COURSE OVERVIEW

DAY 3

Complex Flame Structures

a. Interaction of Multiple Mixing Layers
b. Partially Premixed Combustion. The Structure of Triple Flames
b. Lifted flames and lift-off height
d. Triple flame propagation

Turbulence, Mixing and Aerodynamics

a. Characteristics and Description of Turbulent Flows
b. Turbulent Premixed Combustion. Scales and Dimensionless Quantities.
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e. Flashback and Blowoff
f. Swirl and reverse flows

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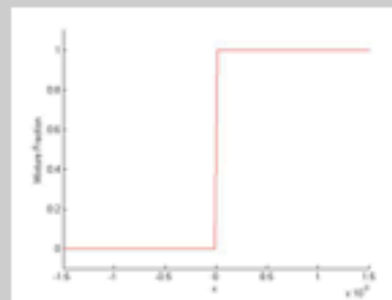
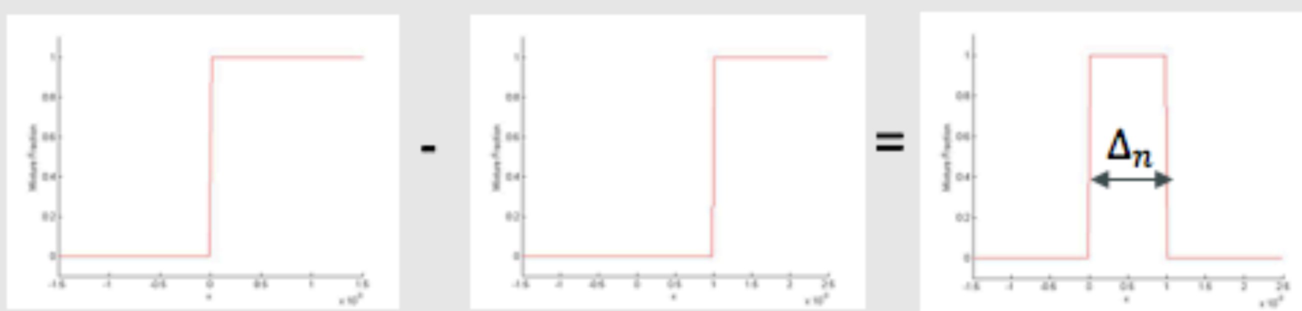
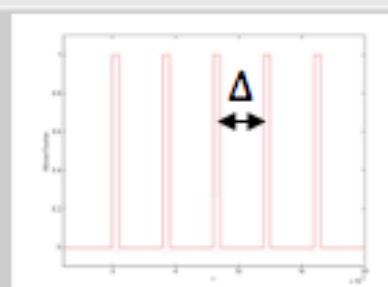
Multiple Mixing Layers

Definition of the class	Schematic representation	Representative equations
Isolated single layer		$Z = \frac{1}{2}\left[1 + erf\left(\frac{x}{\delta_m}\right)\right],$ $\delta_m = \delta_{0.9} = \sqrt{4Dt}$
Double layer		$Z = \frac{1}{2}\left[erf\left(\frac{x}{\delta_m}\right) - erf\left(\frac{x-\Delta_n}{\delta_m}\right)\right]$
Multiple layer		$Z = \sum_{i=0}^{n}\frac{1}{2}\left[\left(erf\left(\frac{x-n\Delta-\Delta_n}{\delta_m}\right)\right) - erf\left(\frac{x-n\Delta}{\delta_m}\right)\right]$

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Single and Multiple Mixing Layers

- The evolution of mixing layer is a well studied problem in different frameworks, referring to several geometrical constraints and to very broad field of applications.
- A synthesis of **one dimensional evolution** is given here since this a sufficient scheme to envisage the physics of the process and its insert in more complex models.
- The same information can be obtained for multidimensional conditions if this implementation is required, but it makes the analysis and the control of more complicated process.
- Whatever conservative quantity, for instance the mixture fraction Z, can only be transported. In reference coordinates fixed in the origin on the interface and oriented with one axis perpendicularly to the interface, the mixture fraction along this coordinate is given by the following equation:

$$Z = \frac{1}{2}\left[1 + erf\left(\xi = \frac{x}{\delta_m}\right)\right]$$

where erf is the error function, x is the coordinate normal to the interface and δ_m Is mixing layer thickness, given by:

$$\delta_m = \sqrt{4Dt} * \gamma, \qquad \gamma = \frac{\sqrt{SR^2}}{SR}$$

Where γ is the Stretching factor

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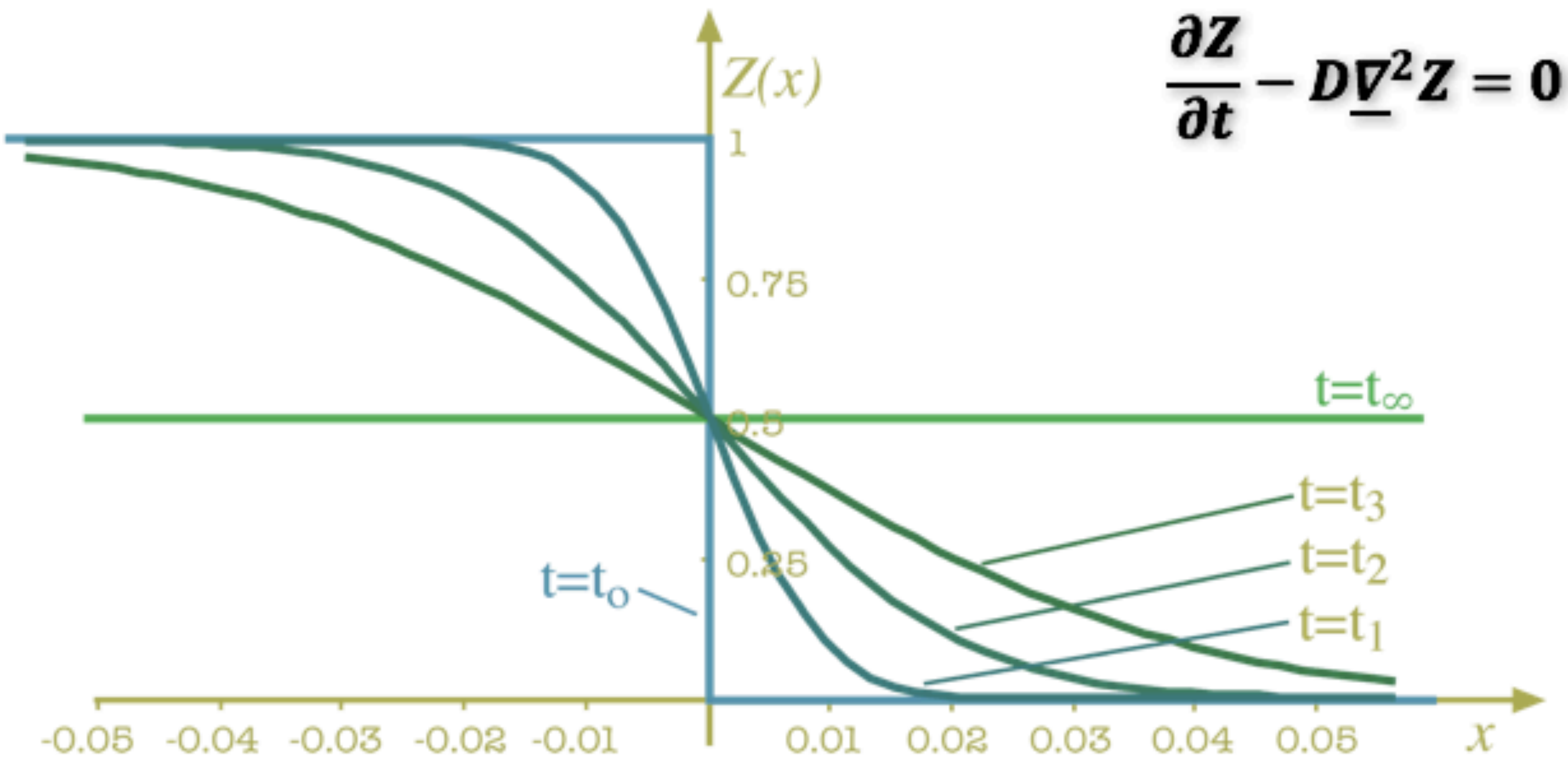
Single and Multiple Mixing Layers

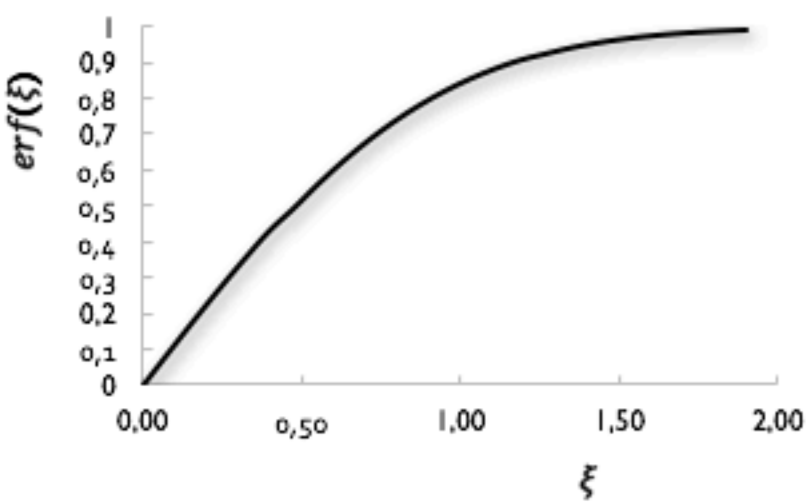


$$\frac{\partial \boldsymbol{Z}}{\partial \boldsymbol{t}} - \boldsymbol{D}\underline{\boldsymbol{\nabla}}^{2}\boldsymbol{Z} = \boldsymbol{0}$$

$$\frac{Z - Z_0}{Z_\infty - Z_0} = erf\left(\xi = \frac{x}{\delta_m}\right)$$

$$erf(\xi) = \frac{2}{\sqrt{\pi}}\int_0^{\xi} e^{-x^2}dx$$

$$\delta_m = \delta_{0.9} = \sqrt{4Dt}$$



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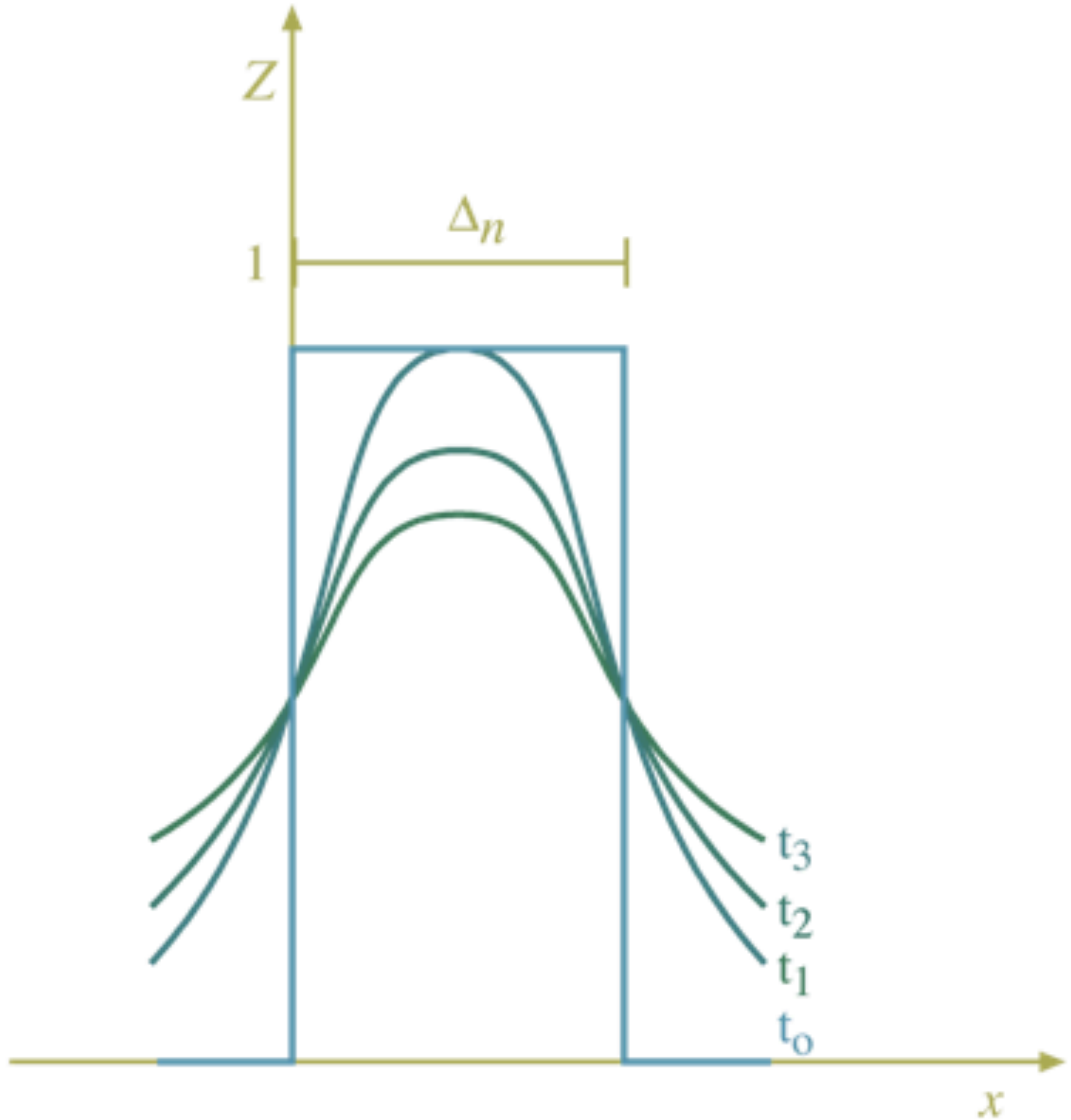
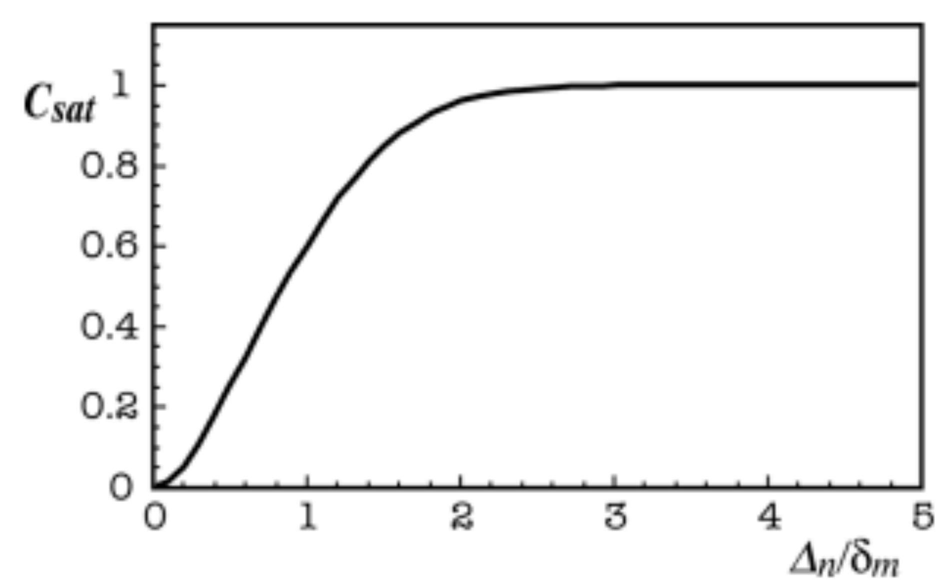
Double Mixing Layers



$$Z = \frac{1}{2}\left[erf\left(\frac{x}{\delta_m}\right) - erf\left(\frac{x-\Delta_n}{\delta_m}\right)\right]$$

$$\frac{\phi_{\Delta_n}}{\phi_{\Delta_\infty}} = C_{st} = 4 - e^{-\left(\frac{\Delta_n}{\delta_m}\right)^2}$$

$$\phi_{\Delta_\infty}(\mathrm{t}, x_n) = \frac{\rho DSR}{\sqrt{\pi}\delta_m}$$



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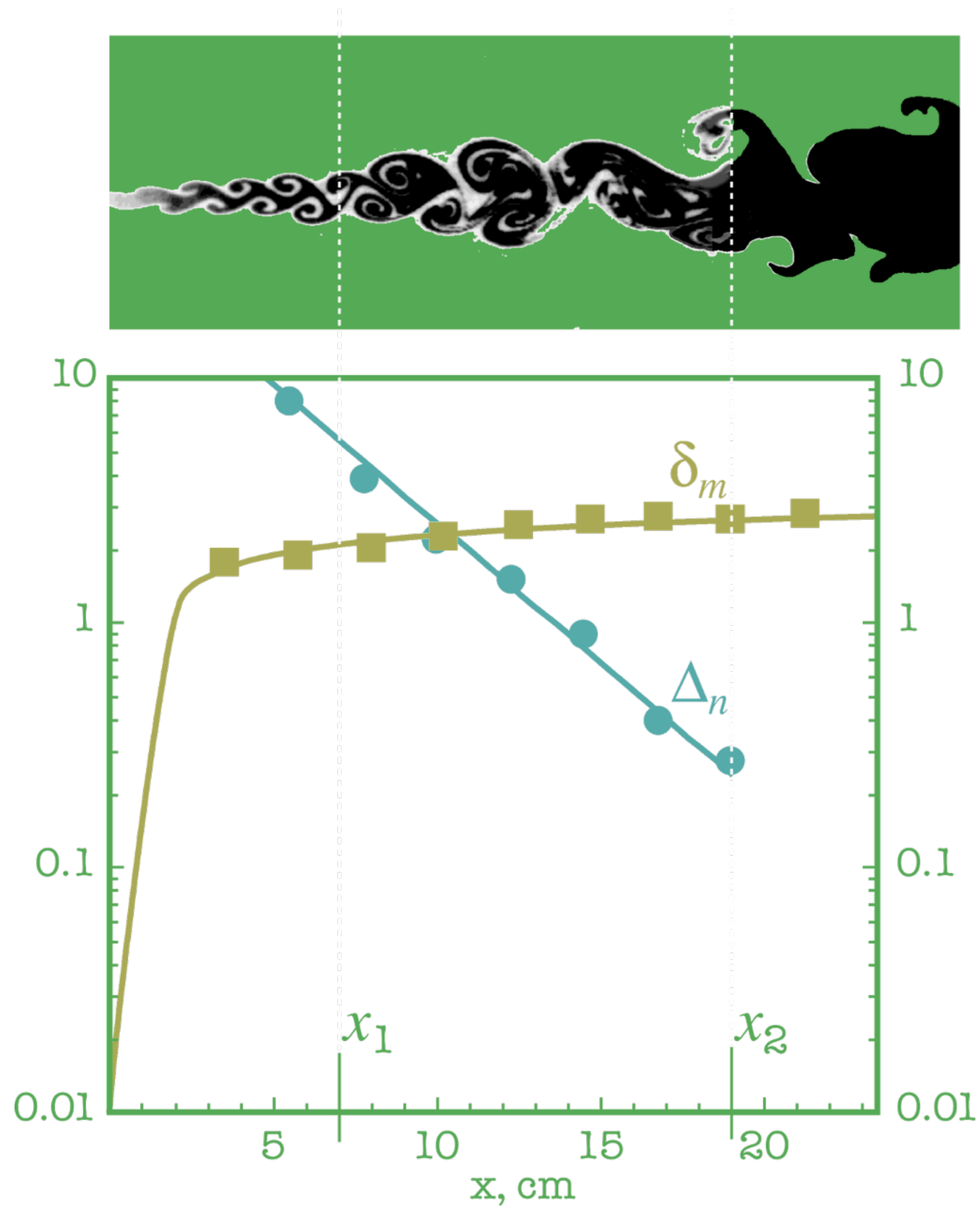
Double Mixing Layers



