Detonation.

Q: Differences between

- Explosion
- Deflagration
- Detonation
- Flame

Explosion → . Somewhat generic Term
- Rapid heat Release
  - Chain Branching Reactions, Runaway Reactions
- Can be homogeneous
- often means violent, uncontrolled

Deflagration
- Subsonic wave
- Combustion wave usually means Deflagration,
- Sustained by Reaction,
- Propagated by Diffusion :

  A Diffusion wave Sustained by Rxn.

Flame
- Usually means Deflagration,
- Flame synonymous w/ Deflagration, combustion wave,

Detonation
- Supersonic wave sustained by Rxn.

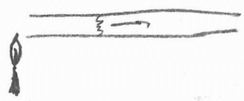
  High ΔP compresses → Auto ignition.

  Not Diffusion - Limited

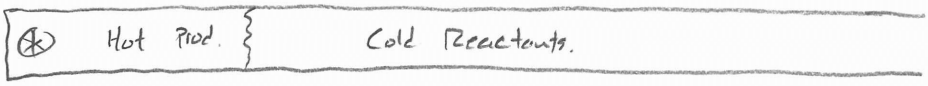
Table : See slide.

Videos : Chemical Plant
PDE

Detonation Process:

- Tube with premixture  open at Both ends → Deflagration,

- light at Closed End:



1. $\frac{\rho_R}{\rho_P} \approx 7$ → as flame propagates, tube Gases expand (to push Reactants out.)

2. Gas expansion Sends out Compression waves at the Sound speed.

3. Compression → higher flame Speed →
   - Succeeding waves catch up
   - Preheating also increases flame Speed.

4. Higher Speed → Gases pushed out faster → turbulent flow

5. High speed flames → Compression waves pile up, form a Shock → high ΔP

6. Shock Compresses/ ignites

7. Rxn Zone behind The shock Sends a Continuous Compression wave That keeps The Shock from Decaying. → Detonation.

- Products expand as Choked Flow → $Ma = 1$

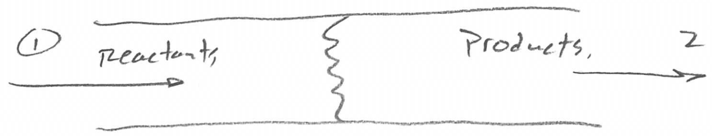
$$Ma = \frac{V}{c(T, Y_i)}$$

- Compression w/o a compressor

  Can't expand faster Than Sound → Compression

Analysis.

- Flow in a tube: 1-D, SS, Const A, Ideal Gas



- Frame Following Detonation $\rightarrow$ Det is Stationary with Flow in / out.

* Mass: $\dot{m}''_1 = \dot{m}''_2 \rightarrow \boxed{\rho_1 V_1 = \rho_2 V_2}$

* Momentum: $\boxed{P_1 + \rho_1 V_1^2 = P_2 + \rho_2 V_2^2}$

$$\underbrace{\cancel{\frac{d\rho V}{dt}}}_{SS} + \frac{\partial}{\partial x}(\rho V V) = -\frac{dP}{dx} + \frac{d\tau}{dx} + \left(\cancel{\text{Body Force}}\right)$$

$\int \rightarrow \tau = 0$ at inlet, outlet $\rightarrow$ Get

* Energy: $h_1 + \dfrac{V_1^2}{2} = h_2 + \dfrac{V_2^2}{2}$

(argue / show this.)

$$h = h_o + C_p (T - T_r)$$

- Assume C_p is Const, $C_{p1} = C_{p2}$

- $h_{o,1} + C_p T_1 - \cancel{C_p T_r} + \dfrac{V_1^2}{2} = h_{o,2} + C_p T_2 - \cancel{C_p T_r} + \dfrac{V_2^2}{2}$

- $C_p T_1 + \dfrac{V_1^2}{2} + \underbrace{(h_{o1} - h_{o2})}_{q} = C_p T_2 + \dfrac{V_2^2}{2}$

$\hookrightarrow$ "heat addition.

$$\boxed{C_p T_1 + \frac{V_1^2}{2} + q = C_p T_2 + \frac{V_2^2}{2}}$$

* Ideal Gas Law: $\boxed{\rho = \dfrac{MP}{RT}}$ • Assume $M_1 = M_2$

- Given State 1 : T_1, ρ_1, V_1 $(\longrightarrow \dot{m}'' = \rho_1 V_1)$
- Have 4 eqns in 4 unknowns : V_2, T_2, ρ_2, P_2

(Technically we don't know V_1 $\longrightarrow$ specify it for now)

- $\frac{1}{\rho_2} = \nu_2$
- we can think of Mom, Energy as

2 eqns in $P_2, \underbrace{\frac{1}{\rho_2}}_{\nu_2}$ with $\underline{\text{mass}} \rightarrow V_2$

$\underline{\text{I.G.L}} \longrightarrow T_2$

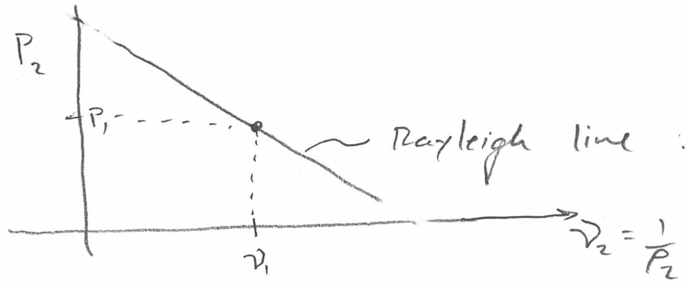
Rayleigh Line (R.L.)

