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, Flashback and Blowoff
f. Swirl and cyclonic flows

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TURBULENCE - a complex problem

Horace Lamb during a meeting at the London British Association on 1932 :

"I am an old man now, and when I die and go to Heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am really rather optimistic."

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TURBULENCE - a complex problem

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{v}) = 0$$

$$\rho\left[\frac{d(\omega_i)}{dt} + v\nabla(\omega_i)\right] = \rho\frac{D(\omega_i)}{Dt} = -\nabla(\mathbf{j}_i) + \dot{w}_i$$

$$\rho\frac{D\mathbf{v}}{Dt} = -\nabla P - [\nabla\tau] + \rho\mathbf{g}$$

$$\frac{\partial}{\partial t}\rho\left(u + \frac{1}{2}v^2 + \phi\right) = -\left(\nabla \bullet \rho\mathbf{v}\left(u + \frac{1}{2}v^2 + \phi\right)\right) - (\nabla \bullet \mathbf{q}) + \rho(\mathbf{v} \bullet \mathbf{g}) - (\nabla \bullet p\mathbf{v}) - (\nabla \bullet (\tau \bullet \mathbf{v}))$$

$$f(\rho, \omega_i, T, P) = 0.$$

Ns + 6 equation in Ns + 6 variables: ρ, ω, v_x, v_y, v_z, T, P

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TURBULENT FLOWS

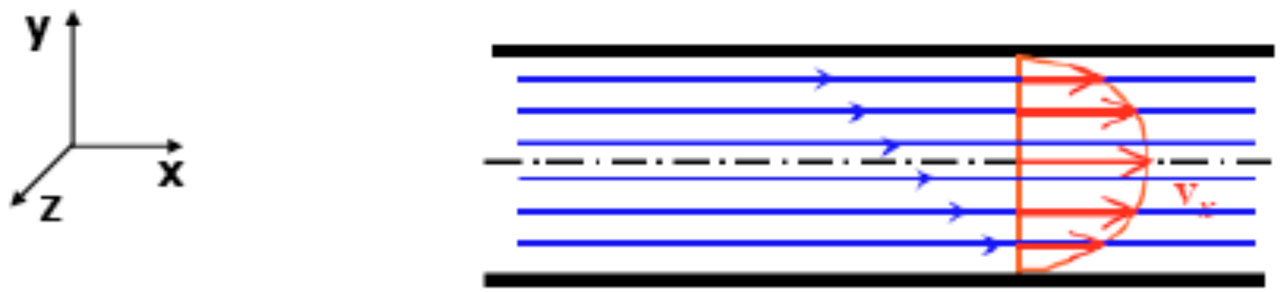
Hypothesis: The (reactive) Navier-Stokes equations govern turbulent combustion.

The Navier-Stokes equations supplemented with initial and boundary conditions are deterministic and are believed to possess a unique solution.
For small Reynolds numbers, exact solutions exist. However, when Re is large, the solution is highly sensitive to the initial conditions, which cannot be specified with sufficient accuracy to obtain a deterministic solution, either computationally or experimentally.

Introduce statistical methods and seek a probabilistic description of turbulent flows.

TURBULENT FLOWS
the numerical problem

LAMINAR FLOW

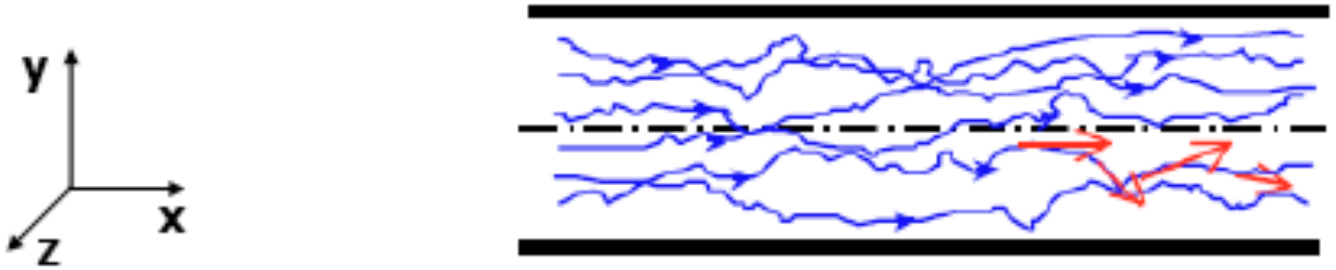


$$v_x = \frac{\gamma}{4\mu} J\left(r_0^2 - r^2\right)$$

$$v_y = 0$$

$$v_z = 0$$

TURBULENT FLOW



$$v_x = ?$$

$$v_y = ?$$

$$v_z = ?$$

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Millennium Problems

Yang–Mills and Mass Gap

Experiment and computer simulations suggest the existence of a "mass gap" in the solution to the quantum versions of the Yang-Mills equations. But no proof of this property is known.

Riemann Hypothesis

The prime number theorem determines the average distribution of the primes. The Riemann hypothesis tells us about the deviation from the average. Formulated in Riemann's 1859 paper, it asserts that all the 'non-obvious' zeros of the zeta function are complex numbers with real part 1/2.

P vs NP Problem

If it is easy to check that a solution to a problem is correct, is it also easy to solve the problem? This is the essence of the P vs NP question. Typical of the NP problems is that of the Hamiltonian Path Problem: given N cities to visit, how can one do this without visiting a city twice? If you give me a solution, I can easily check that it is correct. But I cannot so easily find a solution.

Navier–Stokes Equation

This is the equation which governs the flow of fluids such as water and air. However, there is no proof for the most basic questions one can ask: do solutions exist, and are they unique? Why ask for a proof? Because a proof gives not only certitude, but also understanding.

Hodge Conjecture

The answer to this conjecture determines how much of the topology of the solution set of a system of algebraic equations can be defined in terms of further algebraic equations. The Hodge conjecture is known in certain special cases, e.g., when the solution set has dimension less than four. But in dimension four it is unknown.

Poincaré Conjecture

In 1904 the French mathematician Henri Poincaré asked if the three dimensional sphere is characterized as the unique simply connected three manifold. This question, the Poincaré conjecture, was a special case of Thurston's geometrization conjecture. Perelman's proof tells us that every three manifold is built from a set of standard pieces, each with one of eight well-understood geometries.

Birch and Swinnerton-Dyer Conjecture

Supported by much experimental evidence, this conjecture relates the number of points on an elliptic curve mod p to the rank of the group of rational points. Elliptic curves, defined by cubic equations in two variables, are fundamental mathematical objects that arise in many areas: Wiles' proof of the Fermat Conjecture, factorization of numbers into primes, and cryptography, to name three.

The Millennium Prize Problems are seven problems in mathematics that were stated by the Clay Mathematics Institute on May 24, 2000. A correct solution to any of the problems results in a US$1 million prize being awarded by the institute to the discoverer(s).

TURBULENT FLOWS

We know what a turbulent flow is, when we see it!

It is characterized by disorder, vorticity and mixing

In a fluid flow , turbulence is characterized by fluctuations of velocities and state variables in space and time. This occurs when the Reynolds number

$$Re = UL/\nu \gg 1$$

L is a characteristic dimension of the vessel
U is a characteristic velocity of the flow
ν is the kinematic viscosity μ/ρ (cm^2/s).

$$Re^{-1} = \frac{L/U}{L^2/\nu} = \frac{t_a}{t_d} = \frac{\text{overall time to } \textbf{advect} \text{ a fluid particle a distance } L}{\text{viscous } \textbf{dissipation} \text{ time over distance } L} \ll 1$$

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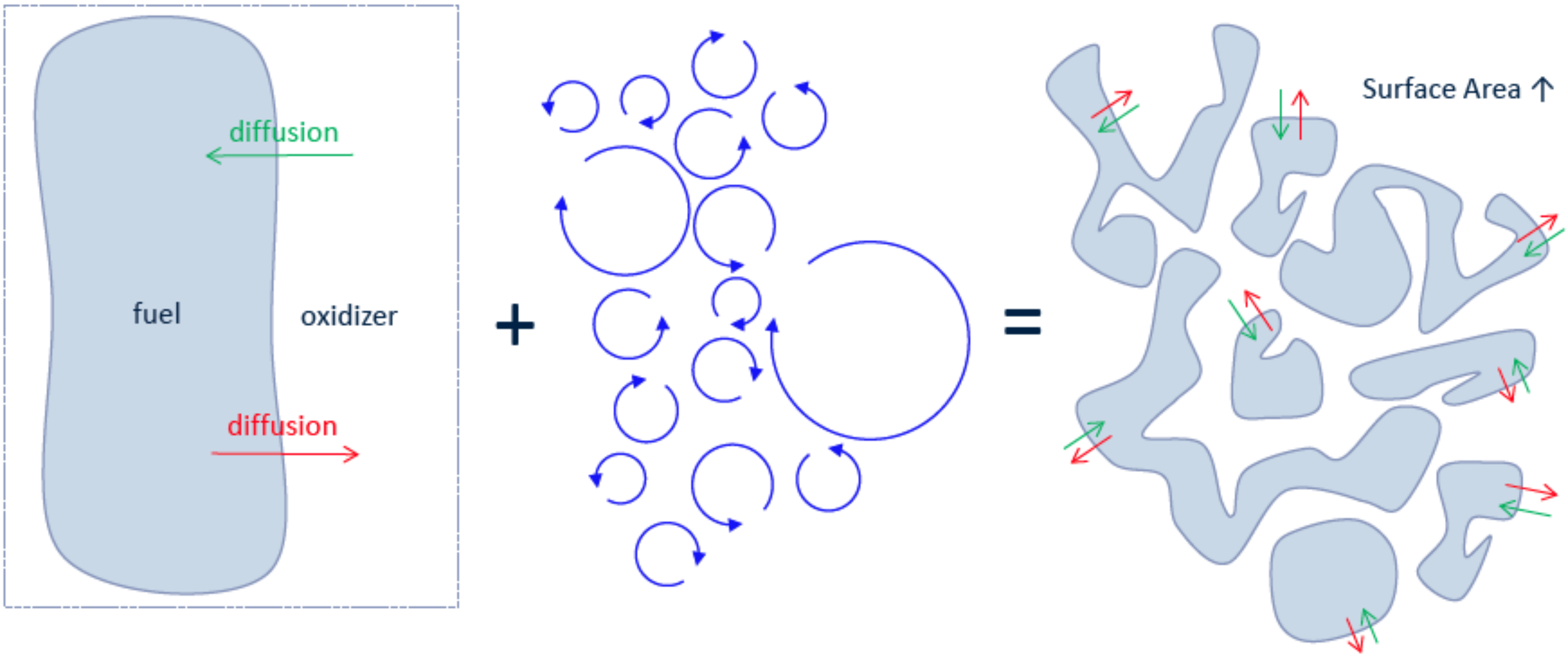
TURBULENT MIXING

- *Combustion requires mixing at the molecular level*
- *Turbulence: convective transport ↑   molecular mixing ↑*



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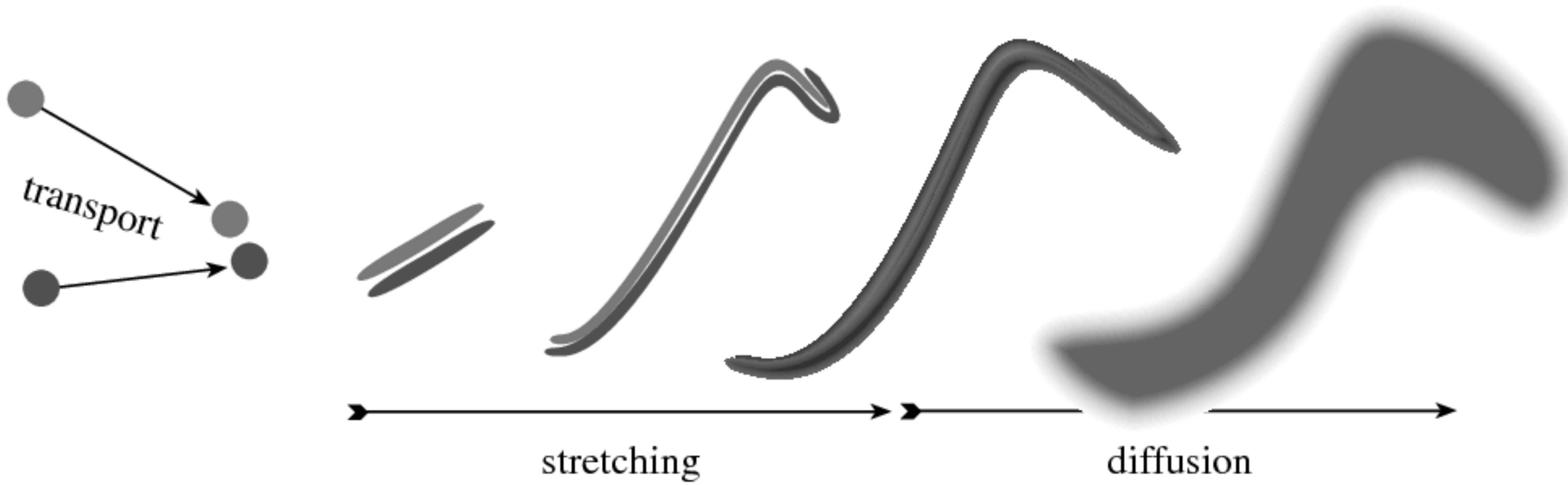
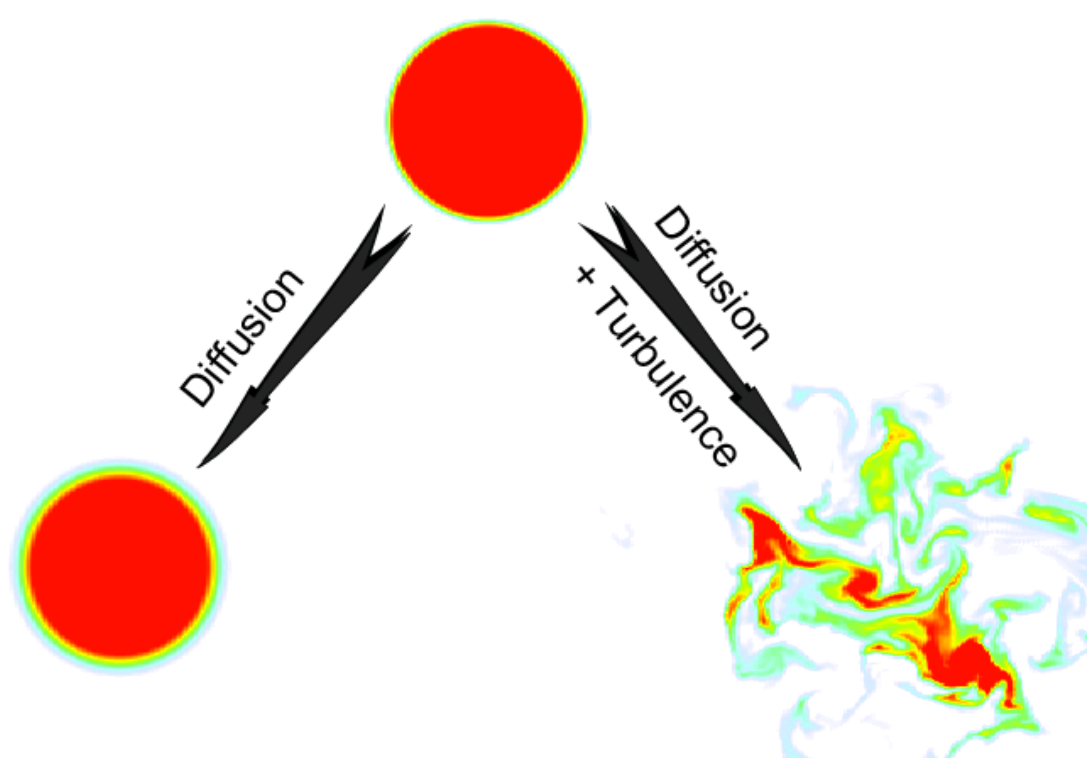
TURBULENT MIXING





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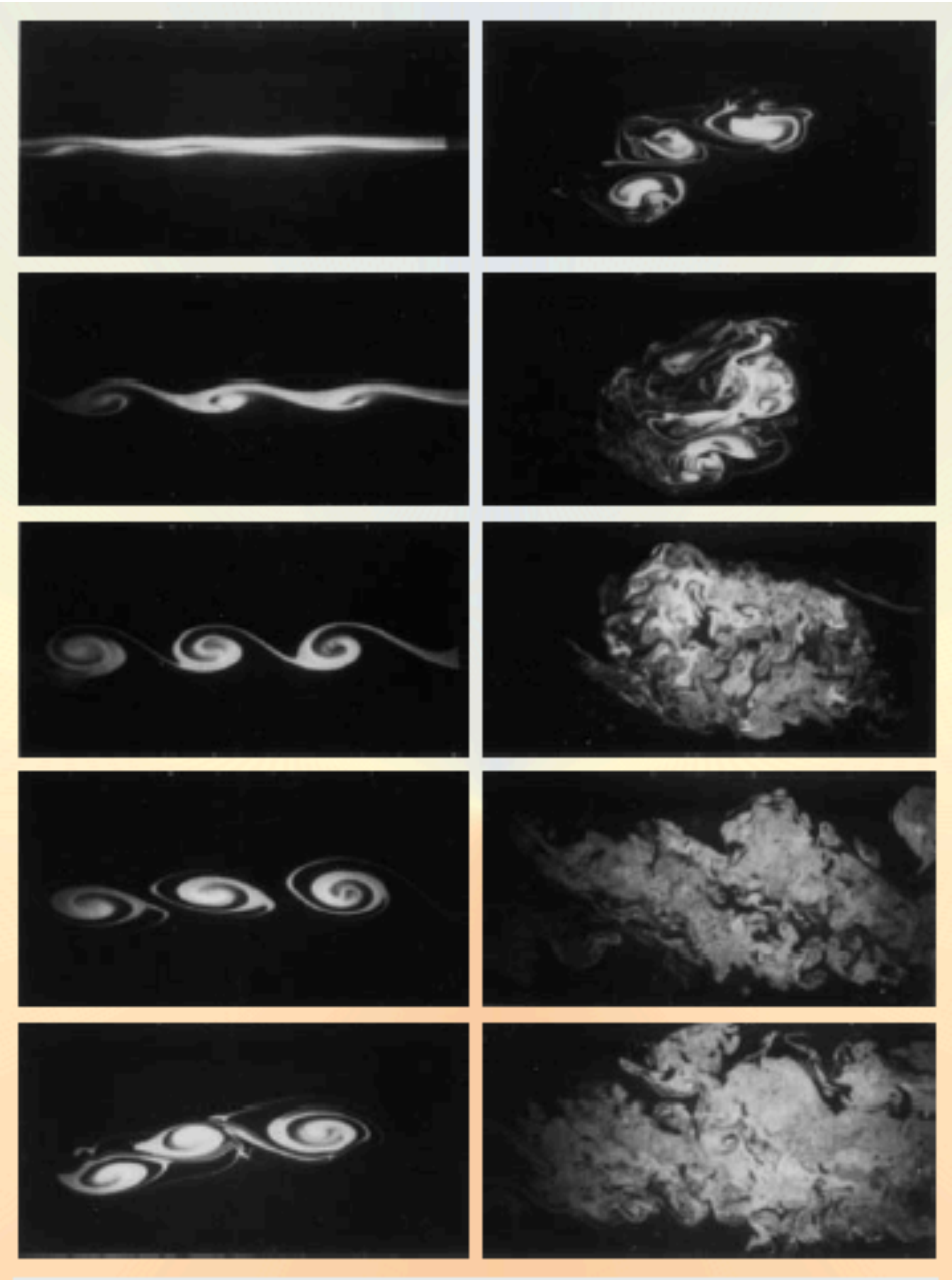
Transition to Turbulence



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basic features of turbulence

– High Reynolds numbers

- Instability of laminar flows
- Non-linearity and randomness make the problem nearly intractable

– Three dimensional vorticity fluctuations

- The large scale structure in tornado is not mainly turbulent!
- Vortex stretching mechanism

– Dissipation

- Energy transfer from large scales to small scale and dissipated to heat

– Turbulence is continuum flow!

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TURBULENT FLOW

STATISTICAL DESCRIPTION

The aim is to describe the fluctuating velocity and scalar fields in terms of their statistical distributions.