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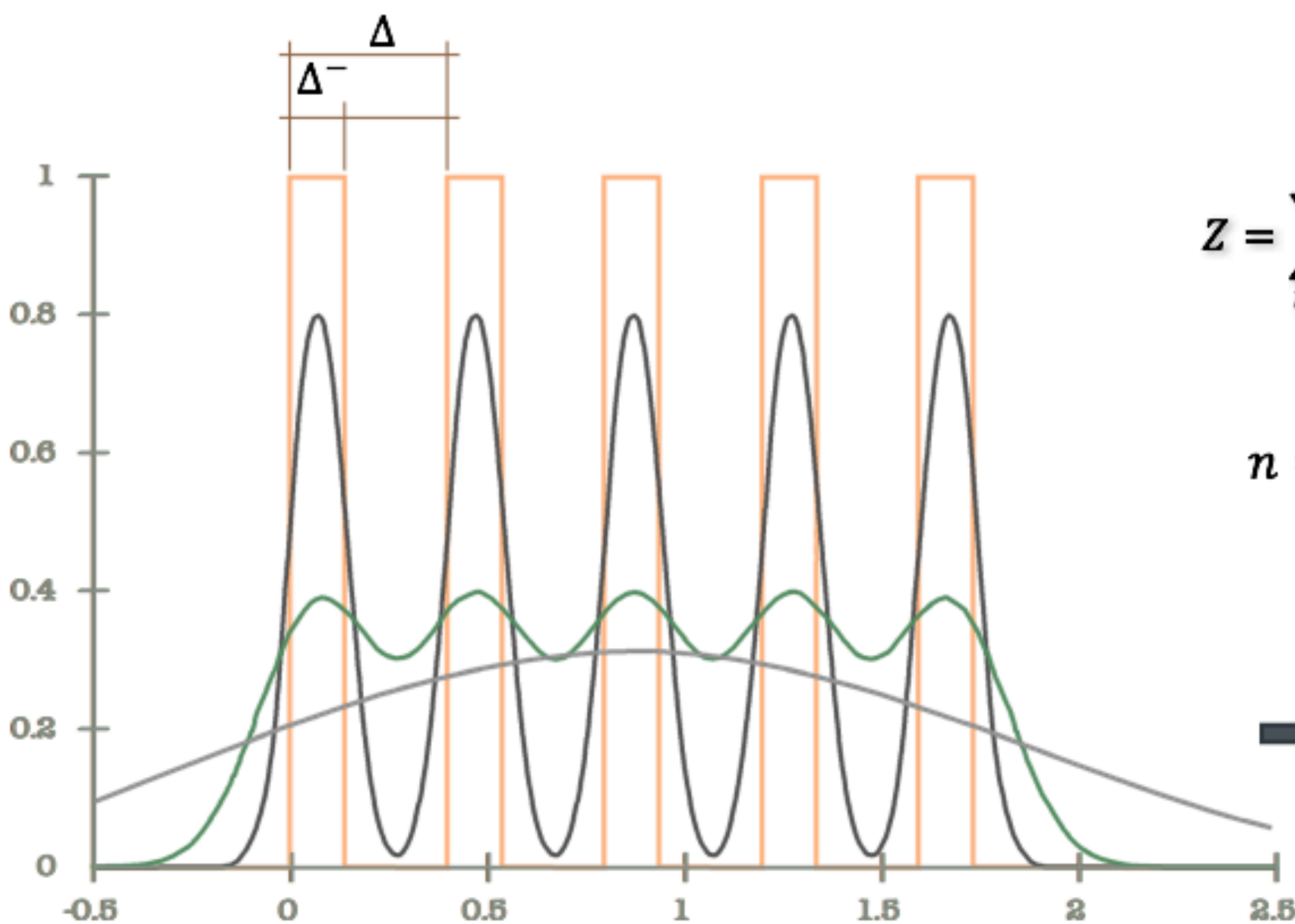
Multiple Mixing Layers



$$Z = \sum_{i=0}^{n} \frac{1}{2}\left[\left(erf\left(\frac{x - n\Delta - \Delta^{-}}{\delta_m}\right)\right) - erf\left(\frac{x - n\Delta}{\delta_m}\right)\right]$$

$$n = number\ of\ double\ mixing\ layer - 1$$

$\underline{n = 4}$

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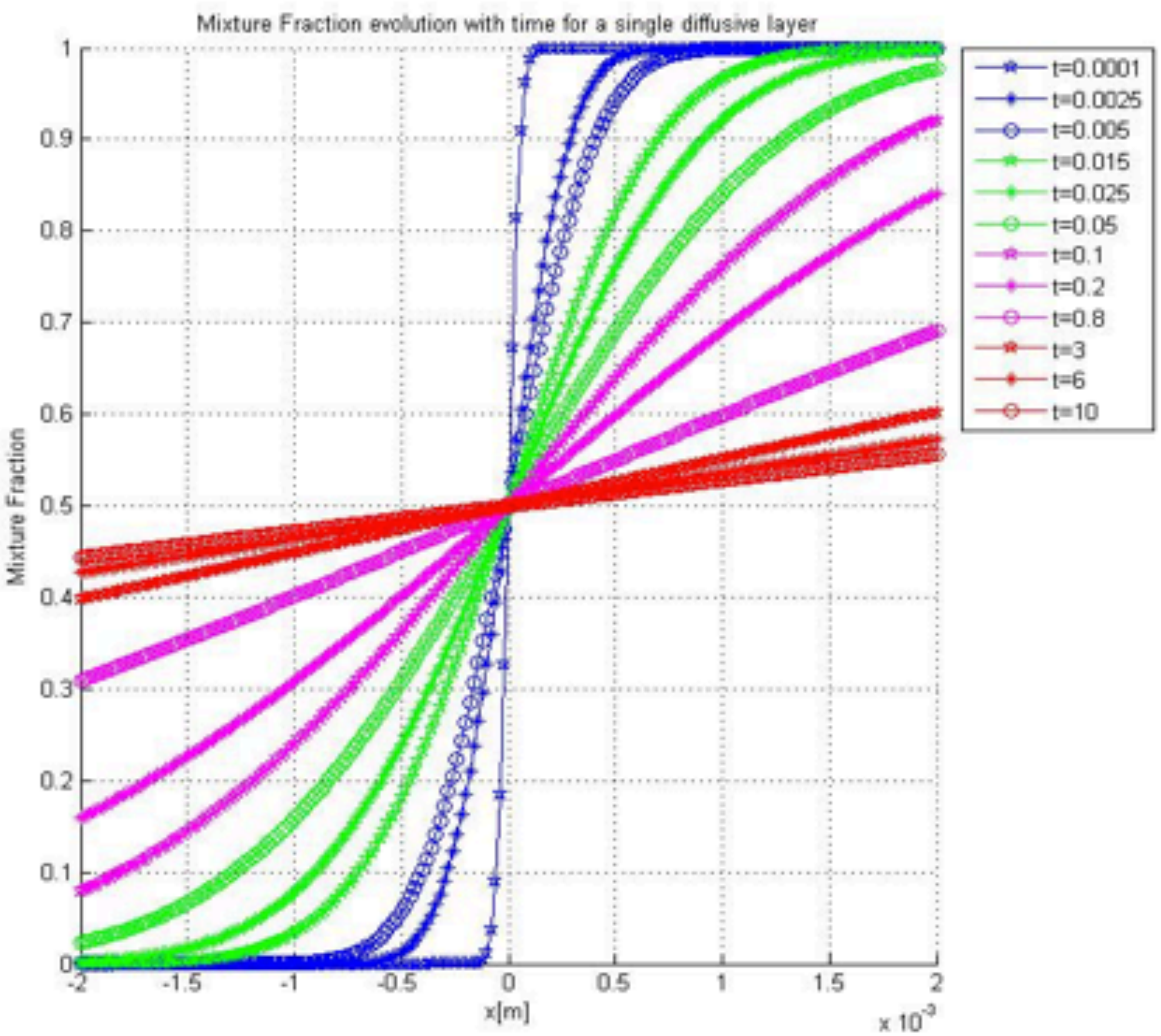
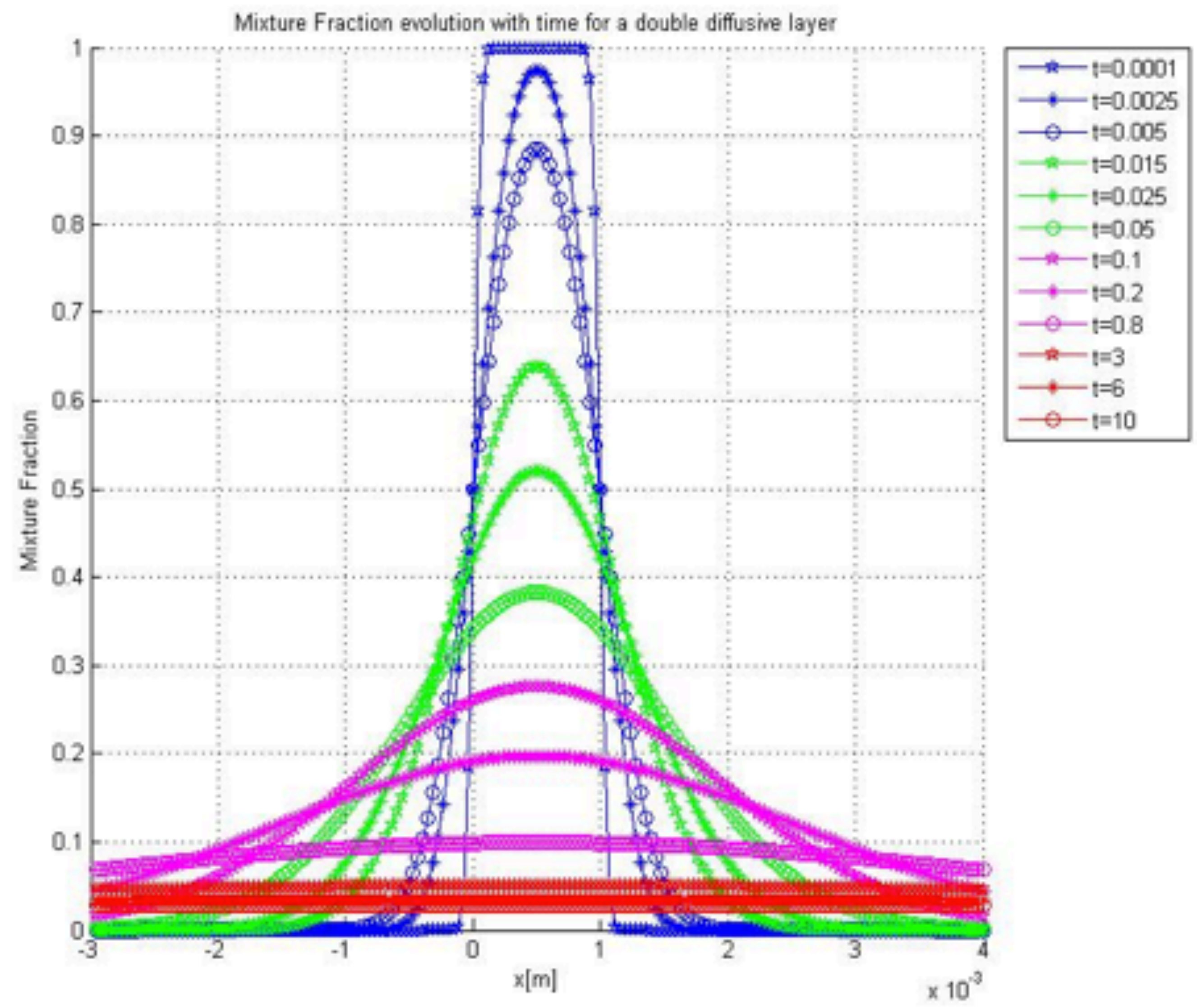
Multiple Mixing Layers





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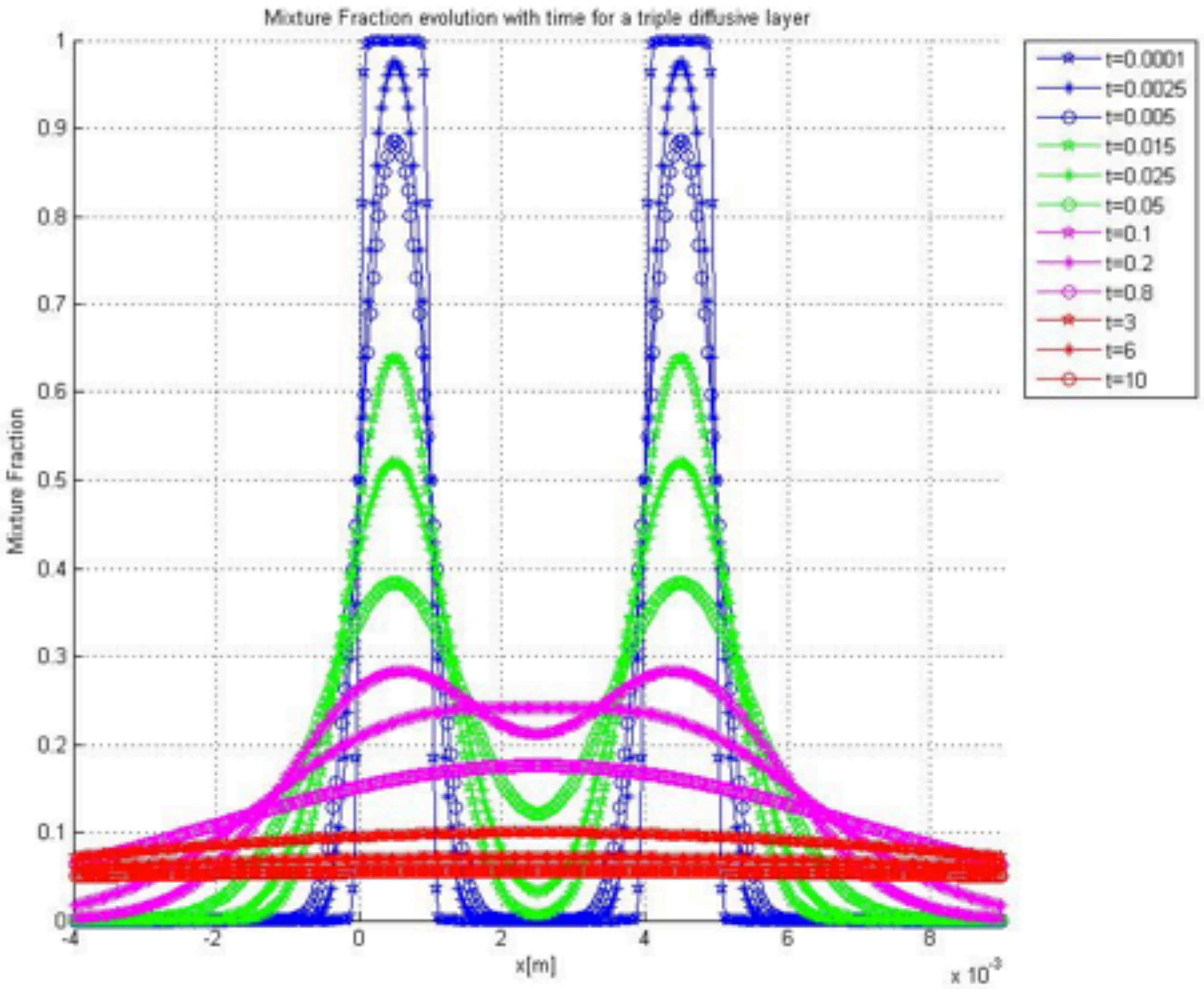
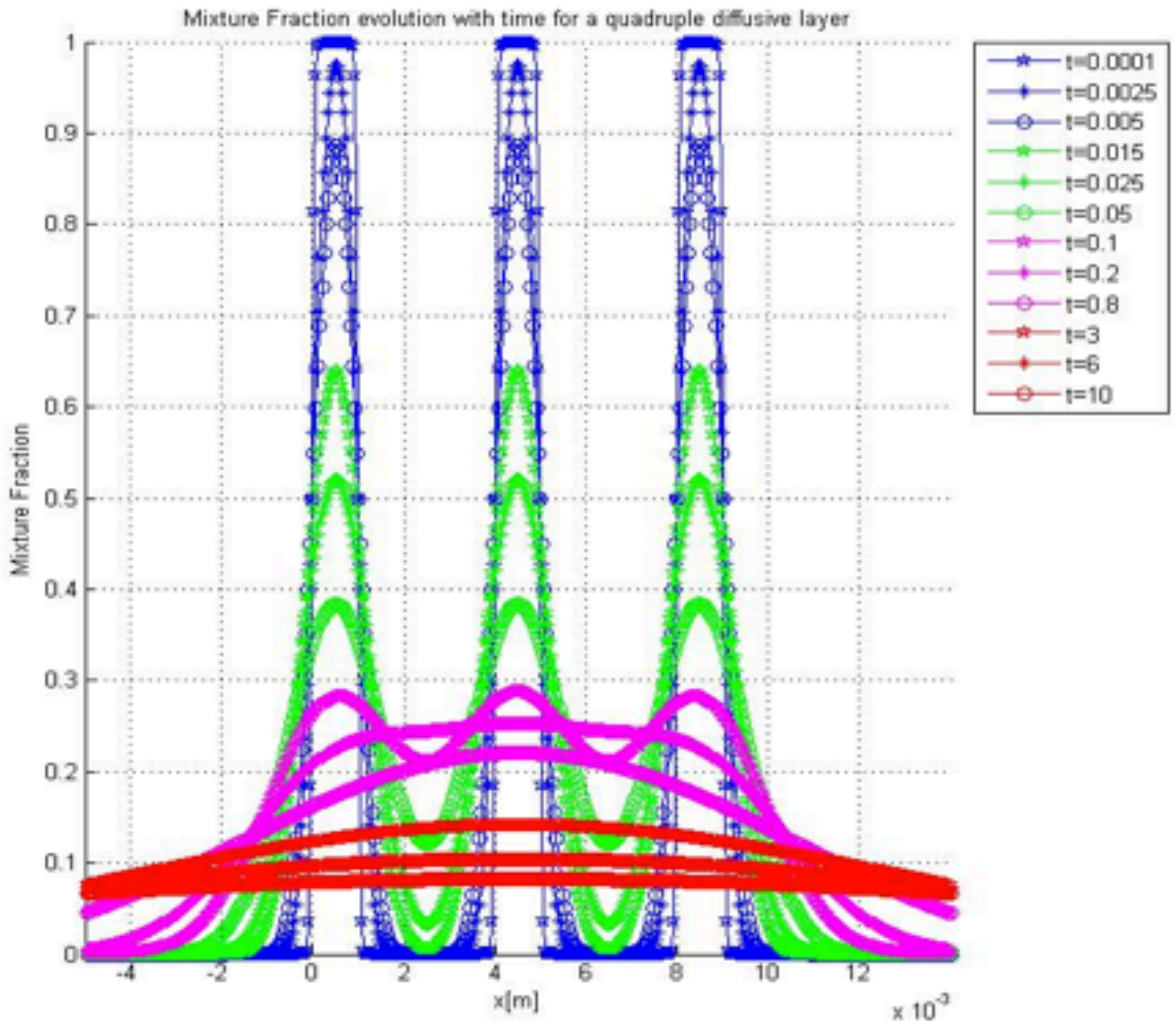
Multiple Mixing Layers





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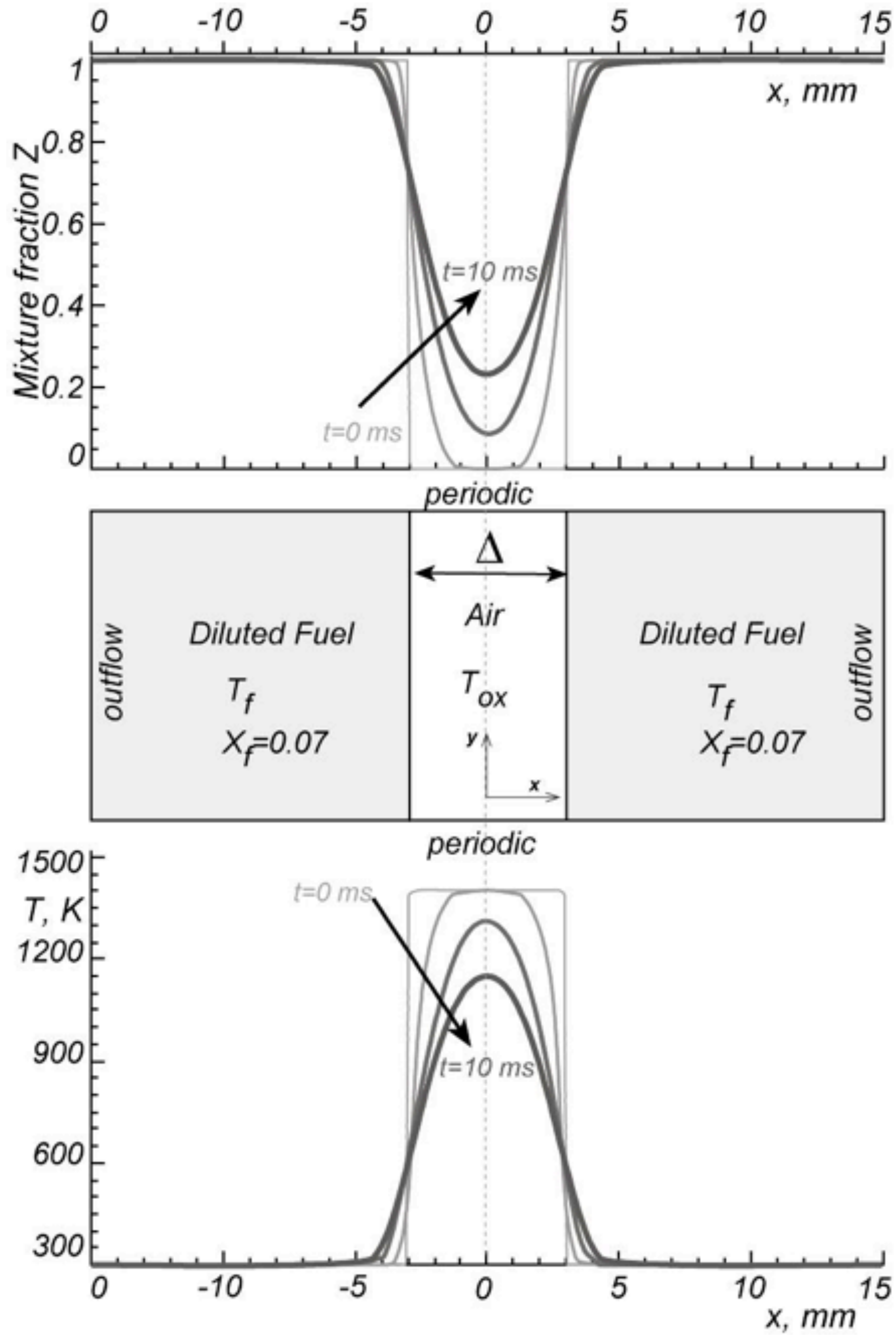
Double Mixing Layers



