Health and Safety
Executive

HSE

BASIC PHENOMENOLOGY OF DEFLAGRATION, DDT AND DETONATION

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Deflagration and Detonation

Deflagration:

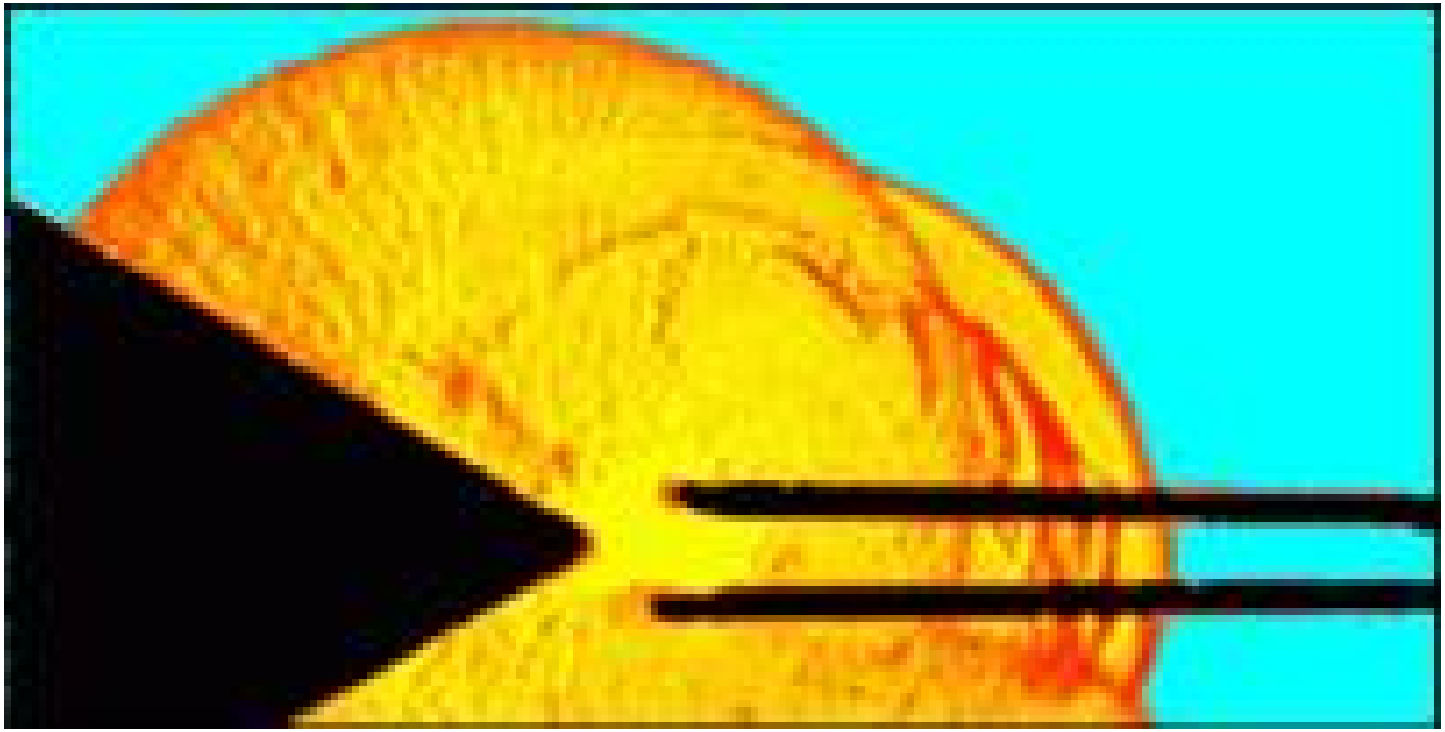
- Subsonic, typically 1 m/s and 7 to 10 bar starting at ambient pressure

Detonation:

- Supersonic
- High pressure shock front ahead of the reaction zone (i.e. flame)
- Adiabatic compression – gas autoignites
- Average pressure 15 to 19 bar (lean), 25 to 30 bar (stoichiometric)
- Typical peak pressure up to 50 bar (but see later)
- Typical velocity 1,500 to 3,500 m/s (Mach 4 to 8)
- Flame temperature 1,600 K (lean) to 2,300 K (stoichiometric)

