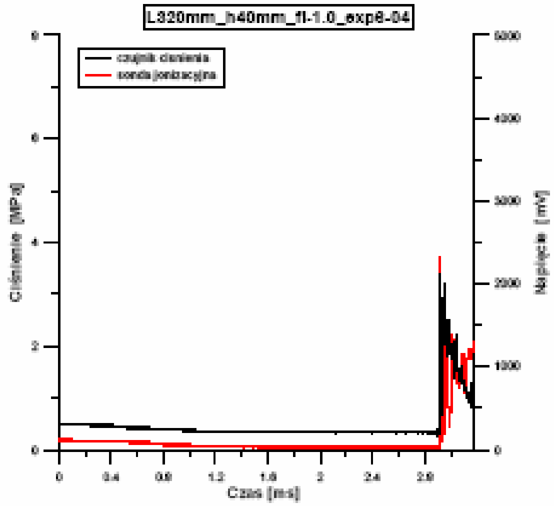
Results – case D (H = 8 cm)

DDT followed by
steady detonation

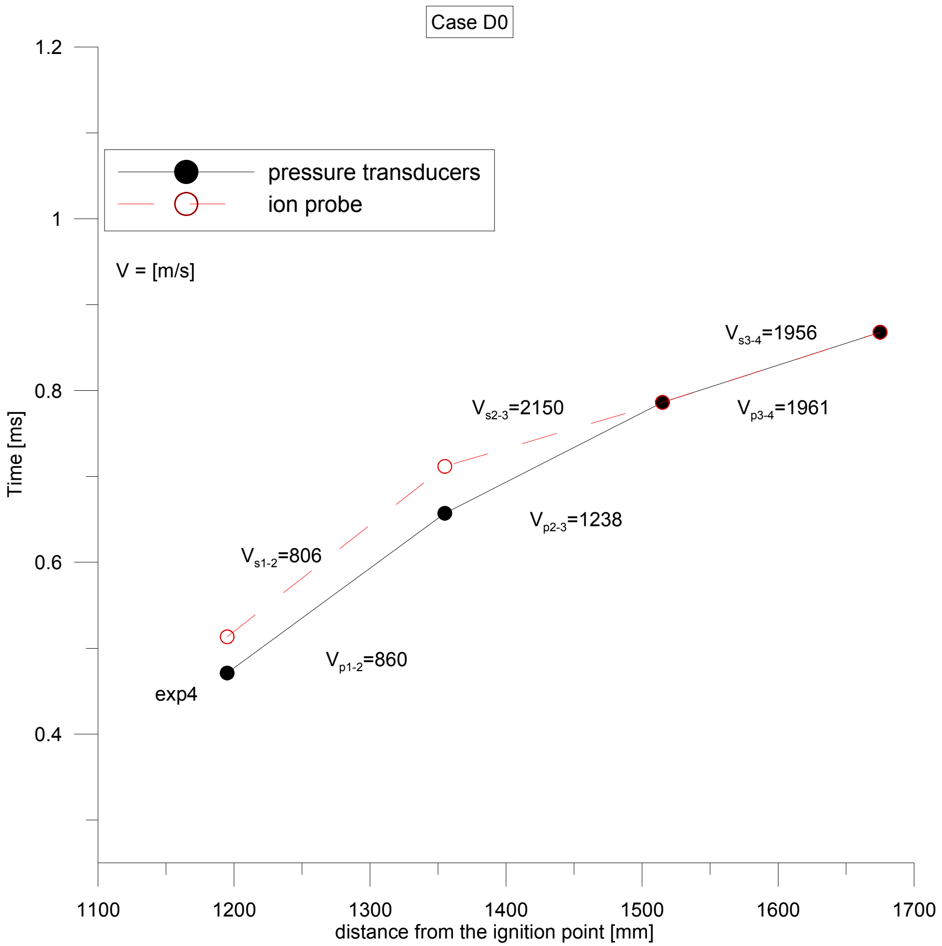


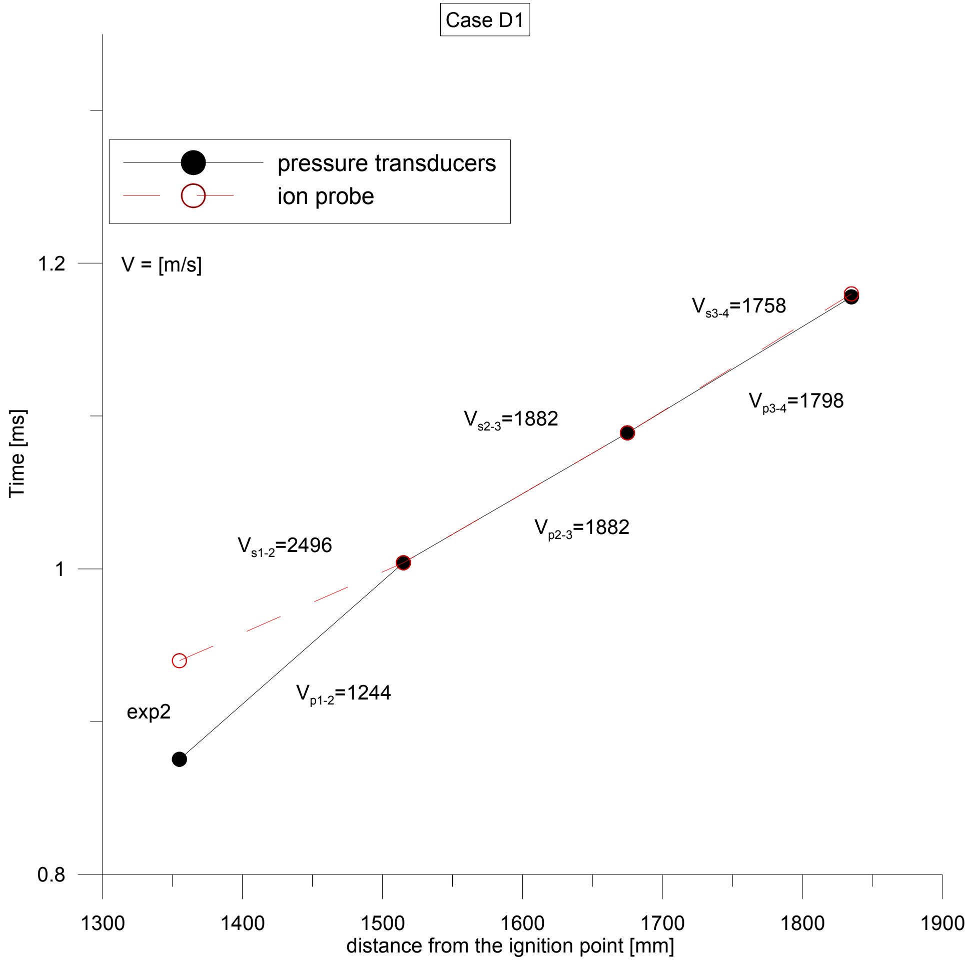






Results – case D (H = 8 cm)





Conclusions

- Geometry of the channel and obstacles is the key factor for DDT
- Advanced simulations show DDT very well qualitatively but still are not able to predict it quantitatively (transition distance ?, transition probability?)