COURSE OVERVIEW

DAY 2

Combustion with Flame Propagation

a. One Dimensional Steady Flow formulation.
b. Rayleigh and Rankine-Hugoniot equations.
c. Detonation.
d. Deflagration. Thermal theory. Flame Speed Dependencies.

Laminar Diffusion Flames

a. Flame Structure and Mixture Fraction.
b. Infinitely fast chemistry. Flamelet concept.
c. 1D Steady Diffusion flames. Strained/Unstrained.
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e. Diluted conditions. Diffusion Ignition processes.

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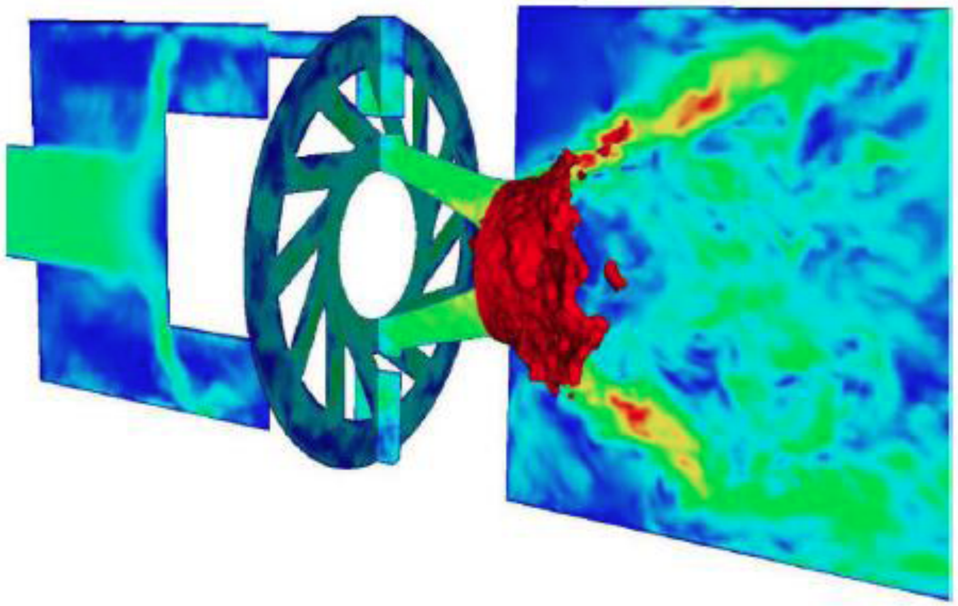
LAMINAR PREMIXED FLAMES

- Premixed combustion used in combustion devices when high heat release rates are desired
  - Small devices
  - Low residence times
- Examples:
  - SI engine
  - Stationary gas turbines
- Advantage → Lean combustion possible
  - Smoke-free combustion
  - Low NO_x
- Disadvantage: Danger of
  - Explosions
  - Combustion instabilities

    → Large-scale industrial furnaces and aircraft engines are typically non-premixed



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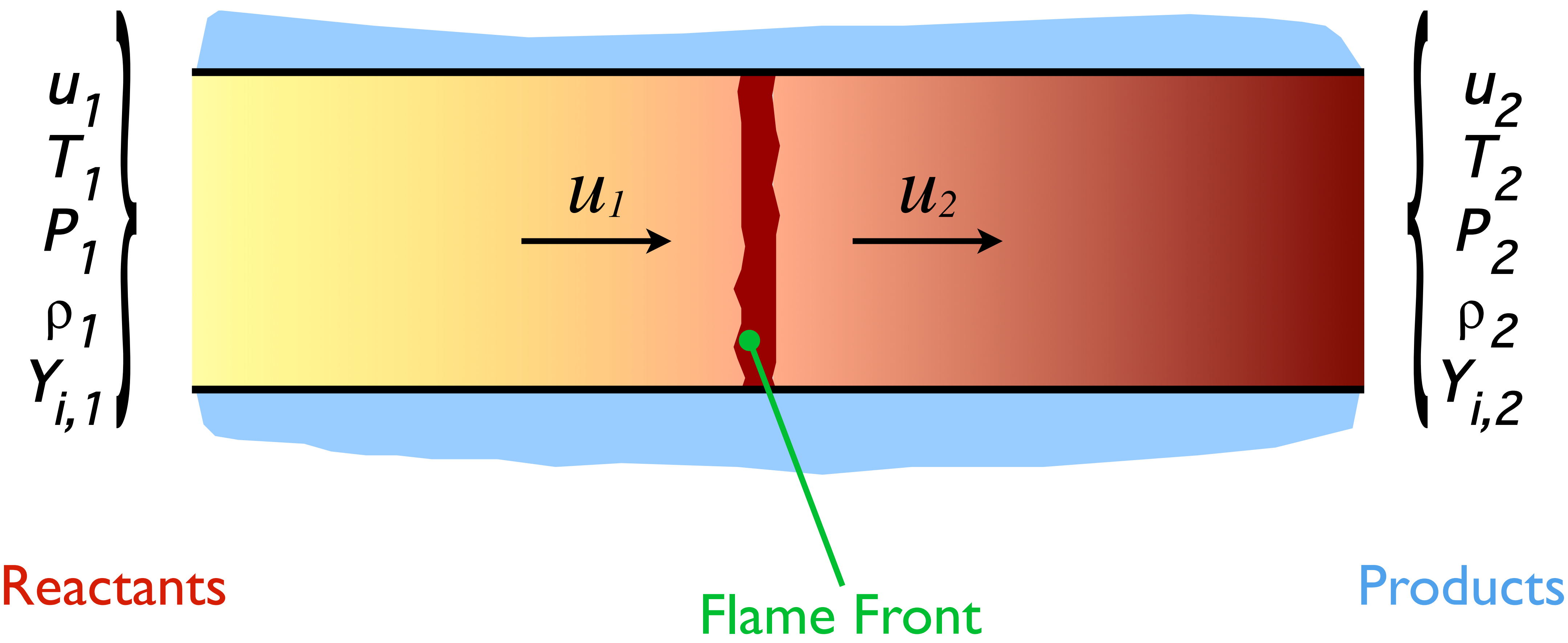
FLAME PROPAGATION
1D STEADY FLOW FORMULATION.



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FLAME PROPAGATION
1D STEADY FLOW FORMULATION.

in the laboratory frame (the flame propagates to the left at a speed v_0)

in a frame attached to the wave (the flow is steady)

fluid particle velocity $u = v + V_{\text{wave}}$

here $V_{\text{wave}} = -v_0$

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FLAME PROPAGATION
BALANCE EQUATIONS

Continuity
$$\frac{\partial \rho}{\partial t} + \underline{\nabla} \cdot (\rho \underline{v}) = 0$$

Momentum
$$\frac{\partial (\rho \underline{v})}{\partial t} + \underline{\nabla} \cdot (\rho \underline{v}\underline{v}) + \underline{\nabla} \cdot J_v = -\underline{\nabla} p$$

Enthalpy
$$\frac{\partial \left(\rho h^{tot}\right)}{\partial t} + \underline{\nabla} \cdot \left(\rho \underline{v} h^{tot}\right) + \underline{\nabla} \cdot J_{h^{tot}} = 0$$

Hp:

-1D

- *Stationary System*

$$\frac{d}{dx}(\rho u) = 0$$
$$\frac{d}{dx}(\rho u u + J_{u,x} + p) = 0$$
$$\frac{d}{dx}(\rho u h^{tot} + J_{h,x}) = 0$$

Integration along the x-direction between IN and OUT conditions

$$\dot{M} = \rho_1 u_1 = \rho_2 u_2$$
$$I = \rho_1 u_1^2 + p_1 = \rho_2 u_2^2 + p_2$$
$$h^{tot} = \frac{u_1^2}{2} + h_1^s + h_1^0 = \frac{u_2^2}{2} + h_2^s + h_2^o$$

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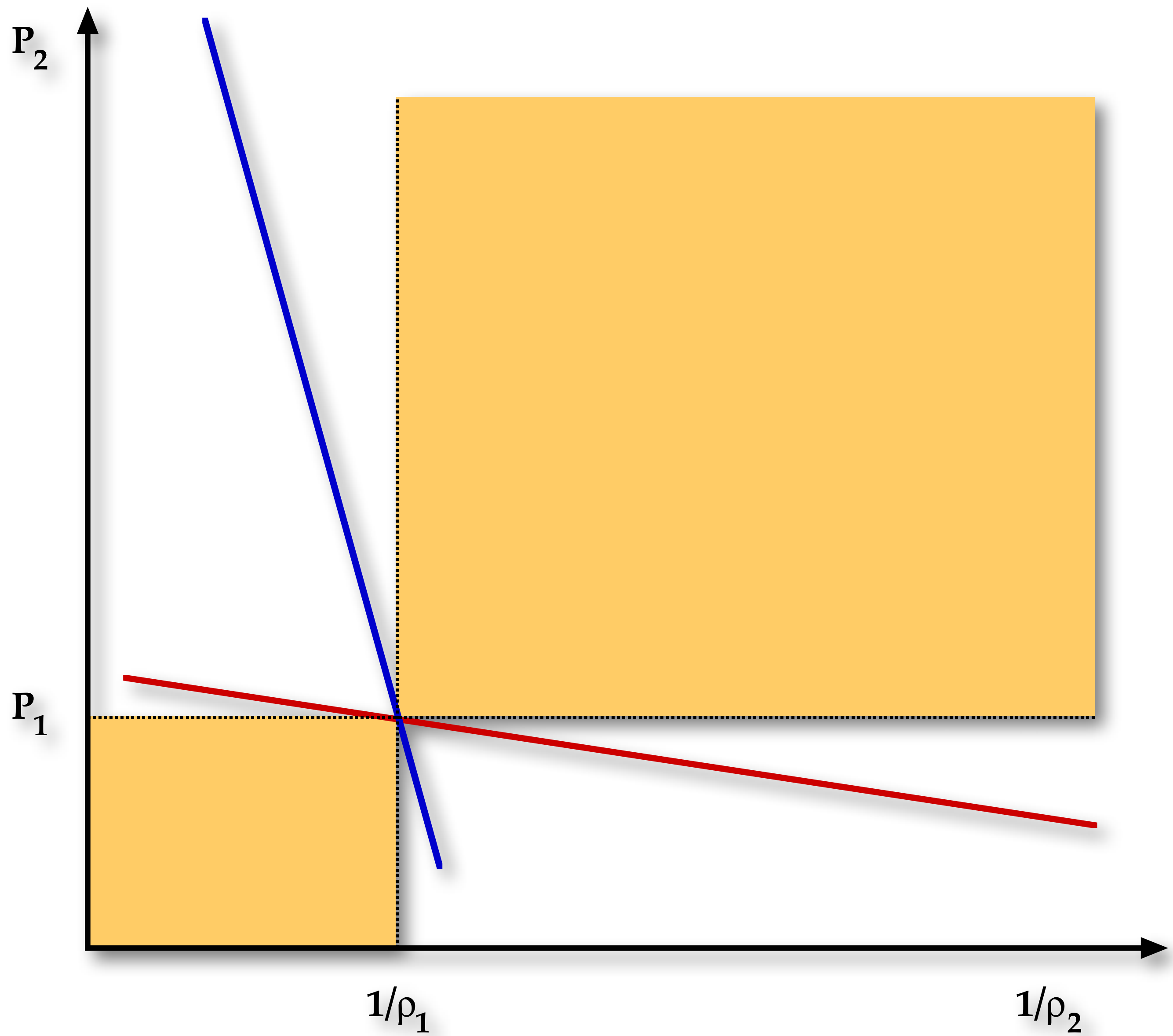
FLAME PROPAGATION
RAYLEIGH LINES

$$\frac{\dot{M}^2}{\rho_1} + p_1 = \frac{\dot{M}^2}{\rho_2} + p_2$$

$$p_2 - p_1 = -\dot{M}^2\left(\frac{1}{\rho_2} - \frac{1}{\rho_1}\right)$$



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FLAME PROPAGATION
DEFLAGRATION

- Expansion waves, propagate subsonically $(0 < M_0 < 1)$
- The burned gas expands and moves away from the wave front
- In a frame attached to the wave, the downstream flow beyond CJ waves is sonic $(M_\infty = 1)$
  for weak deflagrations $M_\infty < 1$
  for strong deflagrations $M_\infty > 1$
- Wave structure consideration forbids strong deflagrations (there is no structure that connects the burned and unburned states)
- There is a unique solution for the (weak) deflagration giving a definite wave speed for each gas mixture
- Deflagrations are nearly-isobaric $(p \approx \text{const.})$ such that $\rho \sim 1/T$ and propagate slowly $v_0 \sim 10 - 100\,\text{cm/s}$, producing heat