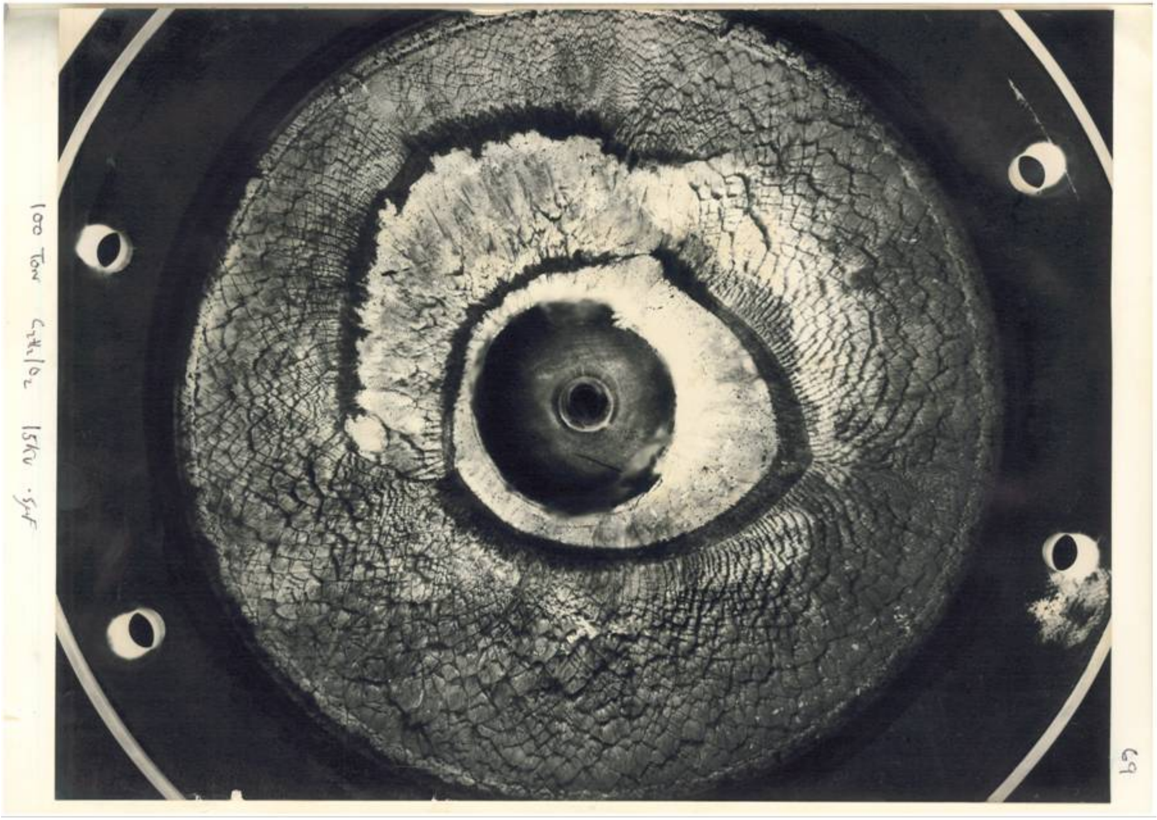
Deflagration and Detonation (cont.)

Direct initiation of a spherical detonation by an exploding wire (courtesy of Geraint Thomas, Combustion Hazard Research)



Deflagration and Detonation (cont.)

Direct initiation of a cylindrical detonation (courtesy of Geraint Thomas, Combustion Hazard Research)



Deflagration and Detonation (cont.)