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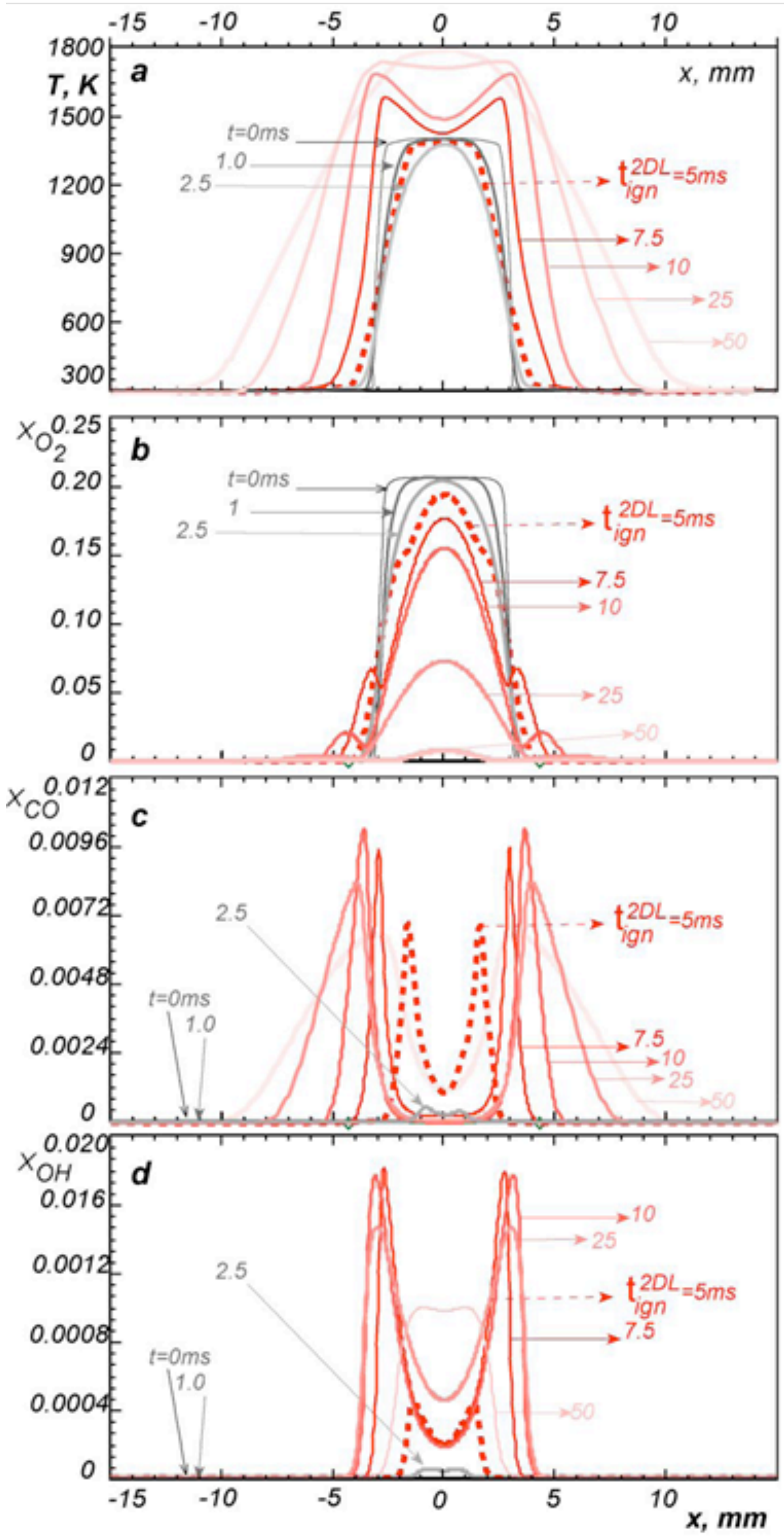
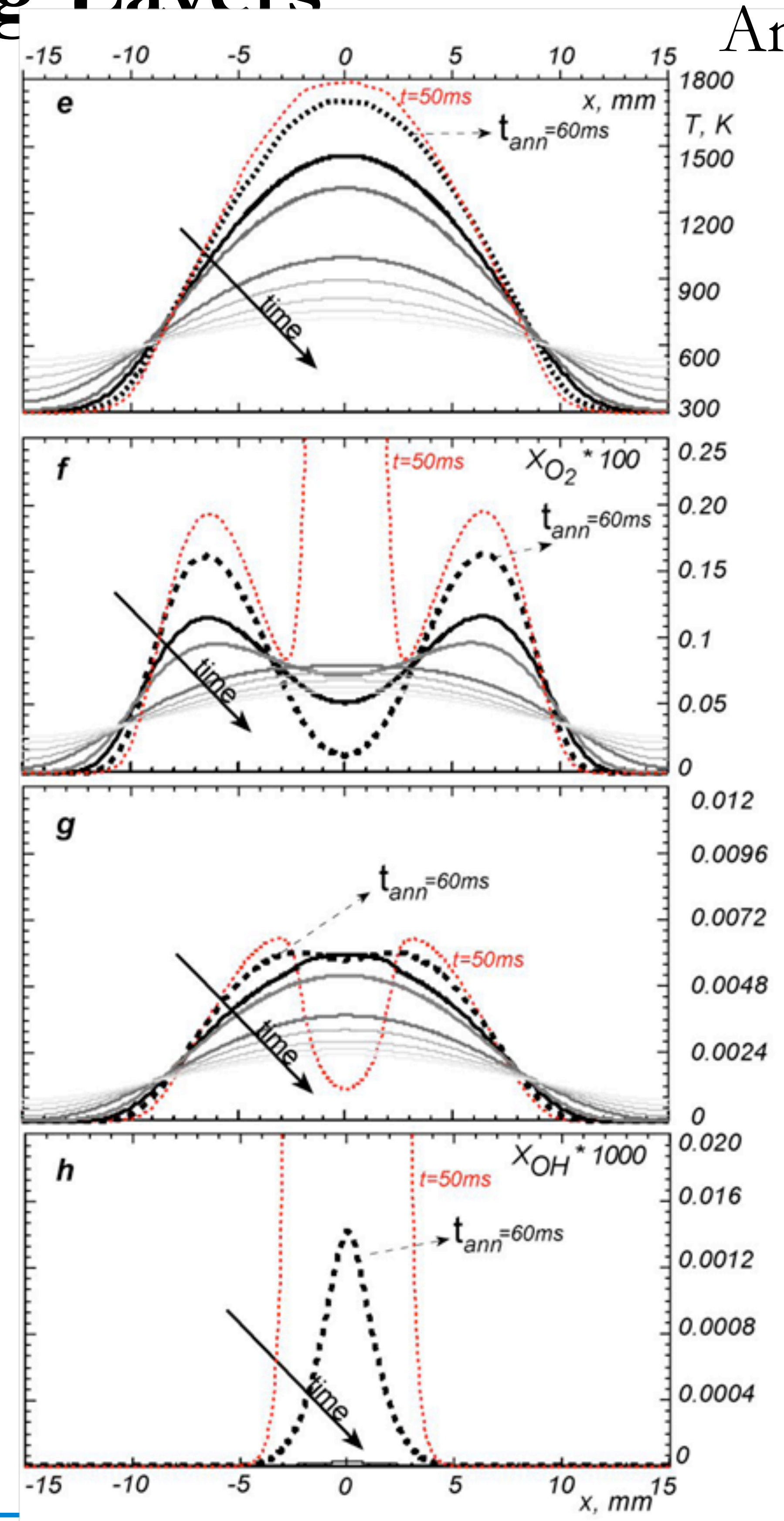
Double Mixing Layers

Ignition



Annihilation



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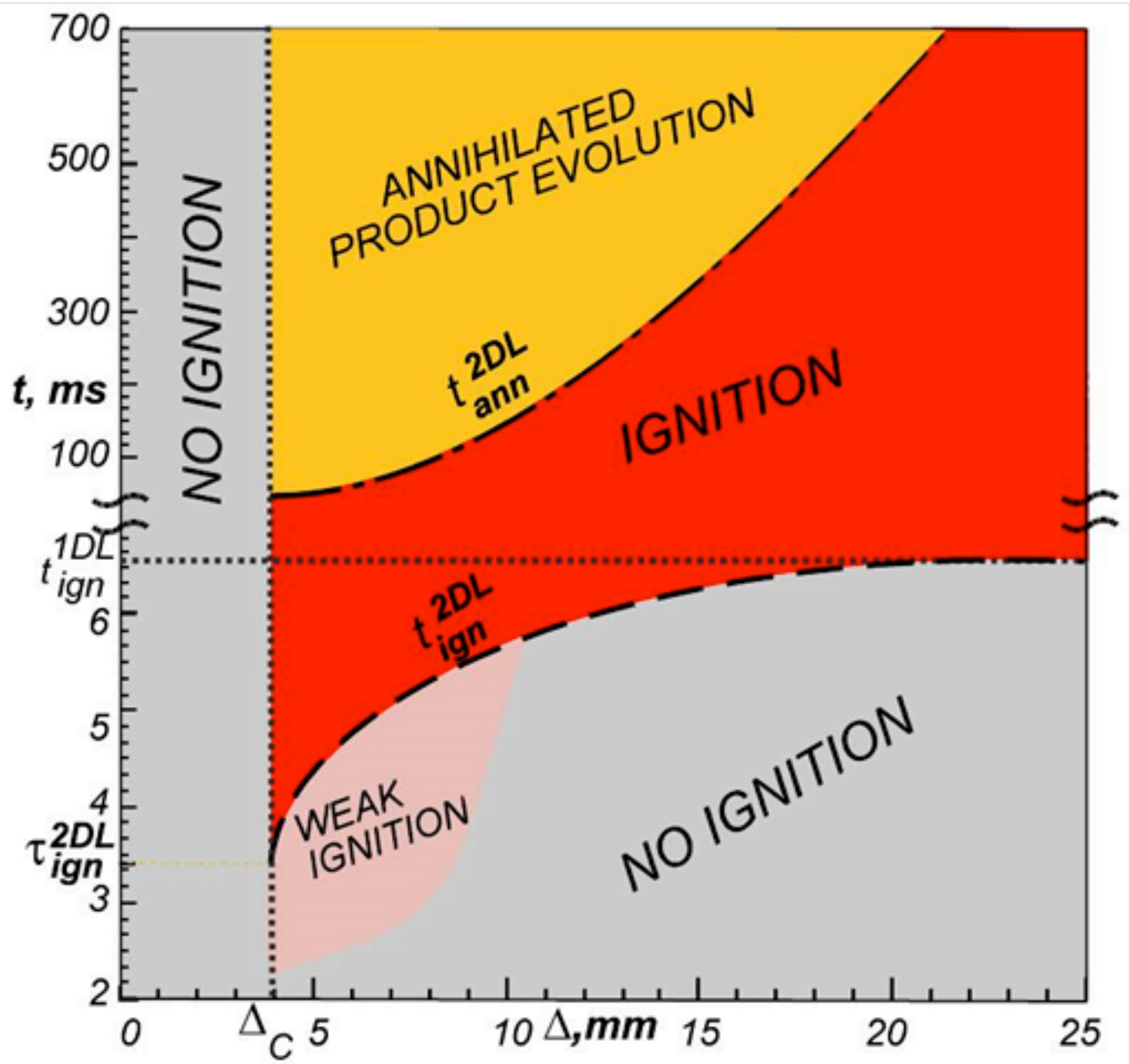
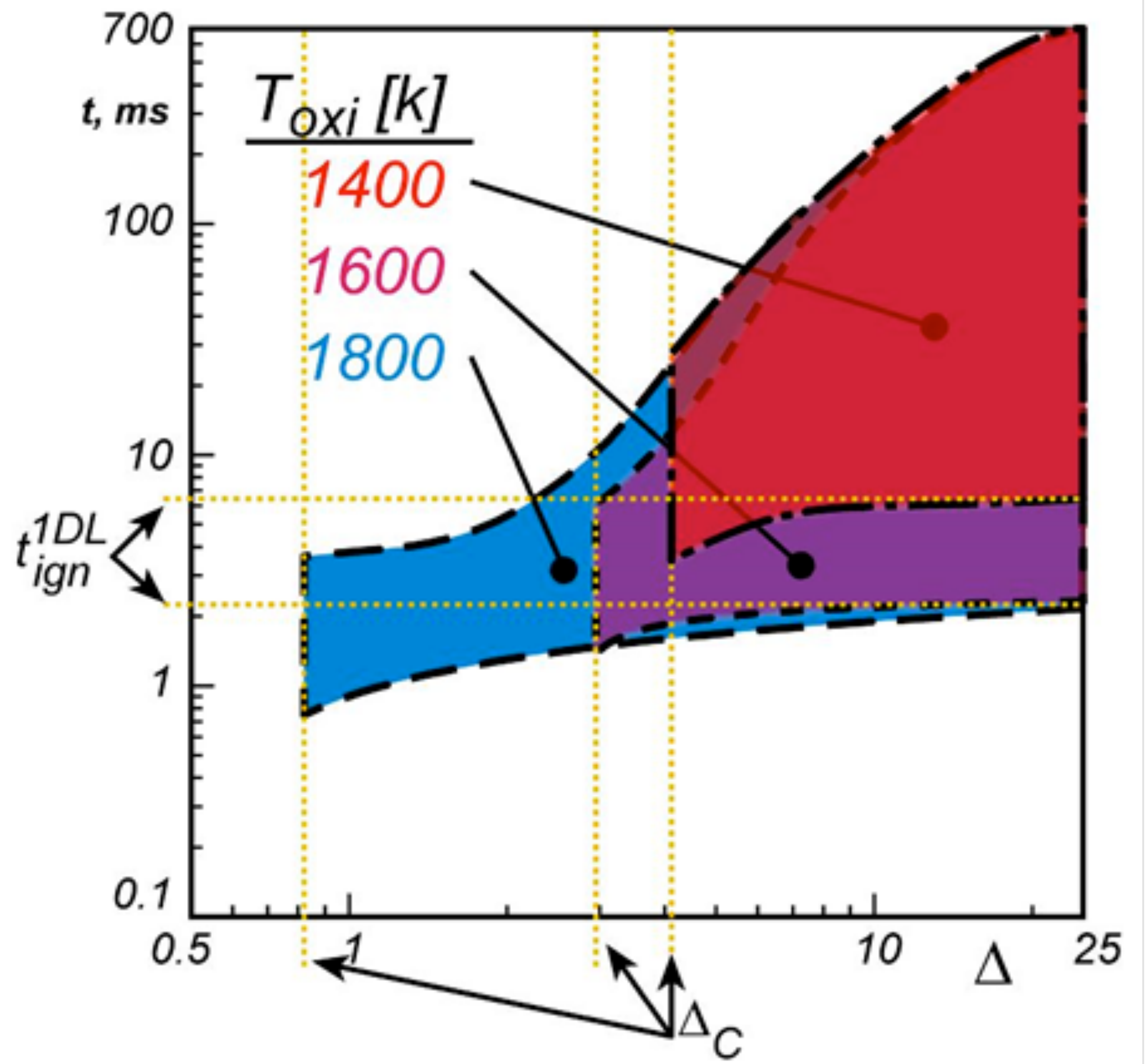
Double Mixing Layers





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COURSE OVERVIEW

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Partially premixed turbulent combustion

Partially premixed combustion combines the formulations for premixed and non-premixed combustion proceses. In this kind of flames when the laminar burning velocity is plotted as a function of mixture fraction the maximum lies close to stoichiometric mixture. Therefore, flames will propagate the fastest along surfaces for which $Z(x; t) = Z_{st}$ in a mixture field. If such a surface exists in a partially premixed field, flame propagation generates a flame structure that is called **triple flame**.

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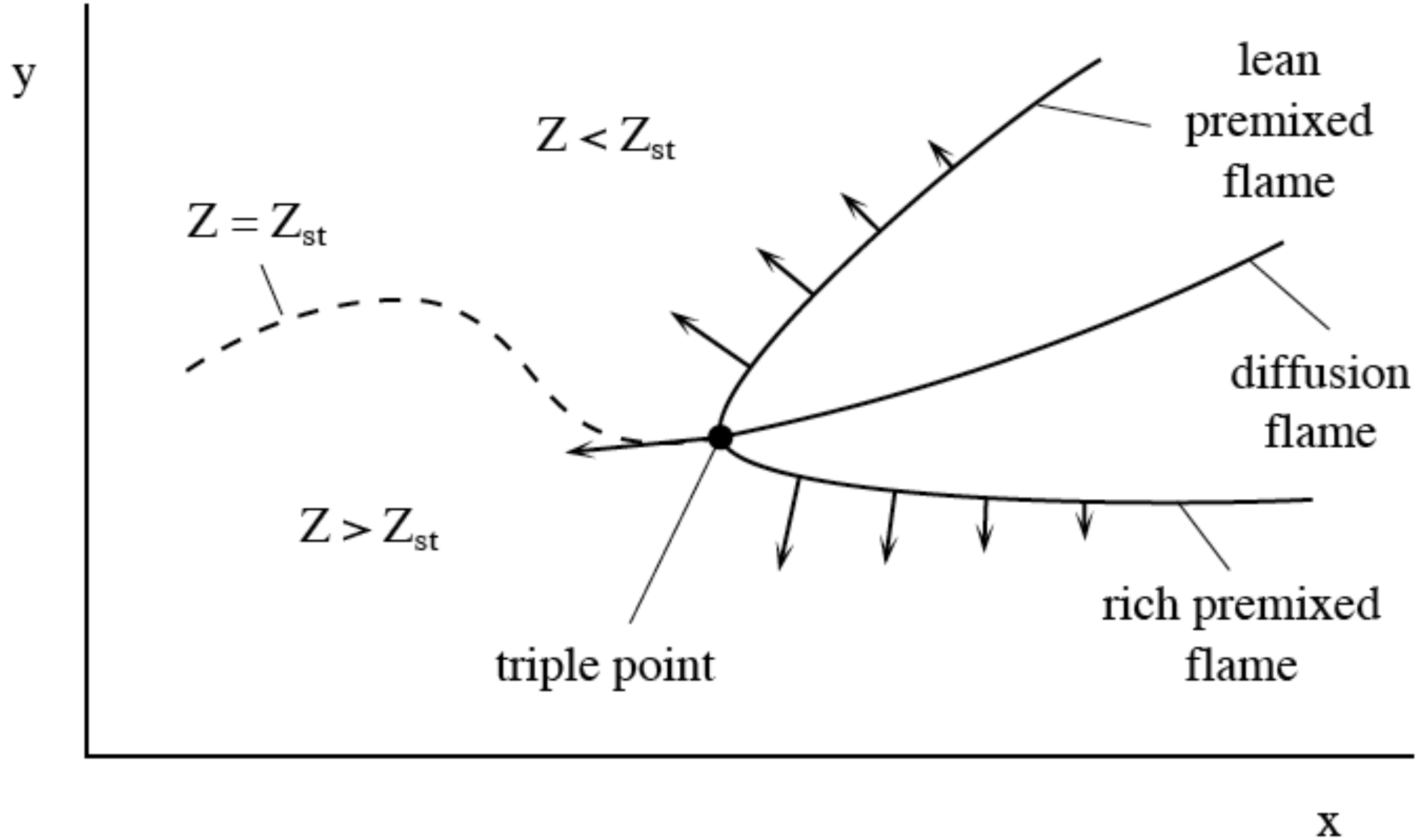
TRIPLE FLAMES - STRUCTURE



The leading edge of the flame, called the triple point, propagates along the surface of stoichiometric mixture. On the lean side of that surface there is a lean premixed flame branch and on the rich side there is a rich premixed flame branch, both propagating with a lower burning velocity. Behind the triple point, on the surface of stoichiometric mixture, a diffusion flame develops where the unburnt intermediates like H2 and CO from the rich premixed flame branch burn with the remaining oxygen from the lean premixed flame branch.

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TRIPLE FLAMES

A flame propagating through a fuel/air mixing layer, especially when the fuel concentration is stratified ranging from lean to rich, may exhibit a triple (or sometimes called tribrachial) flame structure, which is composed of a lean and a rich premixed flame wing together with a trailing diffusion flame, all extending from a single point.