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FLAME PROPAGATION
DETONATION

- Compression waves, propagate supersonically $(1 < M_0 < \infty)$
- The wave retards the burned gas that compresses behind the wave front
- In a frame attached to the wave, the downstream flow beyond CJ waves is sonic $(M_\infty = 1)$
  for weak detonations $M_\infty > 1$
  for strong detonations $M_\infty < 1$
- A strong detonation can be produced by driving a piston at an appropriate speed
- There is only one wave speed at which a weak detonation can propagate (weak detonations are seldom observed)
- Self-sustained detonations are CJ detonations
- Detonations are rapid $(v_0 \sim 3000\,\mathrm{m/s})$ and violent $(p_\infty/p_0 \sim 20)$, with a significant increase in temperature $(T_\infty/T_0 \sim 10)$

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FLAME PROPAGATION
RANKINE-HUGONIOT

FROM BALANCE EQUATIONS:

$$h_2^s - h_1^s = \frac{(p_2 - p_1)}{2}\left(\frac{1}{\rho_2} + \frac{1}{\rho_1}\right) + \Delta h^o$$

HP:
-IDEAL GAS
- C_P= COST

$$h^s = c_p T = \frac{c_p}{R}\frac{p}{\rho} = \frac{\gamma}{\gamma - 1}\frac{p}{\rho}$$

$$\frac{\gamma}{\gamma - 1}\left(\frac{p_2}{\rho_2} - \frac{p_1}{\rho_1}\right) = \frac{(p_2 - p_1)}{2}\left(\frac{1}{\rho_2} + \frac{1}{\rho_1}\right) + \Delta h^o$$

PRESSURE RATIO

$$\frac{p_2}{p_1} = \frac{\frac{\rho_2}{\rho_1}\left(\frac{\gamma+1}{\gamma-1} + \frac{2\Delta h^o}{p_1/\rho_1}\right) - 1}{\frac{\gamma+1}{\gamma-1} - \frac{\rho_2}{\rho_1}} = \frac{(\gamma+1)\frac{1}{\rho_1} - (\gamma-1)\frac{1}{\rho_2} + 2(\gamma-1)\frac{\Delta h^o}{p_1}}{(\gamma+1)\frac{1}{\rho_2} - (\gamma-1)\frac{1}{\rho_1}}$$

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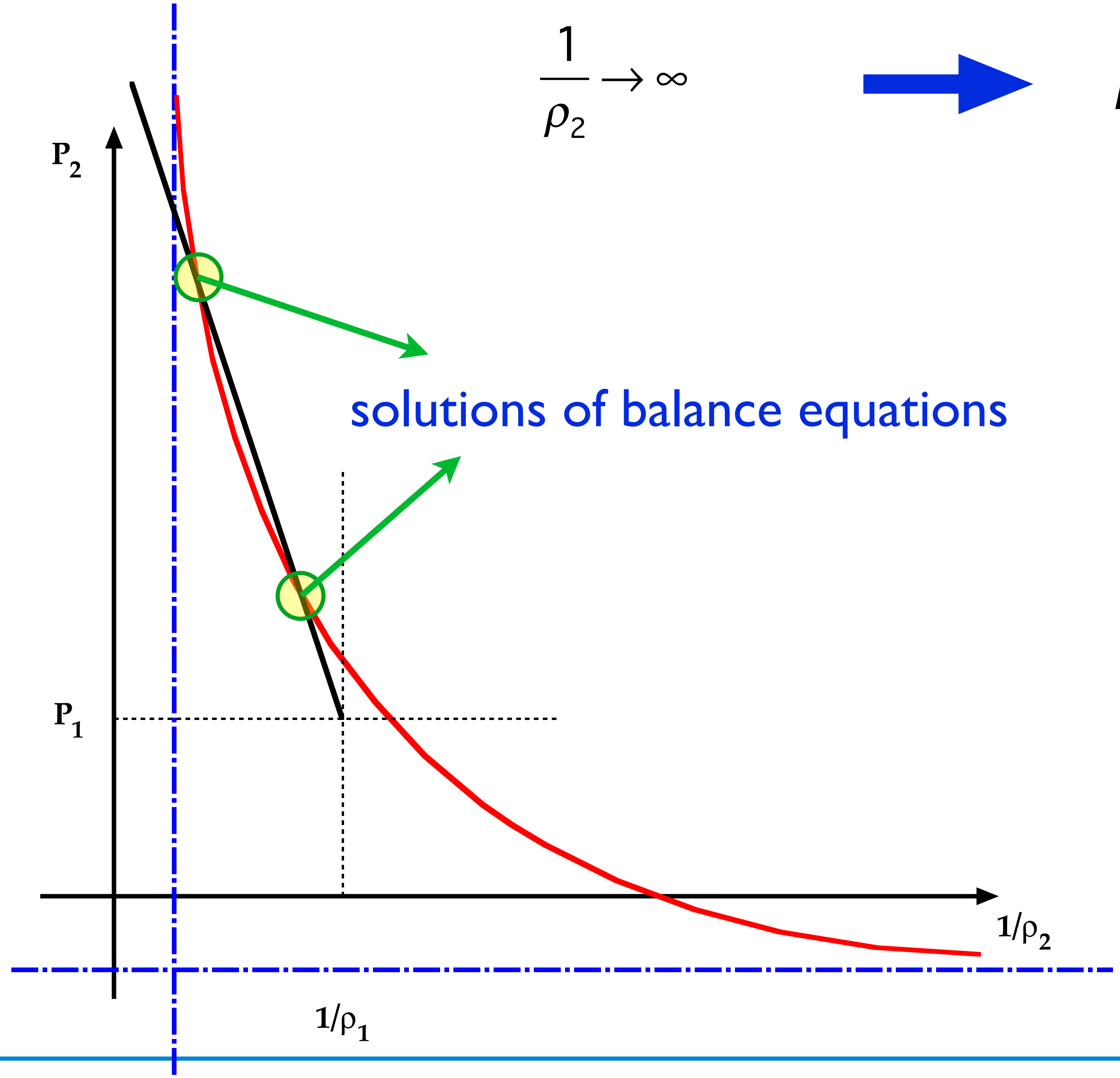
FLAME PROPAGATION
RANKINE-HUGONIOT CURVES

Asymptotic behaviours

$$\frac{1}{\rho_2} = \frac{1}{\rho_1}\frac{\gamma-1}{\gamma+1} \quad \Rightarrow \quad p_2 \to \infty$$

$$\frac{1}{\rho_2} \to \infty \quad \Rightarrow \quad p_2 = -p_1\frac{\gamma+1}{\gamma-1}$$



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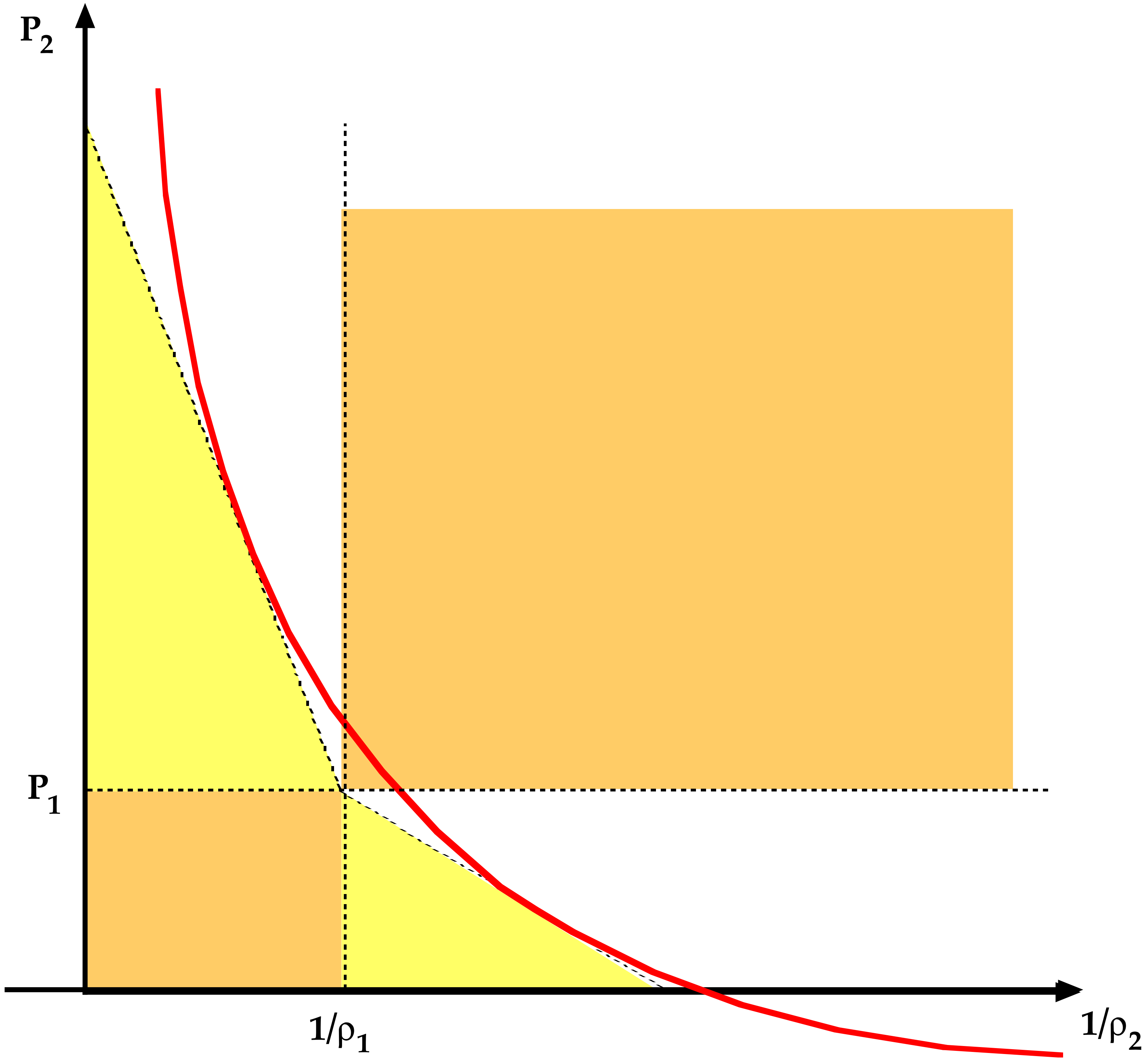
FLAME PROPAGATION



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FLAME PROPAGATION
CLASSIFICATION

Strong Detonation	$p_2 > p_{CJ} > p_1$
Chapman-Jouguet Detonation	$p_2 = p_{CJ} > p_1$
Weak Detonation	$p_{CJ} > p_2 > p_1$
Weak Deflagration	$p_1 > p_2 > p_{\mathrm{lim}}$
Limit Deflagration	$p_1 > p_{\mathrm{lim}} = p_2$
Strong Deflagration	$p_1 > p_{\mathrm{lim}} > p_2$