AVERAGING

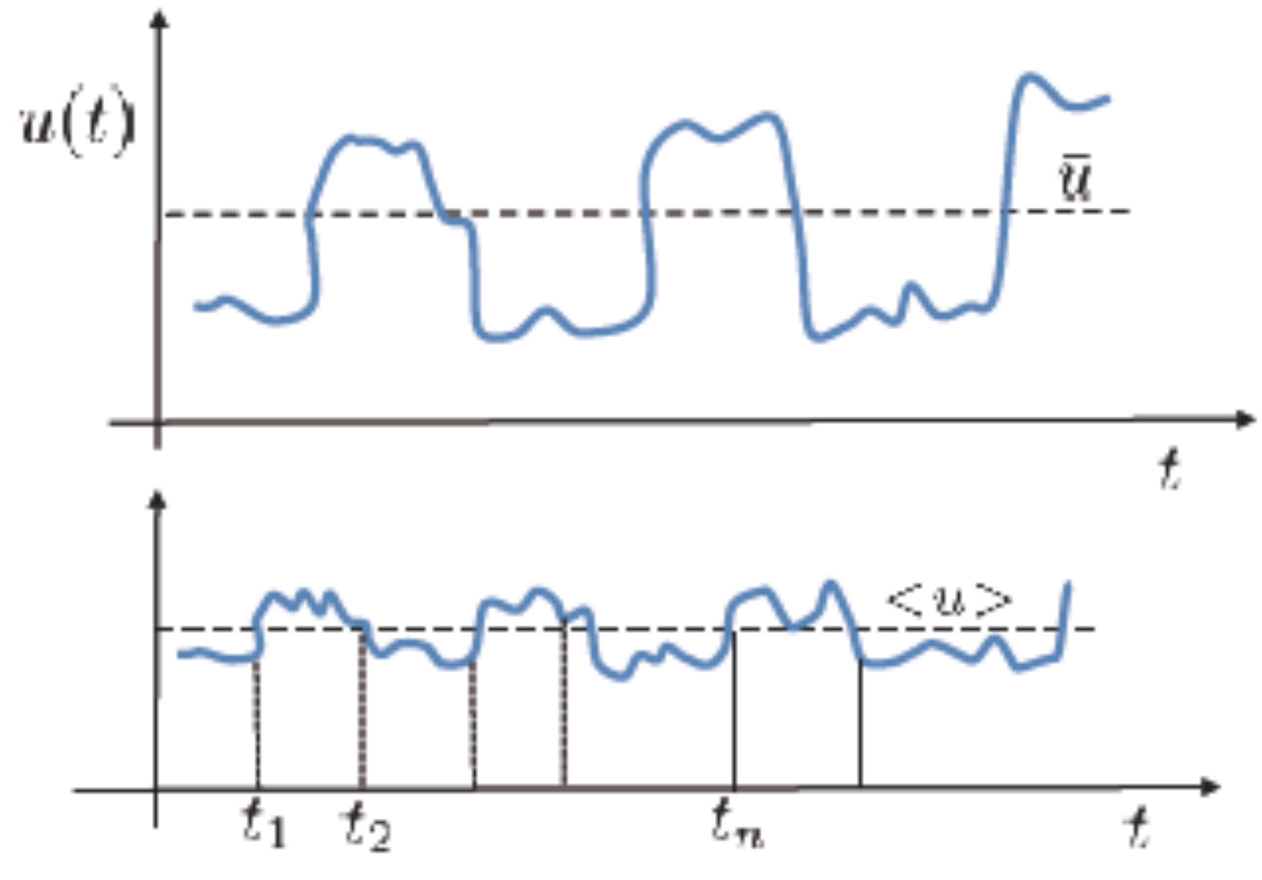
Time averaging

$$\bar{u}(\mathbf{x}) = \lim_{T\to\infty} \frac{1}{T}\int_0^T u(t,\mathbf{x})dt$$

Ensemble averaging

compiled from many different realizations where $u(t_n,\mathbf{x})$ is the n^{th} realization

$$\langle u(t,\mathbf{x})\rangle = \lim_{N\to\infty} \frac{1}{N}\sum_{n=1}^{N} u(t_n,\mathbf{x})$$



measurements taken at a fixed point

Assuming the limiting process converges to a well-defined value, the variable $u(t,\mathbf{x})$ is said to be **statistically stationary**.

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TURBULENT FLOW
STATISTICAL DESCRIPTION

If we decompose *u(t,x)* into a mean and the deviation from the associated mean, namely, $u(t,\mathbf{x}) = \overline{u} + u'(t,\mathbf{x})$, then by definition,

$$\overline{u'(t,\mathbf{x})} = \langle u'(t,\mathbf{x}) \rangle = 0$$

$\overline{u'^2}$ is the **variance** - the extent of variation from the mean

the root mean square $\sqrt{\overline{u'^2}}$ is the **intensity**

the correlation of the fluctuations of two variables is often of interest

$$\overline{u\ v} = \overline{(\bar{u} + u')(\bar{v} + v')} = \bar{u}\,\bar{v} + \bar{u'}\bar{v} + \bar{u}\bar{v'} + \overline{u'\ v'} = \bar{u}\,\bar{v} + \underbrace{\overline{u'\ v'}}_{\text{correlation}}$$

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TURBULENT FLOW
STATISTICAL DESCRIPTION

$$C^{u'v'} = \frac{\overline{u'v'}}{\sqrt{\overline{u'^2}}\sqrt{\overline{v'^2}}}$$

Correlation coefficients indicate the extent of the interdependence of two variables.

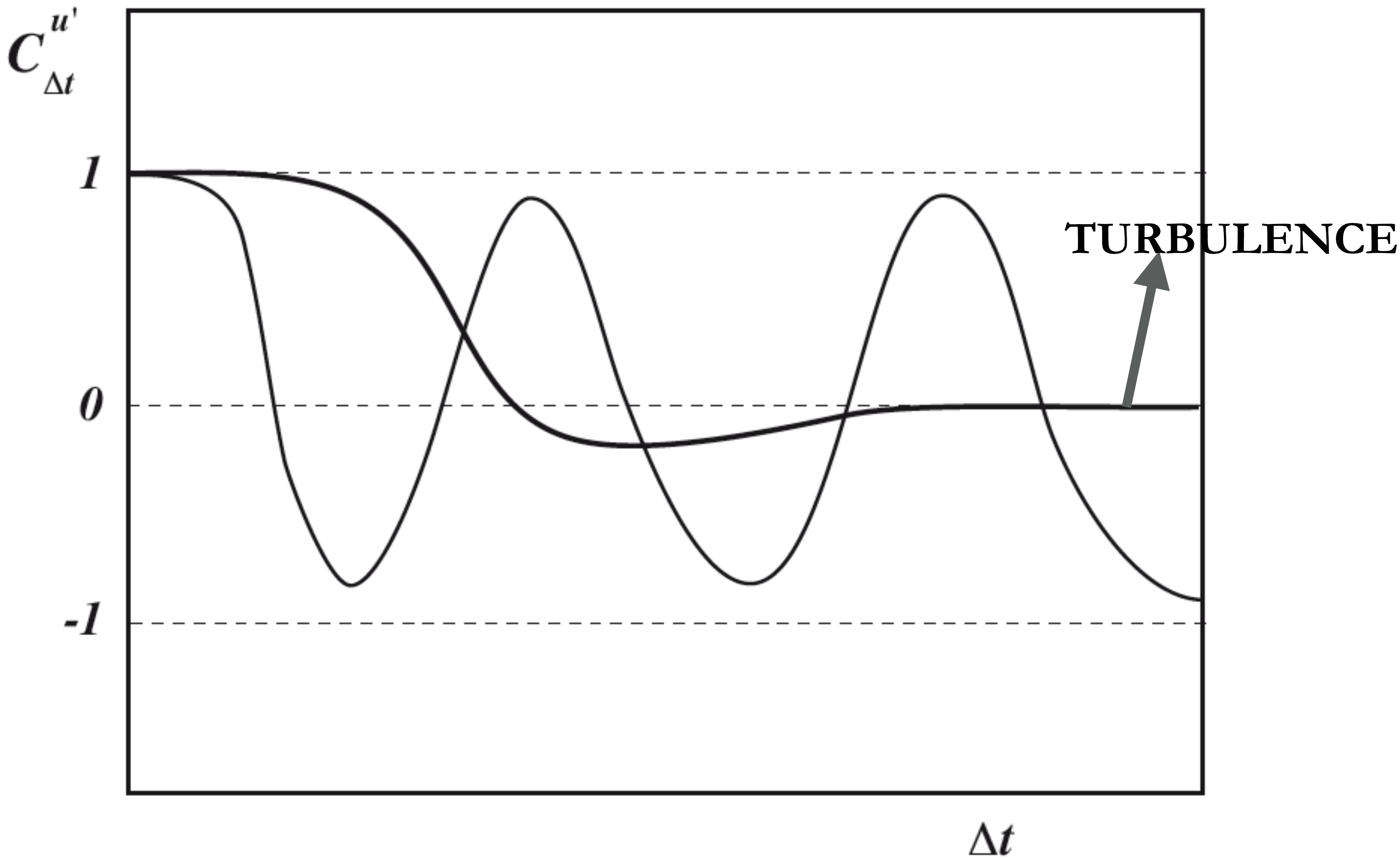
We can also define it on a single variable if we refer to two different points in time or space

$$C_{\Delta r}^{u'} = \frac{\overline{u'(r,t)u'(r+\Delta r,t)}}{\sqrt{\overline{u'^2(r,t)}}\sqrt{\overline{u'^2(r+\Delta r,t)}}}$$

$$C_{\Delta t}^{u'} = \frac{\overline{u'(r,t)u'(r,t+\Delta t)}}{\sqrt{\overline{u'^2(r,t)}}\sqrt{\overline{u'^2(r,t+\Delta t)}}}$$

TURBULENT FLOW

STATISTICAL DESCRIPTION



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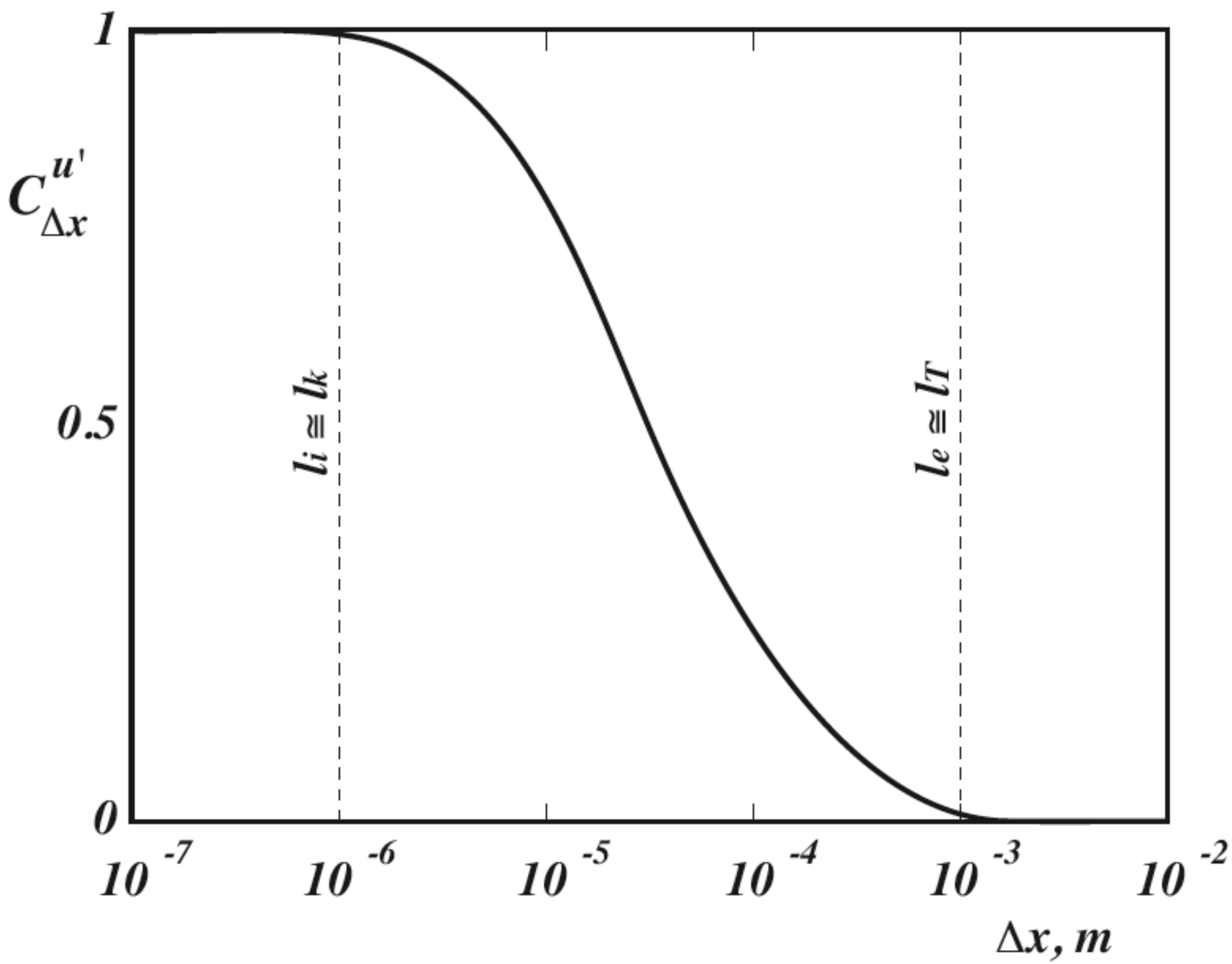
TURBULENT FLOW

Characteristic Scales



$$l_T = \int_o^\infty C_{\Delta x}^{u'} d(\Delta x)$$

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TURBULENT FLOW - Scales

Turbulent flows are said to be made up of small eddies with a multitude of sizes and vorticities. A **fluid eddy** is a macroscopic fluid element in which the microscopic elements comprising the eddy behave as a unit. An eddy is identified by a characteristic size and a characteristic velocity. A number of small eddies may be embedded in a large eddy.

A characteristic of a turbulent flow is the existence of a wide range of length scales, or eddy sizes. The largest size L, is the macroscale or the flow scale. Eddies of size L are characterized by the mean flow velocity U. The Reynolds number of these eddies $Re = UL/\nu$ is large so that the effect of viscosity is negligibly small.

The large eddies, however, break up as a result of instabilities, transferring their energy to smaller eddies, characterized by smaller Reynolds numbers. This process continues until the Reynolds number is sufficiently small; now viscosity acts to smear out large velocity gradients or dissipate the available kinetic energy. This is basically the **eddy cascade hypothesis**, proposed by Kolmogorov for homogeneous isotropic turbulence.

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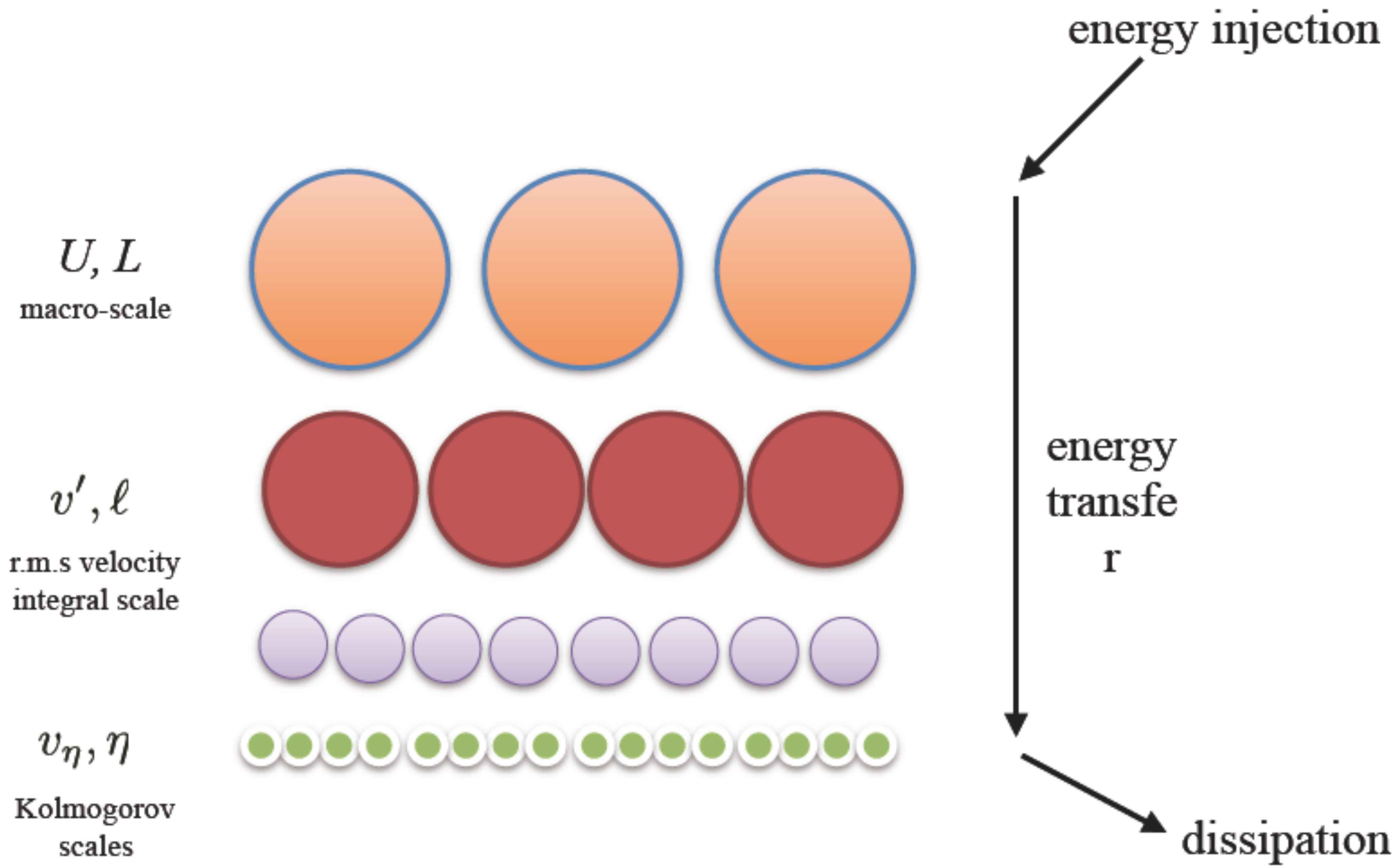
TURBULENT FLOW - Scales



Heat

Energy transfer at a 'constant' rate $\boldsymbol{\varepsilon}$

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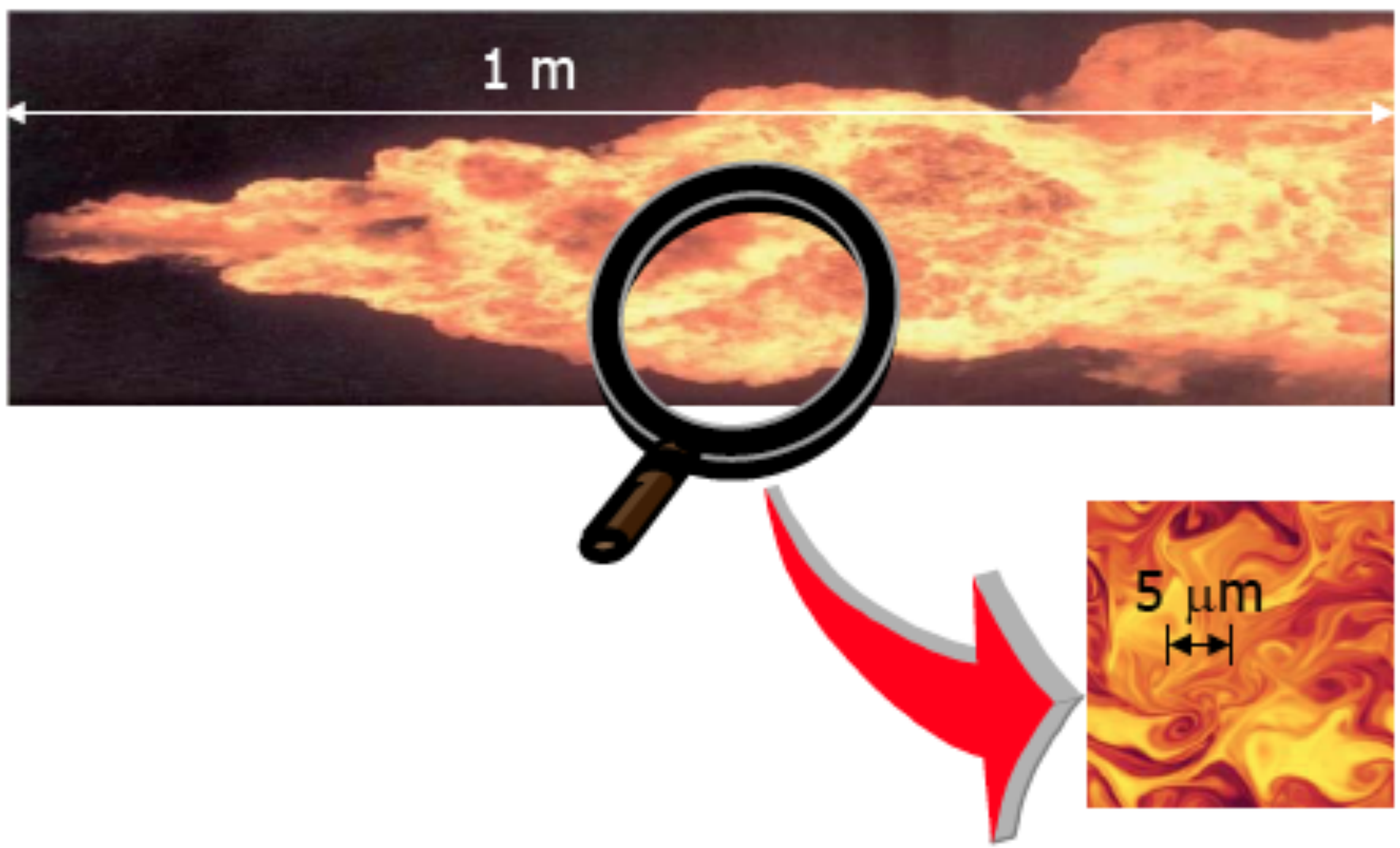
TURBULENT FLOW - Scales