Mixing layers are frequently encountered in combustion problems including two-dimensional (2-D) mixing layers, heterogeneous propellant combustion, opposed flame spread, jets, and boundary layers. Tribrachial flames can also be relevant to inhomogeneously charged premixed conditions, such as autoignition fronts in diesel engines or flame fronts in direct injection gasoline engines, and possibly in premixed-charge compression ignition (PCCI) and stratified-charge compression ignition (SCCI) engines.

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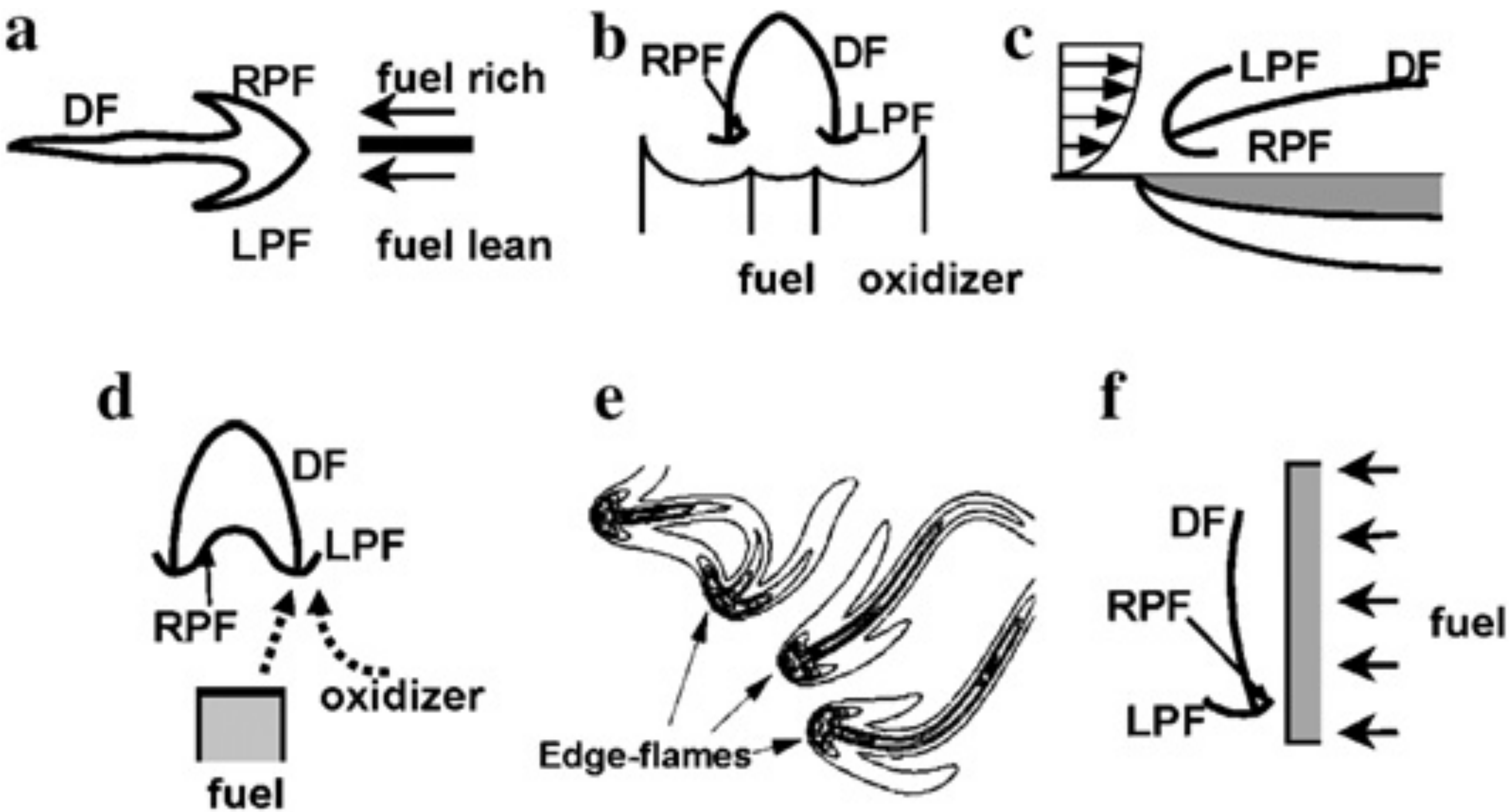
TRIPLE FLAMES



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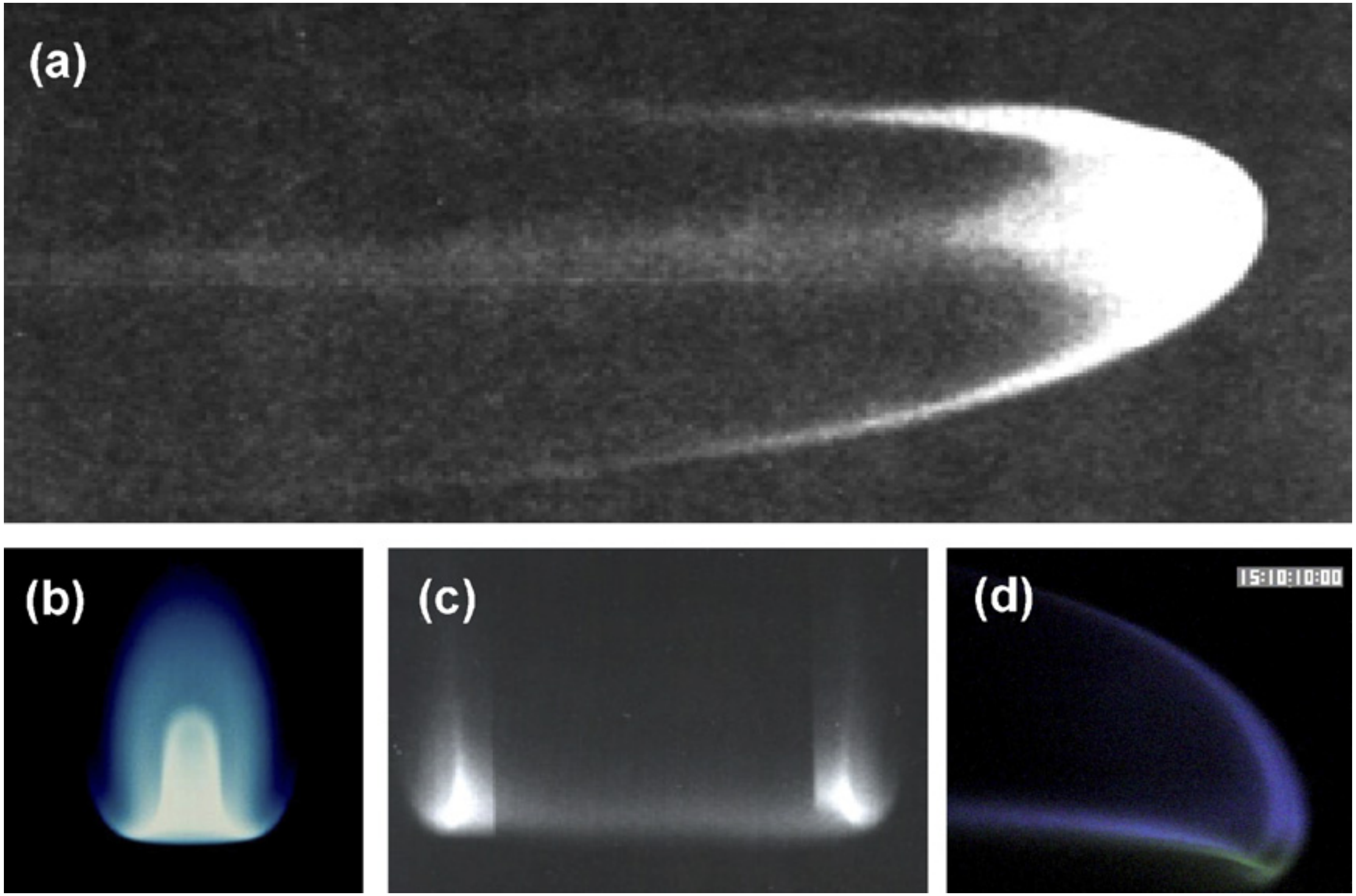
TRIPLE FLAMES

Observed tribrachial flames in various flow configurations; (a) 2-D mixing layer, (b) laminar jet, c) cylindrical boundary layer, and (d) flame spread



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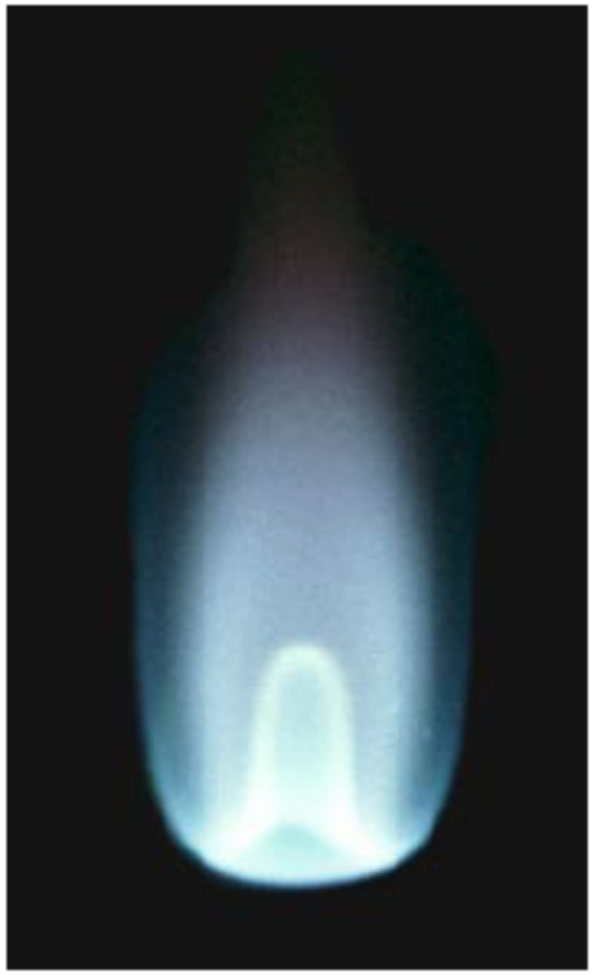
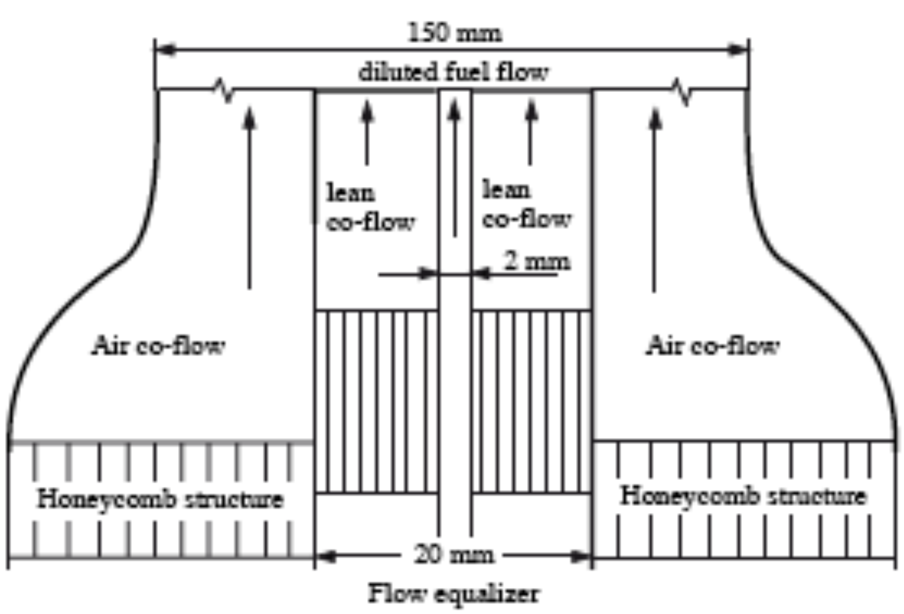
TRIPLE FLAMES - STRUCTURE



(a)



Methane-air triple flame stabilized in a laminar round jet 44 mm above the triple flame burner. The burner generates a staged mixture by issuing a central flow of diluted fuel, surrounded by a lean co-flow, which is again surrounded by an air co-flow. These three mixtures have interdiffused at the stabilization height to form a partially premixed mixture ranging between $Z = 0.15$ on the centerline and $Z = 0$ in the air co-flow. Due to dilution of the central flow the stoichiometric mixture fraction is 0.0789. One can clearly distinguish in Figure the bright rich premixed flame in the center, the broad diffusion flame surrounding it and extending further downstream and the thin lean premixed branches outside.

Triple flames are always curved at the triple point. This is due to the fact that the burning velocity decreases as one moves from the stoichiometric contour to the lean and the rich. The triple point therefore propagates faster against the oncoming flow and the rich and lean premixed flame branches stay behind.

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TRIPLE FLAMES

Figure 6.6: Triple flame visualization in a laminar flow (Kioni et al.[276]).

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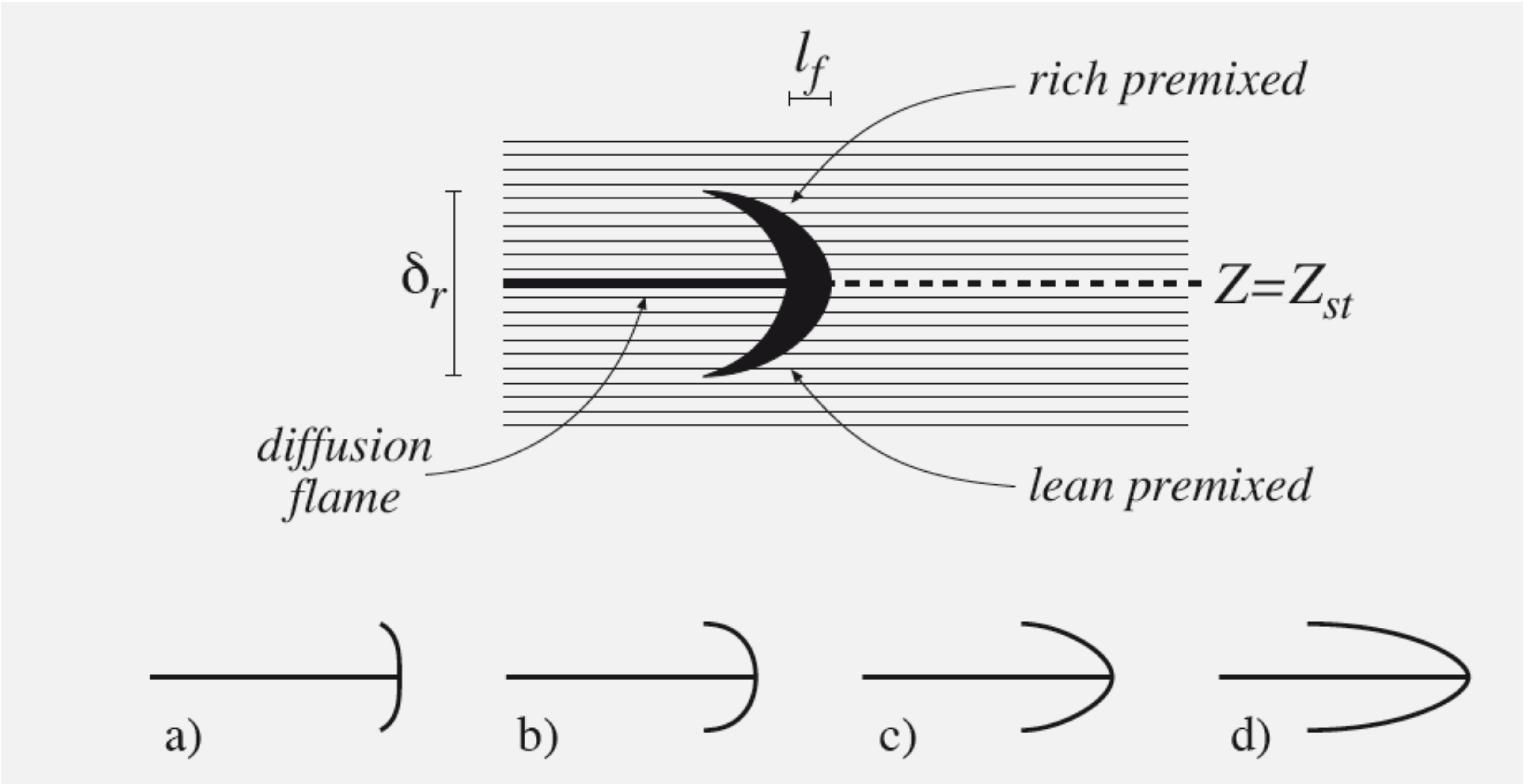
TRIPLE FLAMES



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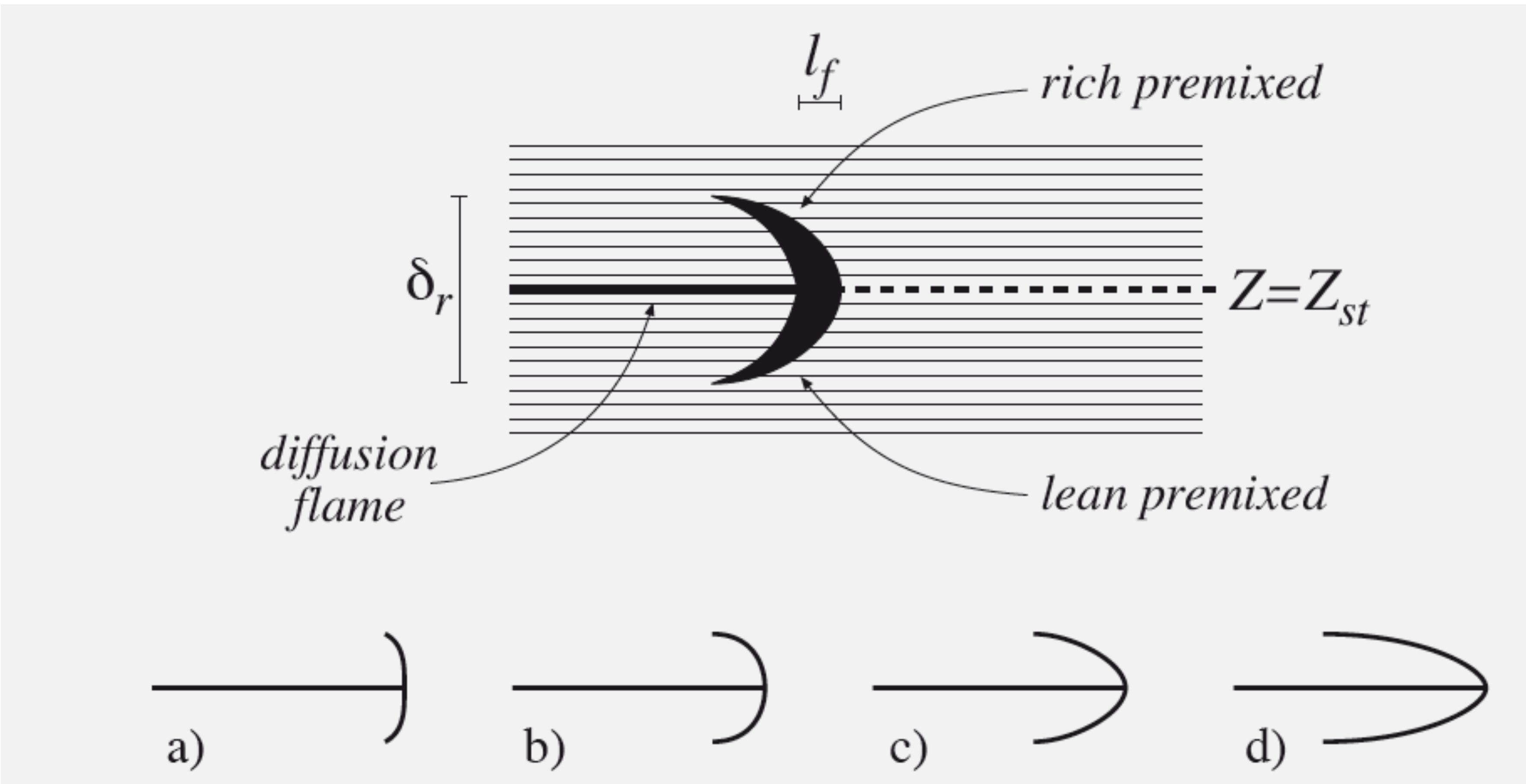
TRIPLE FLAMES