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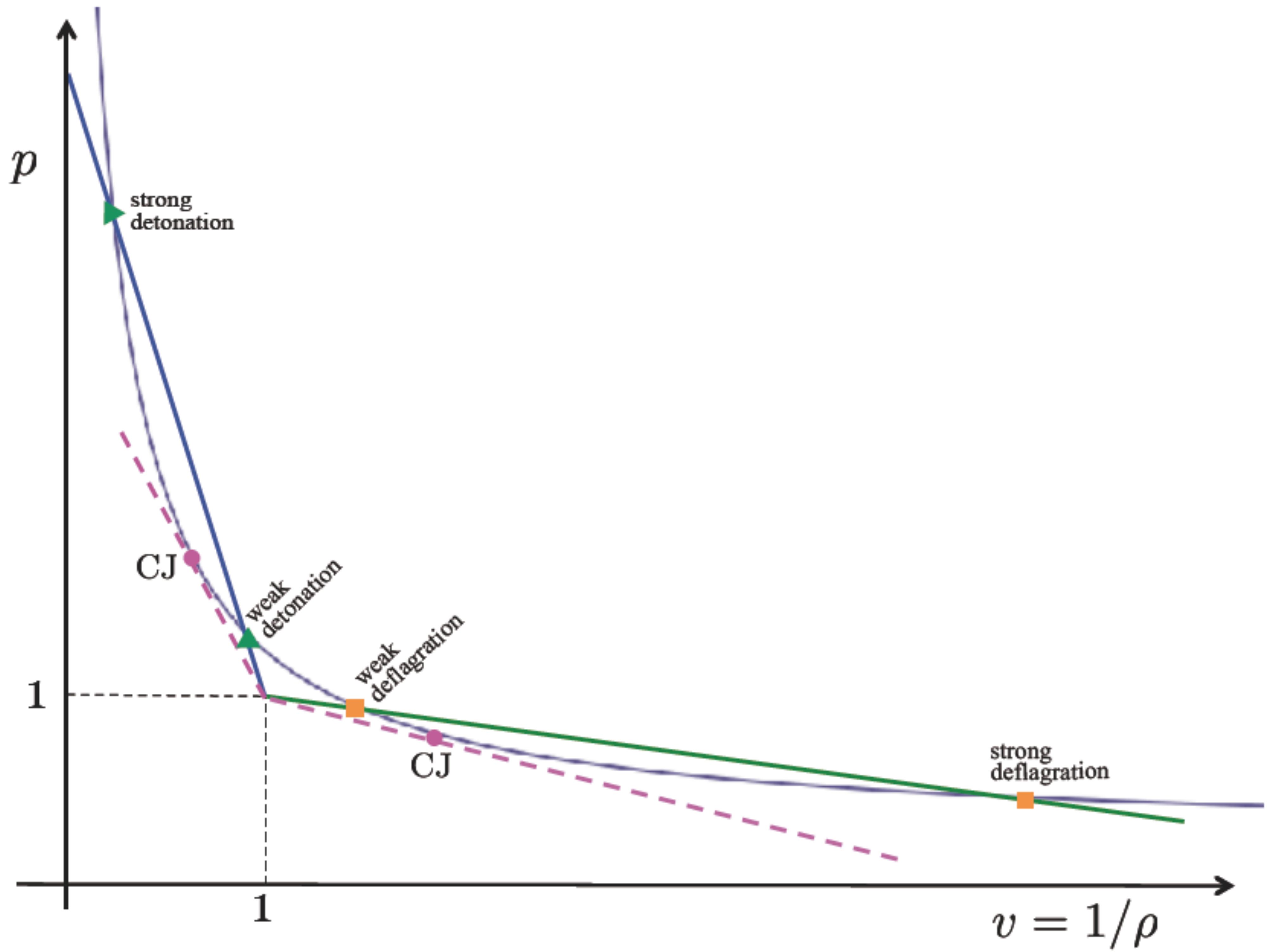
FLAME PROPAGATION
CLASSIFICATION



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DETONATION

Detonation is a combustion process in which there is a compression of the gaseous mixture from the inlet condition to products.

In the case of stationary detonation and due to the constraints imposed by the conservation of mass, momentum and total enthalpy, gases also undergo a density increasing and deceleration.

The detonation is defined as strong or weak depending on whether the pressure is greater or less than that of "Chapman-Jouguet (C-J).

The latter is defined as the solution obtained when the Rayleigh line is tangent to the Rankine-Hugoniot curve and takes its name from the authors (Chapman D.L, 1899; Jouguet E., 1906) .

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DETONATION

C-J CONDITION

Rankine-Hugoniot and Rayleigh curves admit a single solution in the conditions of Chapman-Jouguet (C-J), i.e. where the two curves are tangent to each other.
The generic tangent to the curve of Rankine Hugoniot is given by the derivative of the pressure (p2) in relation to the specific volume (1/ρ2). This can be obtained, in turn, by deriving, with respect to 1/ρ2 both the members of the Rankine Hugoniot .

$$\frac{\gamma}{\gamma-1}\frac{1}{\rho_2}\frac{dp_2}{d(1/\rho_2)}+\frac{\gamma}{\gamma-1}p_2=\frac{1}{2}\frac{dp_2}{d(1/\rho_2)}\left(\frac{1}{\rho_2}+\frac{1}{\rho_1}\right)+\frac{p_2-p_1}{2}$$

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DETONATION
C-J CONDITION

$$\frac{\gamma}{\gamma-1}\frac{1}{\rho_2}\frac{dp_2}{d(1/\rho_2)}+\frac{\gamma}{\gamma-1}p_2=\frac{1}{2}\frac{dp_2}{d(1/\rho_2)}\left(\frac{1}{\rho_2}+\frac{1}{\rho_1}\right)+\frac{p_2-p_1}{2}$$

$$\frac{\gamma}{\gamma-1}\frac{1}{\rho_2}\left(-\dot{M}^2\right)+\frac{\gamma}{\gamma-1}p_2=\frac{1}{2}\left(-\dot{M}^2\right)\left(\frac{1}{\rho_2}+\frac{1}{\rho_1}\right)+\frac{1}{2}\left(-\dot{M}^2\right)\left(\frac{1}{\rho_2}-\frac{1}{\rho_1}\right)$$

$$-\dot{M}^2\left(\frac{\gamma}{\gamma-1}\frac{1}{\rho_2}-\frac{1}{\rho_2}\right)=-\frac{\gamma}{\gamma-1}p_2$$

$$u_2^2=\gamma\frac{p_2}{\rho_2}=\gamma RT_2$$

$$u_2\Big|_{CJ}=a_2\Big|_{CJ}$$

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DETONATION

$$\frac{\gamma + 1}{\gamma} \geq \frac{\rho_2}{\rho_1} \geq 1$$

$$\frac{p_2}{p_1} = \frac{\rho_2}{\rho_1}\frac{T_2}{T_1}$$

$$\mathrm{u}_2\big|_{\mathrm{CJ}} = a_2\big|_{\mathrm{CJ}} = \mathrm{O}(1000\mathrm{ms}^{-1})$$

$$\mathrm{u}_1\big|_{\mathrm{CJ}} = \frac{\rho_2}{\rho_1} u_2\big|_{\mathrm{CJ}} = 2 * O(1000\mathrm{ms}^{-1}) = \mathrm{O}(2000\mathrm{ms}^{-1})$$

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DETONATION

H_2 /O2 100 kPa 298 K	H2 %	D-CJ m/s	D-CJ %
	66	2818	1.6
	80	3408	2
	85	3638	5
	87	3720	6
	88	3755	7
H2/CO/O2/Ar 3..3/30/16.7/50 298 K	**p, kPa**	**D-CJ m/s**	**D-CJ %**
	33.3	1629	3.7
	26.7	1623	3.5
	20.1	1615	5.4
	13.3	1603	7.3

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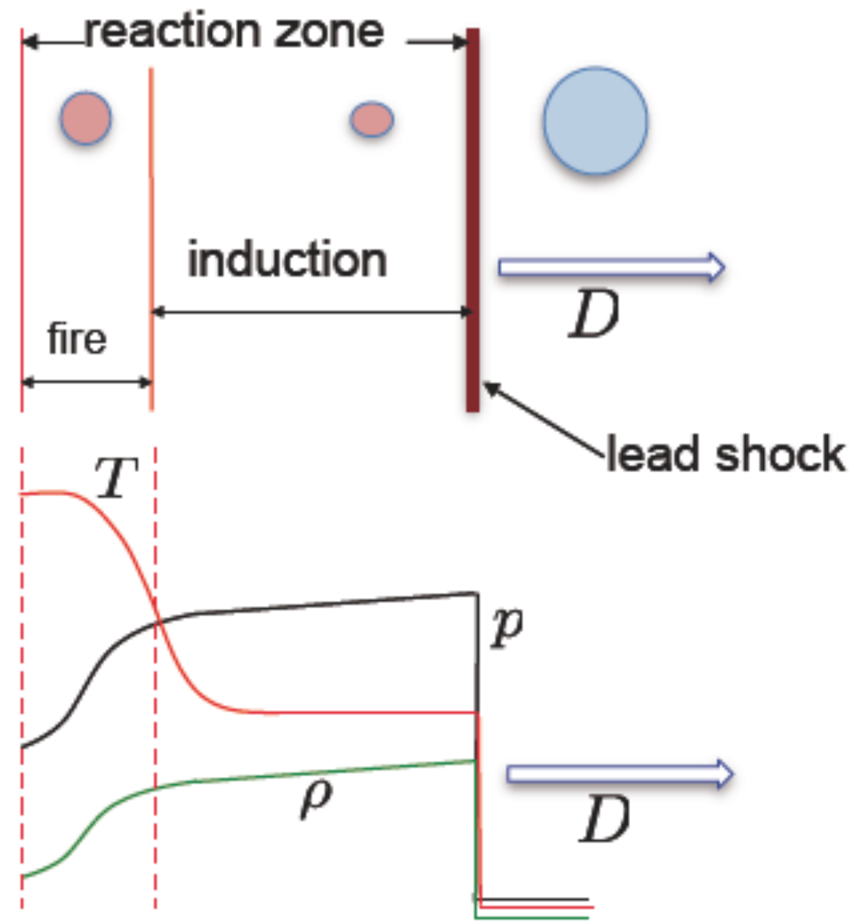
STRUCTURE OF A PLANAR DETONATION

The ZND structure

Zel'dovich (1940), von Neuman (1942), Doring (1944)

inert shock followed by a fast deflagration



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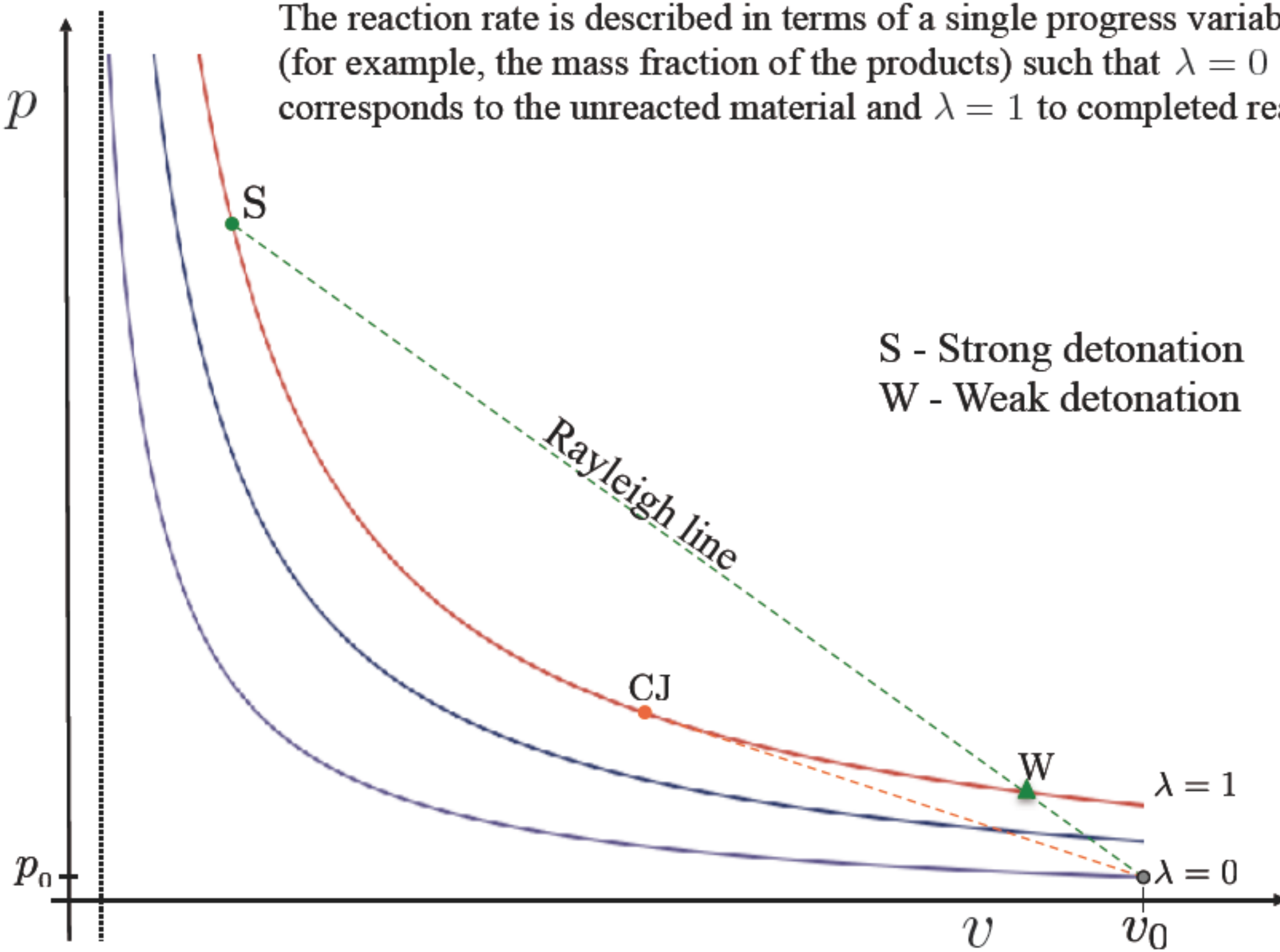
STRUCTURE OF A PLANAR DETONATION

The reaction rate is described in terms of a single progress variable λ, (for example, the mass fraction of the products) such that $\lambda = 0$ corresponds to the unreacted material and $\lambda = 1$ to completed reaction.