Characteristic Scales



Integral Scale

Kolmogorov Scale

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TURBULENT FLOW - Scales

In order to characterize the distribution of eddy length scales at any position in the flow field, we use the correlation of the axial velocity between two points. The correlation of the axial velocity u at time t between two points separated by a distance $\mathbf{r}$, i.e., at $\mathbf{x}$ and $\mathbf{x}+\mathbf{r}$, is

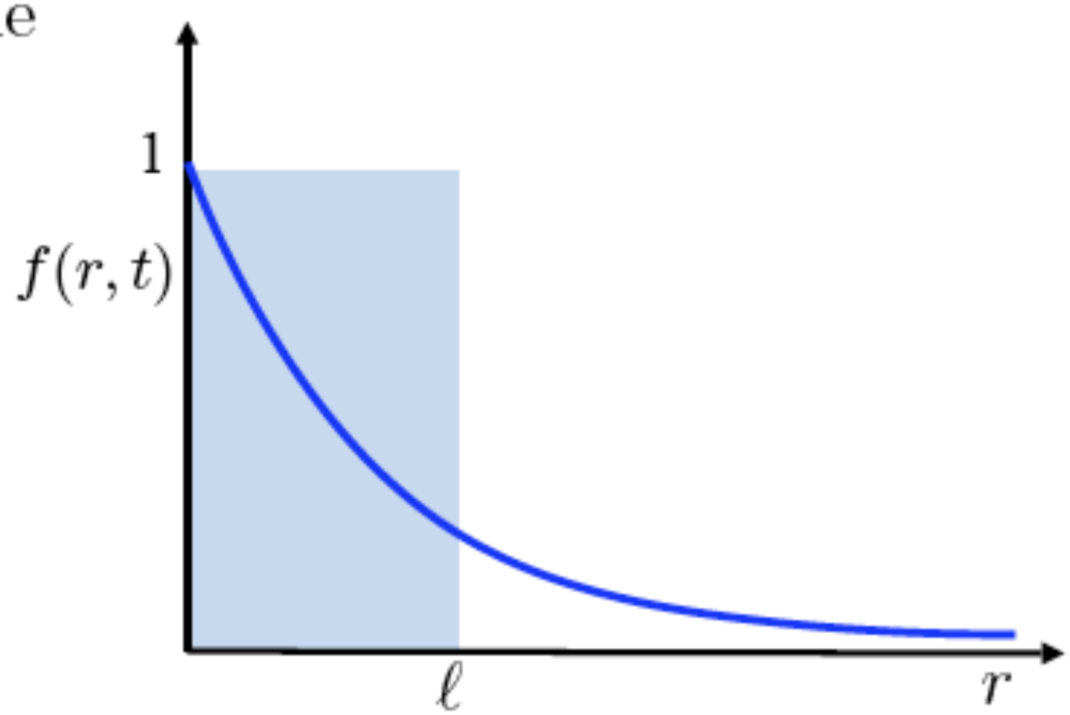
$$R(\mathbf{x},\mathbf{r},t) = \overline{u'(\mathbf{x},t)\,u'(\mathbf{x}+\mathbf{r},t)}$$

it shows how related, or *coherent*, are the velocities at these two points in space

For homogeneous isotropic turbulence the location $\mathbf{x}$ is arbitrary and $\mathbf{r}$ may be replaced by its absolute value $r = |\mathbf{r}|$. The normalized correlation $f(r,t) = R(r,t)/\overline{u'^2(t)}$ defines a length scale

$$\ell(t) = \int_0^\infty f(r,t)dr$$

called the *integral length scale.*



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TURBULENT FLOW - Scales

If v' is a typical velocity scale, i.e., a measure of the velocity fluctuations around the mean, the turbulent kinetic energy may be defined as

$$k = \frac{1}{2}\overline{v_i'v_i'} = \frac{3}{2}v'^2$$

Then,

$$v' = \sqrt{\frac{2k}{3}}$$ turnover velocity of eddies of the size of the integral scale ℓ

$$t = \frac{\ell}{v'}$$ turnover time of eddies of the size of the integral scale

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TURBULENT FLOW - Scales

For very small values of r only very small eddies fit into the distance between $\mathbf{x}$ and $\mathbf{x}+\mathbf{r}$. The motion of these small eddies is influenced by viscosity which provides an additional dimensional quantity for scaling.

We denote the dissipation of kinetic energy, per unit mass, by ϵ.

$$[\epsilon] = \frac{(\mathrm{m/s})^2}{\mathrm{s}} = \mathrm{m}^2/\mathrm{s}^3$$

Dimensional analysis then yields the Kolmogorov length scale η

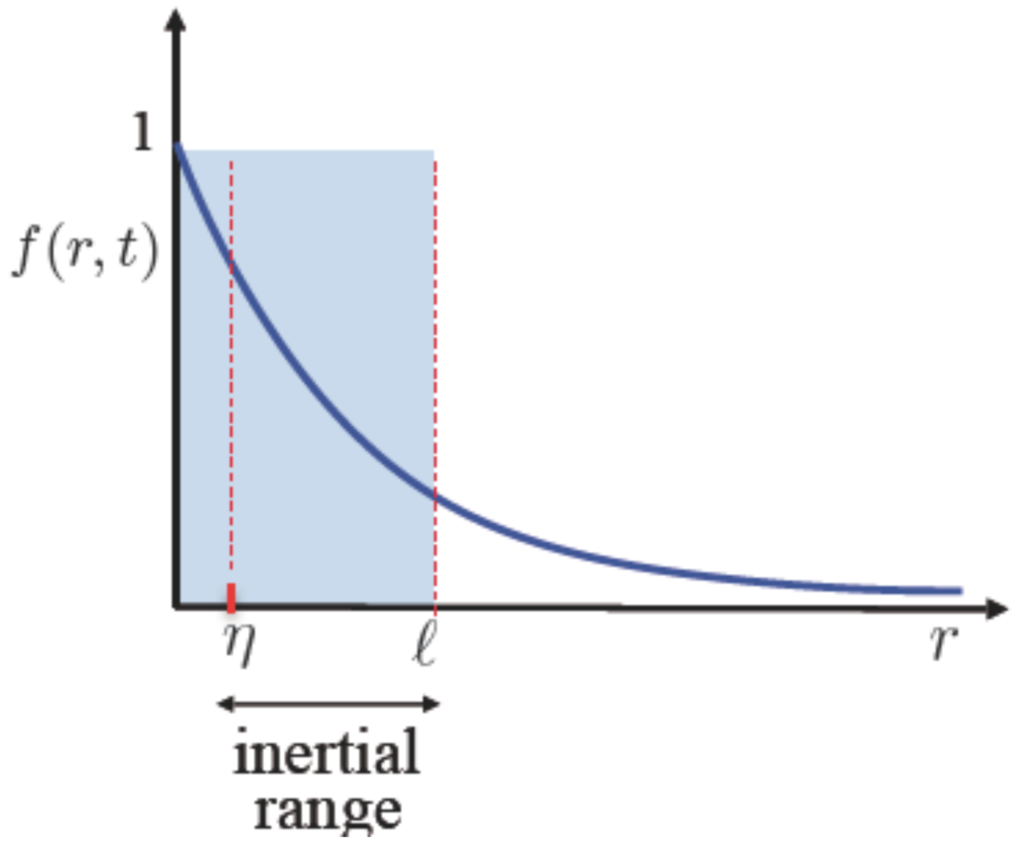
$$\eta = \left(\frac{\nu^3}{\epsilon}\right)^{1/4} \qquad [\nu] = \mathrm{m}^2/\mathrm{s}$$

We can also define a Kolmogorov time scale

$$t_\eta = \left(\frac{\nu}{\epsilon}\right)^{1/2}$$

and velocity scale

$$v_\eta = (\epsilon\nu)^{1/4}$$



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TURBULENT FLOW - Scales

Kolmogorov scales

length: $\eta = \left(\frac{\nu^3}{\epsilon}\right)^{1/4}$

velocity: $v_\eta = (\epsilon\nu)^{1/4}$

time: $t_\eta = \left(\frac{\nu}{\epsilon}\right)^{1/2}$

$\Rightarrow$

Reynolds number $\frac{\eta v_\eta}{\nu} = 1$

cascade proceeds until the Re number is small enough for dissipation to be effective

$$\epsilon = \nu \left(\frac{v_\eta}{\eta}\right)^2 = \frac{\nu}{t_\eta^2}$$

$v_\eta/\eta = 1/t_\eta$ provides a consistent characterization of the velocity gradients of the dissipative eddies.

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According to Kolmogorov's theory the energy transfer from the large eddies at the integral scale (i.e, of length scale ℓ) is equal to the dissipation of energy at the Kolmogorov scale.

Since at the integral scale the energy transfer rate $\epsilon = \dfrac{v'^2}{\ell/v'} = \dfrac{v'^3}{\ell} = \dfrac{k^{3/2}}{\ell}$

$$\Rightarrow \qquad \boxed{\ell = \frac{k^{3/2}}{\epsilon}}$$

If we define the turbulent Reynolds number as $Re_{\mathrm{T}} = \ell v'/\nu$, the ratios of the smallest to largest length, time and velocity scales are

$$\frac{\eta}{\ell} = \frac{(\nu^3/\epsilon)^{1/4}}{\ell} = \left(\frac{\nu}{\ell v'}\right)^{3/4} = Re_{\mathrm{T}}^{-3/4}$$

$$\frac{t_\eta}{t} = \frac{(\nu/\epsilon)^{1/2}}{v'/\ell} = \left(\frac{\nu}{\ell v'}\right)^{1/2} = Re_{\mathrm{T}}^{-1/2}$$

$$\frac{v_\eta}{v'} = \frac{(\epsilon\nu)^{1/4}}{v'} = \left(\frac{\nu}{\ell v'}\right)^{1/4} = Re_{\mathrm{T}}^{-1/4}$$

evidently, at high Reynolds number ($Re_T \gg 1$), the velocity and time scales of the smallest eddies are small compared with those of the largest eddies on the order of the integral scale.

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Turbulence, Mixing and Aerodynamics

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TURBULENT PREMIXED COMBUSTION

Scales

- Integral turbulent scales

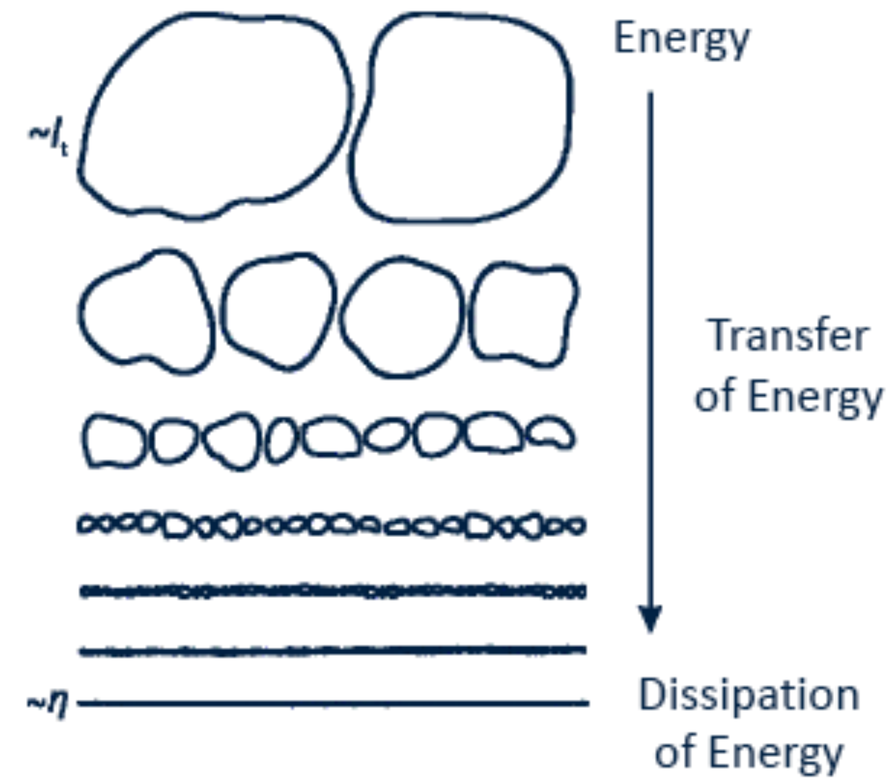
$$l_t = c_1 \frac{\bar{k}^{3/2}}{\bar{\varepsilon}}, \qquad u' = \sqrt{\frac{2}{3}\bar{k}}, \qquad \tau = \frac{l_t}{u'} \sim \frac{\bar{k}}{\bar{\varepsilon}}$$

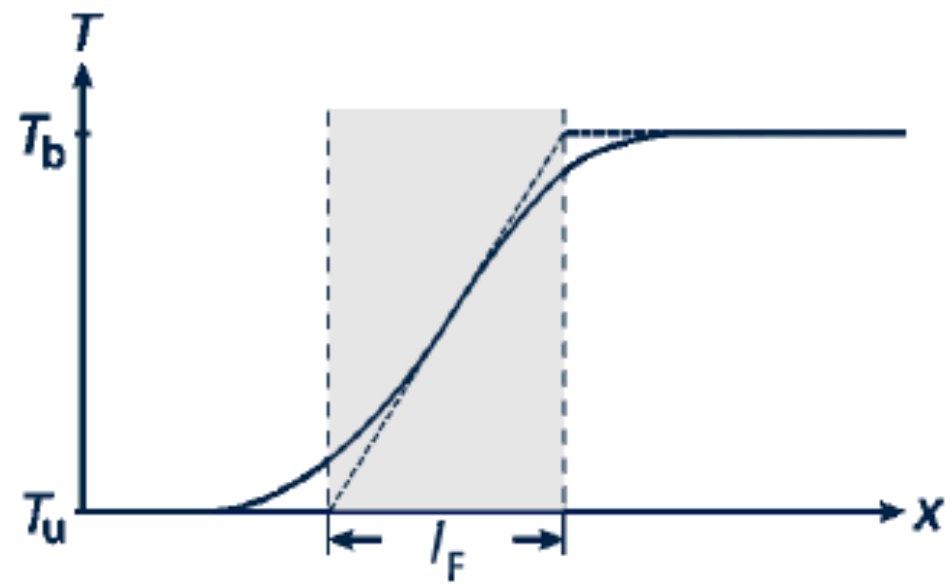
- Smallest turbulent scales/Kolmogorov scales

$$\eta = \left(\frac{\nu^3}{\bar{\varepsilon}}\right)^{1/4}, \qquad u_\eta = (\nu\bar{\varepsilon})^{1/4}, \qquad t_\eta = \left(\frac{\nu}{\bar{\varepsilon}}\right)^{1/2}$$

- Flame thickness and time, reaction zone thickness

$$l_F = \frac{D}{s_L} = \frac{\lambda_b}{\rho_u c_p s_L}, \qquad t_F = \frac{l_F}{s_L} = \frac{D}{s_L^2}, \qquad l_\delta \ll l_F$$





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TURBULENT PREMIXED COMBUSTION

Dimensionless Quantities

We assume equal diffusivities for all reactive scalars, and a Schmidt number equal to one

$$\mathcal{D}_{th} = \mathcal{D}_F = \mathcal{D}_O \equiv \mathcal{D}; \qquad \nu/\mathcal{D} = 1$$

The flame thickness and flame (residence) time are then given by

$$l_f = \mathcal{D}/S_L \qquad t_f = \mathcal{D}/S_L^2$$

As a result, the turbulent Reynolds number, may be expressed as

$$Re_{\mathrm{T}} = \frac{\ell v'}{\nu} \quad \Rightarrow \quad Re_{\mathrm{T}} = \frac{\ell v'}{\mathcal{D}} = \frac{v'}{S_L}\frac{\ell}{l_f}$$

The Damköhler number number (flow time/reaction time) may be defined as

$$D = \frac{\ell/v'}{l_f/S_L} = \frac{\ell}{l_f}\frac{S_L}{v'}$$

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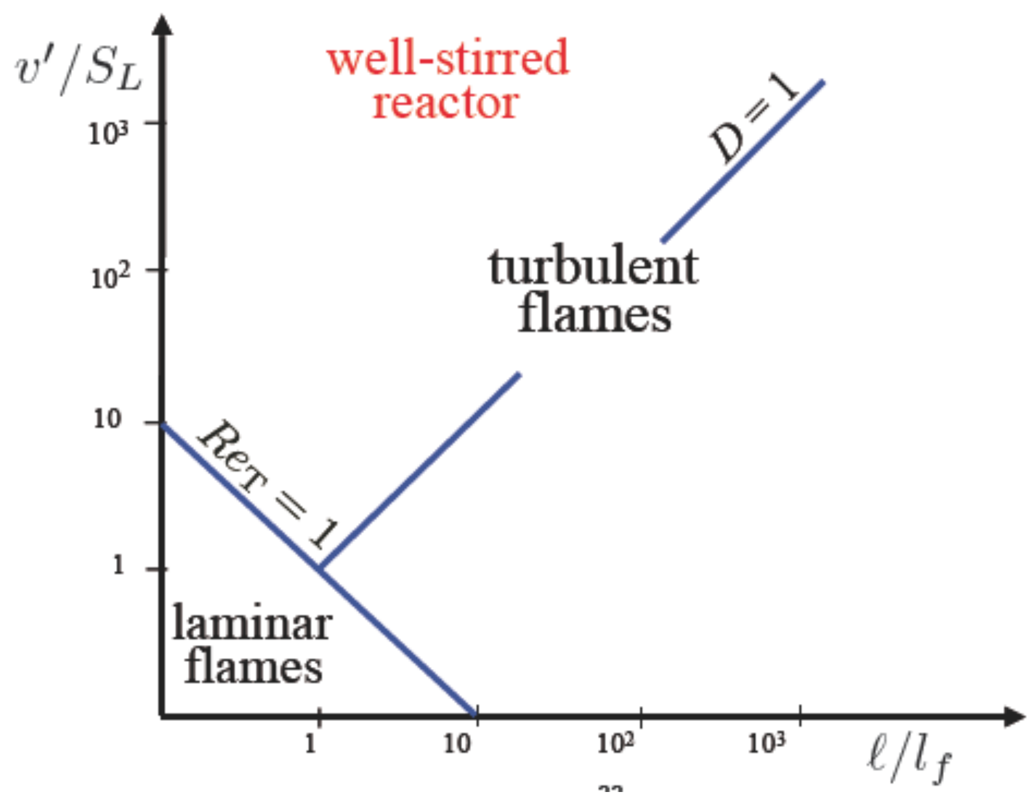
TURBULENT PREMIXED COMBUSTION

Dimensionless Quantities

The various regimes of turbulent combustion will be presented on a log-log graph depicting

v'/S_L vs ℓ/l_f

The first characterization is the line $Re_T = 1$
separating **laminar** and **turbulent combustion** (turbulent combustion corresponds to large Reynolds numbers).
Another distinction is between small and large Damköhler numbers. "Flames" are typically characterized by fast chemistry, or D>>1, while the region D<<1 corresponds to "well stirred reactors" where all turbulent scales are smaller than the chemical time scale.



$$D = \frac{\ell}{l_f}\frac{S_L}{v'}$$

$$Re_T = \frac{v'}{S_L}\frac{\ell}{l_f}$$

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TURBULENT PREMIXED COMBUSTION

Dimensionless Quantities

Further refinement of this diagram involves the Karlovitz number *Ka*, which relates the flame scales to the Kolmogorov scales. Two such numbers can be defined, one based on the flame thickness and the other on the thickness of the reaction zone l_R. They represents the ratio of the residence time in the flame zone, or reaction zone, relative to the smallest turbulent turnover time, and thus whether turbulence penetrate and distort the flame or reaction zone structures.

$$Ka = \frac{t_f}{t_\eta} = \frac{l_f^2/\nu}{\eta^2/\nu} = \frac{l_f^2}{\eta^2} \qquad \text{or} \qquad Ka = \frac{l_f^2}{\eta^2} = \frac{(\nu/S_L)^2}{(\nu/v_\eta)^2} = \frac{v_\eta^2}{S_L^2}$$

$$\text{and using } \delta = l_R/l_f \qquad Ka_\delta = \frac{l_R^2}{\eta^2} = \delta^2 Ka$$

$$\left.\begin{aligned} Re_T &= \frac{v'}{S_L}\frac{\ell}{l_f} = \left(\frac{S_L}{v'}\frac{\ell}{l_f}\right)\left(\frac{v'}{S_L}\right)^2 = D\left(\frac{v'}{v_\eta}\right)^2\left(\frac{v_\eta}{S_L}\right)^2 \\ \frac{v_\eta}{v'} &= \frac{(\epsilon\nu)^{1/4}}{v'} = Re_T^{-1/4} \end{aligned}\right\} \Rightarrow \qquad Re_T = D \cdot Re_T^{1/2} \cdot Ka$$

$$\boxed{Re_T = D^2 \cdot Ka^2}$$

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Borghi Diagram

-When Ka < 1 the flame residence time is much shorter than any turbulent time scales and the flame thickness is smaller than the smallest turbulent scale. The flame retains the laminar structure but is wrinkled by the turbulence motions.