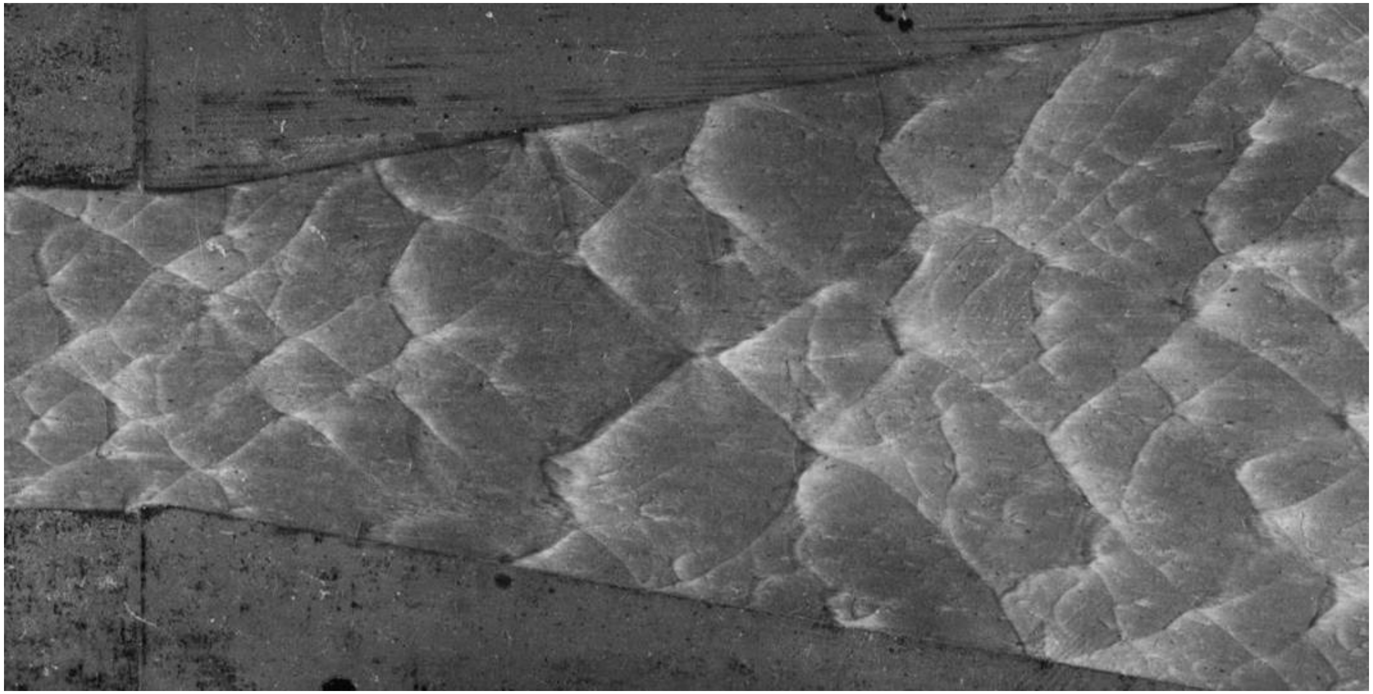
- Examples of materials that can detonate in air: hydrogen, acetylene, ethylene, ethane, propane
- Solvent vapours in tests – depends on size of ignition source
- Detonation limits:
  - Use with caution!
  - Examples from literature: ethane/air 3 to 7% v/v (2 to 10% v/v for deflagration), hydrogen/air 18 to 59% v/v
  - Widen as confined volume increases
  - Narrower if unconfined
  - Effect of temp – very limited data, tend to widen with increasing temp

Structure of a Detonation

- From high speed photography and soot tubes
- 3D cellular structure, constantly changing
- Cell width λ is a fundamental parameter. Typical values:
  - 8 mm for hydrogen
  - 20 mm for ethylene
- For detonation emerging from end of pipe, critical pipe diameter diameter typically:
  - 13λ for a pipe with circular cross-section
  - 10λ for square cross-section
- Also criteria in literature for propagation of detonations:
  - Emerging from confined to unconfined areas
  - Through orifices and slots
- Unconfined clouds:
  - Can calculate minimum cloud diameter for detonation
  - Likely to be at least 50 m based on current understanding

Structure of a Detonation (cont.)

Smoked foil of detonation propagating through an area change (courtesy of Geraint Thomas, Combustion Hazard Research)



Theories

Chapman-Jouguet

- Early 1900's
- 1D model, reaction infinitely fast
- Average CJ pressure ≈ $(\gamma M^2/\gamma+1)P_i$, where $\gamma = c_p/c_v$, M = Mach number and P_i = initial pressure
- Peak CJ pressure = $[(2\gamma M^2/\gamma+1) - (\gamma-1/\gamma+1)]P_i$
- Calcs on pressure (average and peak) and velocity compare fairly well with data
- May need to increase calculated pressures (e.g. double suggested in George Munday paper – see refs) for industrial applications, due to effects of high sustained pressures and shock loadings on real plant
- CAN'T use to calc detonation limits, critical pipe diameters etc.

Theories (cont.)