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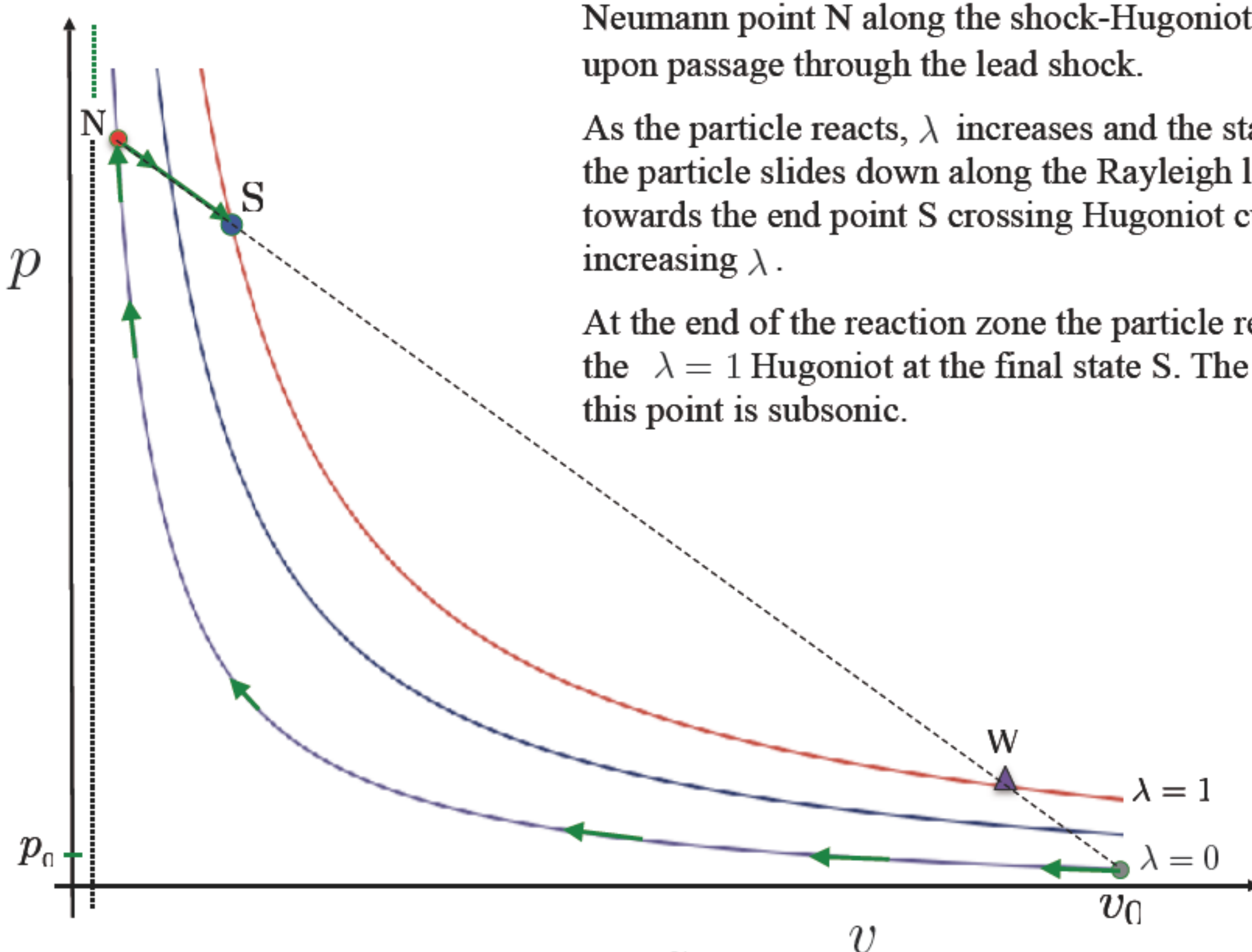
STRUCTURE OF A PLANAR DETONATION



Starting at (v_0, p_0) the state of the gas jumps to the Neumann point N along the shock-Hugoniot ($\lambda = 0$) upon passage through the lead shock.

As the particle reacts, λ increases and the state of the particle slides down along the Rayleigh line towards the end point S crossing Hugoniot curves of increasing λ.

At the end of the reaction zone the particle reaches the $\lambda = 1$ Hugoniot at the final state S. The flow at this point is subsonic.

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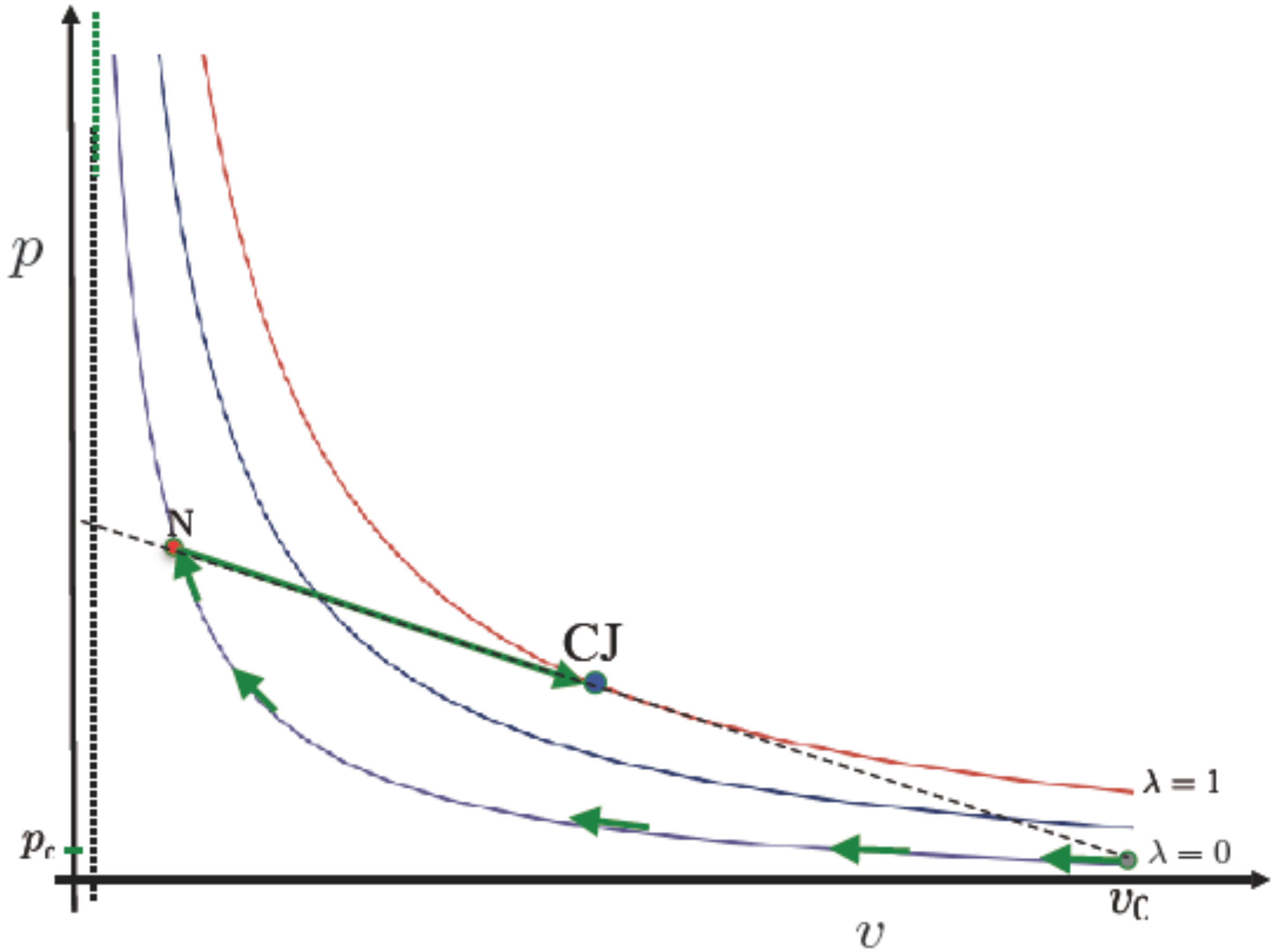
STRUCTURE OF A PLANAR DETONATION

The lowest possible Rayleigh line is the one tangent to the complete-reaction Hugoniot (i.e., corresponding to $\lambda = 1$). The final state in this case is the Chapman-Jouguet (CJ) state. The corresponding detonation speed D_{CJ} is the minimum speed consistent with the conservation laws.



The ZND structure is not possible for weak detonations

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DEFLAGRATION

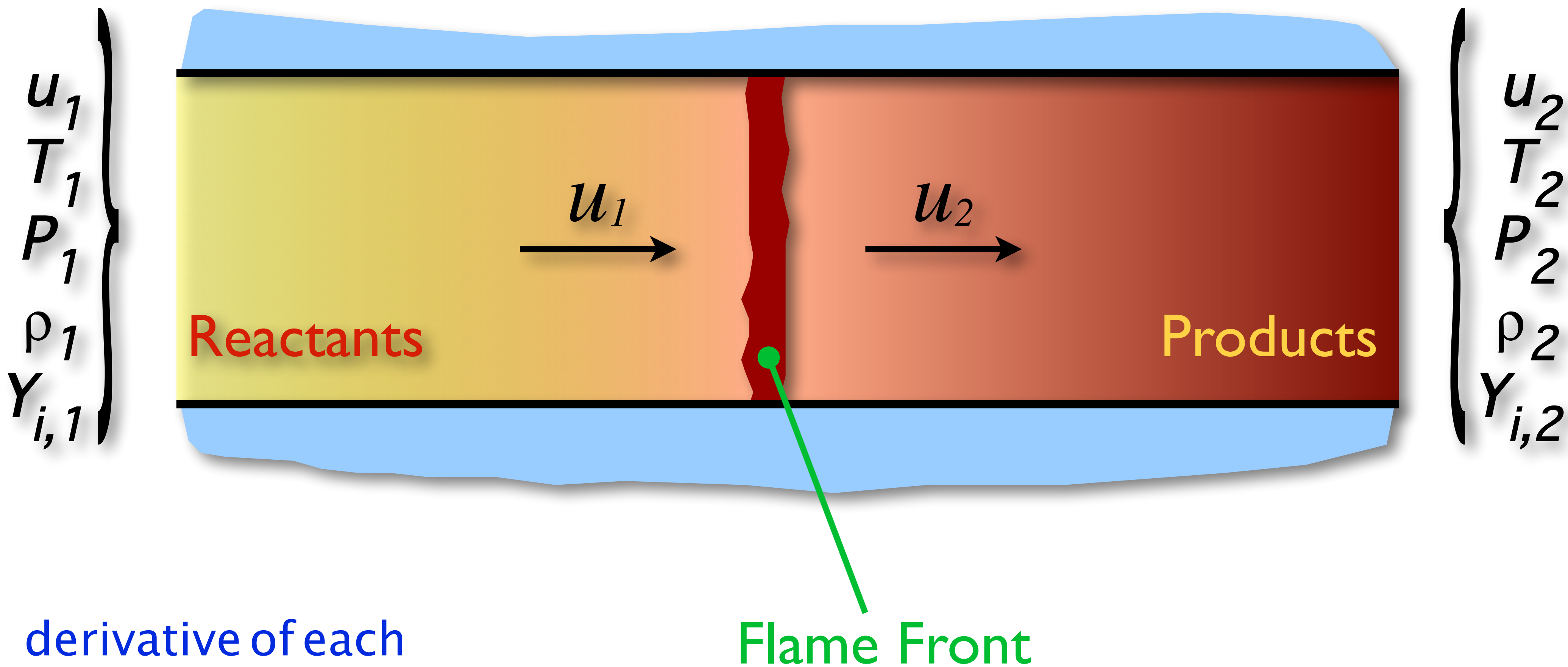
A propagation process, in which the release of energy generates an expansion (lowering of density and pressure) in the region occupied by the products of the oxidation reaction, is called **deflagration**.

The lowering of the pressure is almost always a negligible fraction of the average pressure detectable in the whole region affected by the combustion process. Therefore, the process is considered almost isobaric.
The expansion of the part of the mixture in which the combustion took place generates the velocity increase.