(a) **Wrinkled flamelet regime**. Here $v' < S_L$, the turnover velocity v' of even the large eddies is not sufficient to compete with the advancement of the flame front at the laminar speed S_L. The only effect of turbulence is to disturb the flame front.

(b) **corrugated flamelet regime**. Here $v' > S_L$, the entire flame is embedded in eddies with velocities exceeding S_L, which are able to wrinkle the flame and form pockets of fresh and burned gas.

- When $Ka > 1$ the flame residence time is on the order of the turbulent times (based on integral scale) but much larger then the Kolmogorov turnover times, and the Kolmogorov scales are smaller than the laminar flame thickness. Here the small eddies can presumably interact and modify the flame internal structure.

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TURBULENT PREMIXED COMBUSTION

Borghi Diagram

Although when Ka > 1 the small eddies penetrate the flame zone, they may or may not modify the much thinner reaction zone. The distinction is between what has been referred to as *thin reaction zones* and *broken, or distributed reaction zones*. In the latter, the laminar structure could no longer be identified. The boundary between these two regions depends on the relative thickness of the reaction zone δ.

$$\text{For } \delta \approx 10^{-1} \quad \Rightarrow \quad Ka = 100$$

$$\frac{v'}{S_L} = 10^{4/3} \left(\frac{\ell}{l_f} \right)^{1/3}$$

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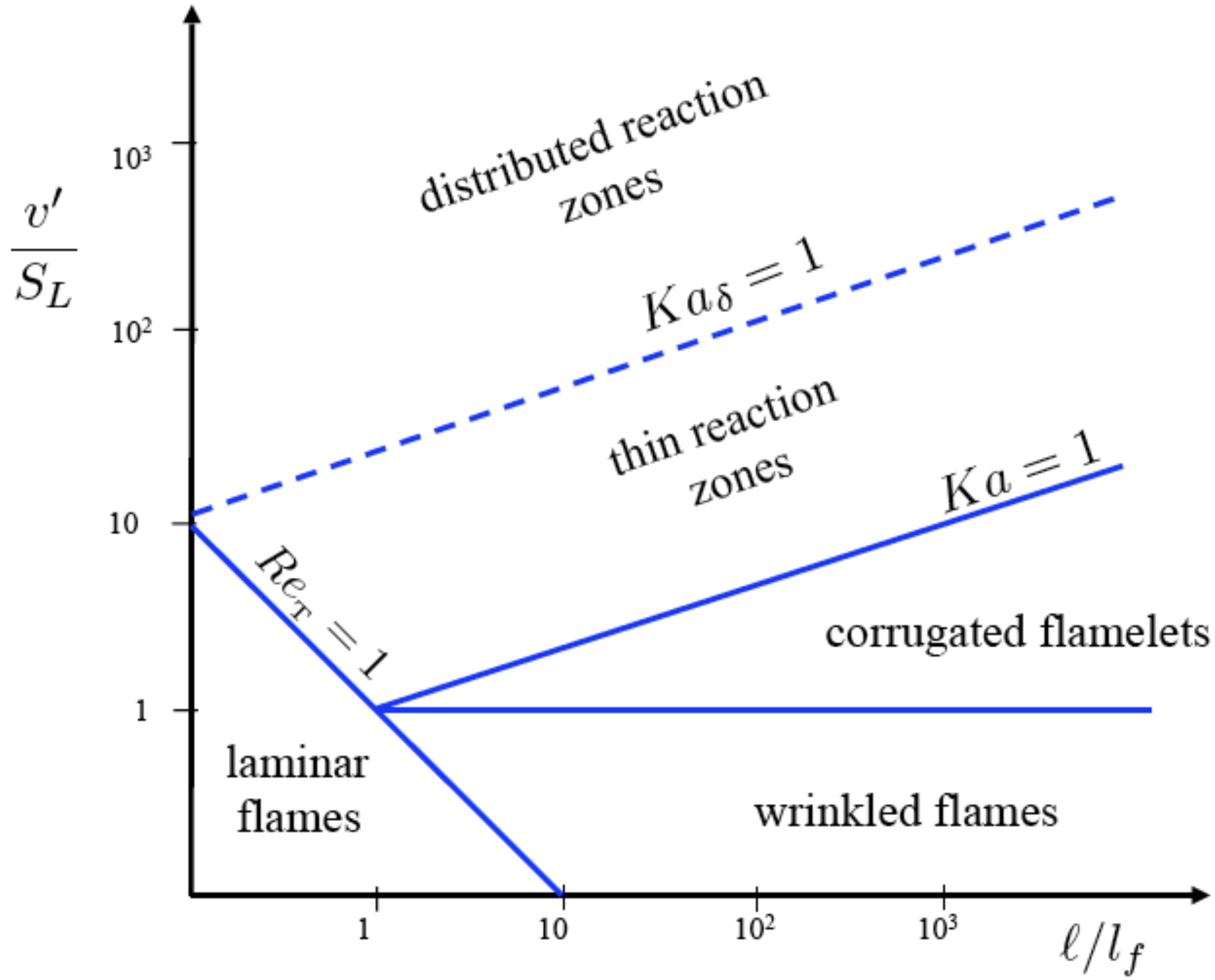
TURBULENT PREMIXED COMBUSTION

Borghi Diagram



Regime diagram of premixed turbulent combustion in log-log plot

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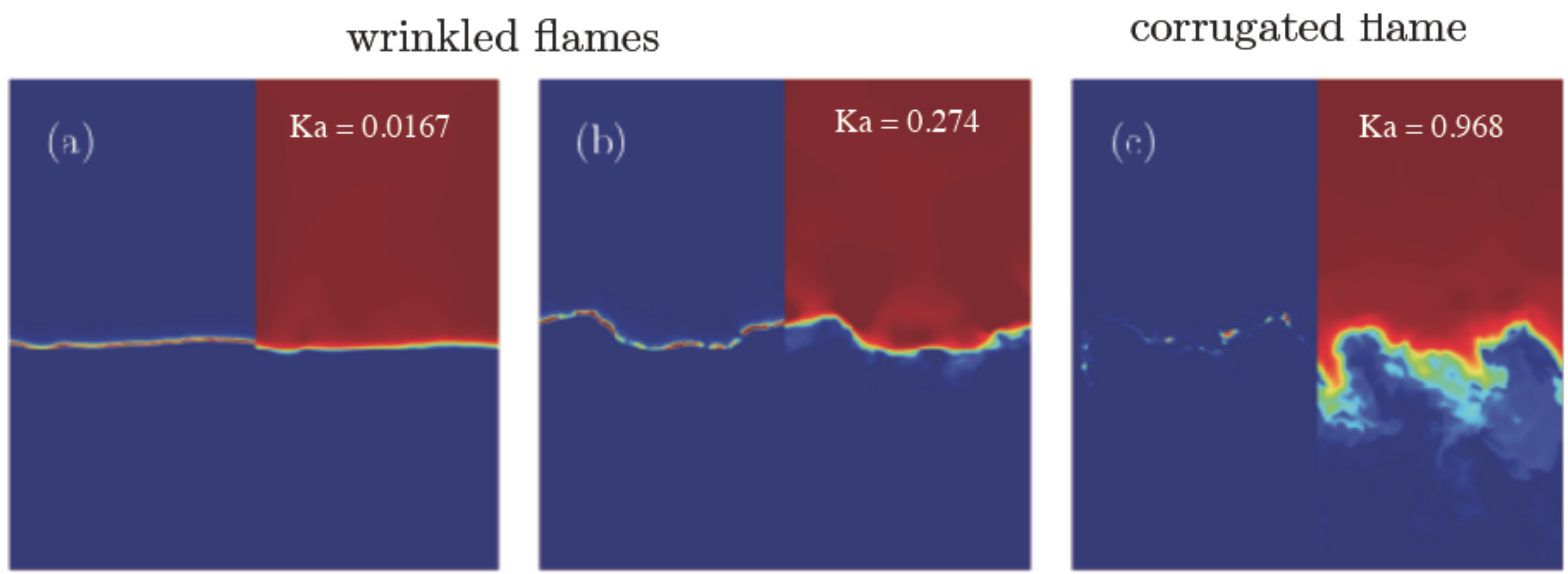
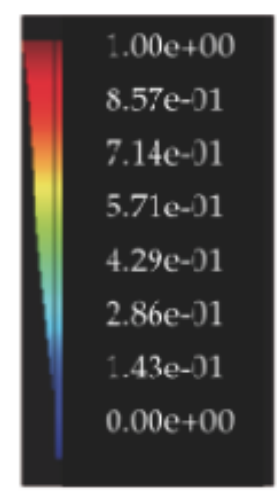
TURBULENT PREMIXED COMBUSTION

Borghi Diagram





Wrinkled flames.
(a) A nearly smooth, even burning; the flame is perturbed very little.
(b) The flame surface is deformed by the turbulence, and there are regions of enhanced/decreased burning along its surface.
Corrugated flames. (c) Flame surface deformation increases; folds and pockets of intensive burning appear.

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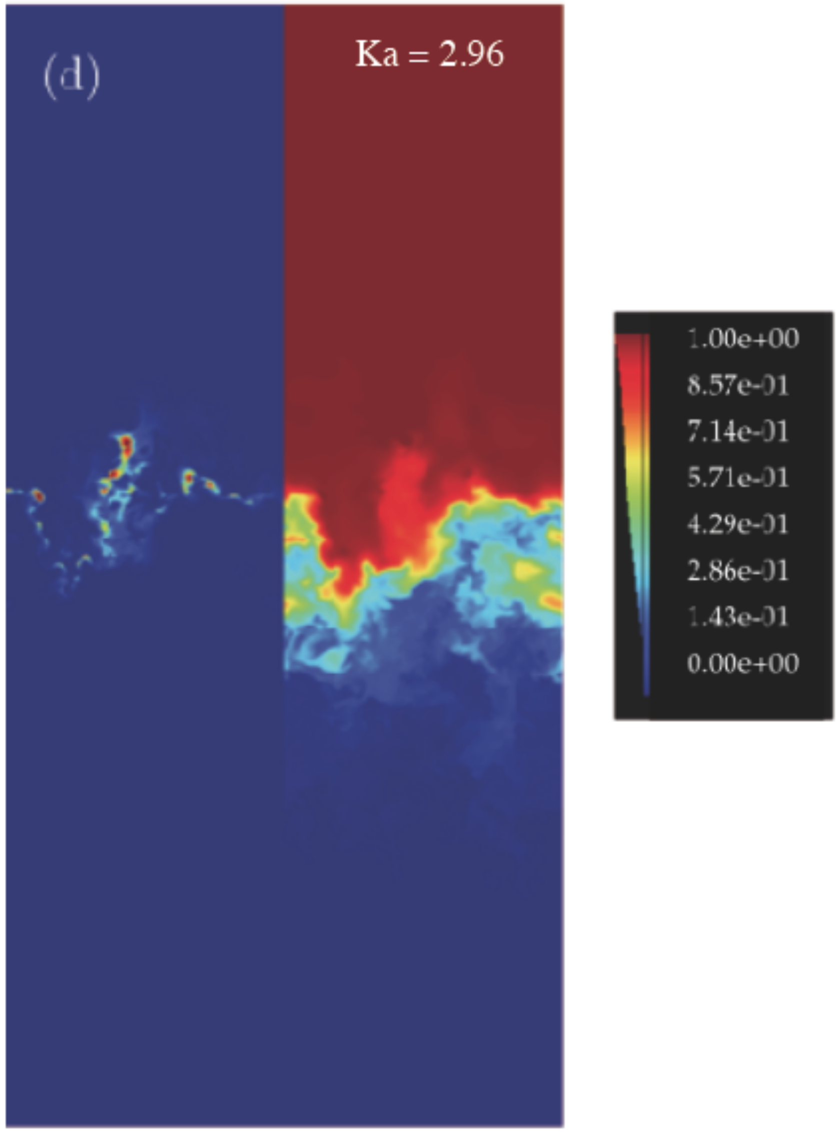
Borghi Diagram

Thin reaction zones. The temperature field becomes more mixed, and the deformation of the flame surface increases. The burning appears to occur in small high-intensity pockets, punctuated by regions of local extinction.



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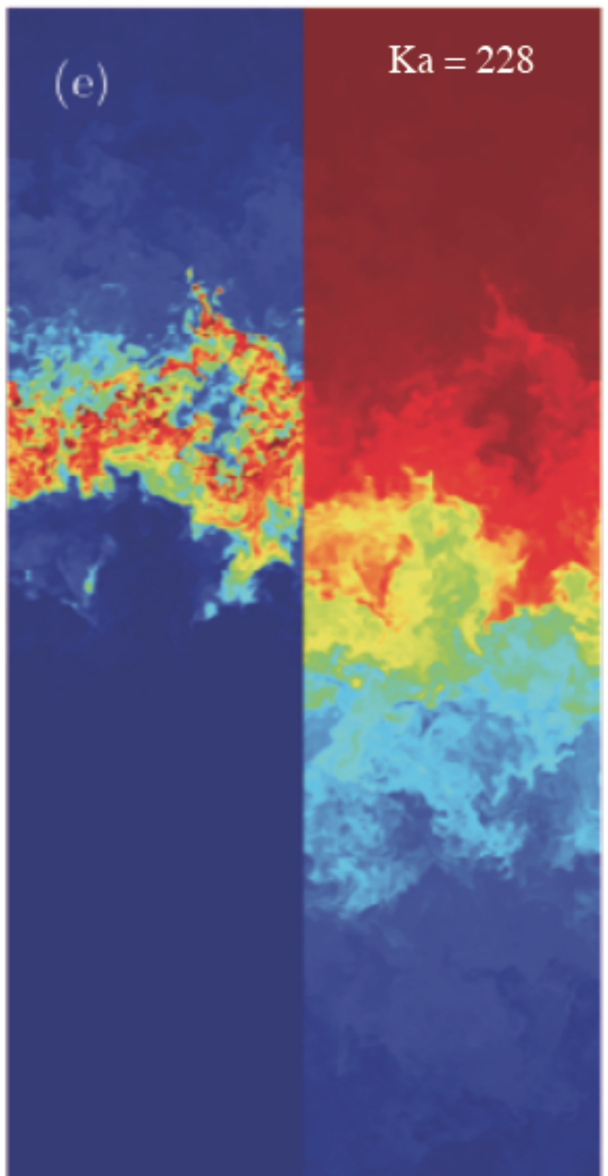
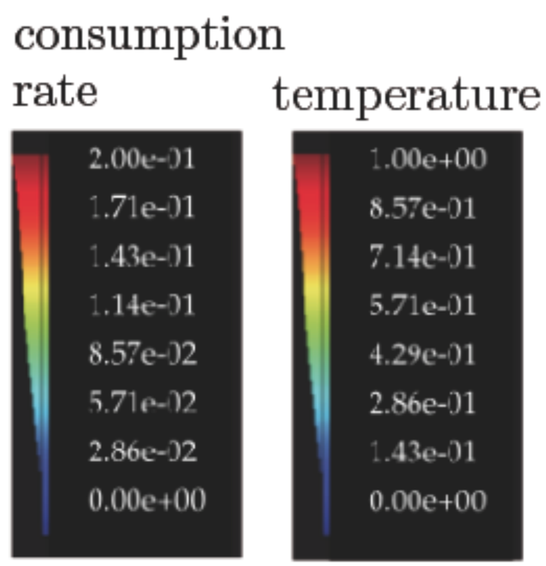
TURBULENT PREMIXED COMBUSTION

Borghi Diagram

Distributed reaction zones. The burning appears to be much less intense and is restricted to the high-temperature end of the mixing zone. There is no well defined flame surface, but a broad flame brush.





Here the fuel consumption rate has been normalized by a fifth of the laminar value, because of their low local values.

COURSE OVERVIEW

DAY 3

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FLAME STABILITY
THE BIG PICTURE

Stability (often related to Limits)

• Ability to exist in a given environment
- Flammability limits
-Quenching distance

• Ability to stabilize in a given flow configuration
- Flashback, blowoff
-Burner stabilization

• Ability to maintain temporal & spatial uniformity
-Intrinsic flame instability
- Flame stretch: response to flow perturbation

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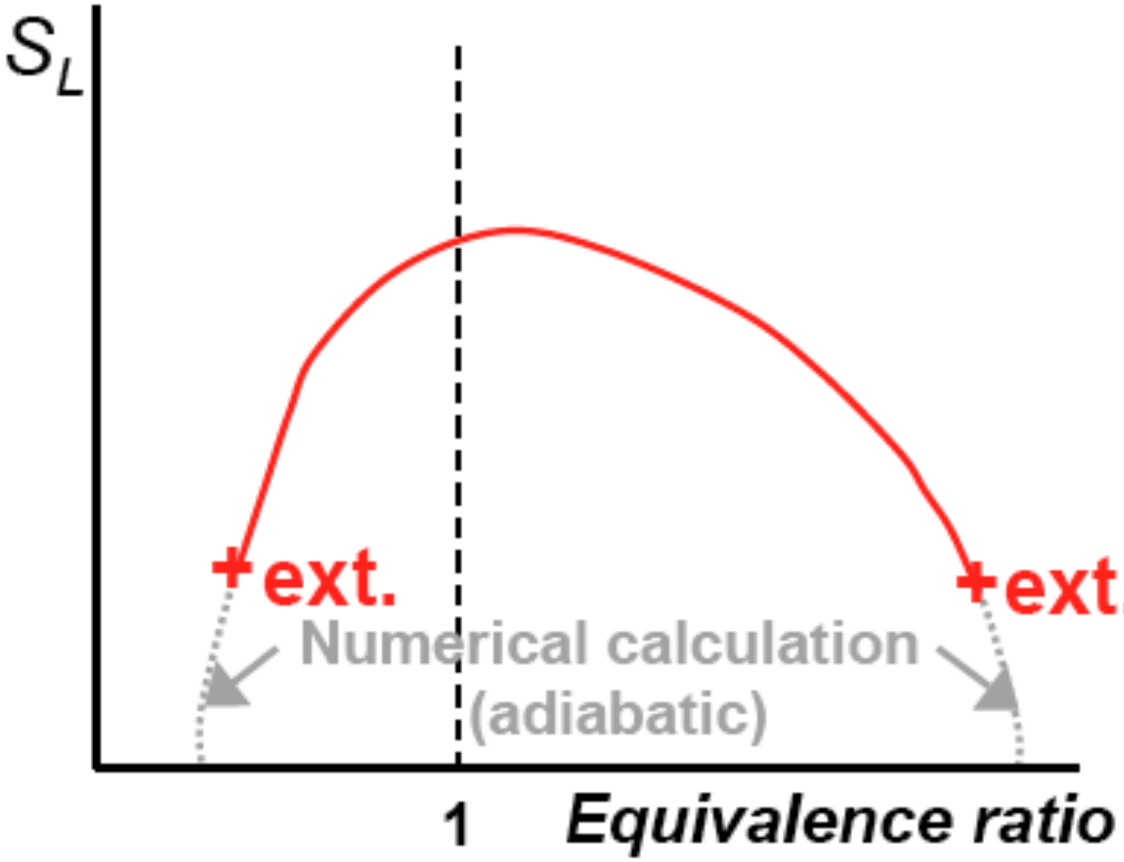
FLAME STABILITY
FLAMMABILITY LIMITS

- **Definition:**

  - Limiting composition for (premixed) flame propagation
  ⇒ 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.



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FLAME STABILITY
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).