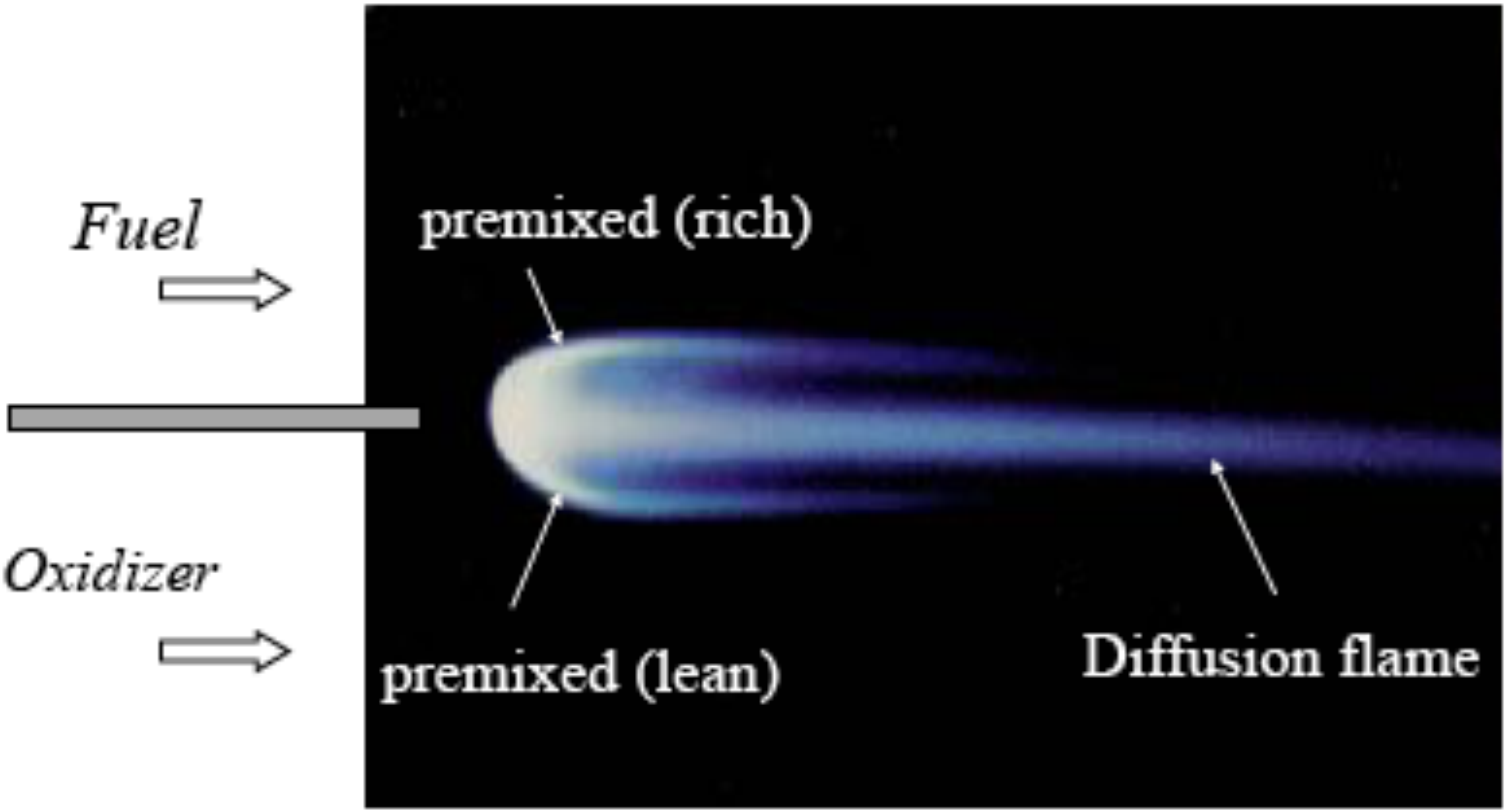


$$B = \frac{l_f}{\delta_r} \propto \sqrt{\frac{\chi}{\dot{\eta}^*(x)}}$$

$$l_f = \frac{\alpha}{v_f} \propto \sqrt{\frac{\alpha}{\dot{\eta}^*(x)}}$$

$$\delta_r \propto \delta_m = \gamma\sqrt{4\alpha t} \propto \sqrt{\frac{\alpha}{\chi}}$$

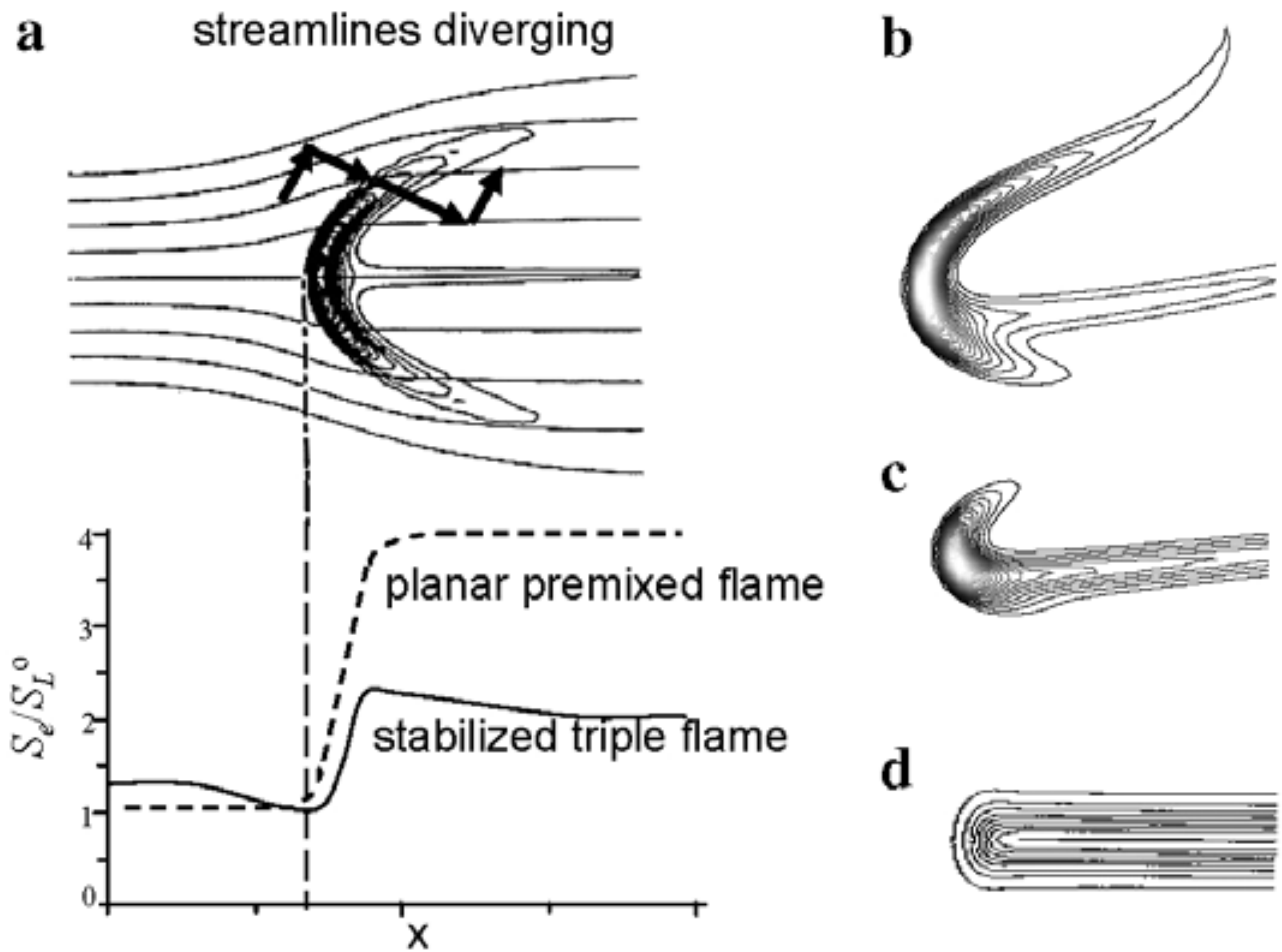
TRIPLE FLAMES



Kioni et al., C&F 1993

TRIPLE FLAMES

Propagation speed



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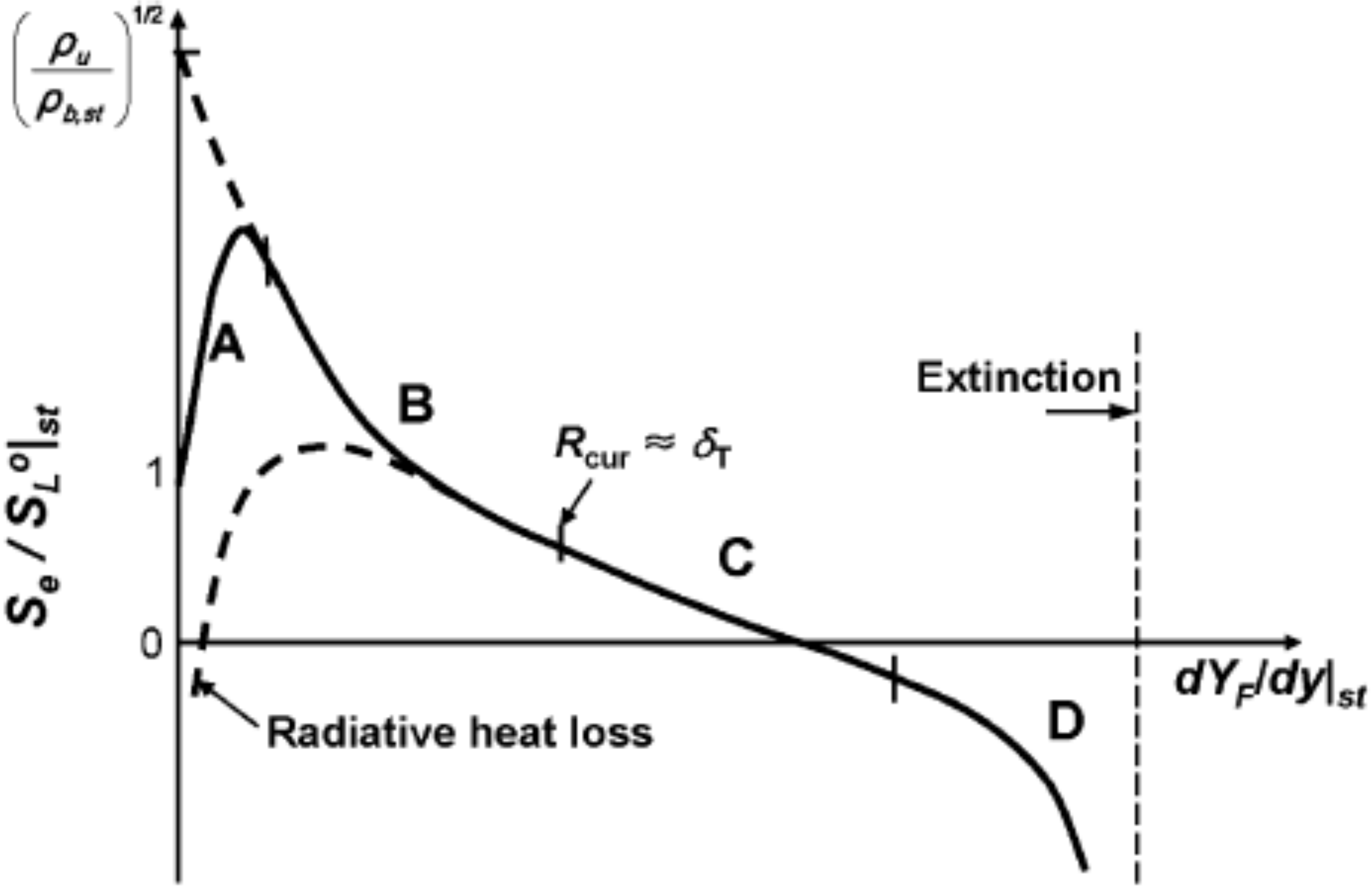
TRIPLE FLAMES

Propagation speed



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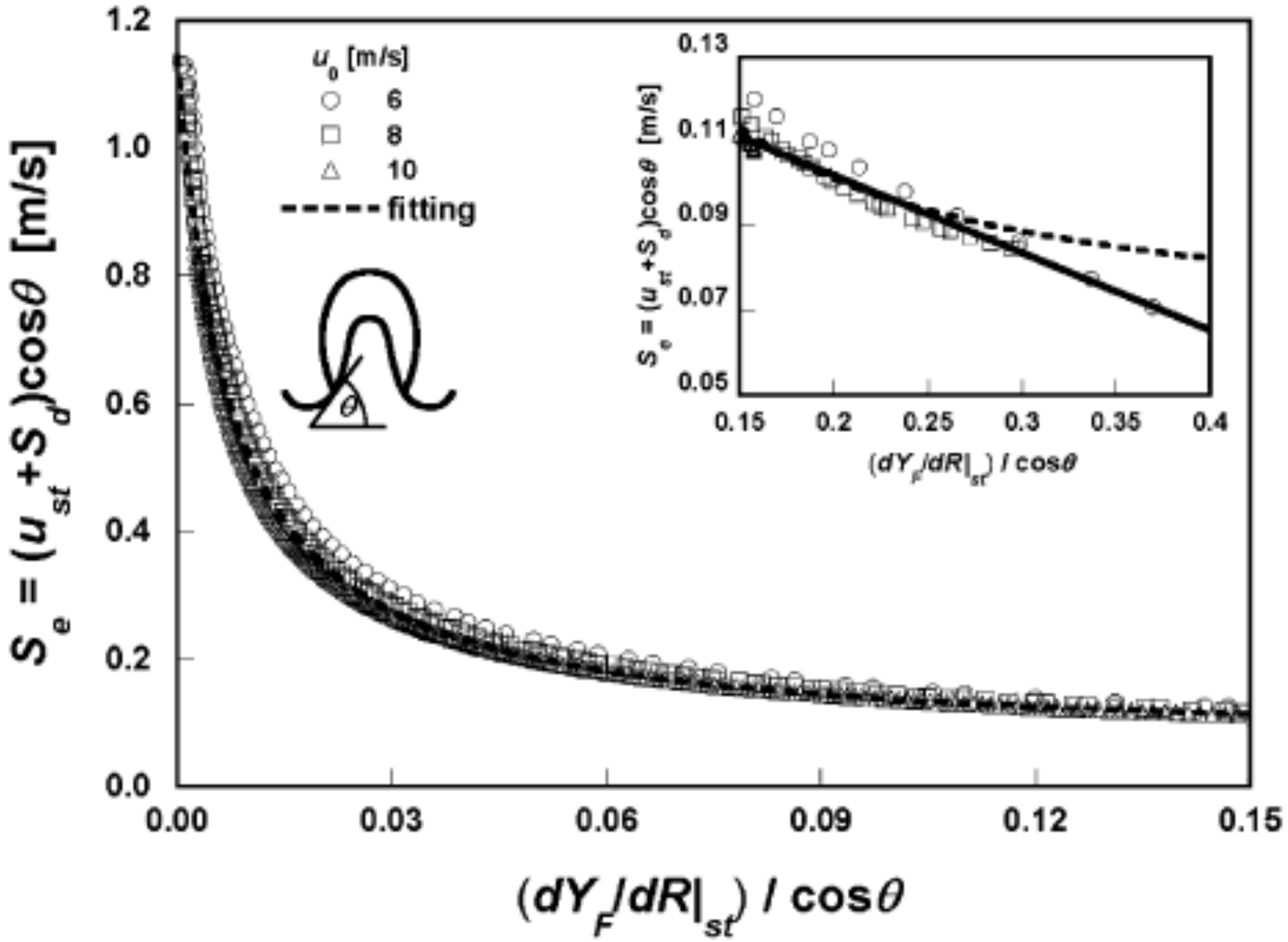
TRIPLE FLAMES

Propagation speed



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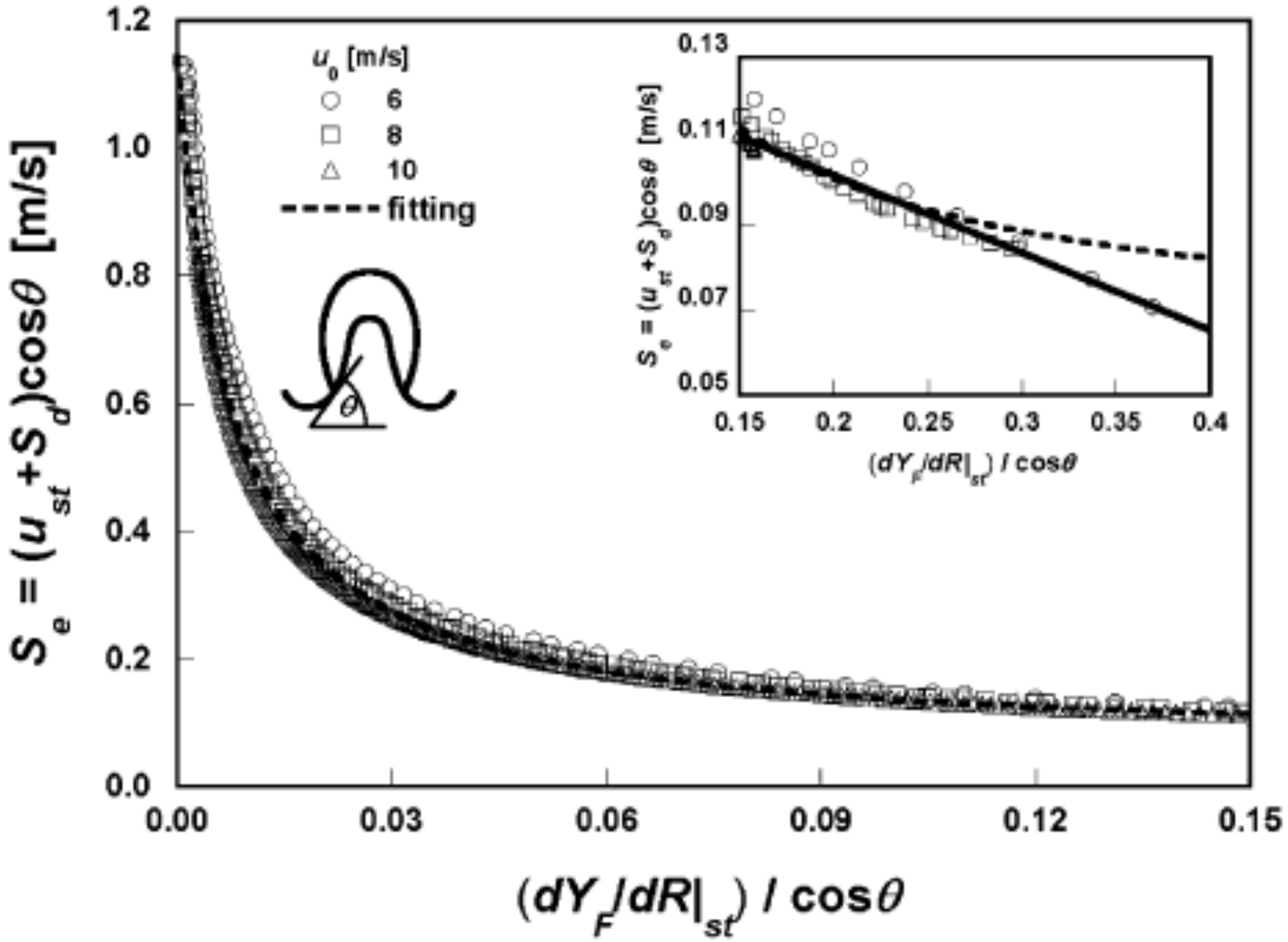
TRIPLE FLAMES

Propagation speed

$$\frac{S_{e,\max}}{S_L^0|_{st}} \cong \left(\frac{\rho_u}{\rho_{b,st}}\right)^{1/2}$$

$$\frac{S_e}{S_L^0|_{st}} = \frac{0.02018}{0.0077155 + \mathrm{d}Y_F/\mathrm{d}R|_{st}/\cos\theta} + 0.155196,$$