The region of the space in which the combustion process propagates during deflagration is usually referred to as the "flame front" or "combustion wave". The terms "deflagration" and "laminar premixed flame" are used in practice in the same scientific sense, although the second (flame) is generally associated with phenomena of light emission that extend its meaning in common use.

DEFLAGRATION

$$\rho_2 < \rho_1$$



Hp:

$+\infty$ e $-\infty$ derivative of each primitive variable is null

adiabatic system

$$P_2 < P_1 \quad \text{but} \quad \Delta P = P_1 - P_2 << P_1$$

$$u_2 > u_1$$

Usually reported as Planar premixed flame

DEFLAGRATION

Laboratory frame

$T = T_u$
$\rho = \rho_u$
$Y_F = Y_{F\,u}$
$Y_O = Y_{O\,u}$

$dT/dx = 0$
Y_F or/and $Y_O = 0$

Frame moving with the flame

$T = T_u$
$\rho = \rho_u$
$Y_F = Y_{F\,u}$
$Y_O = Y_{O\,u}$

$dT/dx = 0$
Y_F or/and $Y_O = 0$

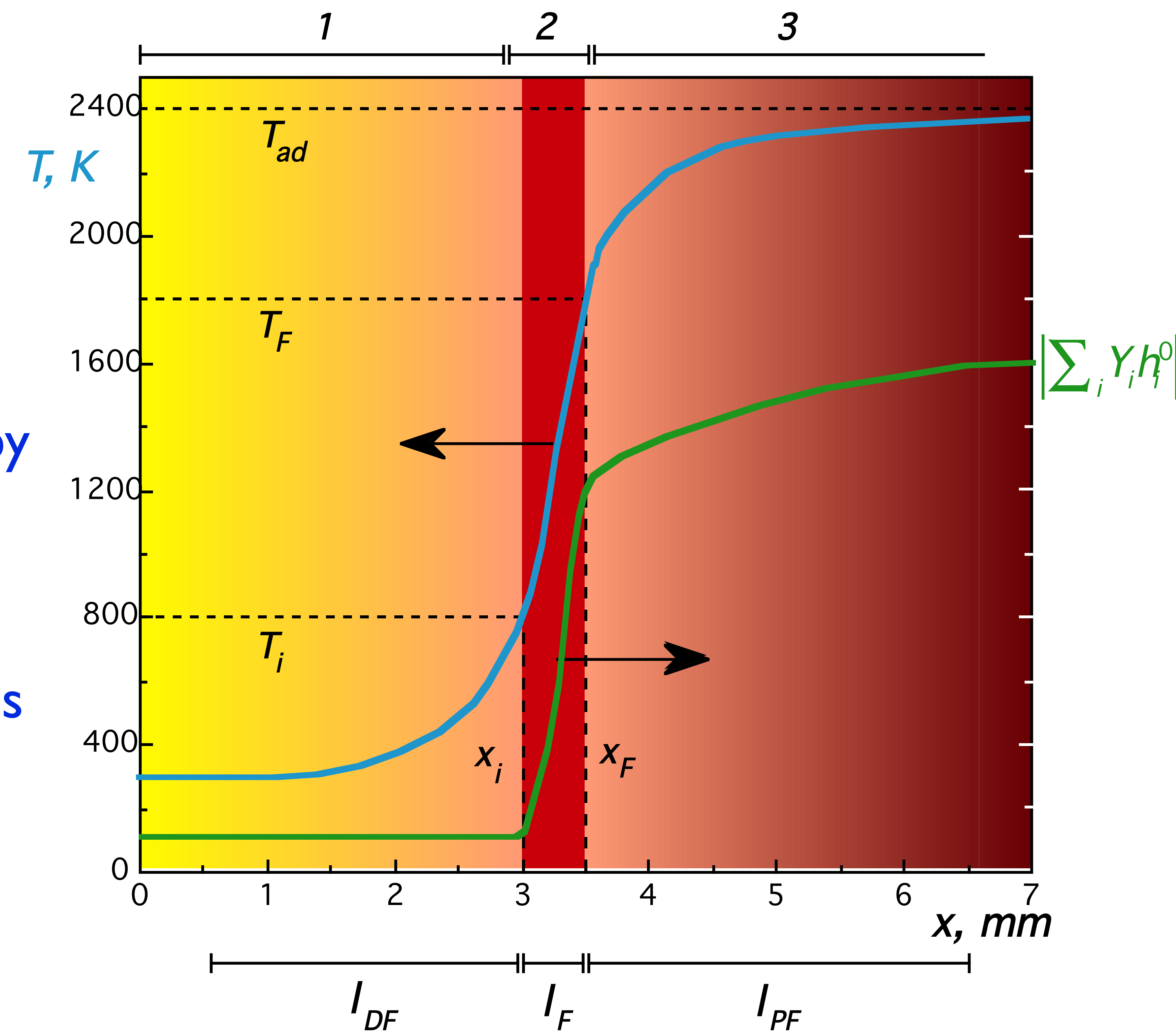
DEFLAGRATION- Thermal Theory
Mallard / Le Chatelier Model

- Hypothesis:
  - 1D motion
  - Stationary

l_{DF} = region controlled by diffusion

l_F = flame front thickness

l_{PF} = post-combustion region



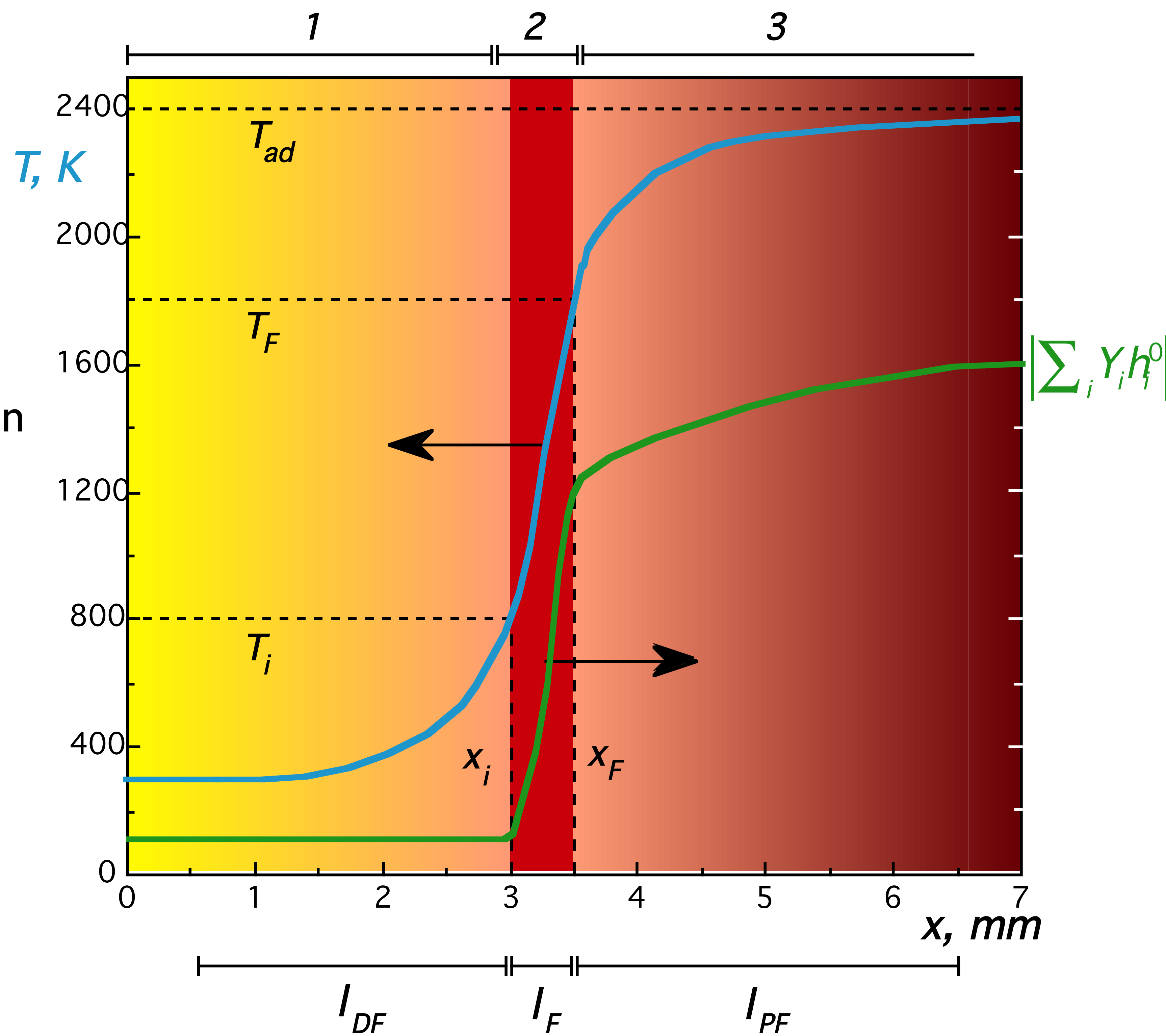
DEFLAGRATION- Thermal Theory
Mallard / Le Chatelier Model

The one-dimensional field is divided in 3 zones in series:

1) Region governed by convection and diffusion

2) Region governed by the convection and production of sensible enthalpy up to T_F

3) Region governed by the convection and enthalpy production up to Tad



DEFLAGRATION- Thermal Theory
Mallard / Le Chatelier Model

Balance of sensible enthalpy

$$\frac{\partial \rho h^s}{\partial t} + \underline{\nabla} \rho \underline{v} h^s - \underline{\nabla}\left(\rho \alpha \underline{\nabla} h^s\right) = -\sum \dot{\rho}_i h_i^o$$

Balance of chemical enthalpy

$$\frac{\partial \rho h^o}{\partial t} + \underline{\nabla} \rho \underline{v} h^o - \underline{\nabla} J_{h^o} = \sum \dot{\rho}_i h_i^o$$

Hp:
- 1D
- Stationary

$$\frac{d(\rho u h^s)}{dx} - \frac{d}{dx}\left(\rho \frac{d}{dx} h^s\right) = 0$$

Balance of Sensible Enthalpy in l_{DF}

$$\frac{d(\rho u h^o)}{dx} = \sum \dot{\rho}_i h_i^o$$

Balance of Chemical Enthalpy l_F

DEFLAGRATION- Thermal Theory
Mallard / Le Chatelier Model

Cp=constant

$$d\left[\rho u T - \rho\alpha\frac{dT}{dx}\right] = 0$$

integrating between the undisturbed condition (subscript 0) and the condition of ignition (subscript i), also considering that the convective flow of mass is a constant, is obtained

$$\rho u\left(T_i - T_o\right) - \rho_i\alpha_i\left(\frac{dT}{dx}\right)_i = 0$$

Hp:

- <u>Linear Temperature gradient in the flame region</u> → $\left(\frac{dT}{dx}\right) = \frac{T_F - T_i}{l_F}$
- Convective flux evaluated in the Ignition point
- Flame Speed is defined as: → $u_i = v_F$

$$v_F l_F = \alpha_i \frac{T_F - T_i}{T_i - T_o}$$

The Laminar Flame Speed v_F is the gas velocity in the ignition point

DEFLAGRATION- Thermal Theory
Mallard / Le Chatelier Model

Relation between flame speed and flame thickness

$$v_F l_F = \alpha_i \frac{T_F - T_i}{T_i - T_o}$$

Burning velocity

$$u_o = \frac{\rho_i}{\rho_o} v_F$$

Integrating twice the balance of sensible enthalpy in the region controlled by the diffusion

$$v_F l_{DF} = \alpha_i \ln\left(\frac{T_i - T_o}{T - T_o}\right)$$

Flame speed estimation

$$v_F l_F = \alpha_i \frac{T_F - T_i}{T_i - T_o}$$

Integrating the balance of chemical enthalpy in the flame region

$$\rho_i u_i \left[h_F^o - h_i^o \right] = \int_{x_i}^{x_F} \sum \left(\dot{\rho}_i h_i^o \right) dx$$

we can define a conversion degree

$$\varepsilon(x) = \frac{\sum \dot{\rho}_i h_i^o}{\rho_i \left[h_F^o - h_i^o \right]}$$

$$v_F = \int_i^F \varepsilon(x)\, dx = \bar{\varepsilon}\, l_F$$

$$v_F = \sqrt{\alpha_i \frac{T_F - T_i}{T_i - T_o} \bar{\varepsilon}}$$

ε(x) :

$$\bar{\varepsilon} \propto \exp\left(-\frac{1}{T} \right) p^{n-1}$$

Deflagration/dependencies

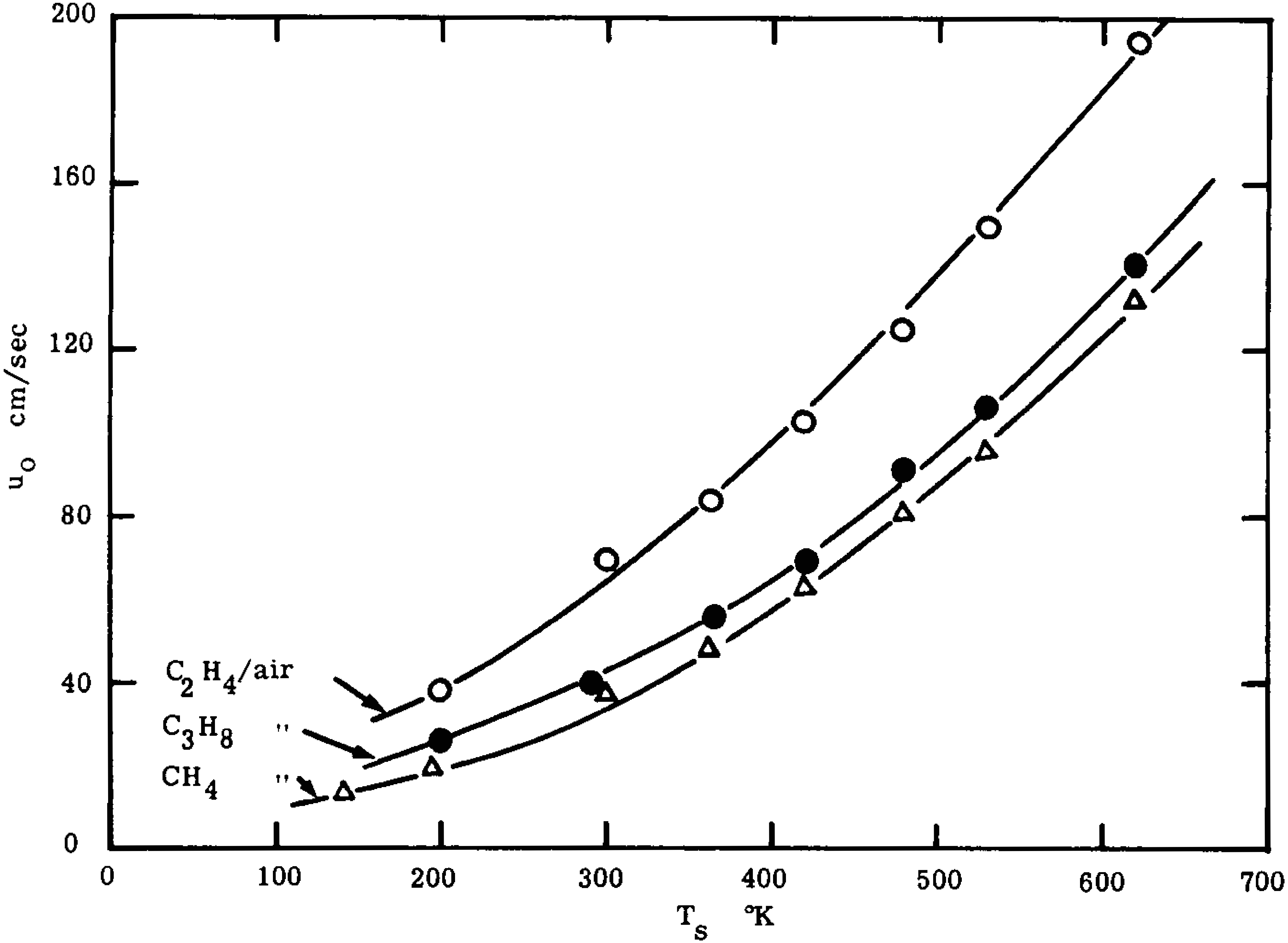
$$v_F l_F = \alpha_i \frac{T_F - T_i}{T_i - T_o}$$

$$v_F l_{DF} = \alpha_i \ln\left(\frac{T_i - T_o}{T - T_o}\right)$$

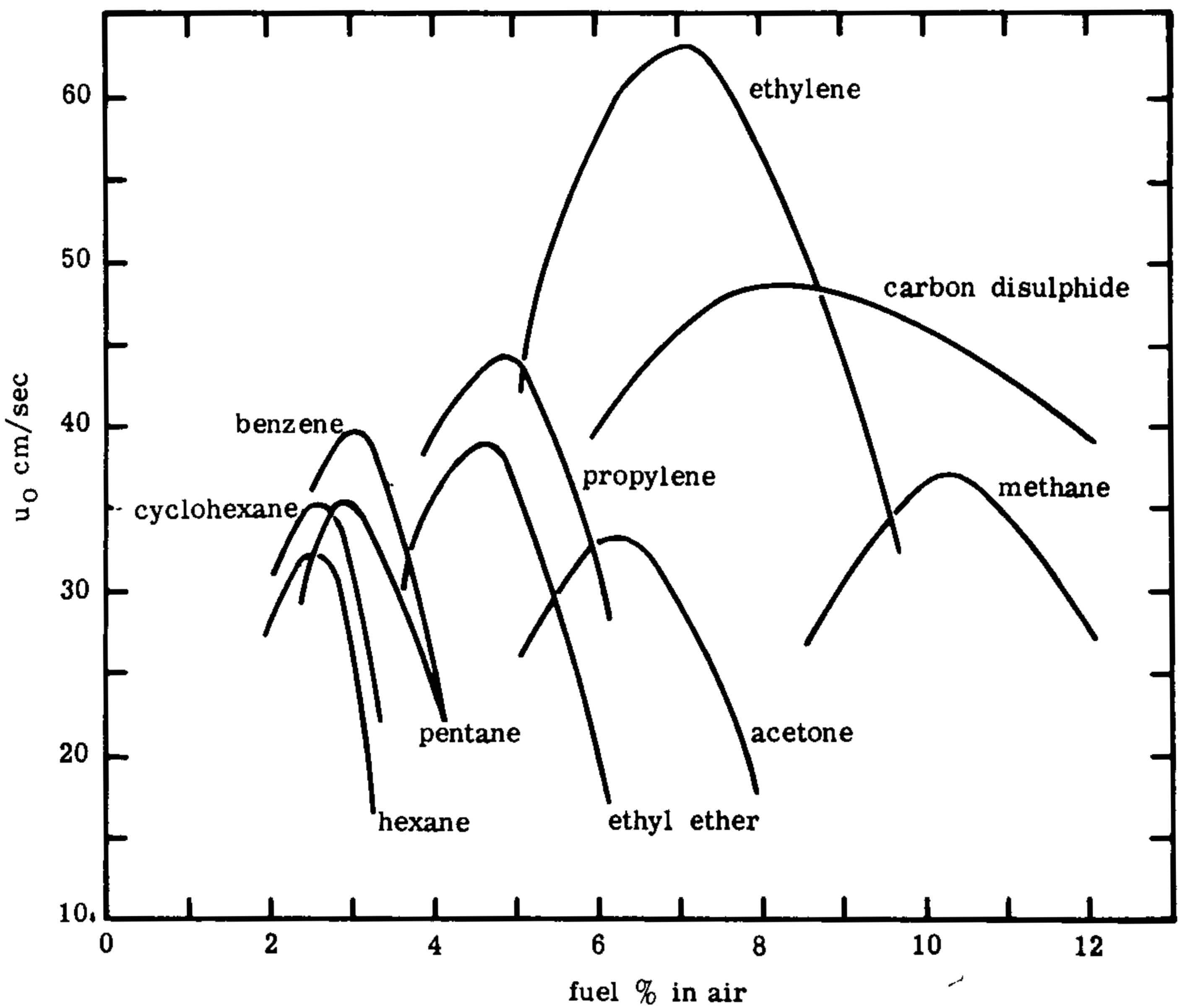
$$v_F = \sqrt{\alpha_i \frac{T_F - T_i}{T_i - T_o}\bar{\varepsilon}}$$

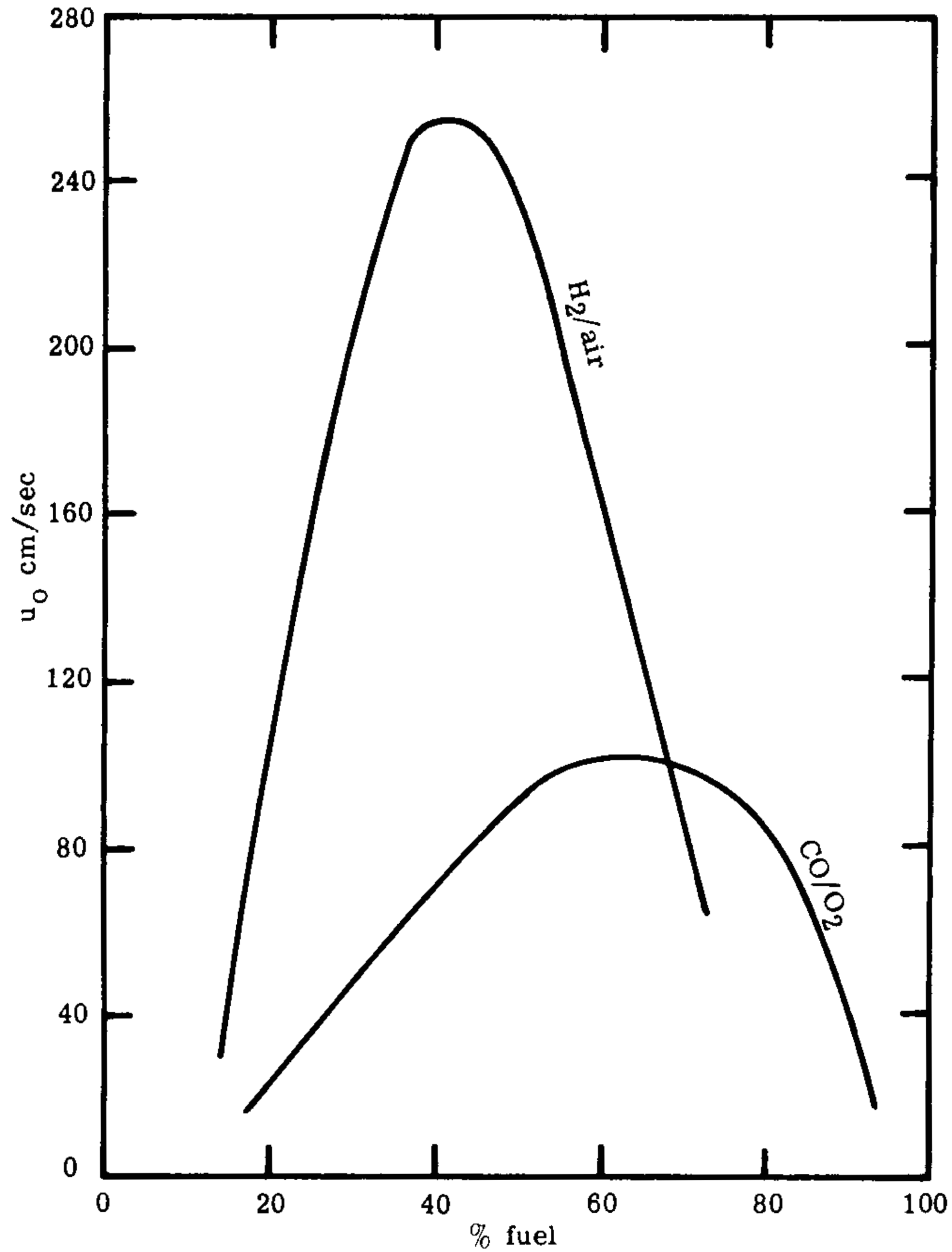
Laminar flame speed depends on various parameters such as ambient temperature, air/fuel ratio, fuel nature and pressure