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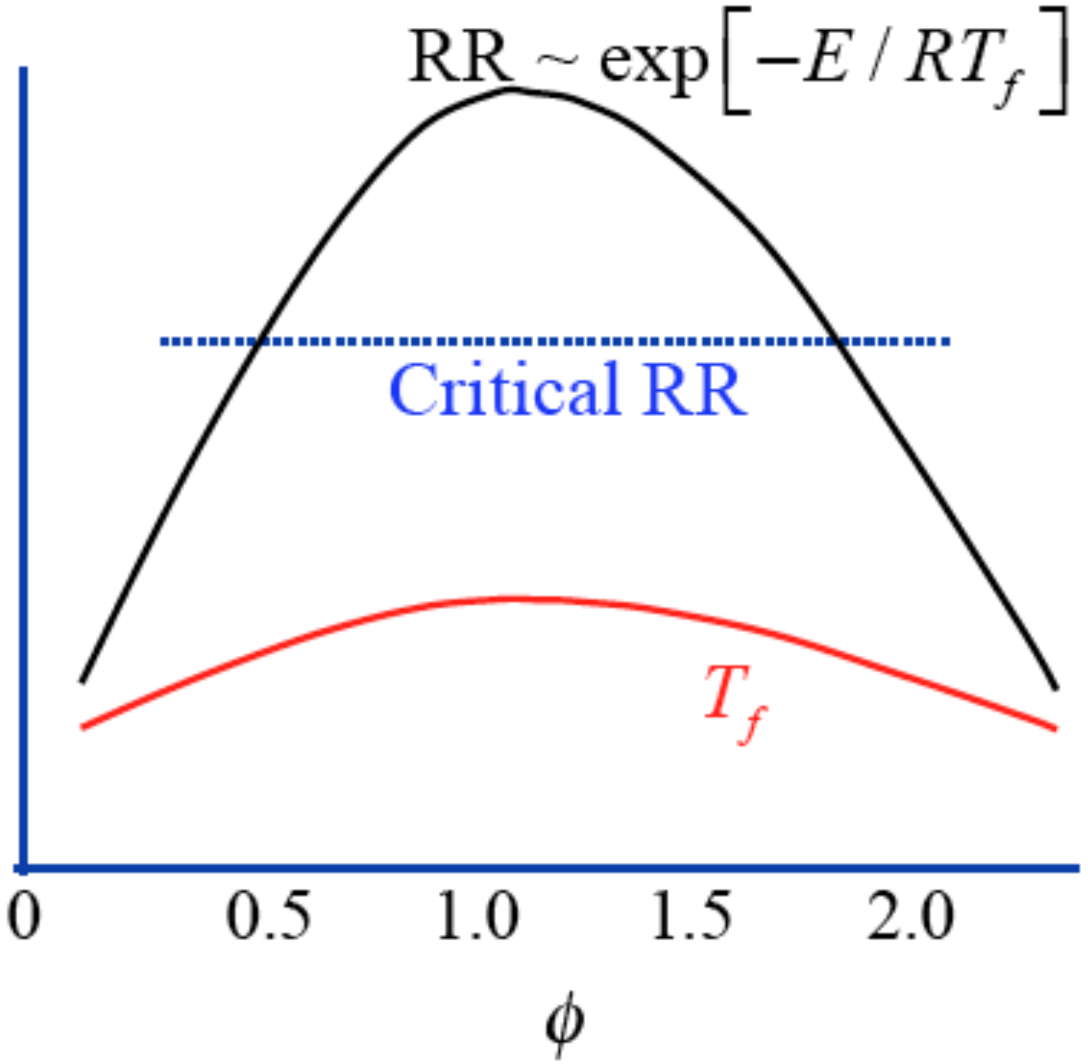
FLAME STABILITY
FLAMMABILITY LIMITS

- **Fundamental Flammability Limit**

Flame extinction when the burning rate is reduced to 61%, which happens at ϕ_{cr} ⇒ flammability limits



Since a roughly fixed rate of heat loss may be expected in a given configuration, the strong variation in RR with ϕ can be responsible for the weak dependences of the limits on specific experimental configurations.
(*Liñán & Williams, p. 97*)

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FLAME STABILITY
QUENCHING DISTANCE

Quenching Distance

- Due to conductive loss to the solid wall
- Rule of thumb:

$$\frac{\text{Loss}}{\text{Generation}} \approx \frac{1}{\beta}$$

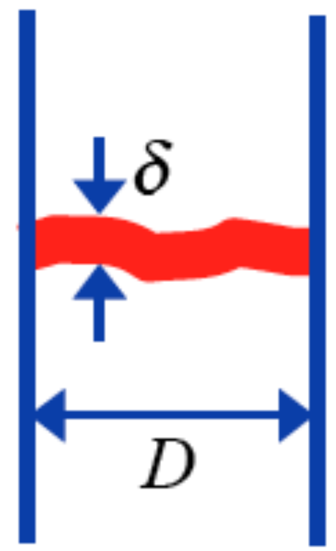
T drop by $O(1/\beta)$ causes RR drop by $O(1)$

Conduction to the wall:

$$L \approx \lambda(\pi D\delta)\frac{\Delta T}{D/2} = 2\pi\lambda\delta(\Delta T)$$

Generation:

$$Q \approx \dot{m}c_p\Delta T = \rho_u S_L\left(\frac{\pi D^2}{4}\right)c_p\Delta T$$



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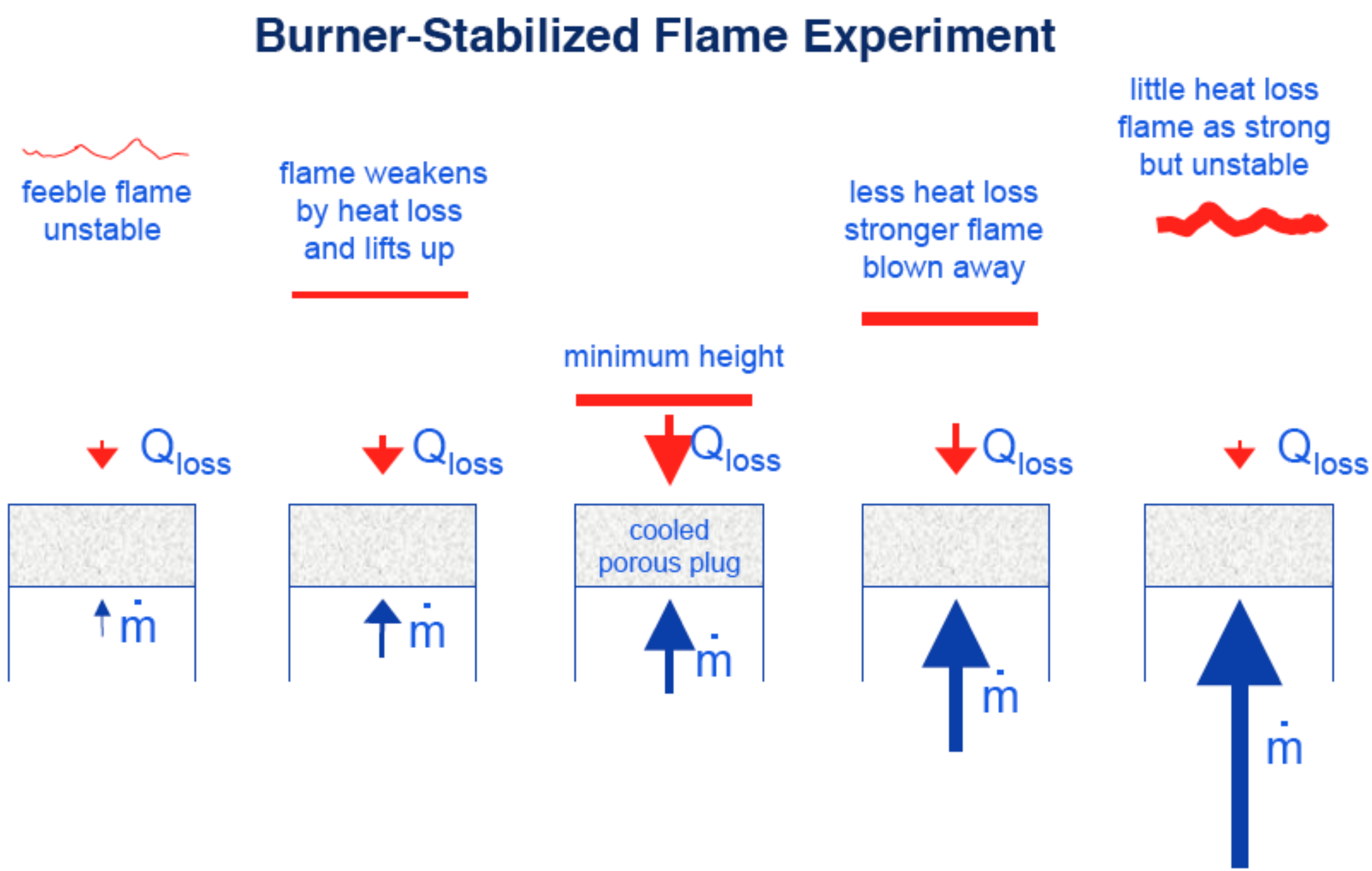
FLAME STABILITY
BURNER STABILIZATION



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FLAME STABILITY
BURNER STABILIZATION

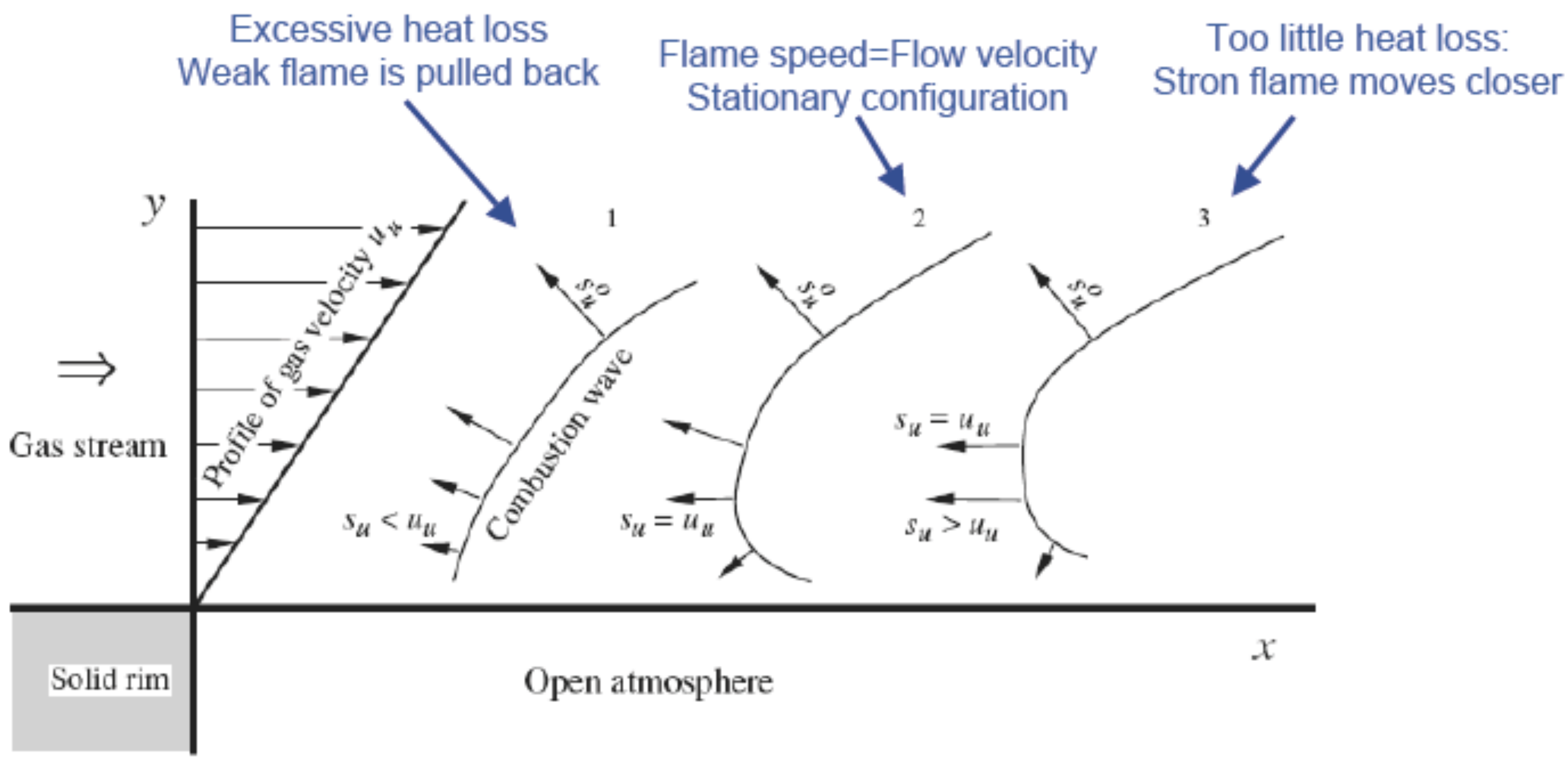

Figure 8.6.5. Stabilization mechanism of Bunsen flames (adapted from Lewis & von Elbe 1987).

$$S_u \neq S_u^0$$

1) cooling from rim: $S_u < S_u^0$

2) diffusion and air entrainment dilute mixture:

a) lean mixture becomes more lean: $S_u < S_u^0$

b) rich mixture becomes more stoichio: $S_u > S_u^0$

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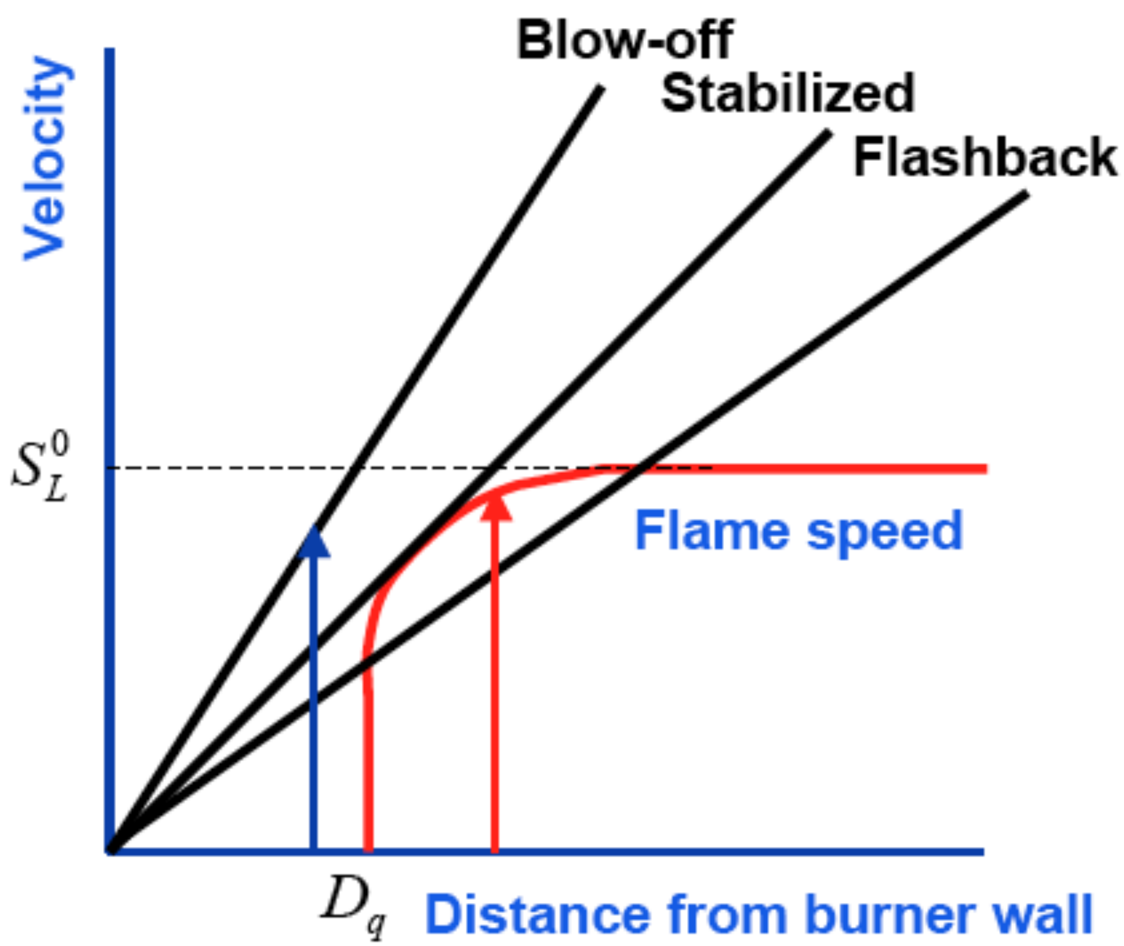
FLAME STABILITY
FLASHBACK

Flashback Mechanism (Lewis & von Elbe, 1987)



Recall $\mathrm{Pe} = \dfrac{S_L D_q}{\alpha_u}$,

$$\frac{dU}{dr} \approx \frac{S_L}{D_q} = \frac{S_L^2}{60\alpha_u}$$

$$\approx \begin{cases} 130 \text{ s}^{-1} \text{ (stoich. HC-air)} \\ 500 \text{ s}^{-1} \text{ (actual experiment)} \end{cases}$$

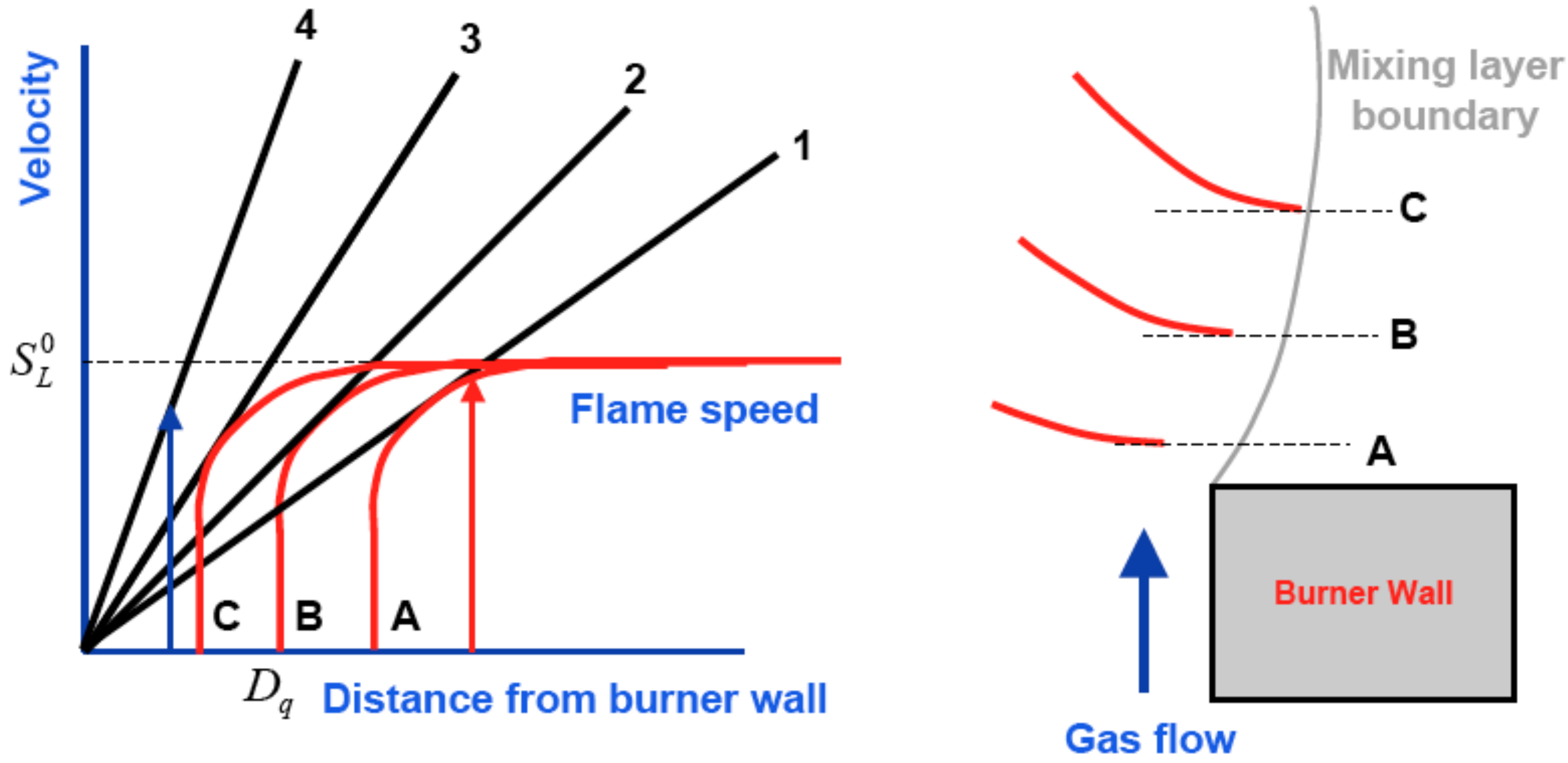
For Poiseuille flow

$$\left.\frac{dU}{dr}\right|_{r=R} = \frac{4\bar{U}}{R}$$

How can the stabilization point be so sensitive? (only one value of velocity)