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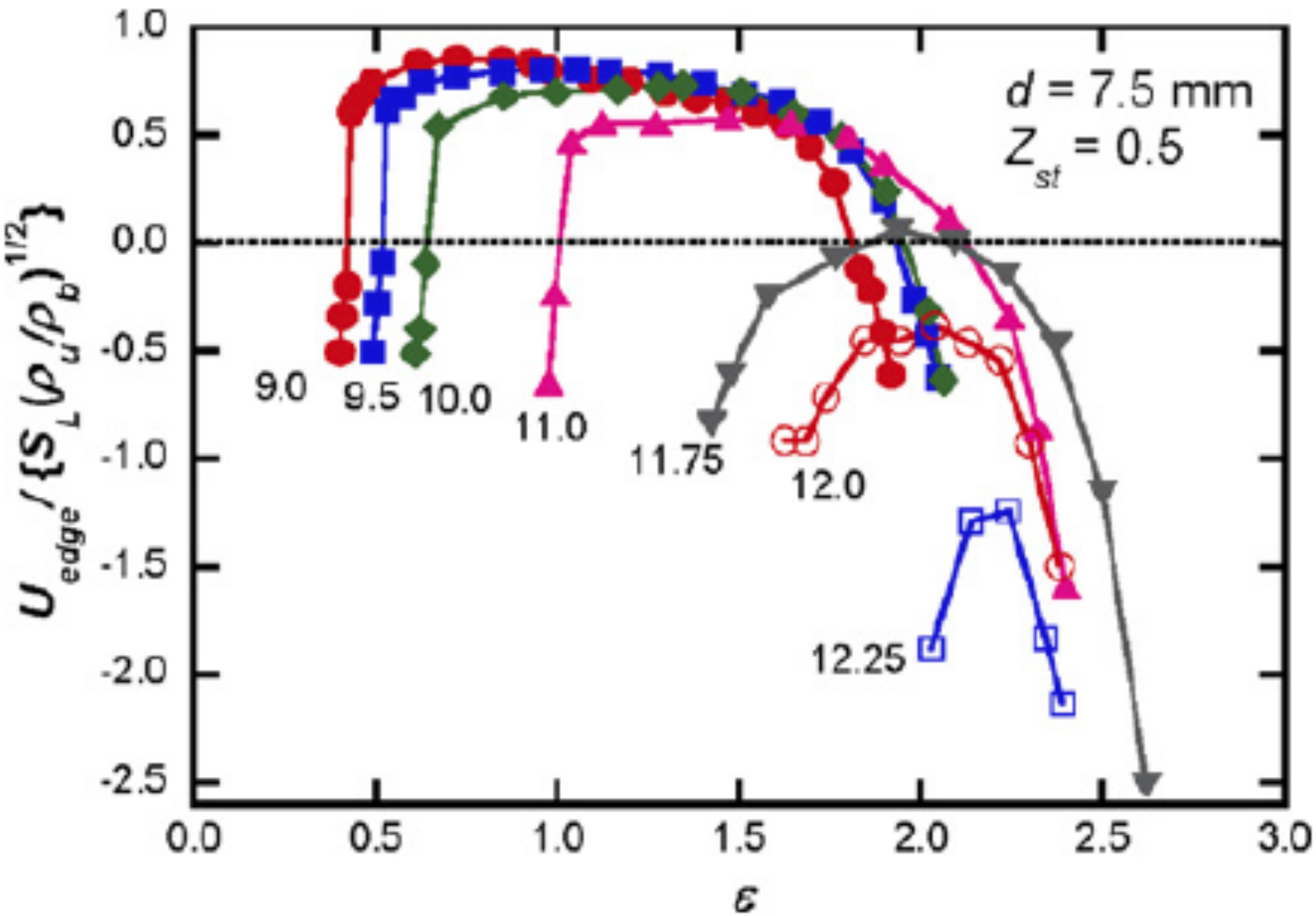
TRIPLE FLAMES

Propagation speed- effect of strain rate



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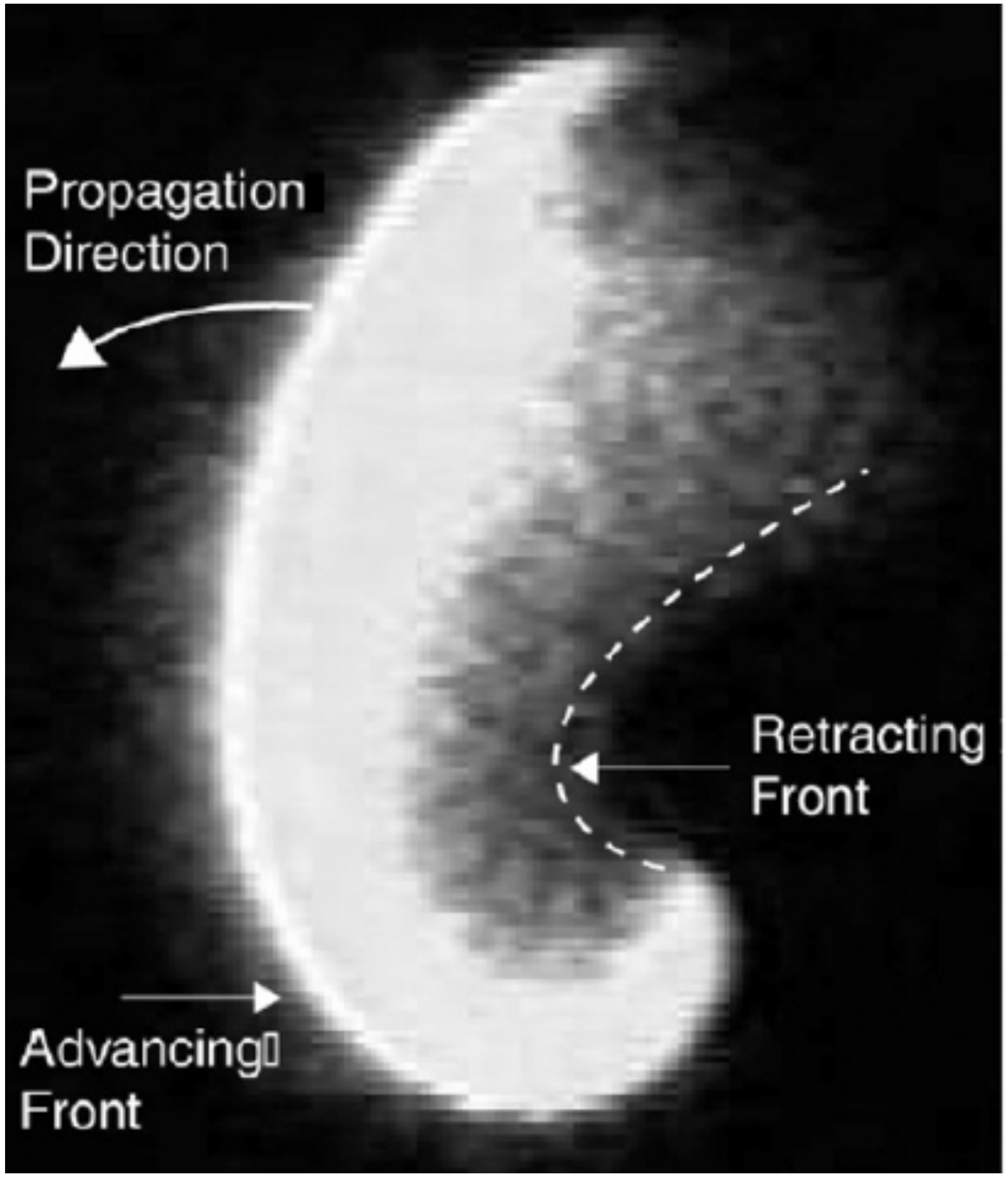
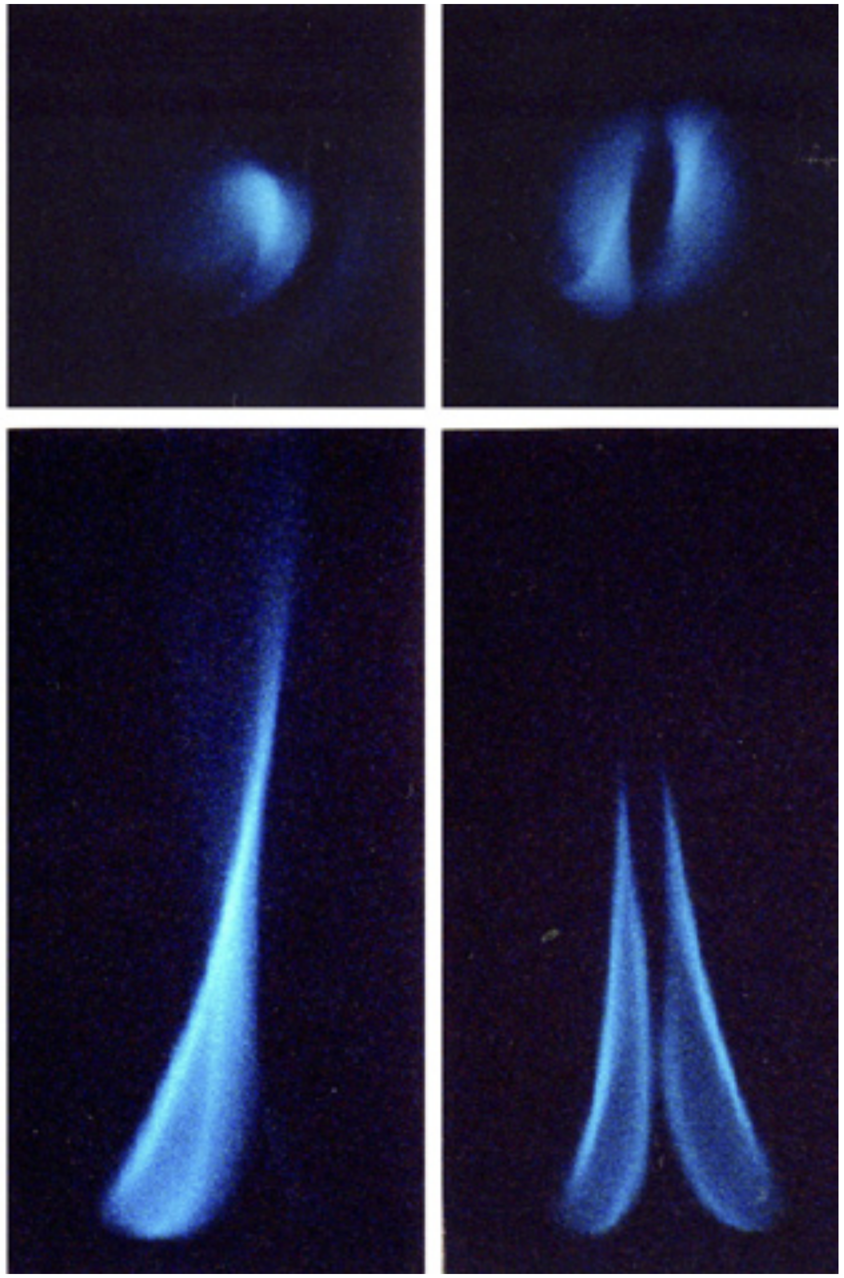
TRIPLE FLAMES

various effects





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COURSE OVERVIEW

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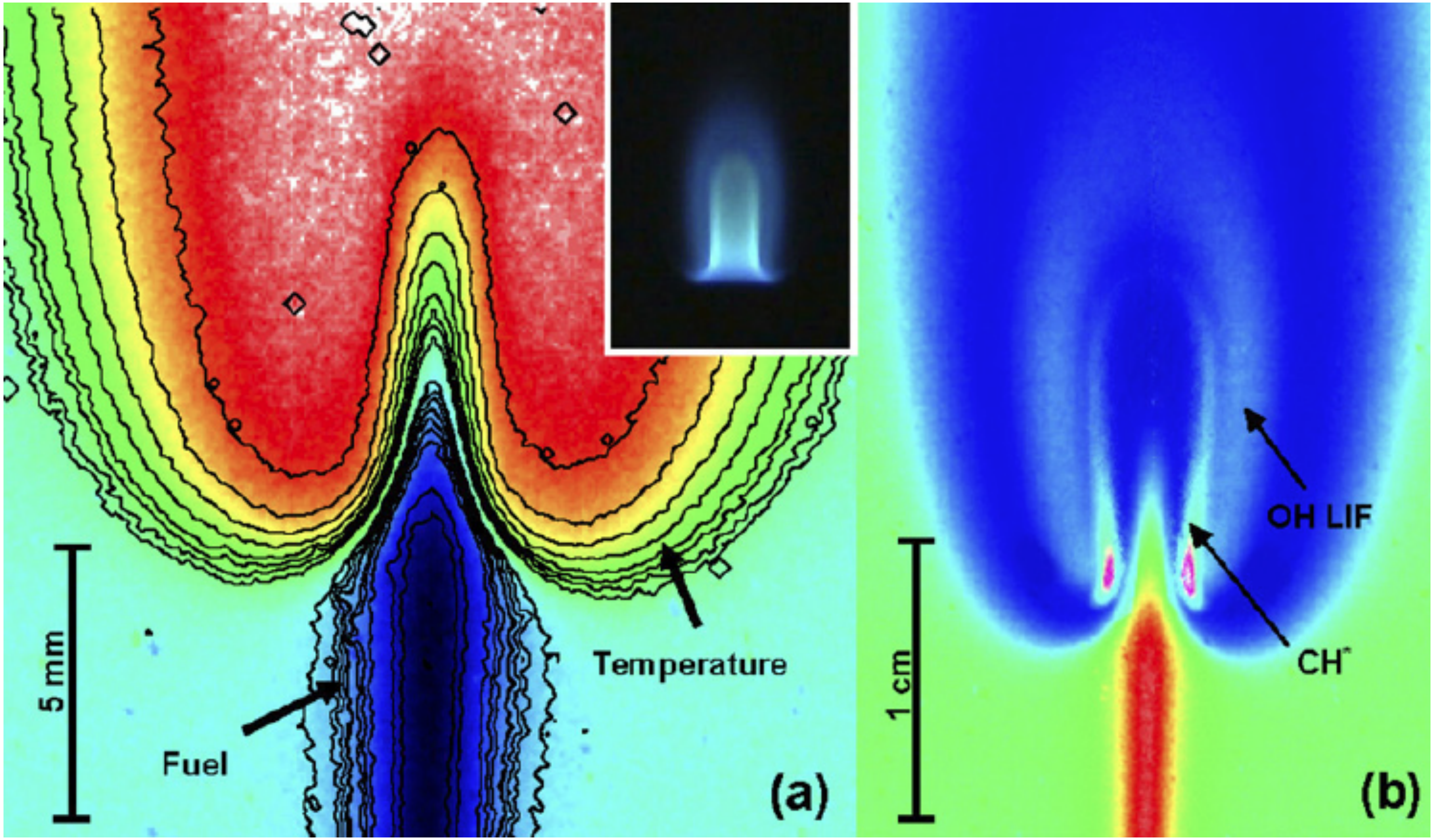
LIFTED FLAMES

The tribrachial structure at the base of lifted flame dictates that the characteristics of tribrachial point control the stabilization. The coexistence of three different types of flames implies that the edge is located along the stoichiometric contour and has the characteristics of propagation.



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LIFTED FLAMES

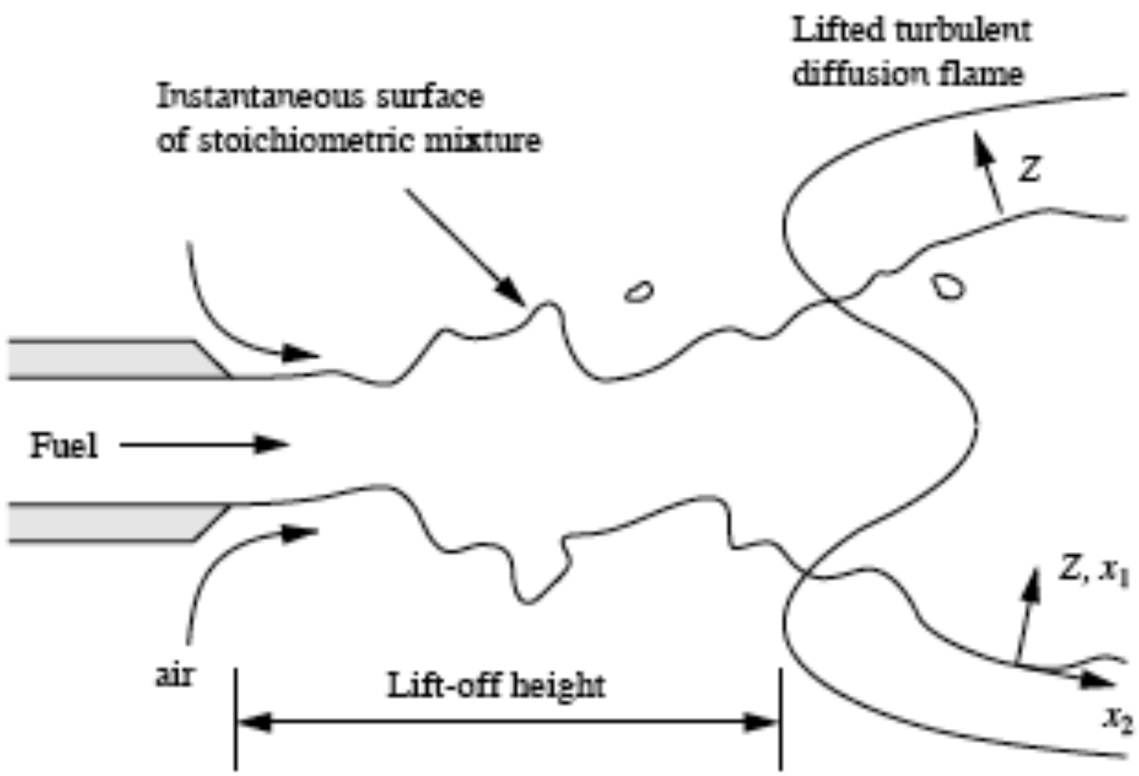
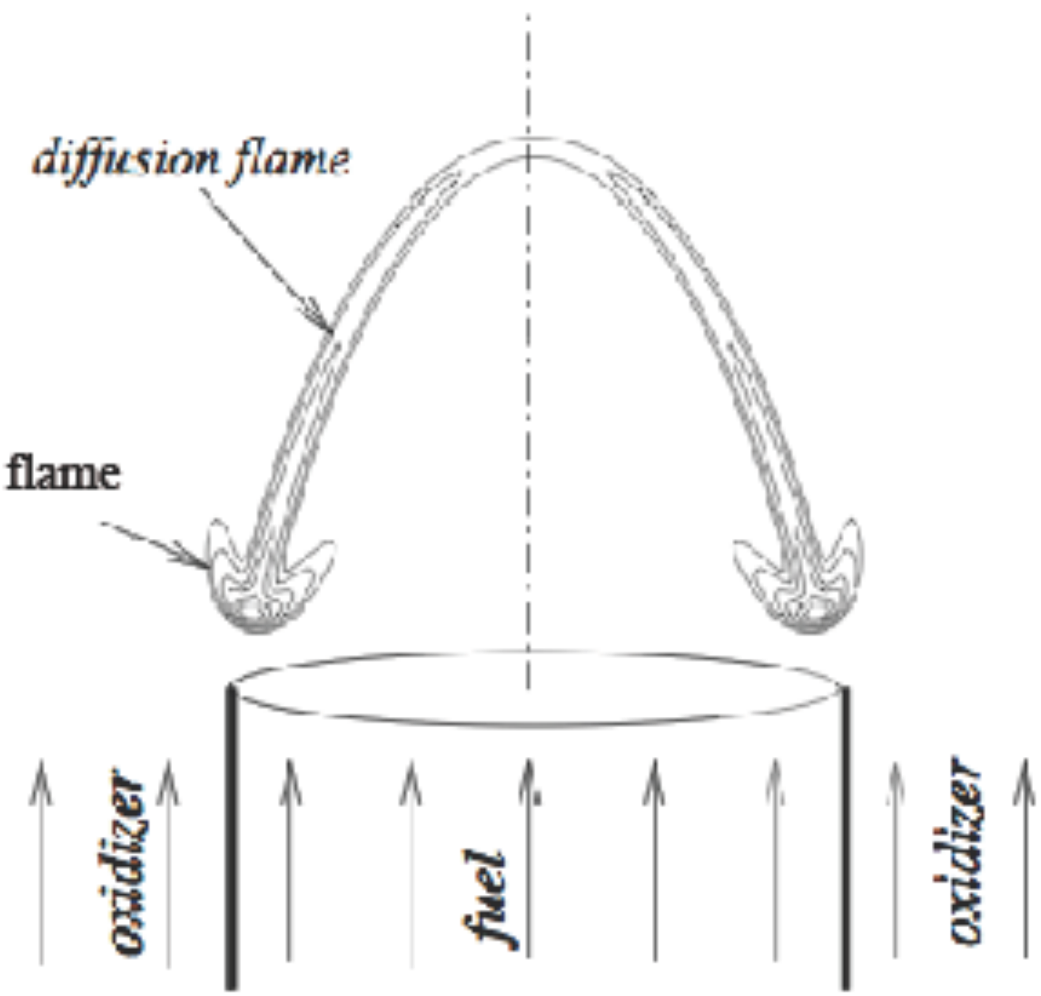


Figure 4.9: Schematic presentation of a lifted jet diffusion flame.