Effect of ambient temperature



effect of fuel/air ratio





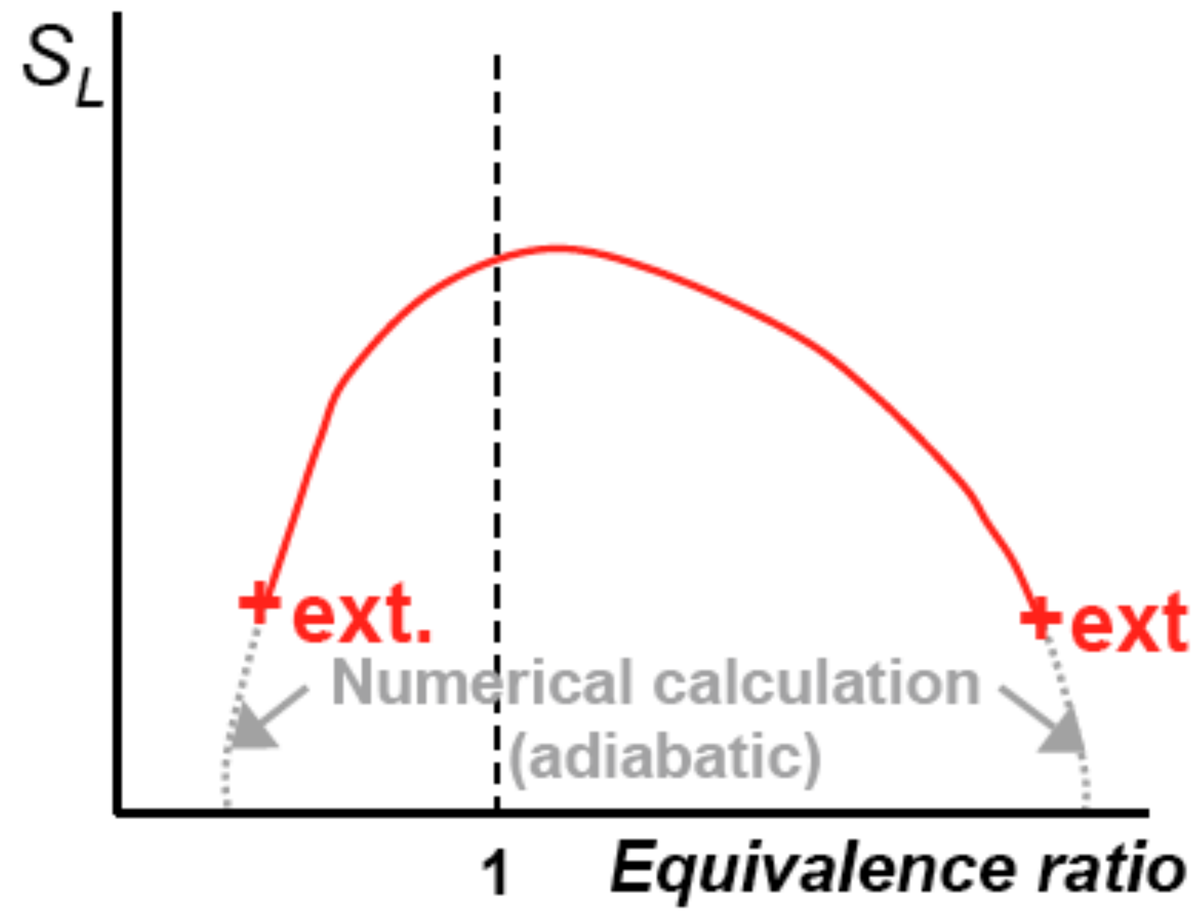
flammability limits

- **Definition:**

  - Limiting composition for (premixed) flame propagation
    $\Rightarrow$ a limit at which heat generation cannot keep up with (heat) loss

  - Some amount of heat or radical loss is essential

  - Ideally, it is believed to be a fundamental quantity for a given fuel/oxidizer mixture.



flammability limits

- **Empirical Limits**
  - LFL (lean) and UFL (rich)
  - Depends on experimental configuration
  - US Bureau of Mines
    51mm x 1.5m tube
    Upward (more conservative)
    & downward propagation
  - Temperature increase
    ⇒ both LFL/UFL widens
  - Pressure increase
    ⇒ LFL: narrows
    ⇒ UFL: narrows for H_2
    widens for other hydrocarbons

Fuel	Lean Limit	Rich Limit
H_2	4.00 (0.10)	75.0 (7.14)
CO	12.5 (0.34)	74.0 (6.8)
NH_3	15.0 (0.63)	28.0 (1.4)
CH_4	5.0 (0.50)	14.9 (1.67)
C_2H_6	3.0 (0.52)	12.4 (2.4)
C_3H_8	2.1 (0.56)	9.5 (2.7)
C_4H_{10}	1.8 (0.57)	8.4 (2.8)
C_2H_4	2.7 (0.40)	36.0 (8.0)
C_2H_2	2.5 (0.31)	100.0 (∞)
C_6H_6	1.3 (0.56)	7.9 (3.7)
CH_3OH	6.7 (0.51)	36.0 (4.0)
C_2H_5OH	3.3 (0.41)	19.0 (2.8)

Flammability limits at 1atm, in mole % and (ϕ):
Zabetakis, US Dept. of Mines Bulletin 627 (1965).

flammability limits

- **Le Chatelier's Rule (Empirical Rule for Mixture)**

  For a mixture of *N* components:

$$(LFL)_{mixture} = \left[\sum_{i=1}^{N} \frac{X_i}{(LFL)_i} \right]^{-1}$$

where X_i : mole fraction of the ith component

e.g. for 50% hydrogen and 50% CO:

$$(LFL)_{mixture} = \left[\frac{0.5}{4} + \frac{0.5}{12.5} \right]^{-1} = 6.1\%$$

  The rule can be extended for a fuel with dilution:

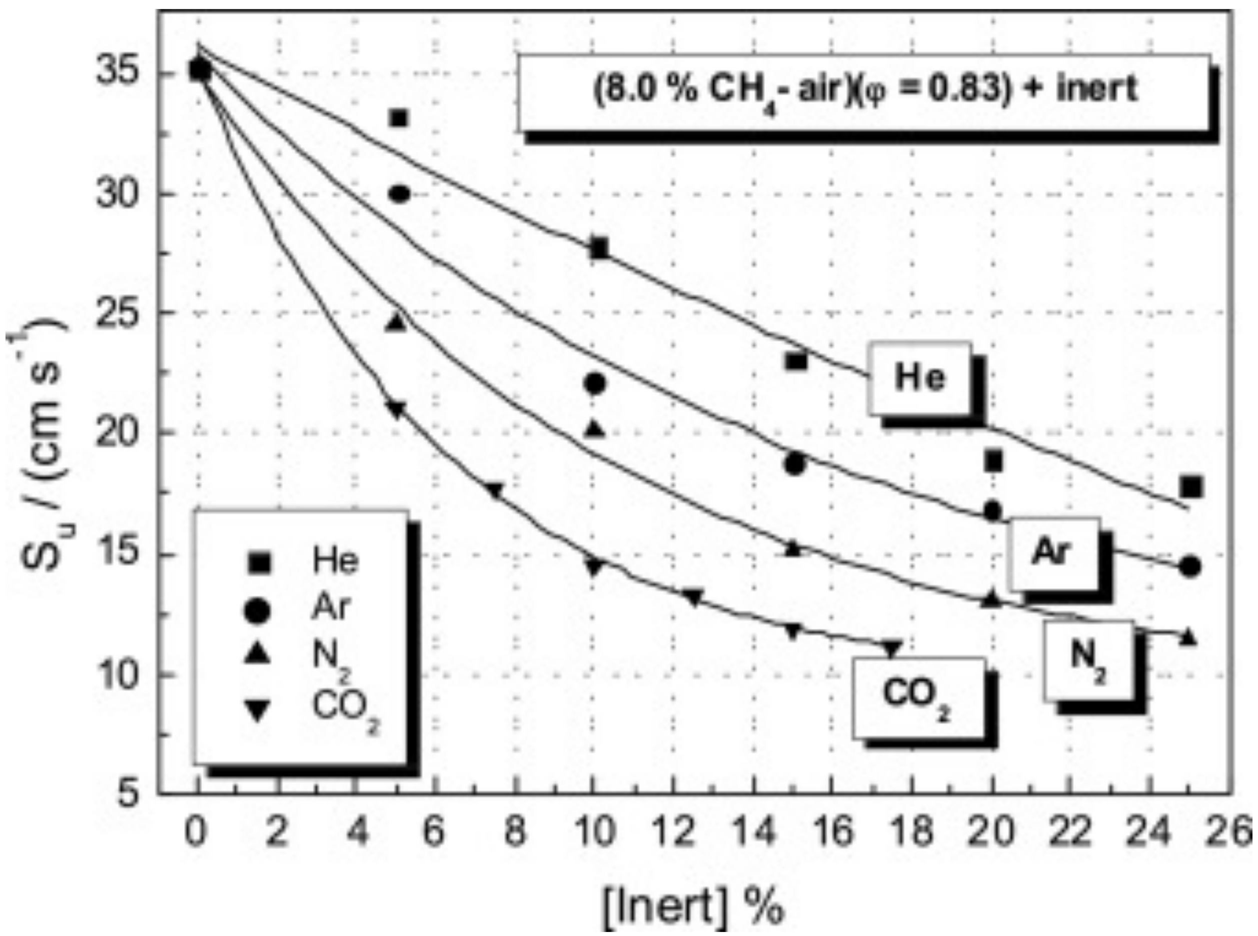
$$(LFL)_{dilution} = \left[\frac{X_F}{(LFL)_F} + \frac{X_I}{(LFL)_I} \right]^{-1} = \frac{(LFL)_F}{X_F}$$

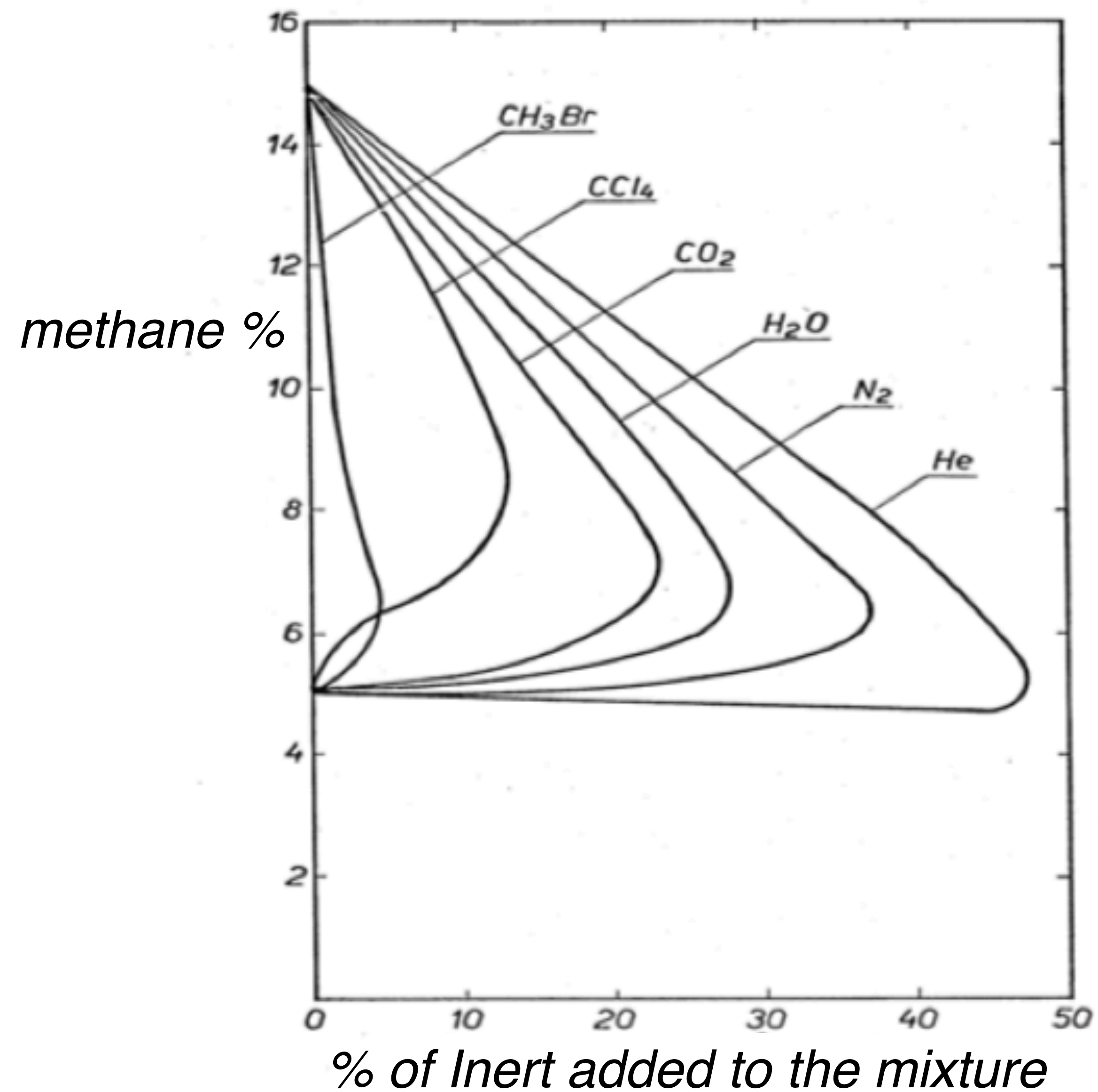
since $(LFL)_I \to \infty$

  For a mixture of fuels and dilution:

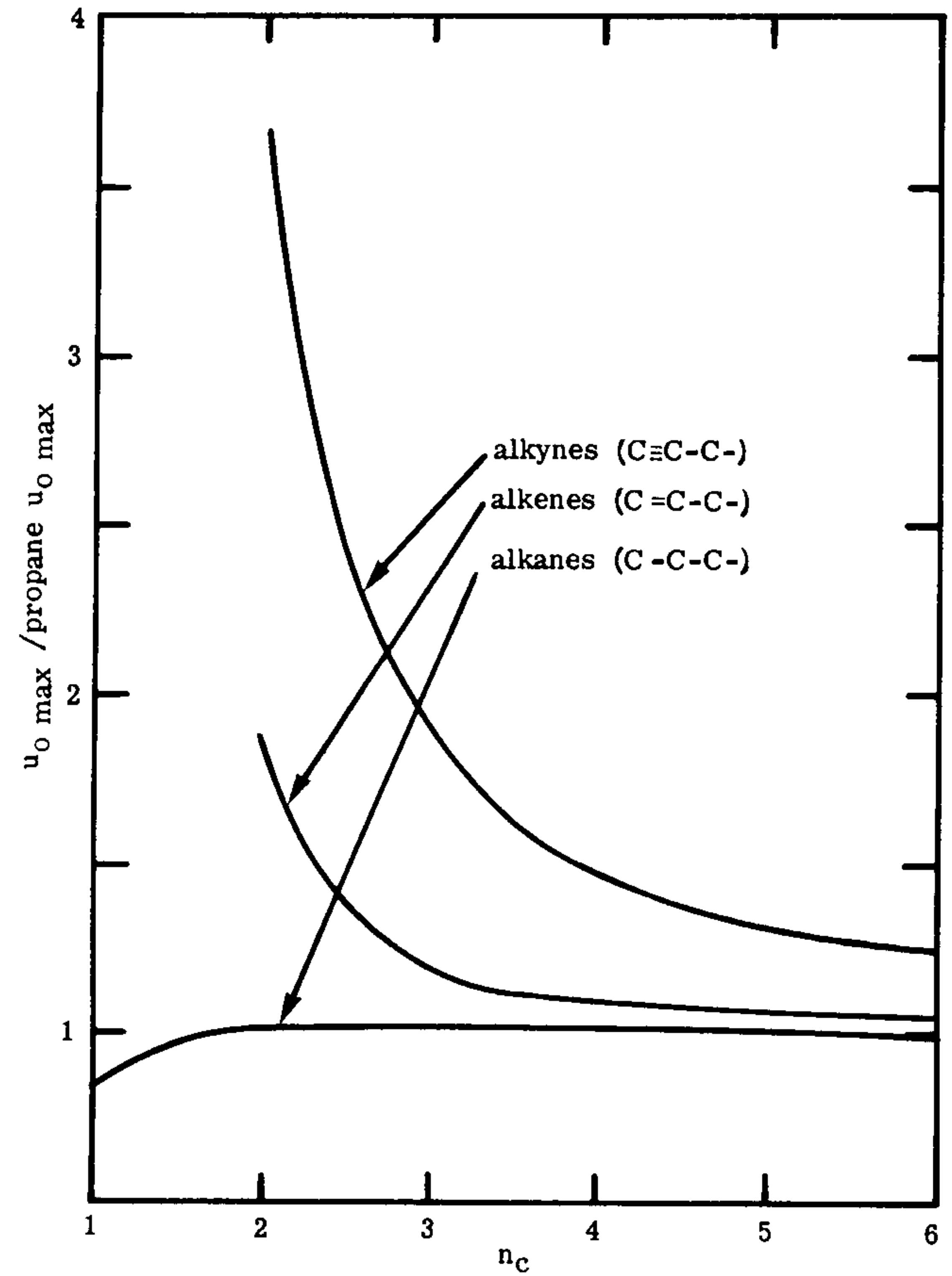
$$(LFL)_{mixture,dilution} = \frac{(LFL)_{mixture}}{X_{mixture}}$$

Inert effect





Fuel nature effects



Effect of the Pressure

Diffusivity $D \propto \frac{1}{\rho} \propto \frac{1}{p}$

Conversion degree $\bar{\varepsilon} \propto \exp\left(-\frac{1}{T}\right) p^{n-1}$

$$u_o \propto v_F \propto \sqrt{p^{n-1-1}} = p^{\frac{n-2}{2}}$$

It is observed experimentally that u_0 does not depend on the pressure for many fuels so it can be assumed that the overall order n of the reaction is about 2.

single-step reaction rate parameters

(best agreement between experimental/computational flammability limits)

$$\omega = \mathcal{B} \exp -(E_a/\mathcal{R}T)\ [\text{Fuel}]^a [\text{Oxidizer}]^b$$

Single-step reaction rate parameters giving best agreement between experimental flammability limits (ϕ_L' and ϕ_R') and computed flammability limits (ϕ_L and ϕ_R). Units are cm-sec-mole-kcal-Kelvins

Fuel	A	E_a	a	b	ϕ_L'	ϕ_L	ϕ_R'	ϕ_R
CH_4	1.3×10^{8}	48.4	−0.3	1.3	0.5	0.5	1.6	1.6
CH_4	8.3×10^{5}	30.0	−0.3	1.3	0.5	0.5	1.6	1.6
C_2H_6	1.1×10^{12}	30.0	0.1	1.65	0.5	0.5	2.7	3.1
C_3H_8	8.6×10^{11}	30.0	0.1	1.65	0.5	0.5	2.8	3.2
C_4H_{10}	7.4×10^{11}	30.0	0.15	1.6	0.5	0.5	3.3	3.4
C_5H_{12}	6.4×10^{11}	30.0	0.25	1.5	0.5	0.5	3.6	3.7
C_6H_{14}	5.7×10^{11}	30.0	0.25	1.5	0.5	0.5	4.0	4.1
C_7H_{16}	5.1×10^{11}	30.0	0.25	1.5	0.5	0.5	4.5	4.5
C_8H_{18}	4.6×10^{11}	30.0	0.25	1.5	0.5	0.5	4.3	4.5
C_8H_{18}	7.2×10^{12}	40.0	0.25	1.5	0.5	0.5	4.3	4.5
C_9H_{20}	4.2×10^{11}	30.0	0.25	1.5	0.5	0.5	4.3	4.5
$C_{10}H_{22}$	3.8×10^{11}	30.0	0.25	1.5	0.5	0.5	4.2	4.5
CH_3OH	3.2×10^{12}	30.0	0.25	1.5	0.5	0.5	4.1	4.0
C_2H_5OH	1.5×10^{12}	30.0	0.15	1.6	0.5	0.5	3.4	3.6
C_6H_6	2.0×10^{11}	30.0	−0.1	1.85	0.5	0.5	3.4	3.6
C_7H_8	1.6×10^{11}	30.0	−0.1	1.85	0.5	0.5	3.2	3.5
C_2H_4	2.0×10^{12}	30.0	0.1	1.65	0.4	0.4	6.7	6.5
C_3H_6	4.2×10^{11}	30.0	−0.1	1.85	0.5	0.5	2.8	3.0
C_2H_2	6.5×10^{12}	30.0	0.5	1.25	0.3	0.3	>10.0	>10.0

Westbrook & Dryer, CST 1981

$$E_a \approx 30 - 50\ \text{kcal/mole}\cdot\text{K} \qquad \mathcal{R} = 1.987\,\text{cal/g}\cdot\text{mol}\,\text{K} \quad \Rightarrow \quad E_a/\mathcal{R} \approx 18{,}000\,\text{K}$$

Zel'dovich number

$$\beta = \frac{E(\tilde{T}_a - \tilde{T}_u)}{\mathcal{R}\tilde{T}_a^2}$$ Zel'dovich number

$\beta \sim 10$ for hydrocarbon-air flames

$$\beta_0 = \frac{\beta T_a^2}{T_a - 1} \quad \Rightarrow \quad \omega = D\rho^n Y_F^{n_F} Y_O^{n_O} \exp\left[\frac{\beta T_a}{T_a - 1}\left(\frac{T - T_a}{T}\right)\right]$$

flame thickness

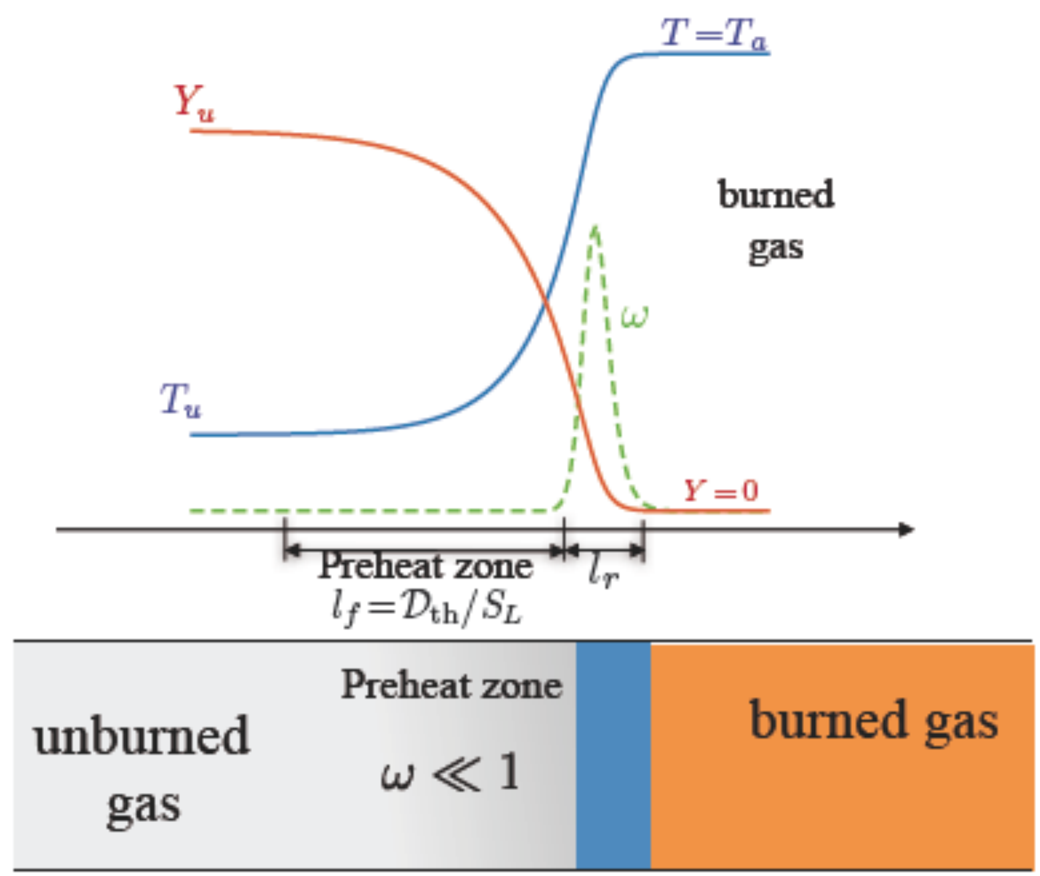
$$l_f = \mathcal{D}_{th}/S_L$$

typically, $l_f \sim 1\,\mathrm{mm}$

reaction zone thickness

$$l_R = \mathcal{D}_{th}/\beta S_L \ll l_f$$

$l_R \sim 0.1\,\mathrm{mm}$



Reaction is confined within a thin layer of $\delta_R \sim \delta_T / \beta$

COURSE OVERVIEW

DAY 2

Combustion with Flame Propagation

a. One Dimensional Steady Flow formulation.
b. Rayleigh and Rankine-Hugoniot equations.
c. Detonation.
d. Deflagration. Thermal theory. Flame Speed Dependencies.

Laminar Diffusion Flames

a. Flame Structure and Mixture Fraction.
b. Infinitely fast chemistry. Flamelet concept.
c. 1D Steady Diffusion flames. Strained/Unstrained.
d. 1D Unsteady Diffusion flames. Strained/Unstrained.
e. Diluted conditions. Diffusion Ignition processes.

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