FLAME STABILITY
BLOWOFF

Blow-off Mechanism (Lewis & von Elbe, 1987)



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FLAME STABILITY
BLOWOFF

Blow-off Mechanism (Lewis & von Elbe, 1987)

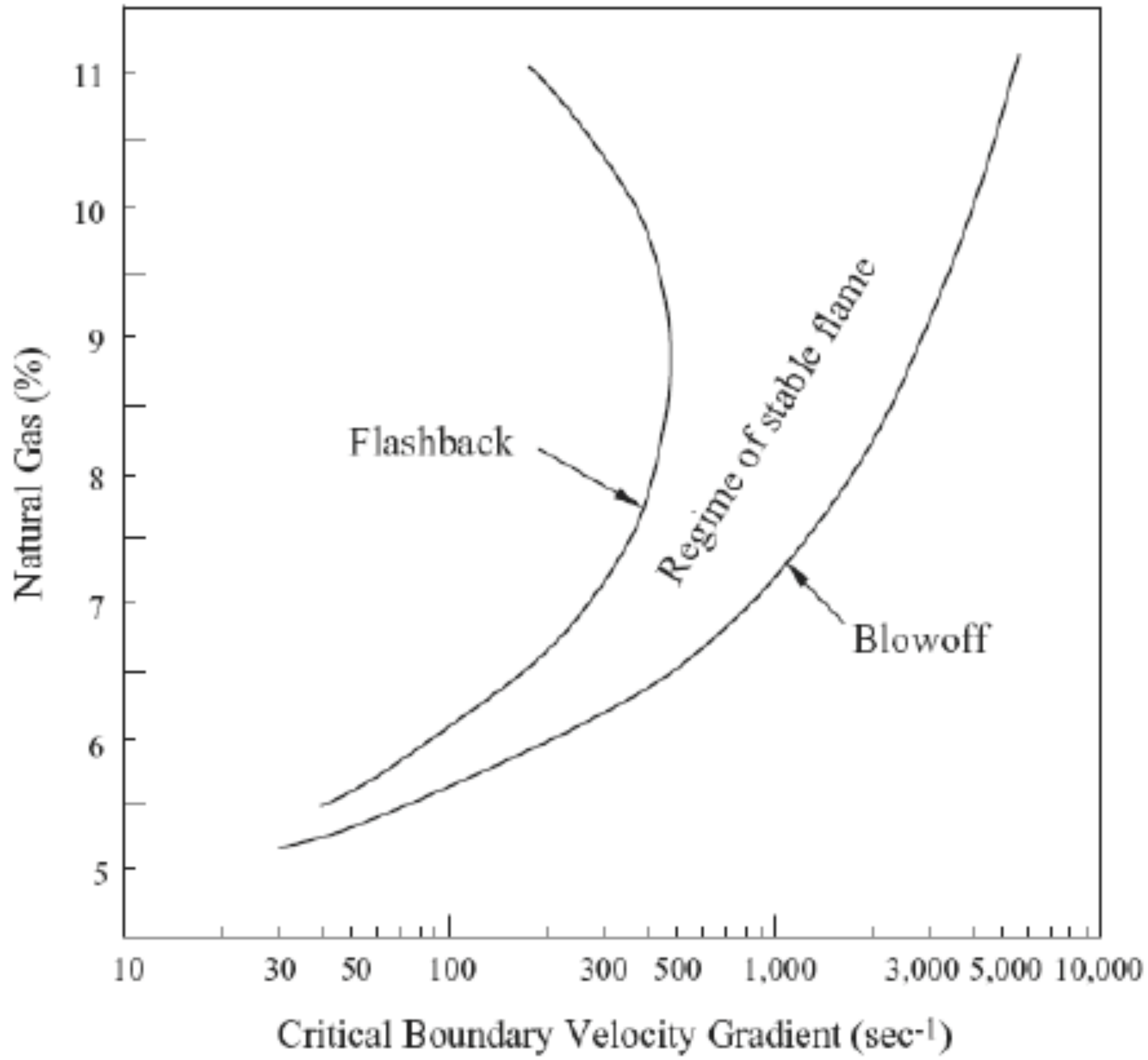

Figure 8.6.8. Blowoff, stable, and flashback regimes of the laminar Bunsen flame (adapted from Lewis & von Elbe 1987).

Note:
Flame speed can be modified by:
1) Heat loss;
2) Aerodynamic straining;
3) Flame curvature;
4) Mixture nonequidiffusion.

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FLAME STABILITY

Flame height from laminar to turbulent flow regimes

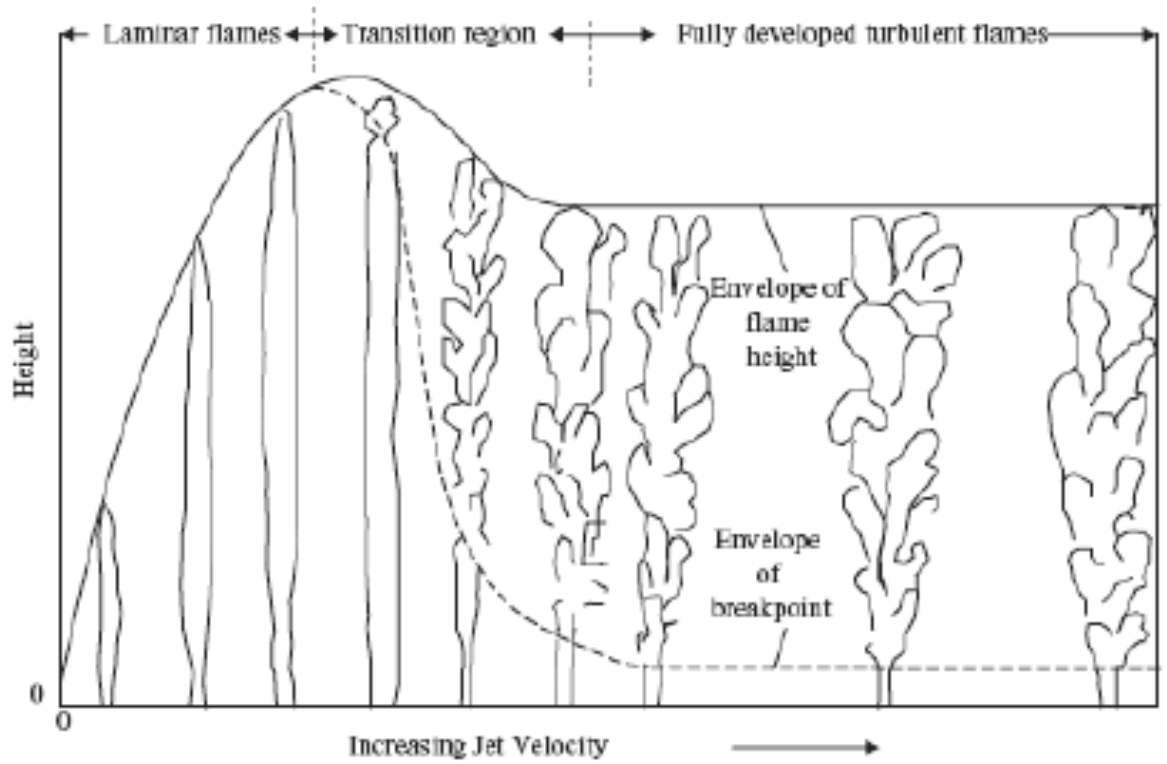

Figure 12.4.2. Schematic showing the experimentally observed flame height with increasing jet velocity (adapted from Hottel & Hawthorne 1949).

$$x_{f,max} \sim \frac{\rho r^2 u}{\mu} = \frac{\rho r^2 u}{\nu \rho} = \frac{r^2 u}{\nu}$$

Laminar flow $\nu_L \sim \text{const} \Rightarrow x_{f,max} \sim u$

Turbulent flow $\nu_T \sim ur \Rightarrow x_{f,max} \sim \frac{r^2 u}{\nu} = \frac{r^2 u}{ur} = r \Rightarrow \frac{x_{f,max}}{r} = \text{const}$

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COURSE OVERVIEW

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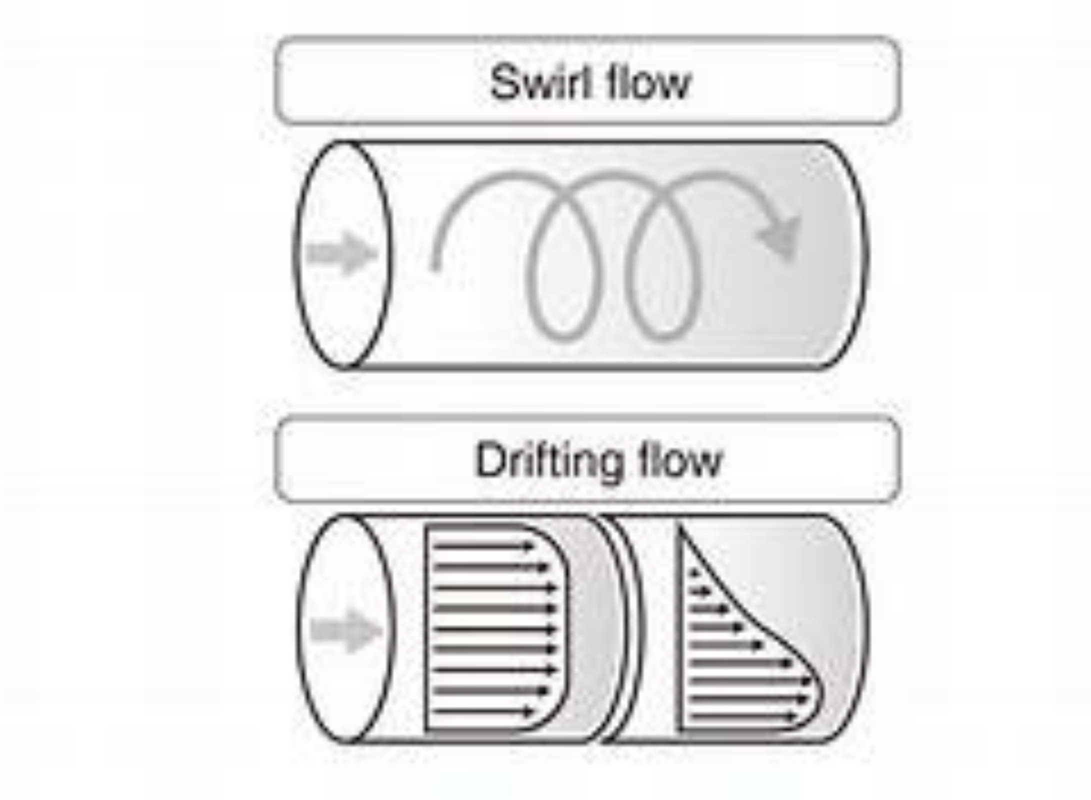
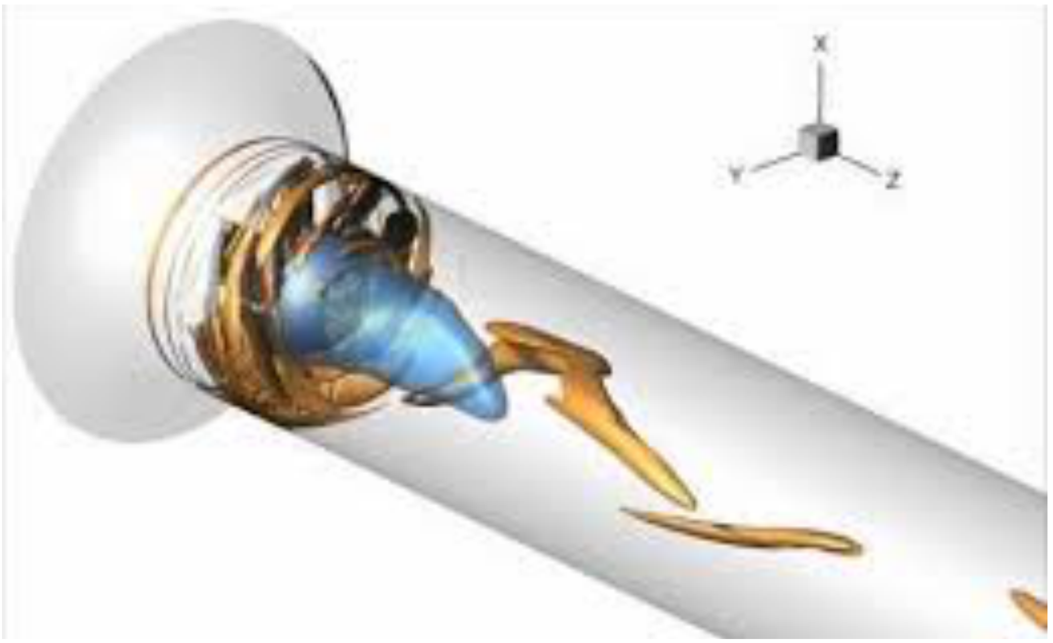
SWIRLING FLOWS

MANY ENGINEERING APPLICATIONS INVOLVE SWIRLING OR ROTATING FLOW:

- IN COMBUSTION CHAMBERS OF JET ENGINES
- TURBOMACHINERY
- MIXING TANKS





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SWIRLING FLOWS

IN SWIRLING FLOW, THE MOTION HAS A TANGENTIAL COMPONENT. THE CONSERVATION OF ANGULAR MOMENTUM RESULTS IN THE CREATION OF A FREE VORTEX FLOW IN WHICH CIRCUMFERENTIAL VELOCITY INCREASES AS THE RADIUS DECREASES AND THEN DECAYS TO ZERO AT THE CENTER OF THE FLOW DUE TO THE ACTION OF VISCOSITY.

FOR NON-IDEAL VORTICES THE RADIAL PRESSURE GRADIENT ALSO CHANGES AFFECTING THE RADIAL AND AXIAL FLOWS.

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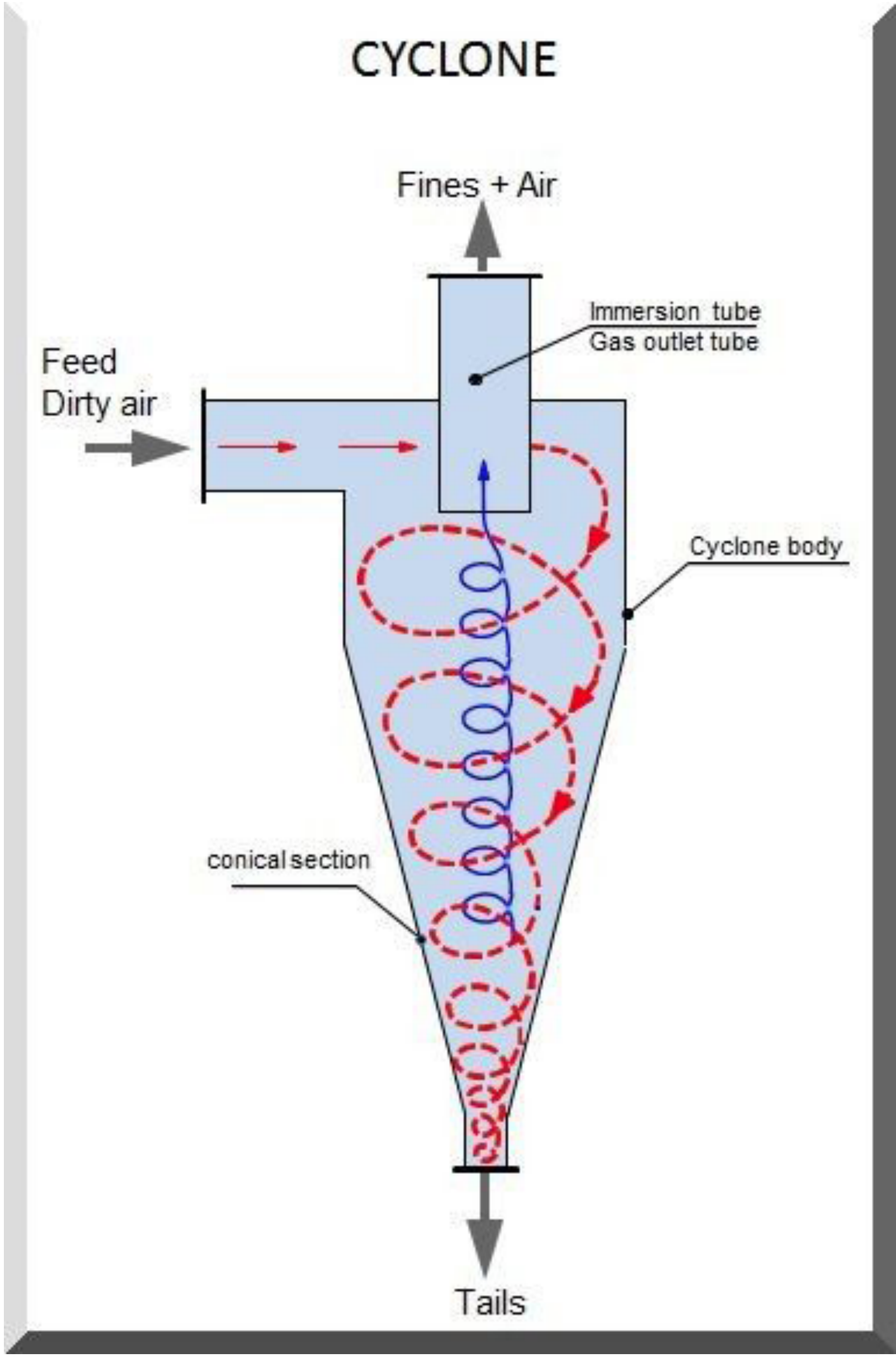
SWIRLING FLOWS

Turbulent flows with significant amount of swirl: swirling jets or cyclone flows.