Combine Mass, Momentum

$$\dot{m}''^2 = \rho_1^2 V_1^2 = \rho_2^2 V_2^2 = \frac{P_2 - P_1}{\frac{1}{\rho_1} - \frac{1}{\rho_2}}$$

$$\hookrightarrow \boxed{P_2 = (P_1 + \dot{m}''^2 \nu_1) - \dot{m}''^2 \nu_2}$$

Plot

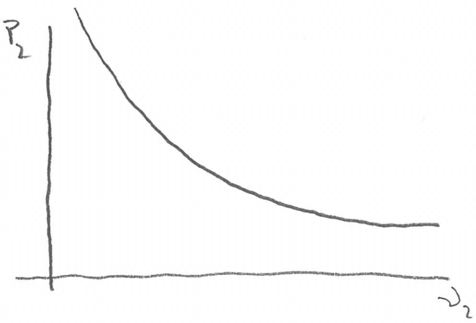


Rankine-Hugoniot Curve (R.H.C)

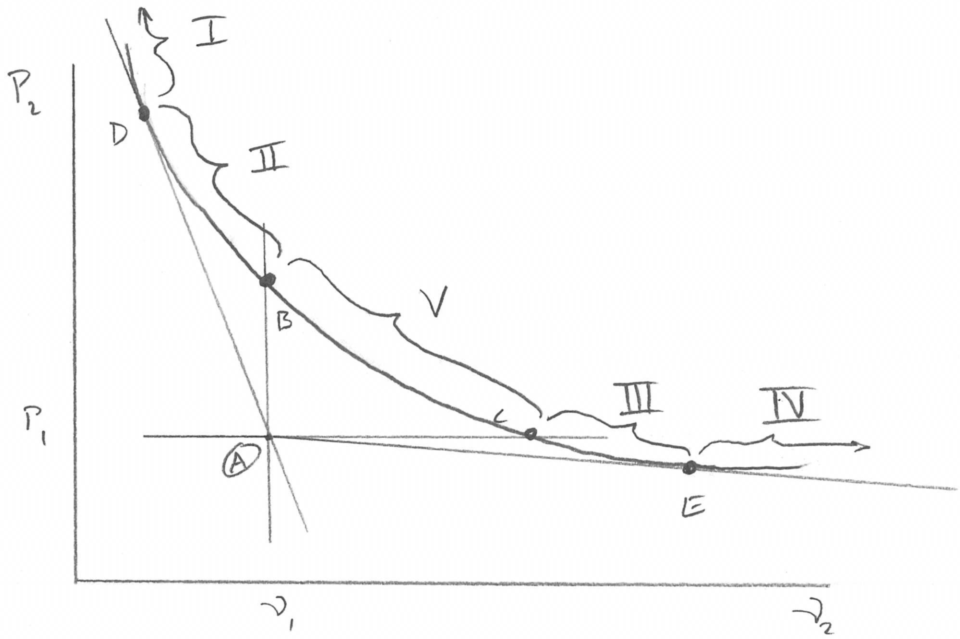
Combine Mass, Momentum, Energy, Ideal Gas law,

with $\gamma = c_p/c_v$, $c_p - c_v = \frac{R}{M}$ (J/kg·K)

$$\hookrightarrow \frac{\gamma}{\gamma-1}(P_2\nu_2 - P_1\nu_1) - \frac{1}{2}(P_2 - P_1)(\nu_1 + \nu_2) - q = 0$$



R.L., RHC:



I: Strong Detonation

Supersonic ⟶ Subsonic. (Slows.)

II Weak Detonation

Supersonic ⟶ Supersonic (slows)

(V Not Possible.) $-\dot{m}''^2$ is slope is positive in V ⟶ not possible.

III Weak Deflagration.

Subsonic ⟶ Subsonic (speeds)

IV Strong Deflagration

Subsonic ⟶ Supersonic (speeds)

I. Possible, but hard to acheive.
"overdriven shock in special config.

II. Most Detonations happen <u>at</u> point D
- Entropy is minimum here (See Supplement)

III "Premixed Flames" are just below Point C

IV Not observed (no subsonic ⟶ super sonic in a Const A Duct).
- Entropy is maximum at Point E. (See supplement.)

