# Turbulence

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# Fire in wind mill, Denmark, 4. august 2017

# Purpose of lecture

## Why is the understanding of turbulence important

- Turbulence is responsible in fires
  - Rate for combustion (mixing) $\mathrm{Da} = \dfrac{\text{flow time scale}}{\text{chemical time scale}}$
  - Entrainment in fire plumes
  - Flow around obtacles
- Explosion
  - Faster mixing, video https://youtu.be/PdfY3EDrGrQ
    - Deflagration > Detonation

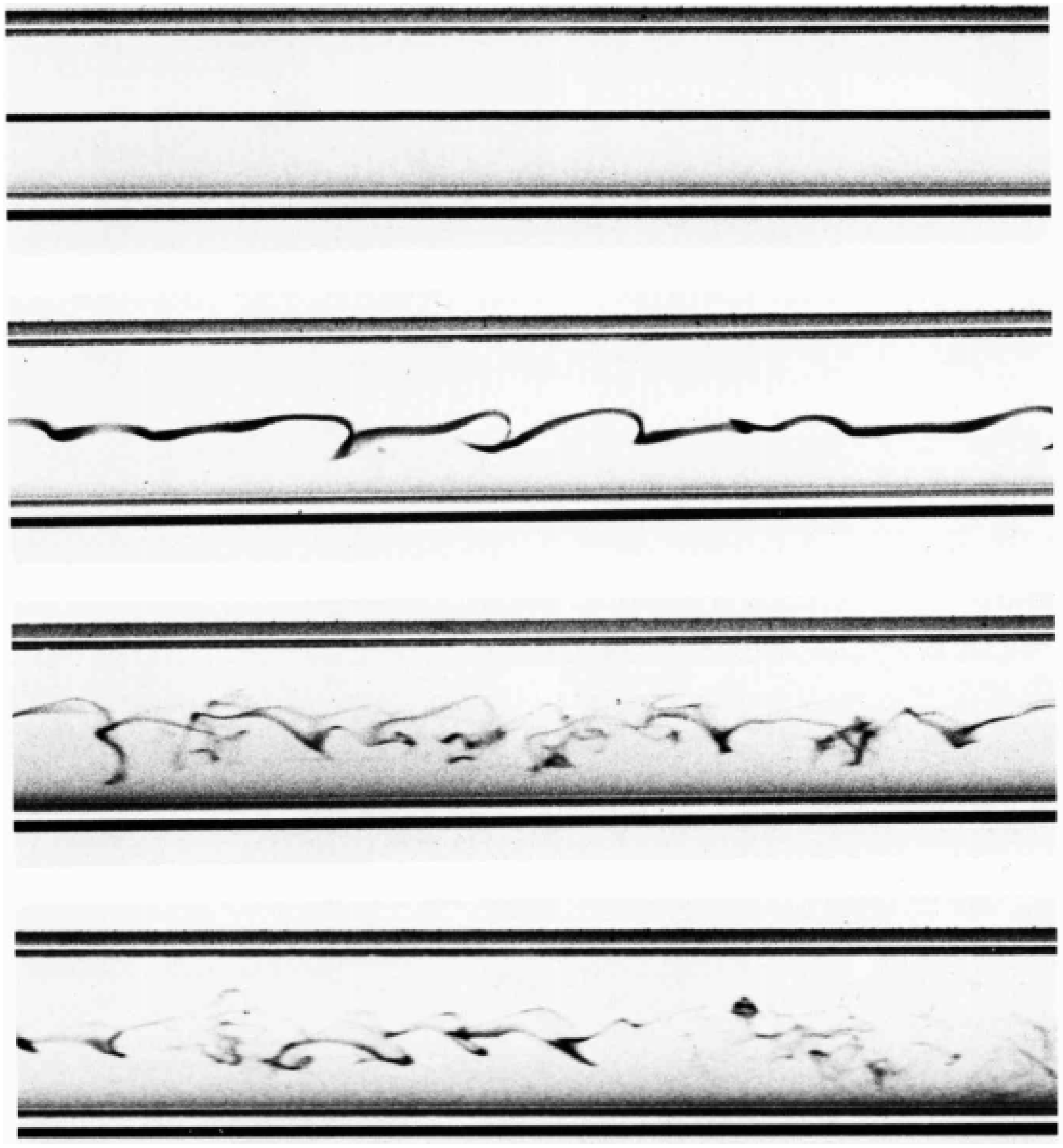
# Overview

- Laminar and turbulent flow
- What is turbulence
- Reynolds number
- Transition from laminar to turbulent flow
- Treatment of turbulence in CFD codes
  - RANS
  - LES
  - DNS