The strength of the swirl is gauged by the swirl number S, defined as the ratio of the axial flux of angular momentum to the axial flux of the axial momentum.

$$S = \frac{\int r w \vec{v} \cdot d\vec{A}}{\bar{R} \int u \vec{v} \cdot d\vec{A}}$$

Where is R is the hydraulic radius*



SWIRLING FLOWS

S<0.5 : weak/ moderate swirl

- k-ε can be used : RNG and realizable

S>0.5 highly swirling flow

- RSM: Reynolds stress model

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SWIRLING FLOWS

- Swirl is used in jet engines systems to stabilize combustion
- It serves to anchor the flame in modern lean premixed gas turbines
- It is exploited in a variety of other combustion processes
- Swirling flame dynamics constitutes a central issue in many applications

Swirling flame dynamics

Thermal power plant

GE-Snecma CFM56

Alstom gas turbine

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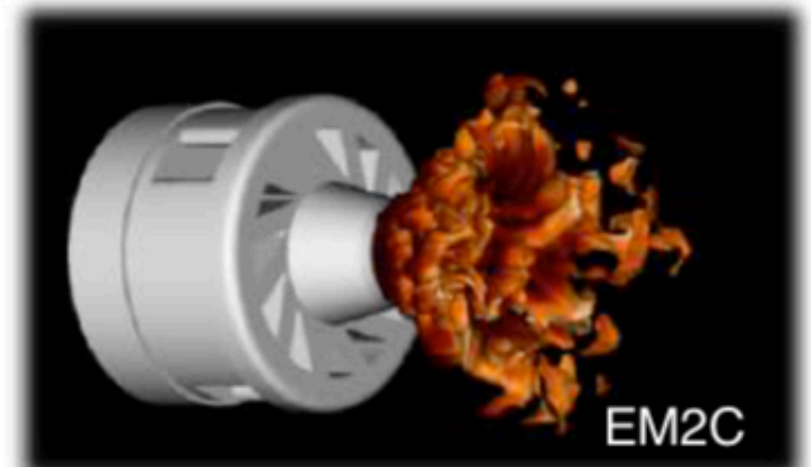
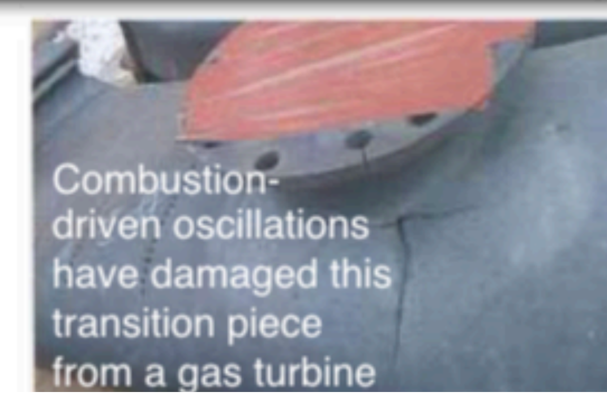
SWIRLING FLOWS

Combustion stabilization and swirl

- Stabilization relies on a central recirculation zone (CRZ) formed by hot combustion products which continuously initiate the reaction process



- Swirling flames are more compact than flames anchored on a bluff body allowing a notable reduction in the chamber size
- However, swirling combustors often develop self-sustained oscillations which have serious consequences



- There are many other dynamical issues which arise in practical systems and deserve fundamental investigations

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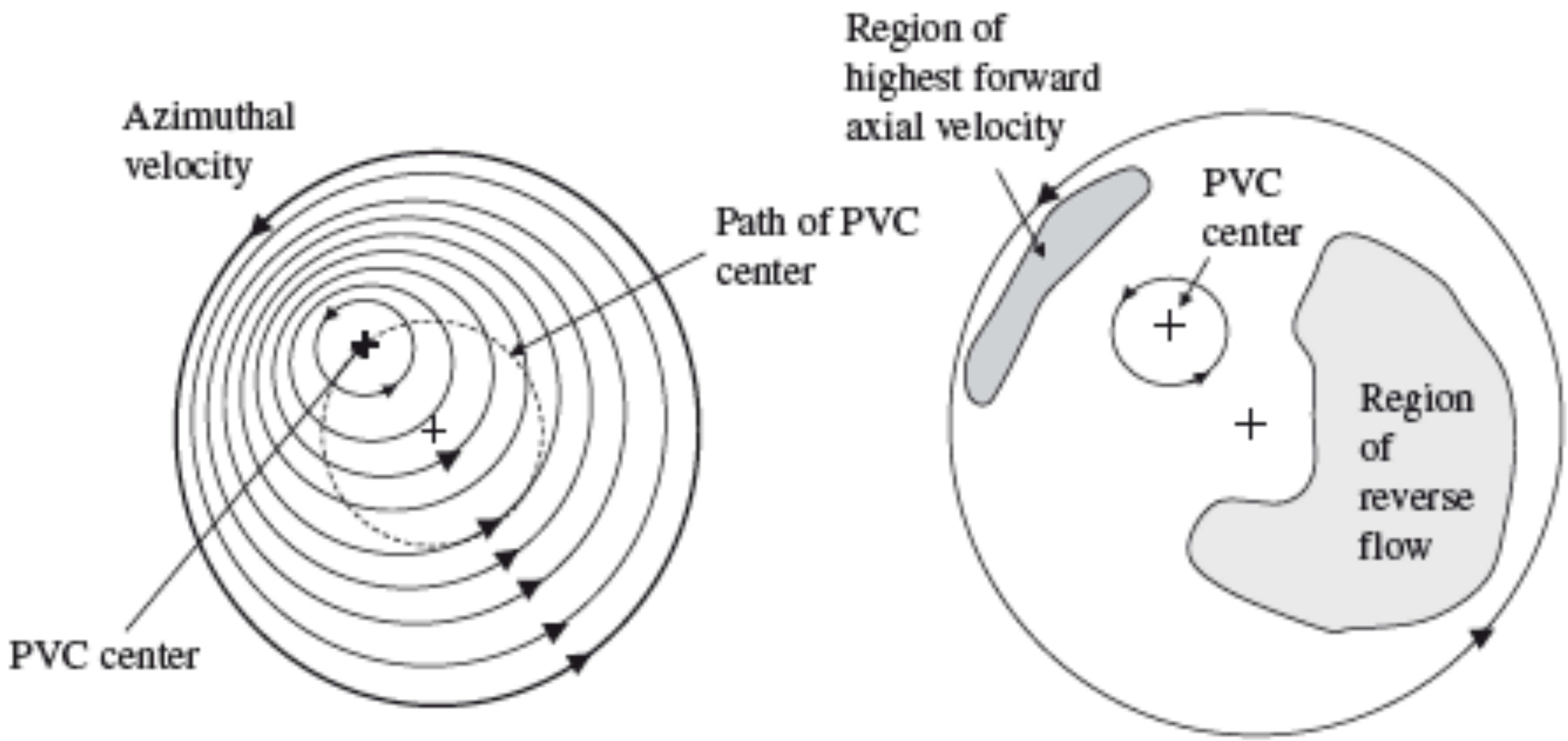
SWIRLING FLOWS



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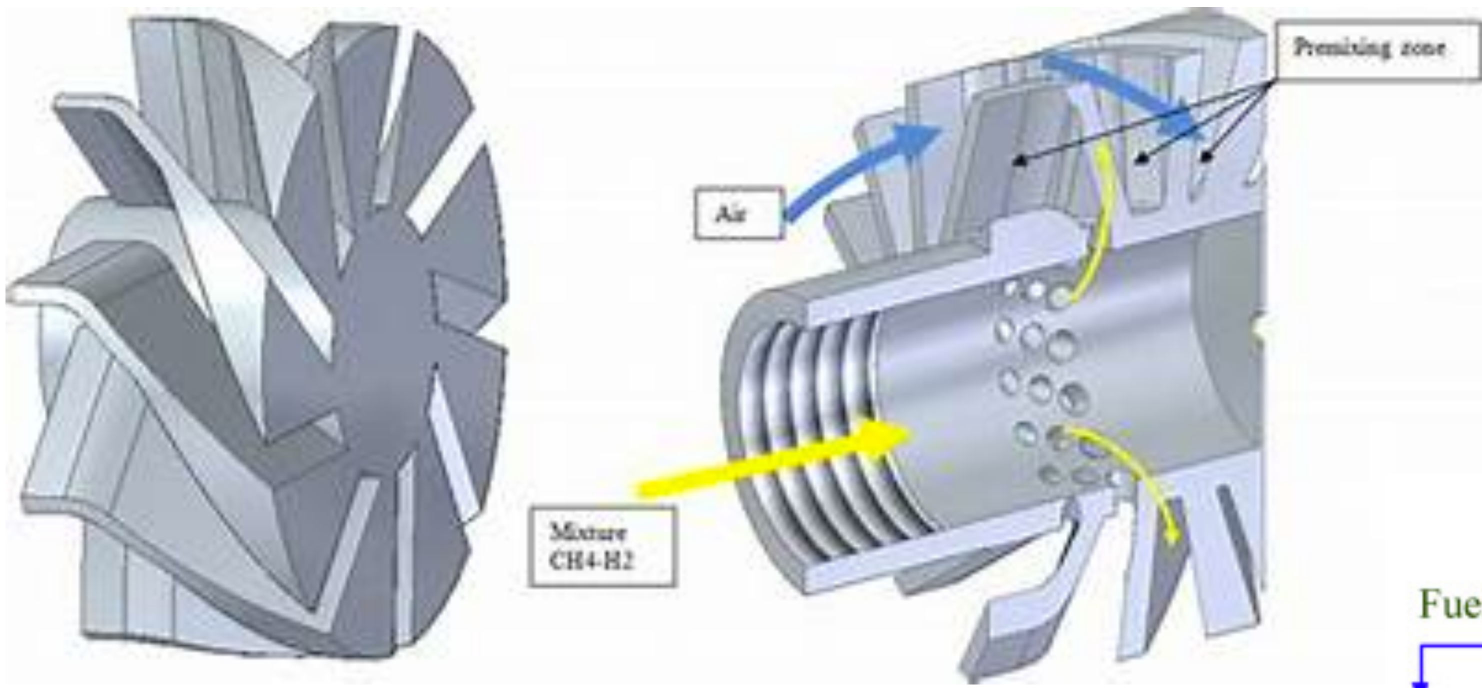
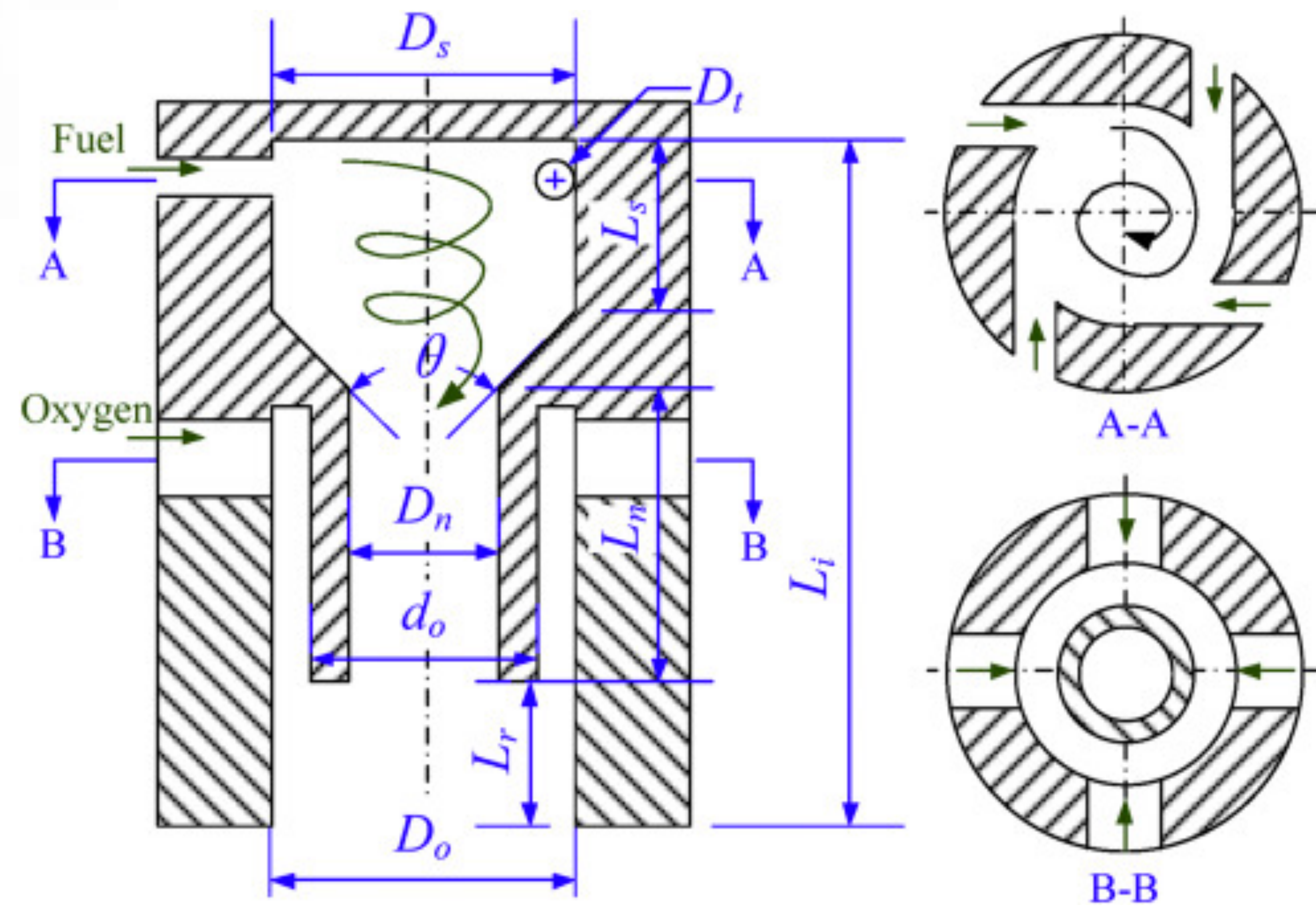
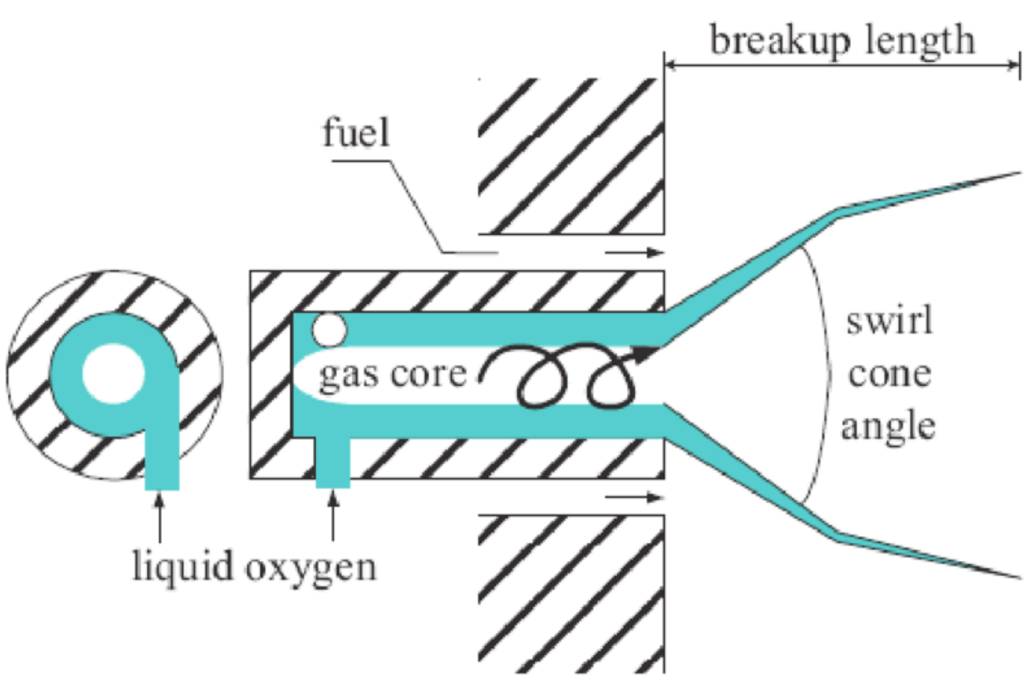
SWIRL INJECTORS



pressure swirl injectors



gas-liquid coaxial swirl injectors



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CYCLONIC FLOWS

- *Cyclones have high stability*
- *They have a three-dimensional evolution*
- *They have recirculation zones with different times compared to residence times*
- *Strong interaction with walls that can be used to achieve catalytic regimes*
- *Intrinsically realize a serial change of aerodynamic configuration that can be used to realize two-stage combustors cyclone-swirl*
- *Can be used usefully for multiphase flows*
- *Used to confine the combustion zone in the central region of the chamber, to protect surfaces from high temperatures (strategy used in rockets).*
- *Classified according to the tangential velocity profile as:*
- *Forced vortex*
- *Free vortex with hyperbolic attenuation profile*
- *Combined vortex with Rankine profile*
- *Multiple vortex*

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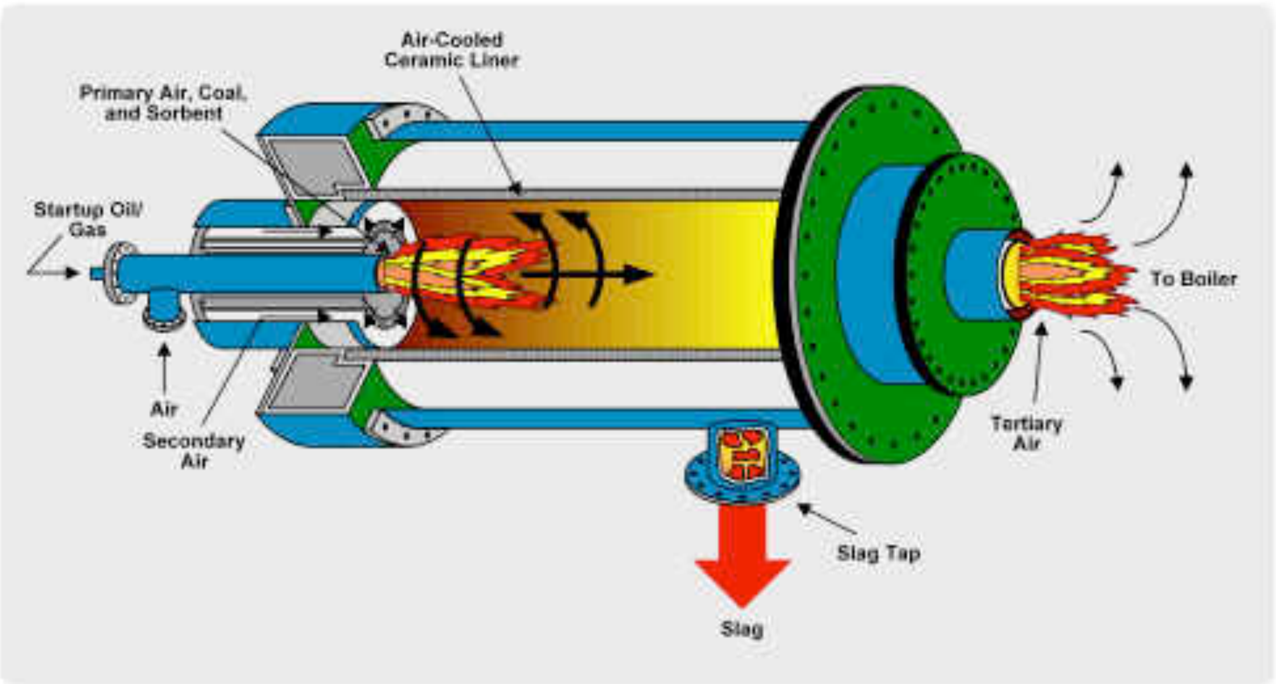
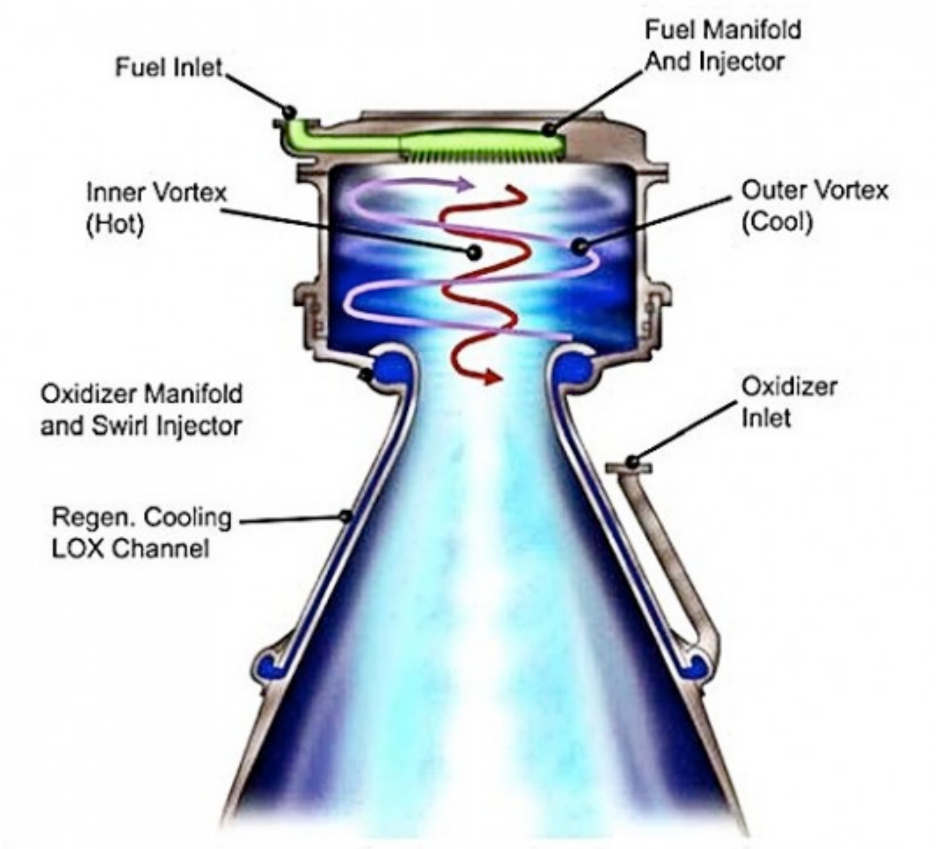
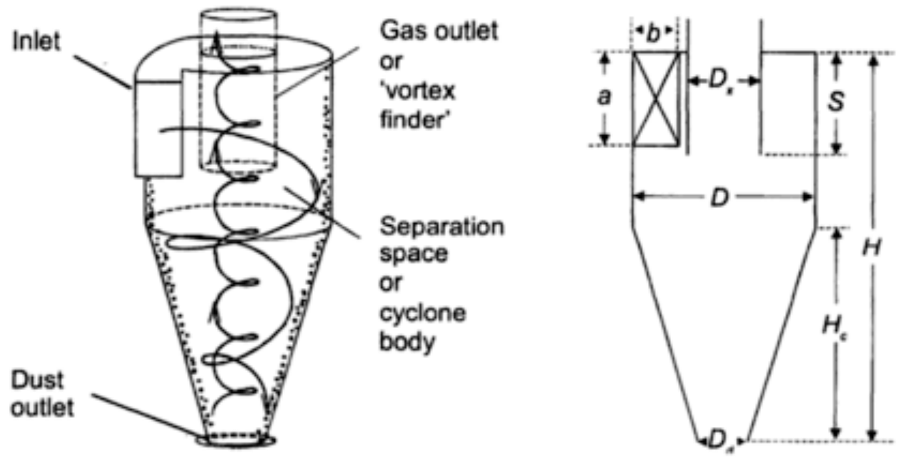
CYCLONIC FLOWS