LIFTED FLAMES

In practical systems, where fuel and oxidizer are supplied in two separate streams, it is often advantageous to run at high flow rates and stabilize the flame further downstream within the jet. Lifting the flame base off the burner has the advantage of (i) avoiding thermal contact between the flame and the rim and (ii) enhancing mixing in the dead-space. <u>Conditions for stabilization, are of practical importance.</u>

Lifted propane/air jet-flame
Chung & Lee, C&F 1991



29

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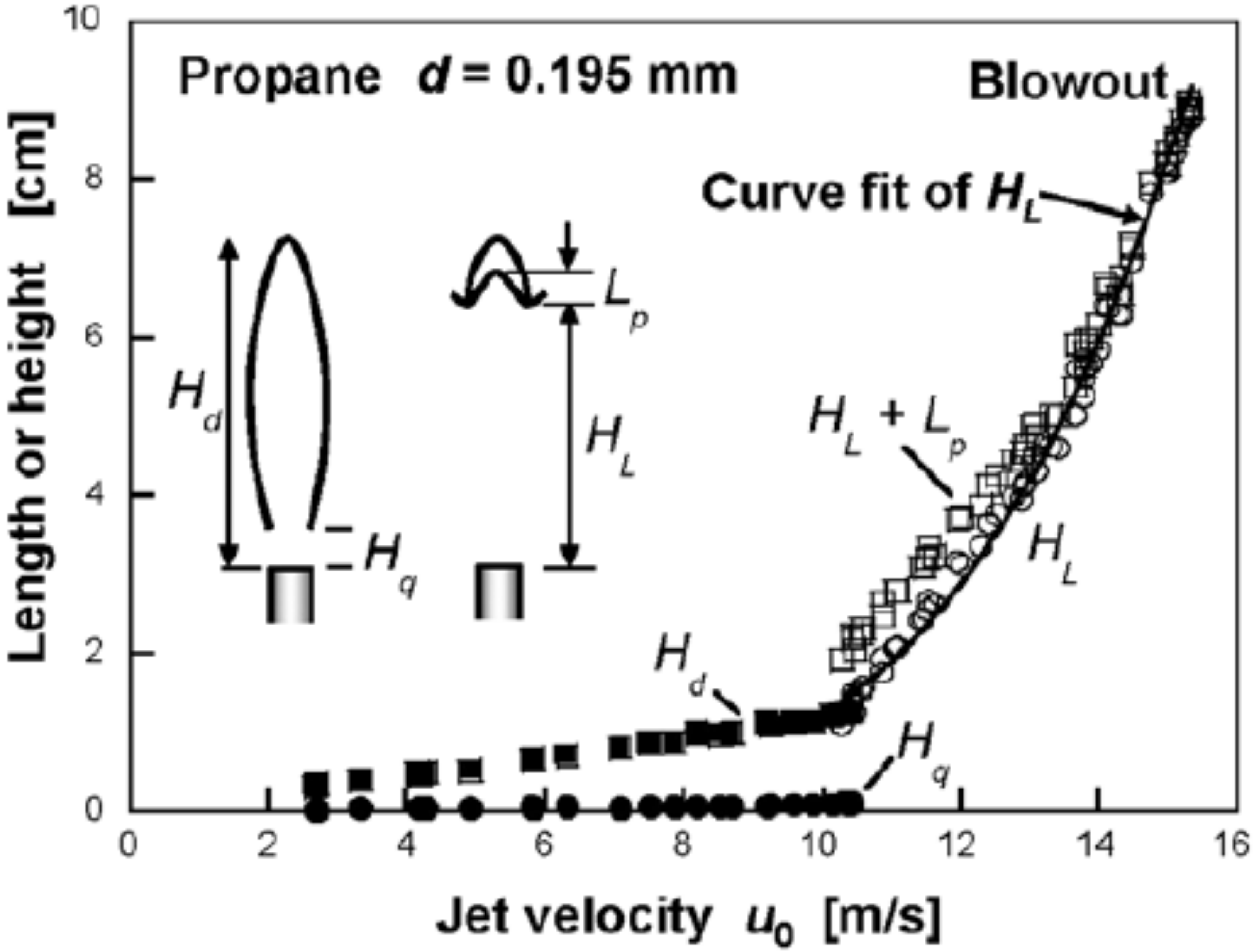
LIFTED FLAMES

Lift off Height



$$\frac{H_L}{d^2}\frac{\nu}{S_e} = \left(\frac{3}{32}\right)\left(\frac{3}{2Sc+1}\frac{Y_{F,st}}{Y_{F,0}}\right)^{1/(Sc-1)} \times \left(\frac{u_0}{S_e}\right)^{(2Sc-1)/(Sc-1)},$$

$$\eta^{*2}/8 = \left(\frac{3}{2Sc+1}\frac{Y_{F,st}}{Y_{F,0}}\frac{u_0}{S_e}\right)^{-1/2(Sc-1)} - 1.$$

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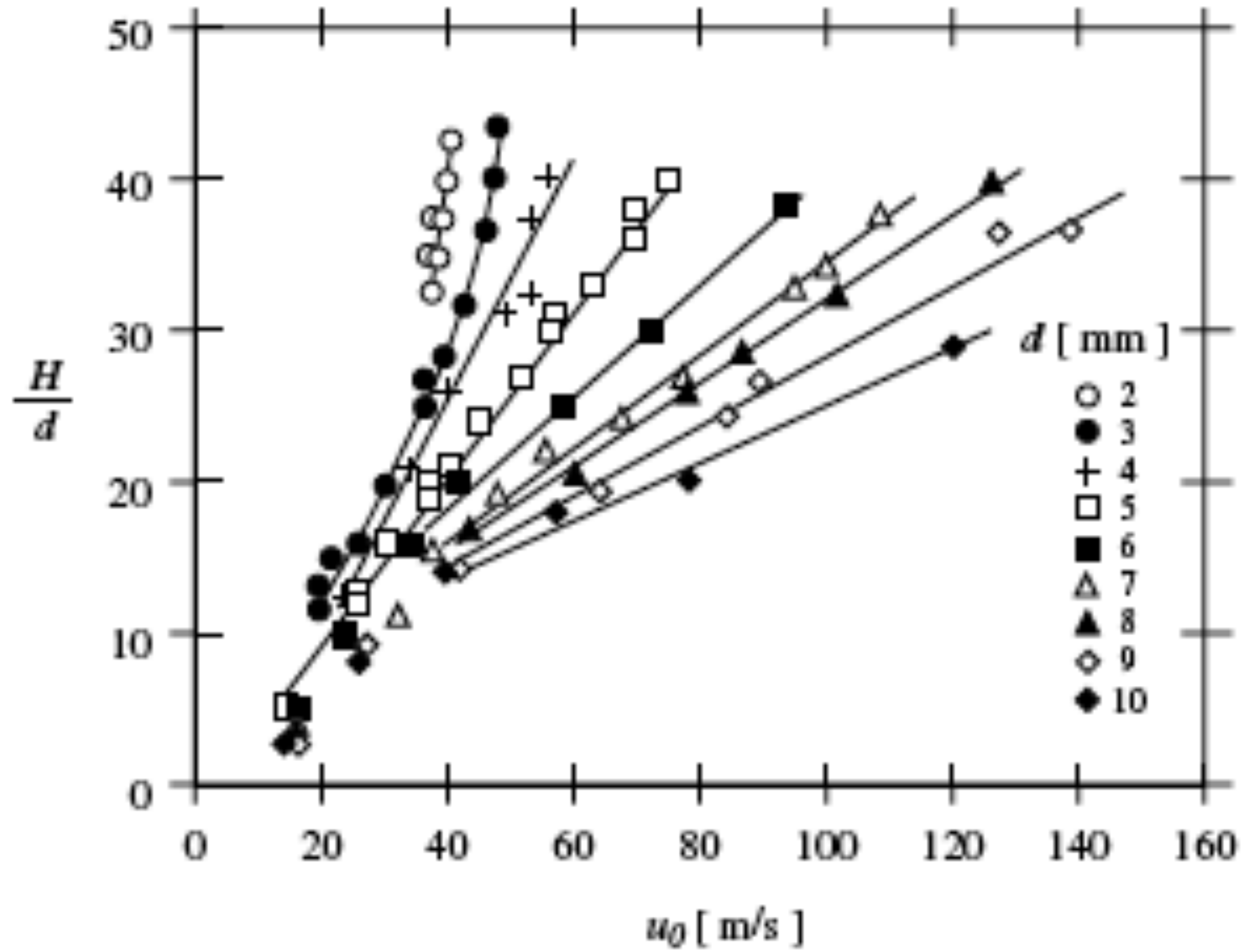
LIFTED FLAMES

Lift off Height - Methane/air Flame



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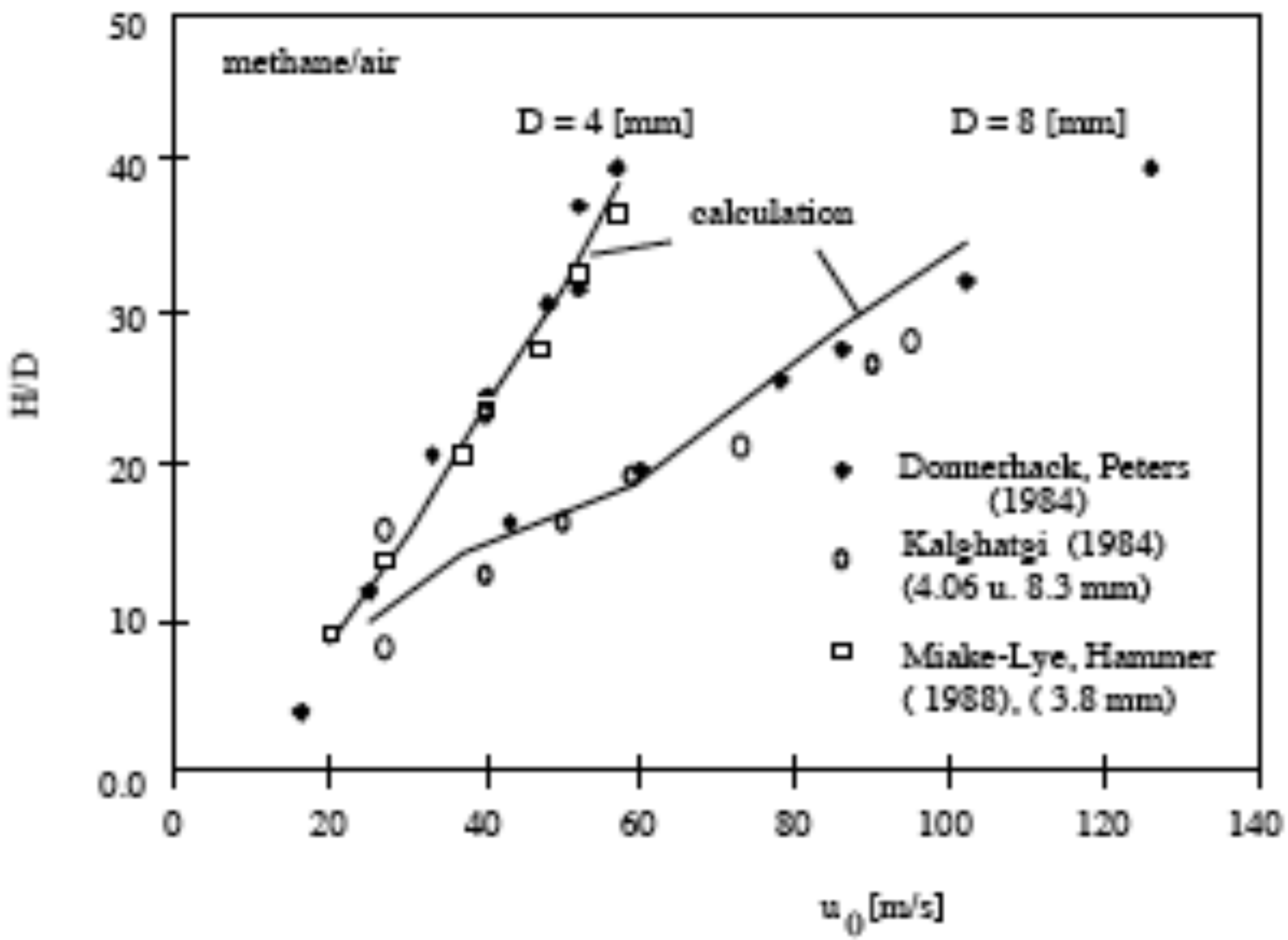
LIFTED FLAMES

Lift off Height - Methane/air Flame



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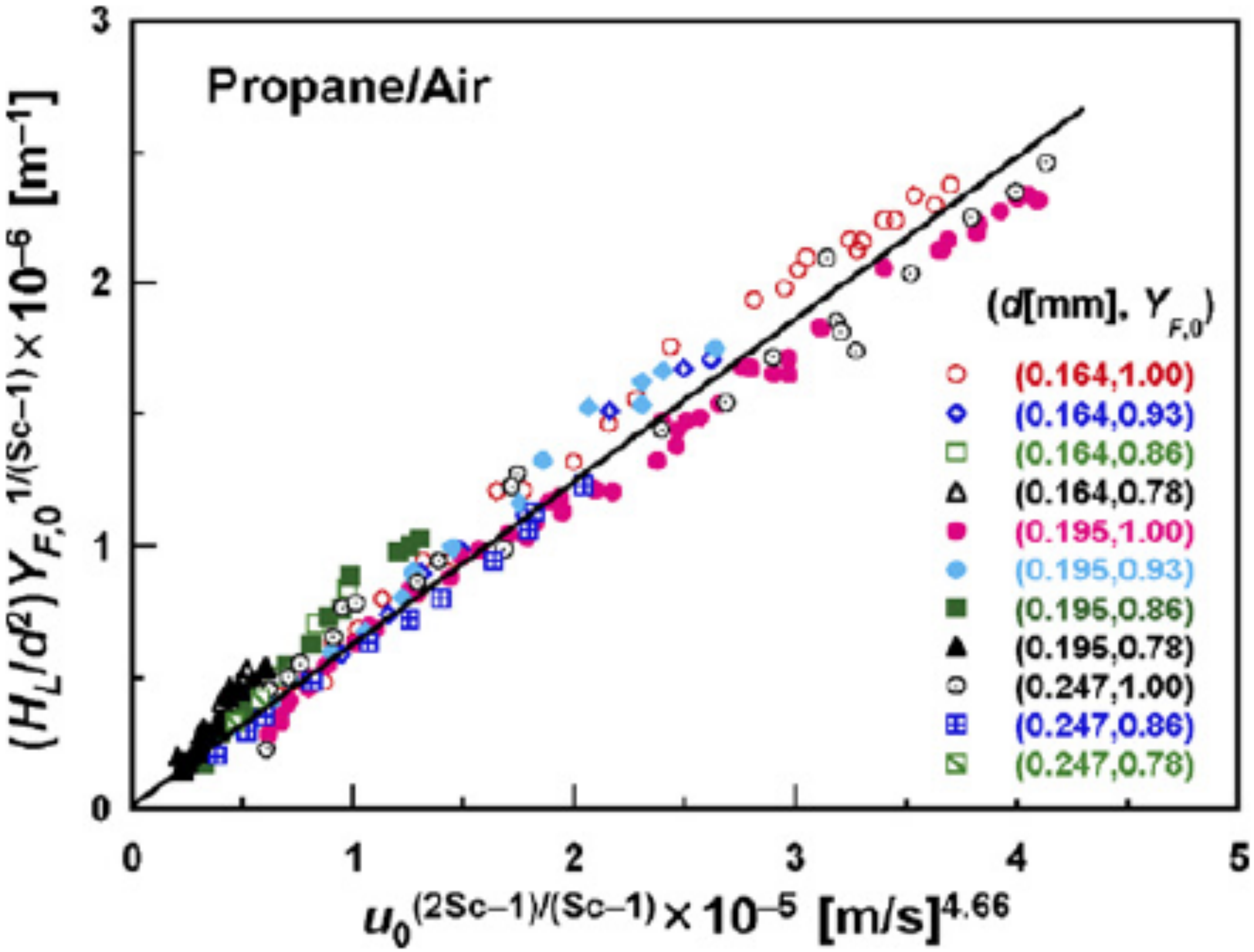
LIFTED FLAMES

Lift off Height



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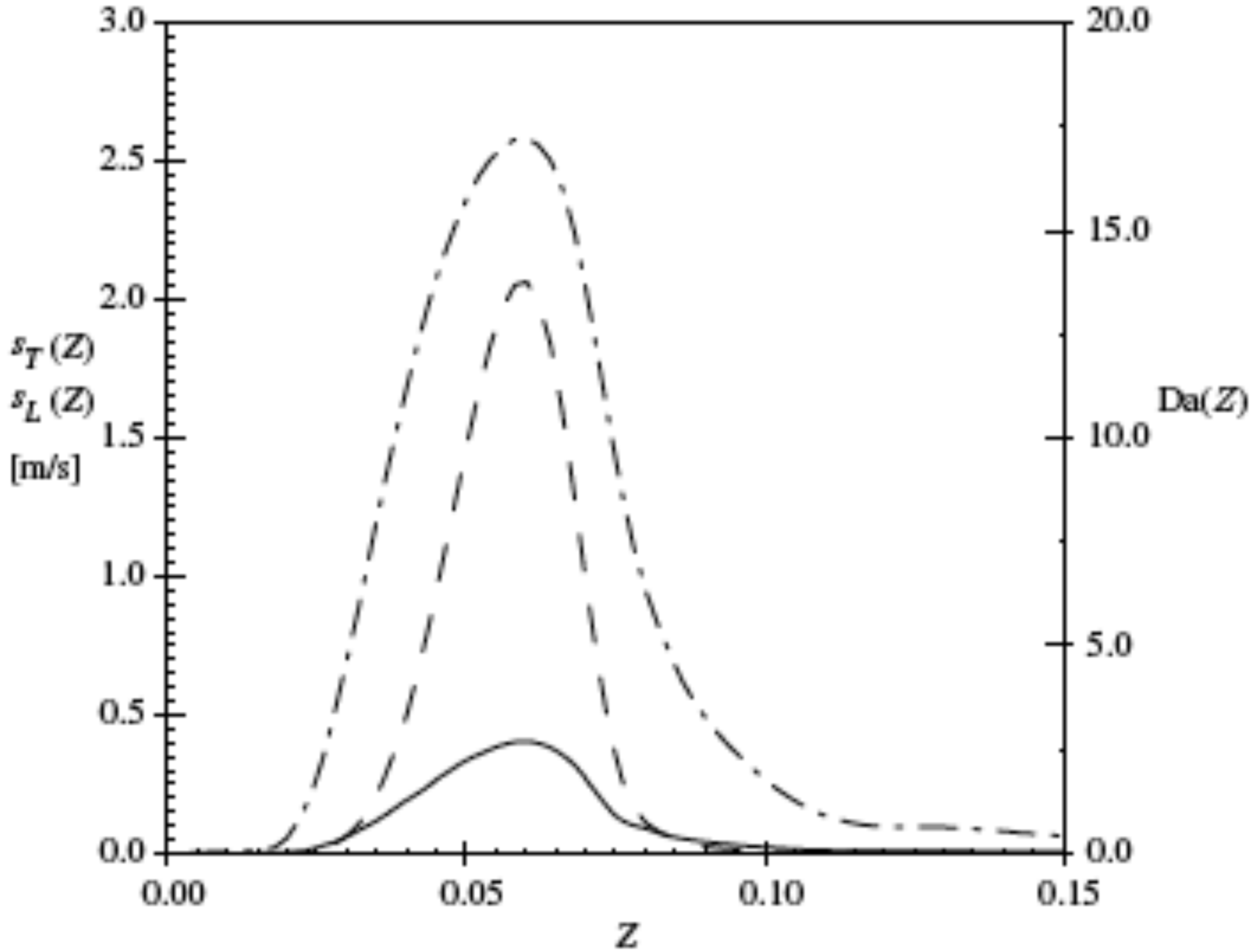
TRIPLE FLAME PROPAGATION

When the laminar burning velocity is plotted as a function of mixture fraction there is a maximum burning velocity that lies close to the stoichiometric mixture.