Zel'dovitch, von Neumann and Doring

- Independently proposed in 1940's
- Shock wave followed by reaction zone
- 1D model
- Calculations of pressure and velocity compare fairly well with data
- Can also calculate detonation limits, critical pipe diameter etc, but don't agree so well with data

Computer modelling

- Three types: empirical, phenomenological, CFD
- Review by Stefan Ledin, Health and Safety Laboratory (see refs)

Deflagration to Detonation Transition

- Turbulence wrinkles flame front
- Flame accelerates
- Critical velocity approx. 150 m/s
- Shock forms ahead of flame – piston
- Very reactive fuels more sensitive to DDT
- Turbulence from:
  - Confinement e.g. gas cloud near pipe track
  - Bends in pipes etc.

Deflagration to Detonation Transition (cont.)

- Run-up distance:
  - L/D approx. 10 to 60 (3 for acetylene)
  - Can be calculated
  - Need suitable safety factor (e.g. half?) for industrial applications:
    - Most tests in smooth glass pipes < 50 mm diameter
    - Industrial pipes have rougher internal surface, so greater friction
    - Also drag effects less significant in wider pipes
  - Tends to decrease as pressure increases, increase as temperature increases
- Critical pipe diameter $d_{crit} \approx \lambda/\pi$:
  - e.g. stoichiometric hydrogen/air: $\lambda \approx 1.5$ cm, so $d_{crit} \approx 0.48$ cm
  - Beware of data from inappropriate test conditions e.g. short, narrow tubes
  - Need suitable safety factor (e.g. half?)

Enhanced Pressure Effects

- Overdriven detonation:
  - Accelerated beyond steady-state due to turbulence
  - Up to 100 bar

- Pressure piling:
  - Mixture pre-pressurised, e.g. by earlier flame, flow restriction in pipe or connected vessels
  - Pressure depends on compression ratio
  - Also by flame reflected at end of line
  - Pressure typically 2 to 5 times steady-state detonation pressure
  - Enhanced pressure effects sometimes very transient, sometimes not

- Galloping detonation:
  - Near to detonation limits
  - Cyclic fluctuation in velocity, typically 0.5 to 1.5 CJ velocity
  - Severe damage where velocity peaks

Enhanced Pressure Effects (cont.)

Retonations

- Part of the shock travels back through the burnt mixture
- Can reflect off e.g. bend or closed end
- Overtakes detonation – increased speed of sound in hot burnt gases
- Combined detonation/retonation
  - Very short-lived
  - Pressure 3 to 8 times higher than usual

Venting

- Vents can induce turbulence and lead to DDT
- Most likely if mixture is sensitive, rich and small amount of venting
- Tests with rich hydrogen/air:
  - 13% top-venting – overpressure increased
  - 50% top-venting – overpressure reduced
- Venting alone unlikely to be adequate for protection against detonations

Effects of Detonations

- High pressures and velocities – enormous dynamic loads
- No general rules
- Often lots of small fragments
- Large distorted fragments if vessel sufficiently strong
- Often pipes fail at bends and joints
- Can get failures at fairly regular intervals:
  - Accelerated to DDT
  - Decelerates when pipe fails
  - Accelerates again
- Positions of fragments and metallurgical examination can be useful

Mitigation

- Don't form a detonation!
- Containment: German standard TRbF100 = 50 bar
- Passive detonation arresters:
  - Need temperature detection
  - Won't usually withstand repeated detonations or oxygen-enriched mixtures
  - Potential for high back-pressure and blockage
  - Tests at Health and Safety Laboratory
- Active detonation arresters:
  - Rapid isolation valves – close in 20 to 40 ms
  - Plus suppressant canisters ahead of valves – activate in 10 to 20 ms
  - May also need venting

References

- “Detonations in Pipes and Vessels”, George Munday, The Chemical Engineer, April 1971, pp.135-144
- “Gaseous Detonations: Their Nature, Effects and Control”, M.A. Nettleton, Chapman and Hall, 1987
- “Detonations”, HSE guidance note ref TD5/039, by Helen James, October 2001: http://www.hse.gov.uk/foi/internalops/hid/din/539.pdf

  (contains over 50 references)
- “A Review of State-of-the-Art in Gas Explosion Modelling”, HSL report HSL/2002/02, by Stefan Ledin:

  http://www.hse.gov.uk/research/hsl_pdf/2002/hsl02-02.pdf