- D, E are Chapman Jouget points: C;J

Velocity

- Take point D $\rightarrow$ $V_2 = C_2$

$$C_2 = \sqrt{\frac{\gamma R T_2}{M}}$$

- Find V_1

Mass: $$V_1 = \underbrace{\frac{\rho_2 C_2}{\rho_1}}$$

Use Mass, Mom, Energy, IG to solve in terms of State 1

$$V_1 = \left[2(\gamma+1)\gamma \frac{R}{M_2} (T_1 + q/c_p) \right]^{1/2}$$

- Assumes $P_2 >> P_1$

(some better eqns also Given)
(16.26, 16.27)

$\rightarrow$ Requires some iteration.

See Slide Comparison.

(Doesn't use our eqns exactly, but close)

See Matlab Code for general solution.

Chemical Engineering 522

Gaseous Detonations

1

Detonation vs. Deflagration

Detonation

P_2/P_1 = 13-55

T_2/T_1 = 8-21

v_2/v_1 = 0.4-0.7

Property	Detonation[b]	Deflagration[c]
Ma_1	5–10	0.001
Ma_2	1.0	0.003
$v_{x,2}/v_{x,1}$	0.4–0.7	7.5
P_2/P_1	13–55	≈ 1
T_2/T_1	8–21	7.5
ρ_2/ρ_1	1.7–2.6	0.13

Deflagration

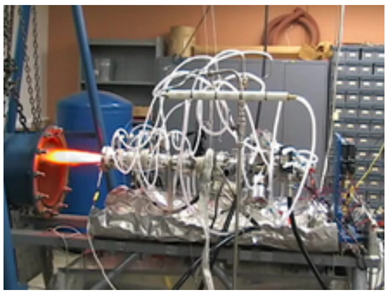
P_2/P_1 = 0.98

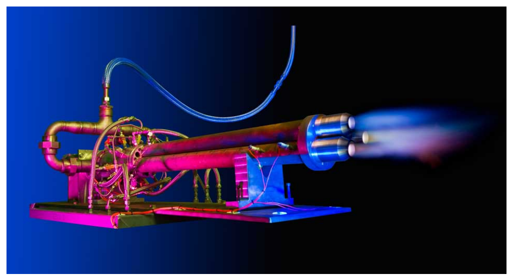
T_2/T_1 = 4-16

v_2/v_1 = 7.5

Pulse Detonation Engines

(High pressure without the compressor)
Gases expaned as "choked flow" at sonic velocity
Detonation wave speed is supersonic





Cellular Structure

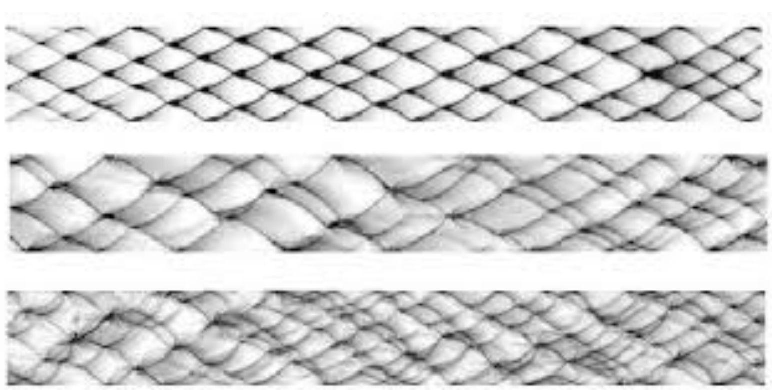


TABLE 5.3 Detonation Velocities of Various Mixtures[a]

	Measured velocity (m/s)	Calculated Velocity (m/s)	Calculated P_2 (atm)	Calculated T_2 (K)
$4H_2 + O_2$	3390	3408	17.77	3439
$2H_2 + O_2$	2825	2841	18.56	3679
$H_2 + 3O_2$	1663	1737	14.02	2667
$CH_4 + O_2$	2528	2639	31.19	3332
$CH_4 + 1.5\,O_2$	2470	2535	31.19	3725
$0.7C_2N_2 + O_2$	2570	2525	45.60	5210

[a] $P_0 = 1\,atm$, $T_0 = 298$ K.

TABLE 5.4 Detonation Velocities of Fuel–Air Mixtures

Fuel–air mixture	Hydrogen–air $\phi = 0.6$: 1	Hydrogen–air $\phi = 0.6$: 2	Hydrogen–air $\phi = 1.0$: 1	Hydrogen–air $\phi = 1.0$: 2	Propane–air $\phi = 0.6$: 1	Propane–air $\phi = 0.6$: 2
M	4.44	1.00	4.84	1.00	4.64	1.00
u (m/s)	1710	973	1971	1092	1588	906
P (atm)	1.0	12.9	1.0	15.6	1.0	13.8
T (K)	298	2430	298	2947	298	2284
ρ/ρ_1	1.00	1.76	1.00	1.80	1.00	1.75
T_{ad} at P_1 (K)		1838		2382		1701
T_{ad} at P_2 (K)		1841		2452		1702