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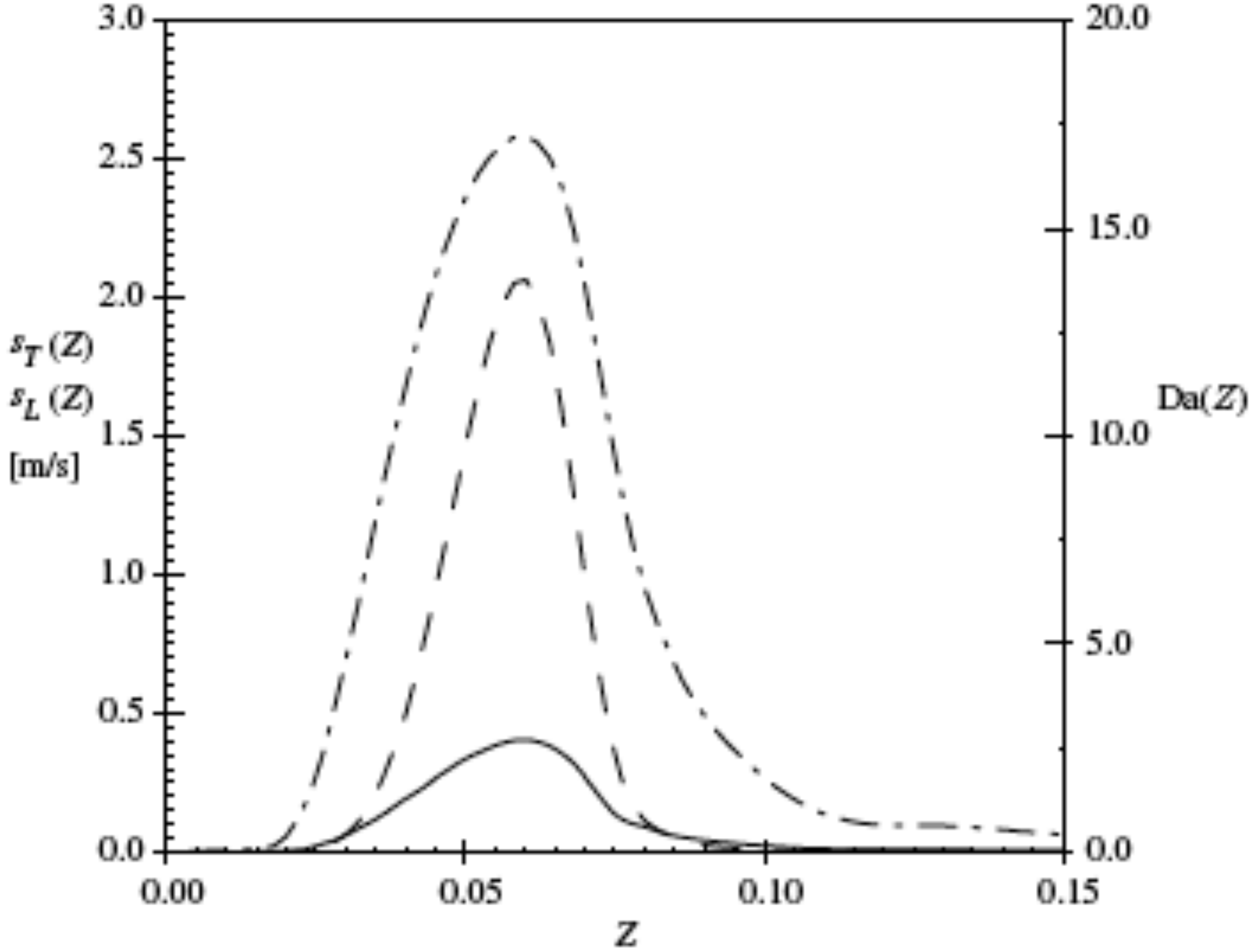
TRIPLE FLAME PROPAGATION



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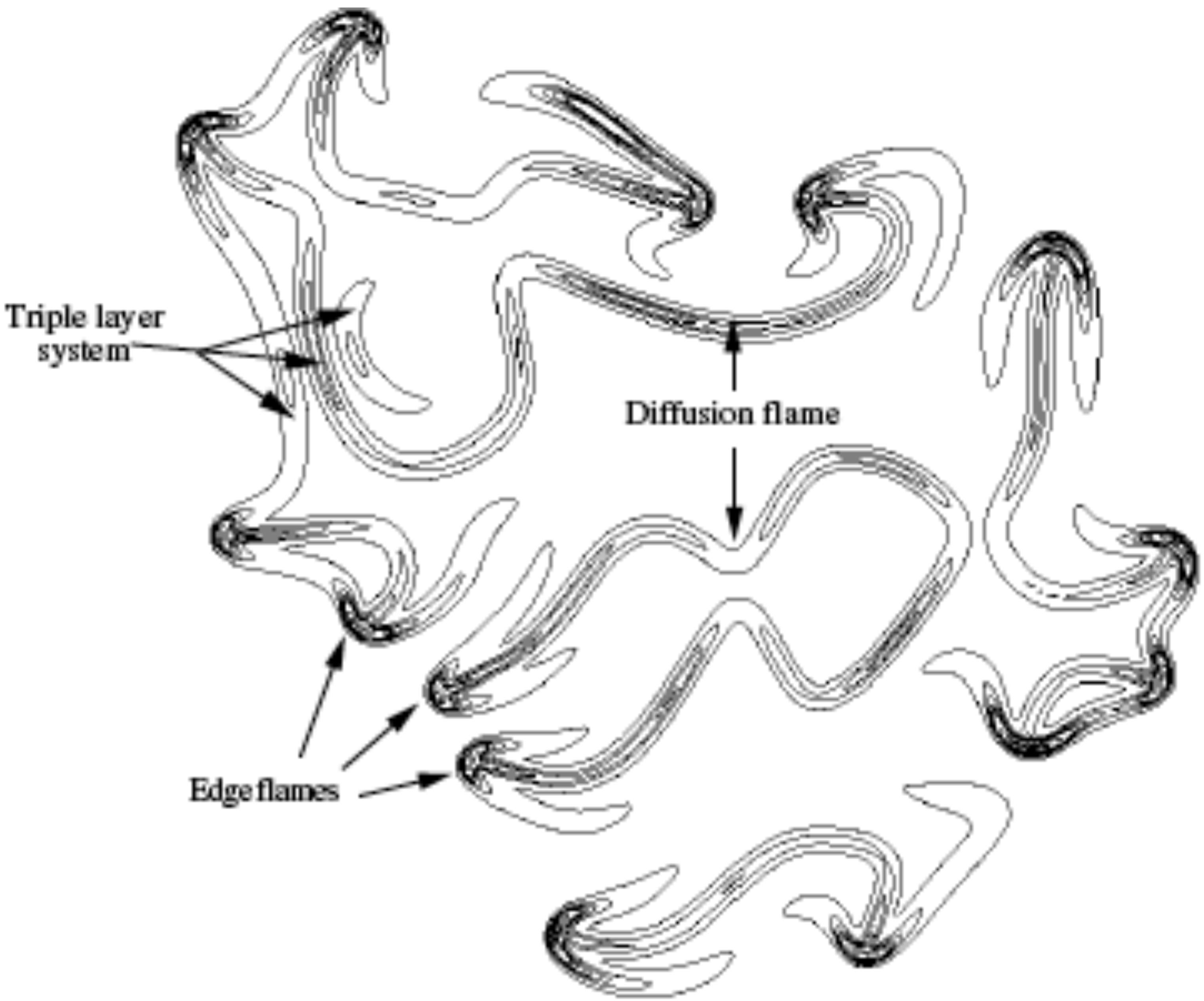
TRIPLE FLAME PROPAGATION



1. Ignition occured in the vicinity of the stoichiometric line in regions where the scalar dissipation rate was low.

2. Two premixed flame fronts containing lean and rich branches propagate in opposite directions along the stoichiometric lines. They have the shapes of arrow-heads.

3. A diffusion flame develops on the stoichiometric line between the premixed flames. The tails of the premixed flames are lying nearly parallel to the diffusion flame and are propagating into the lean and rich mixture. As they depart from the diffusion flame they become weaker and finally disappear.

4. When premixed flame fronts try to propagate into regions of very high scalar dissipation rates, local extinction is likely to occur.

5. The dissipation rate and the heat release rate are inversely correlated. Maximum values of the dissipation rate correspond to minimum levels of heat release and vice versa.

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It is concluded that the conditional mean value of the scalar dissipation rate at stoichiometric mixture controls ignition and subsequent flame propagation in partially premixed systems.

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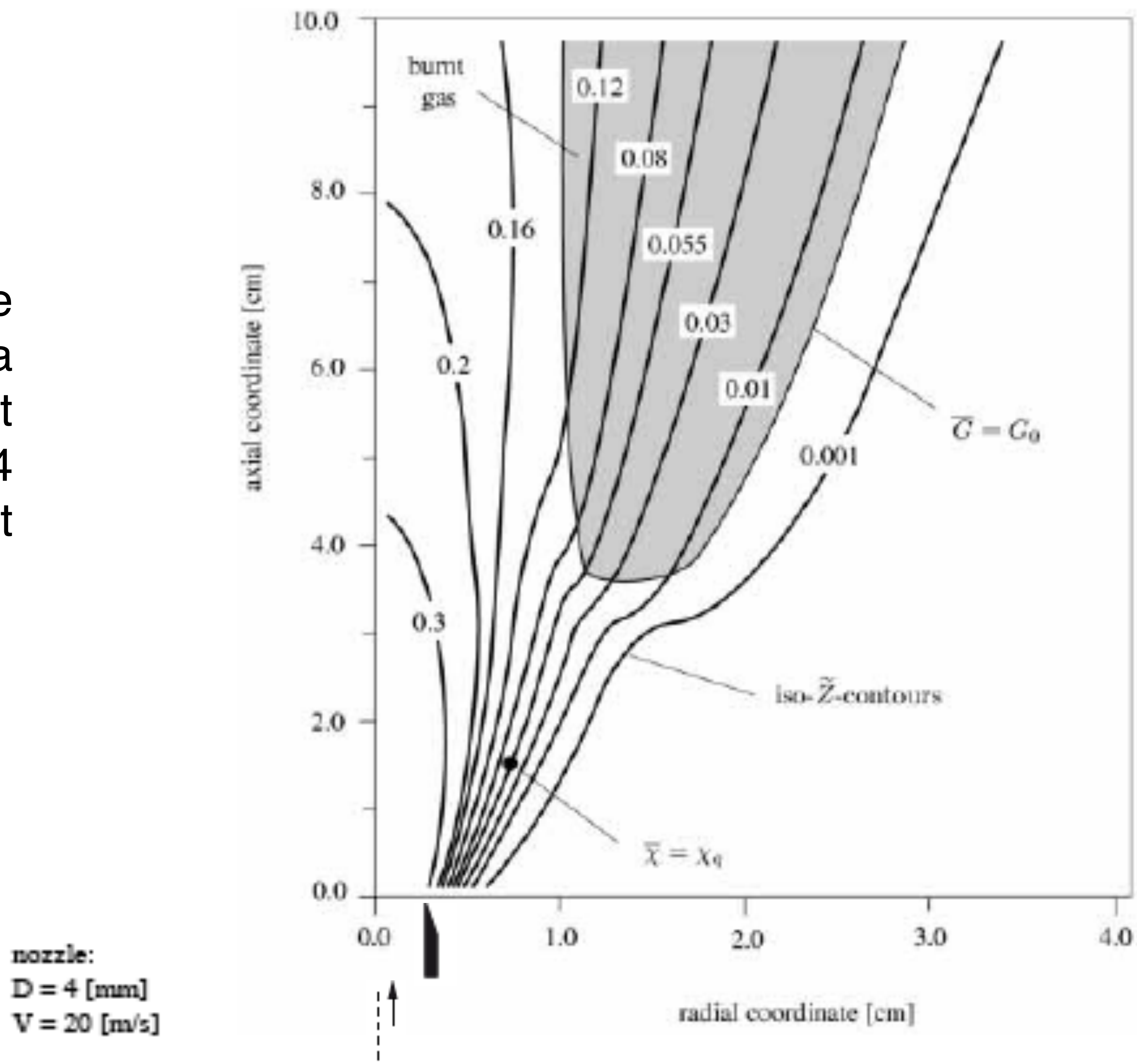
TRIPLE FLAME PROPAGATION

blow-up of the stabilization region in a turbulent methane jet flame with a diameter D=4 mm and a fuel exit velocity of 20 m/s.



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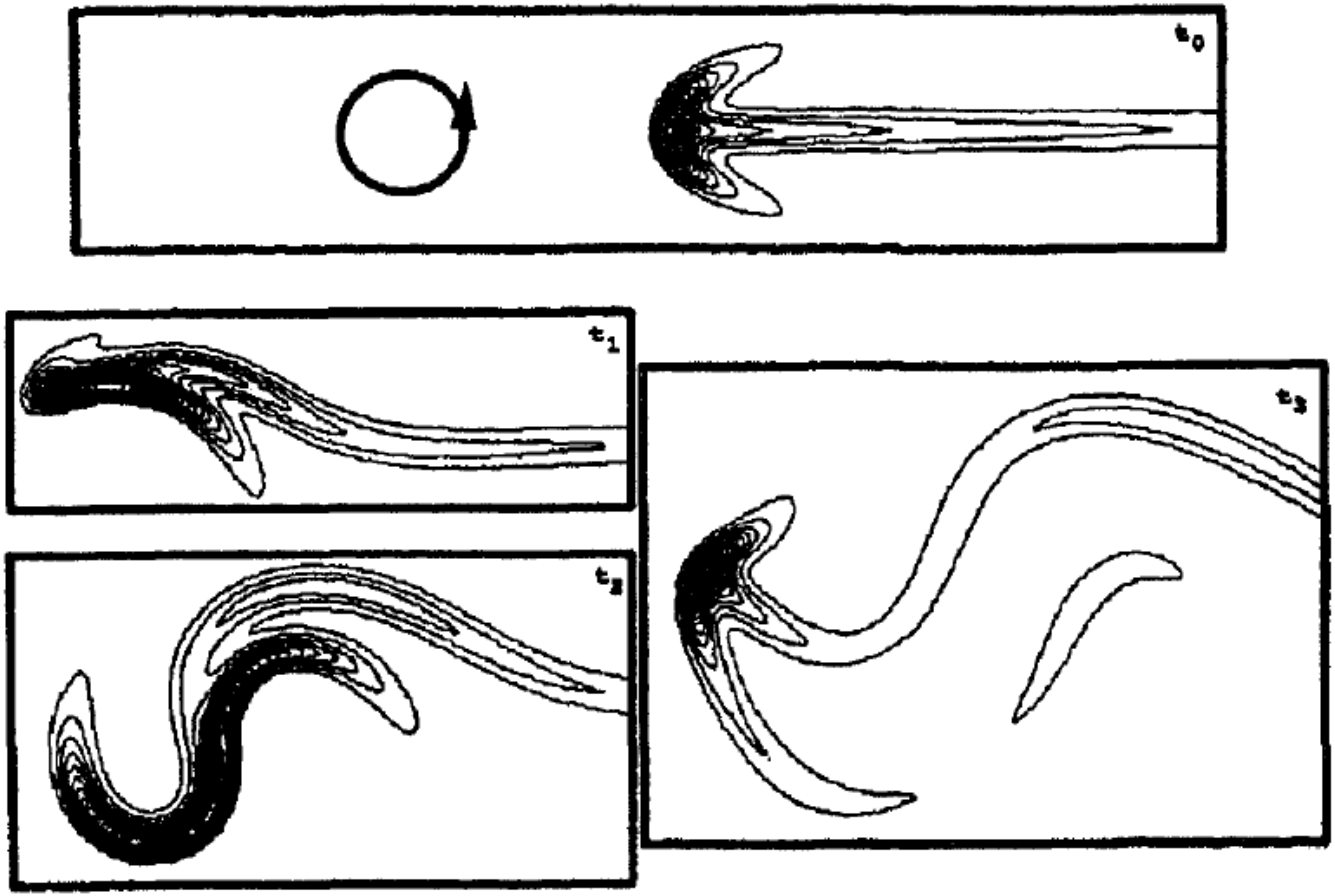
TRIPLE FLAME PROPAGATION

interaction with a single vortex



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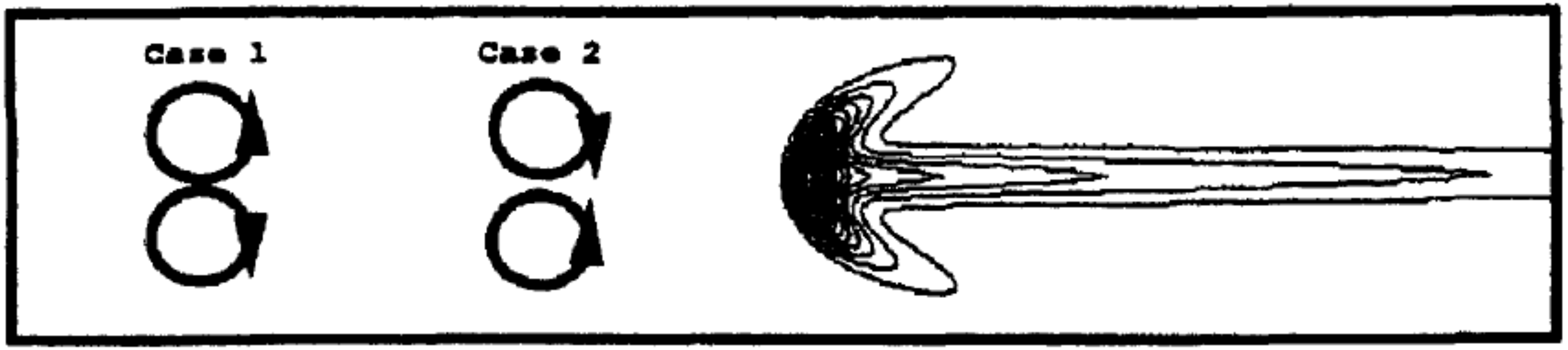
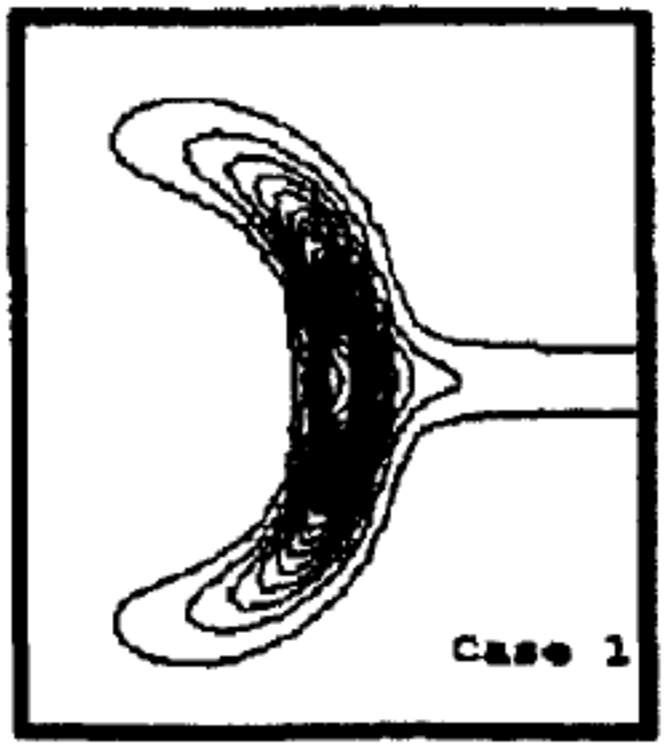
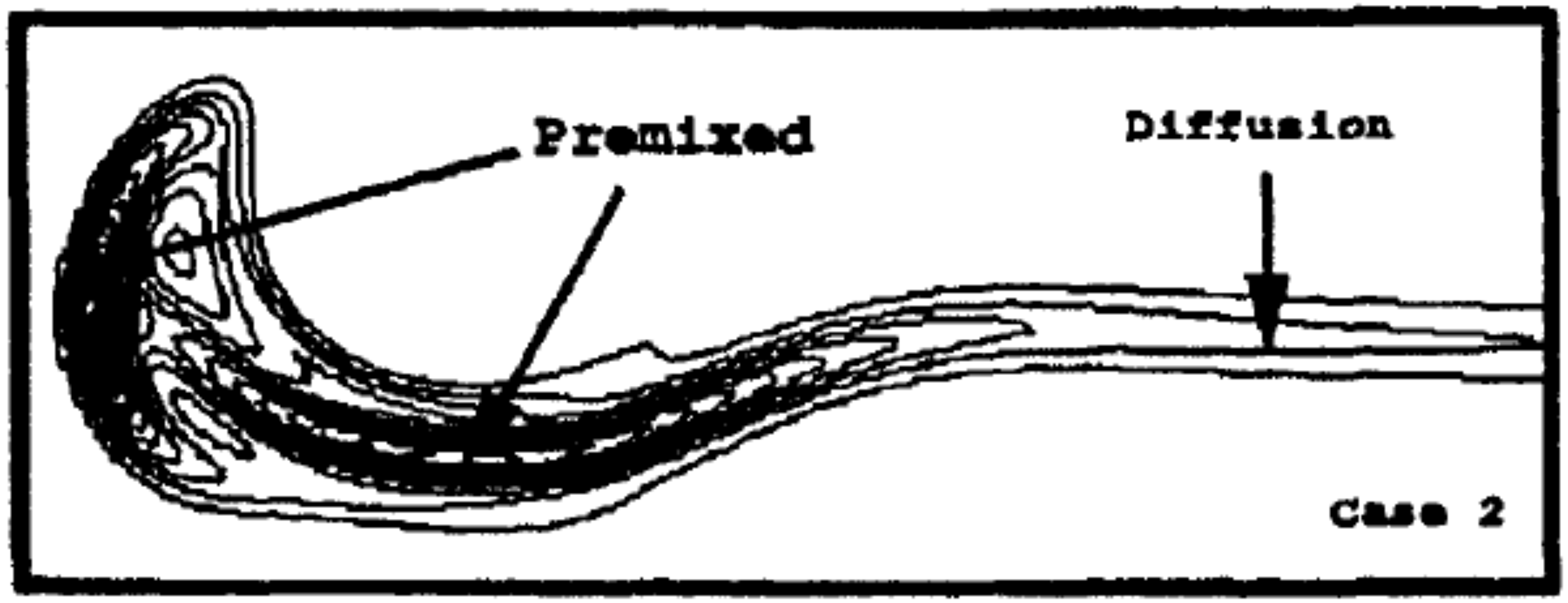
TRIPLE FLAME PROPAGATION

interaction with two vortex pairs







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COURSE OVERVIEW

DAY 3

Complex Flame Structures

a. Interaction of Multiple Mixing Layers
b. Partially Premixed Combustion. The Structure of Triple Flames
b. Lifted flames and lift-off height
d. Triple flame propagation

Turbulence, Mixing and Aerodynamics

a. Characteristics and Description of Turbulent Flows
b. Turbulent Premixed Combustion. Scales and Dimensionless Quantities.
c. Borghi Diagram
d. Flame stabilization, Ignition and Extinction
e. Flashback and Blowoff
f. Swirl and reverse flows

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