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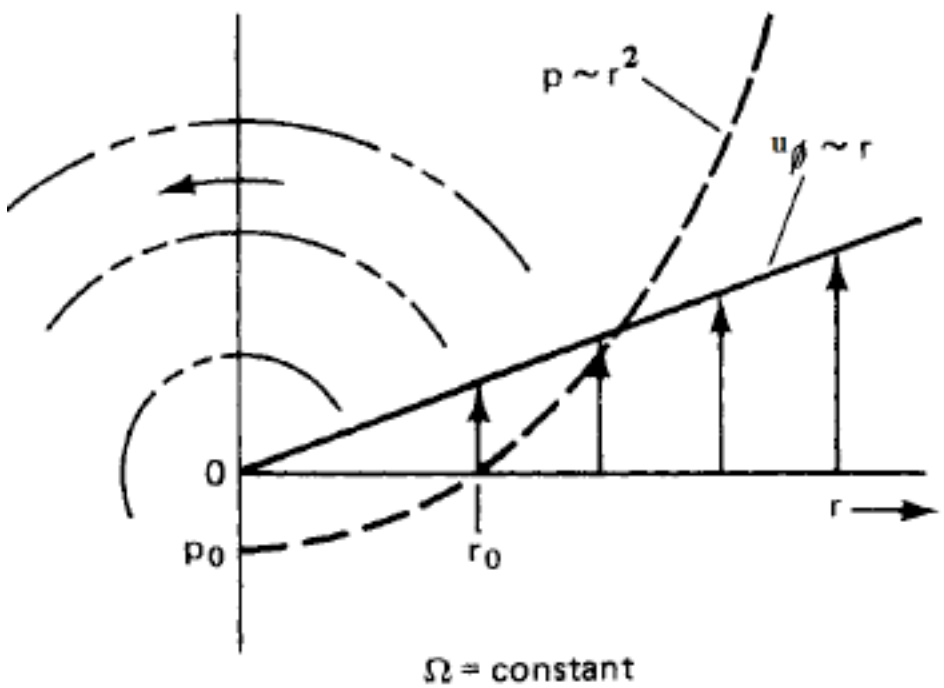
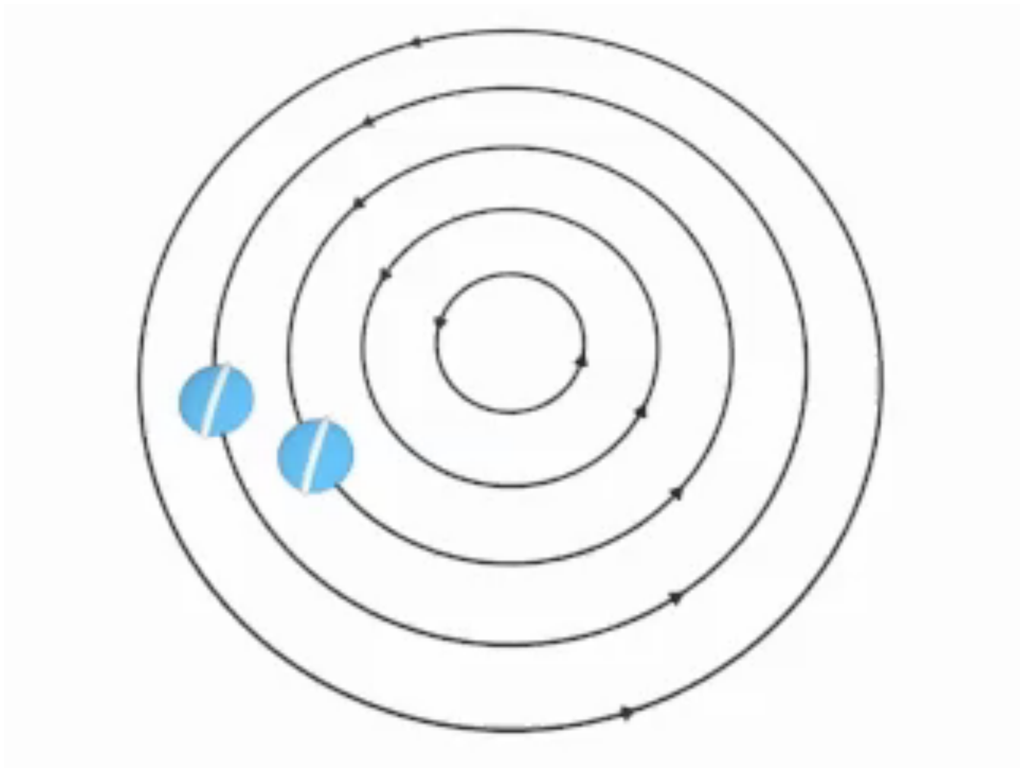
CYCLONIC FLOWS
FORCED VORTEX





$$v_\vartheta = \Omega r$$

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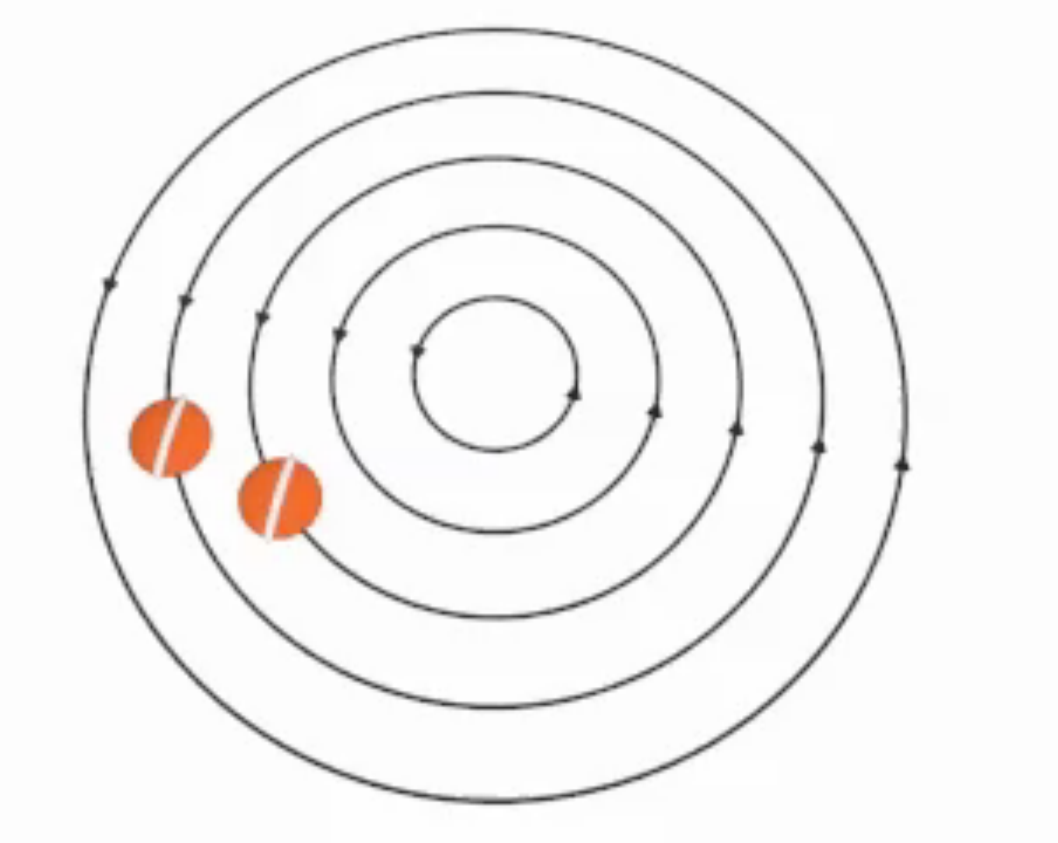
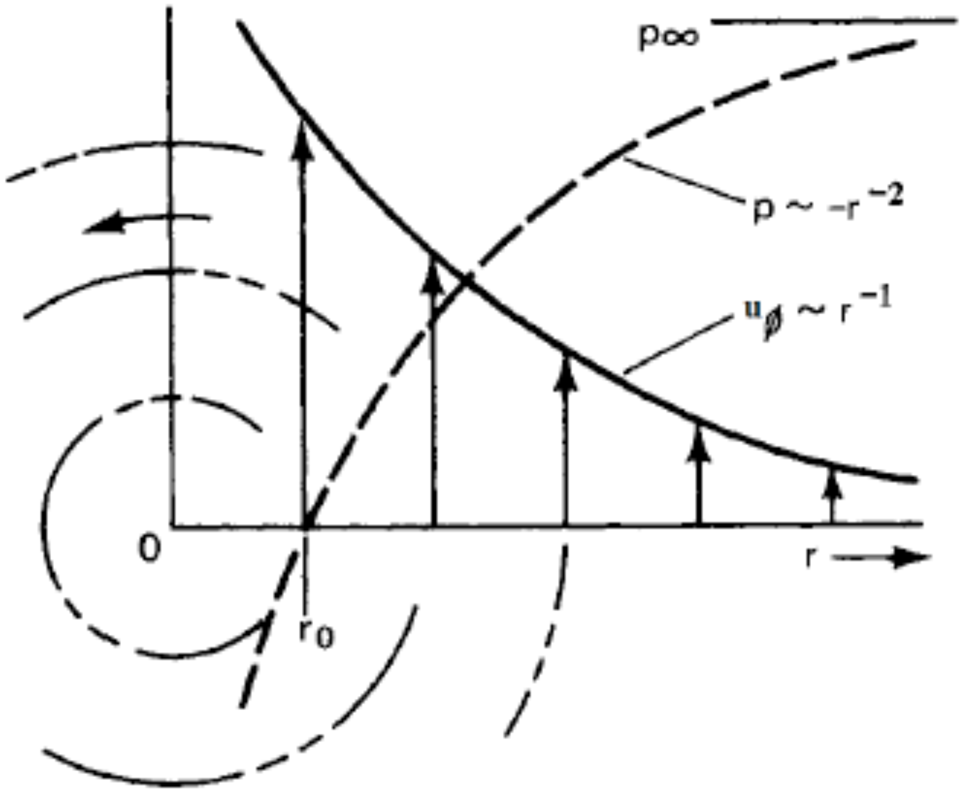
CYCLONIC FLOWS
FREE VORTEX



$$v_\vartheta = \frac{C}{r}$$



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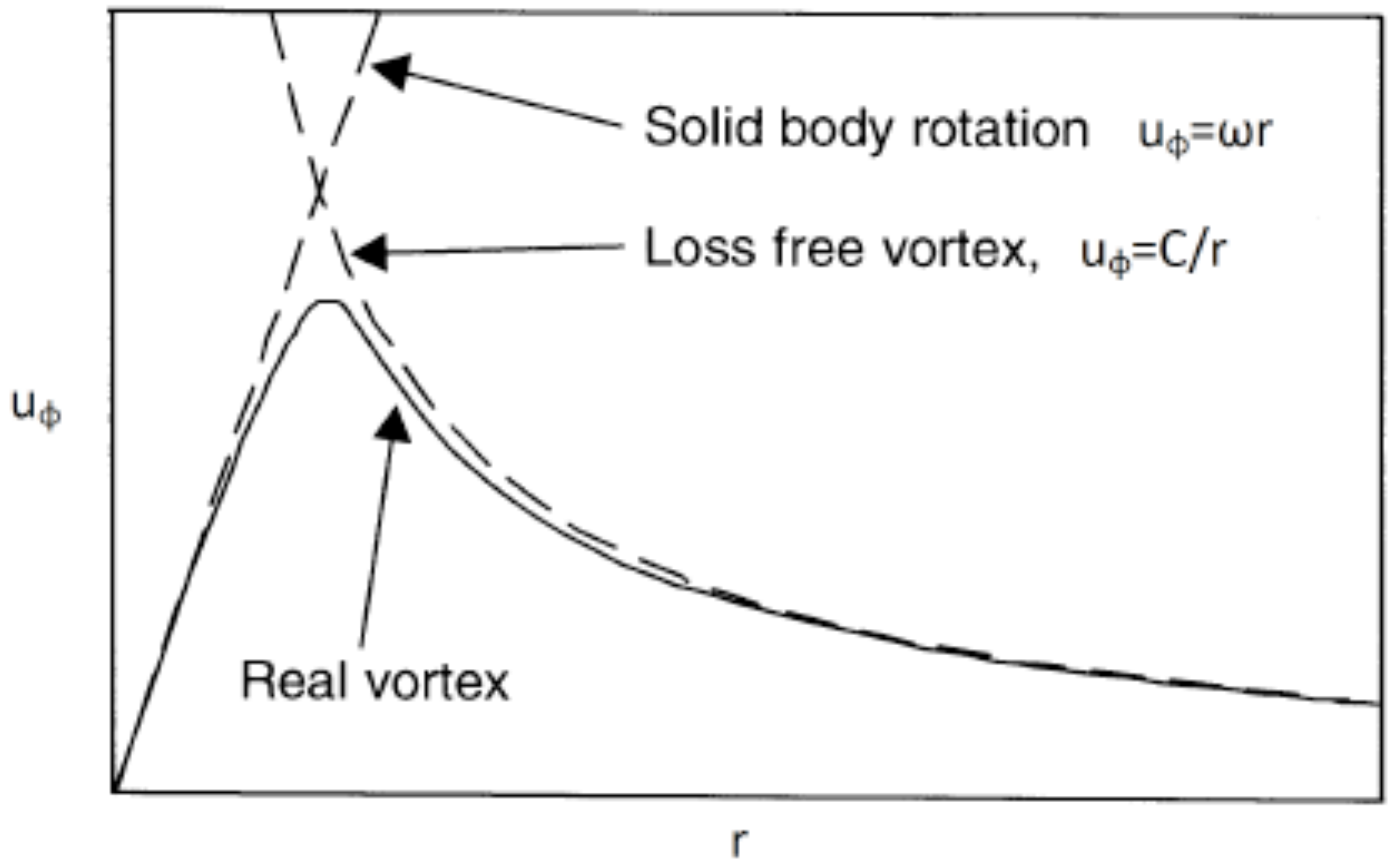
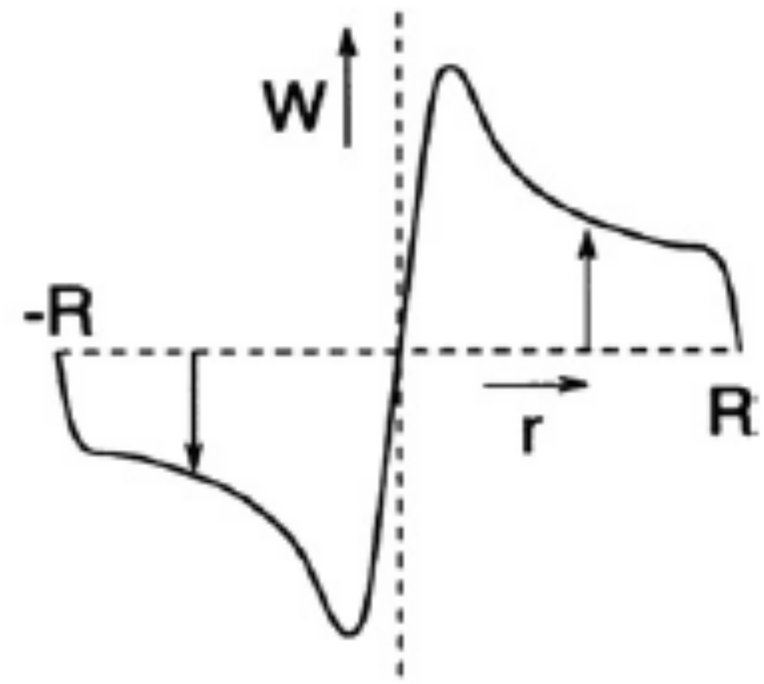
CYCLONIC FLOWS
RANKINE VORTEX



$$v_\vartheta r^n = K$$



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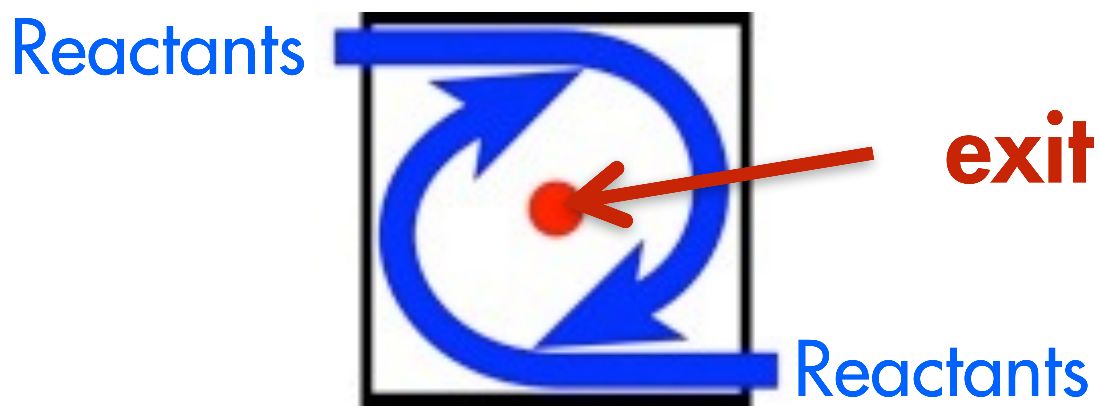
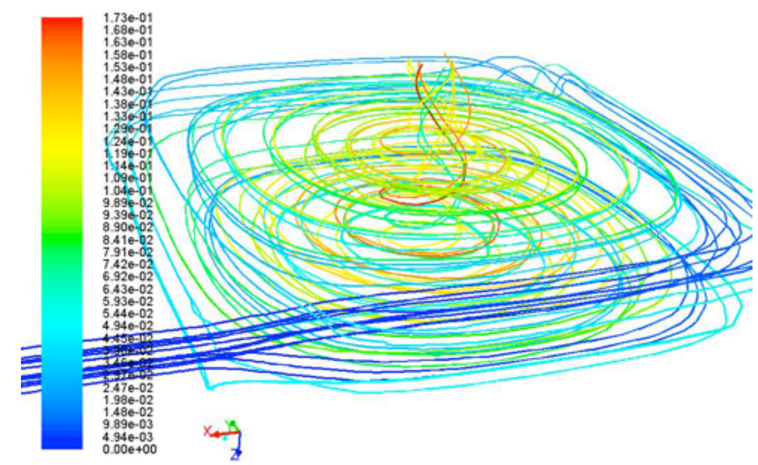
CYCLONIC FLOWS

LUCY BURNER

- *Long residence times in compact systems (H/d <1)*
- *Multiple and large recirculation zones with high levels of turbulence and helical flow inside the chamber*
- *Ease of scale-up, scale-down*
- *Wide operating ranges in terms of flow rates, temperatures, speeds, compositions, external dilutions*



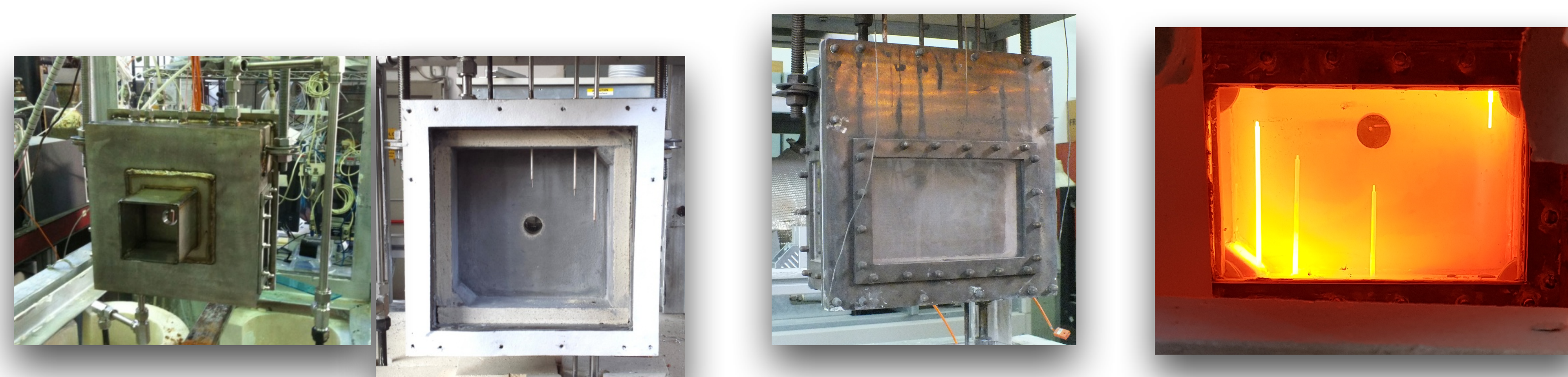


Laboratory

Unit

CYclonic

Burner



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