# Laminar and turbulent flow

- Most flow of interest are turbulent
  - Flow in pipes
  - Mixing process (eg. pharmaceutical industry)
  - Fires
- Transition between laminar and turbulent flow can be determined by the Reynolds number. For a pipe flow the transition happens between 2000 – 3000. Flow over a plate: $\mathrm{Re}_x \approx 5 \cdot 10^5$

Repetition of Osborne Reynolds dye experiment from 1883



Source: Van Dyke, An Album of Fluid Motion, Stanford, 1982 (p. 61)

# Find the Reynolds number

- Definition

$$\mathrm{Re} = \frac{\rho \cdot U \cdot D_h}{\mu} = \frac{U \cdot D_h}{\nu}$$

- Hydraulic diameter

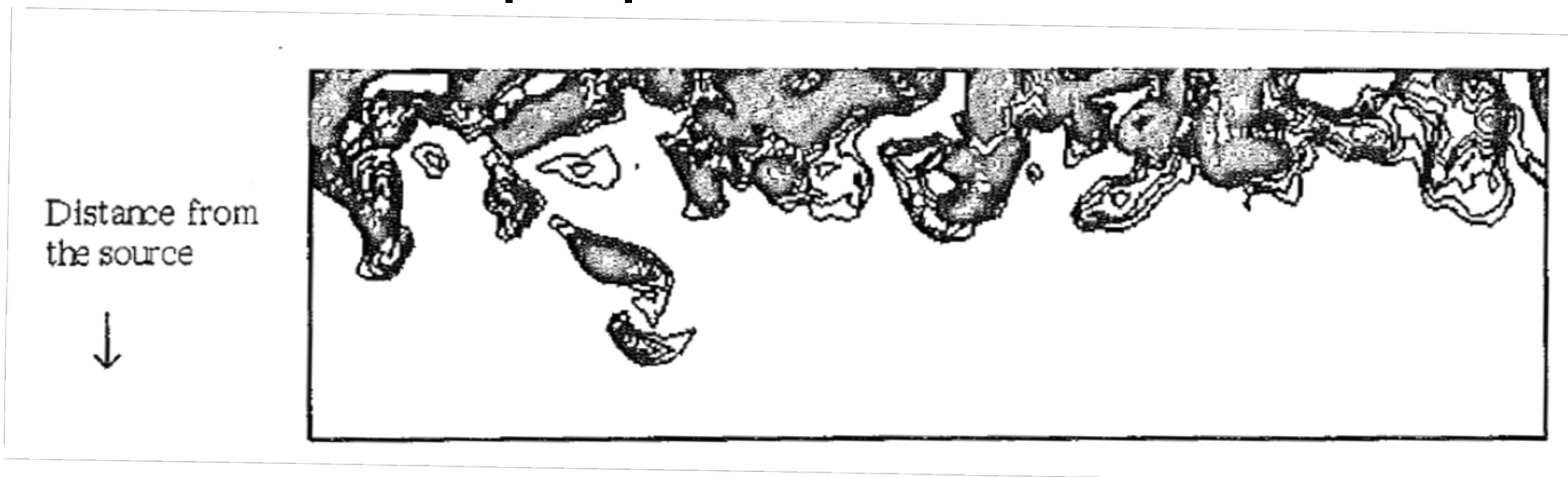
$$D_h = \frac{4 \cdot \mathrm{Area}}{\mathrm{Perimeter}}$$

- Calculate the Reynolds number for a door:
  - 0.8 m wide, 1.9 m in height
  - U is 1.5 m/s, fluid is air at 20 °C
  - The kinematic viscosity is

$$\nu = 1.51 \cdot 10^{-5}$$

# Turbulence

- Chaotic
- Anisotropic phenomena

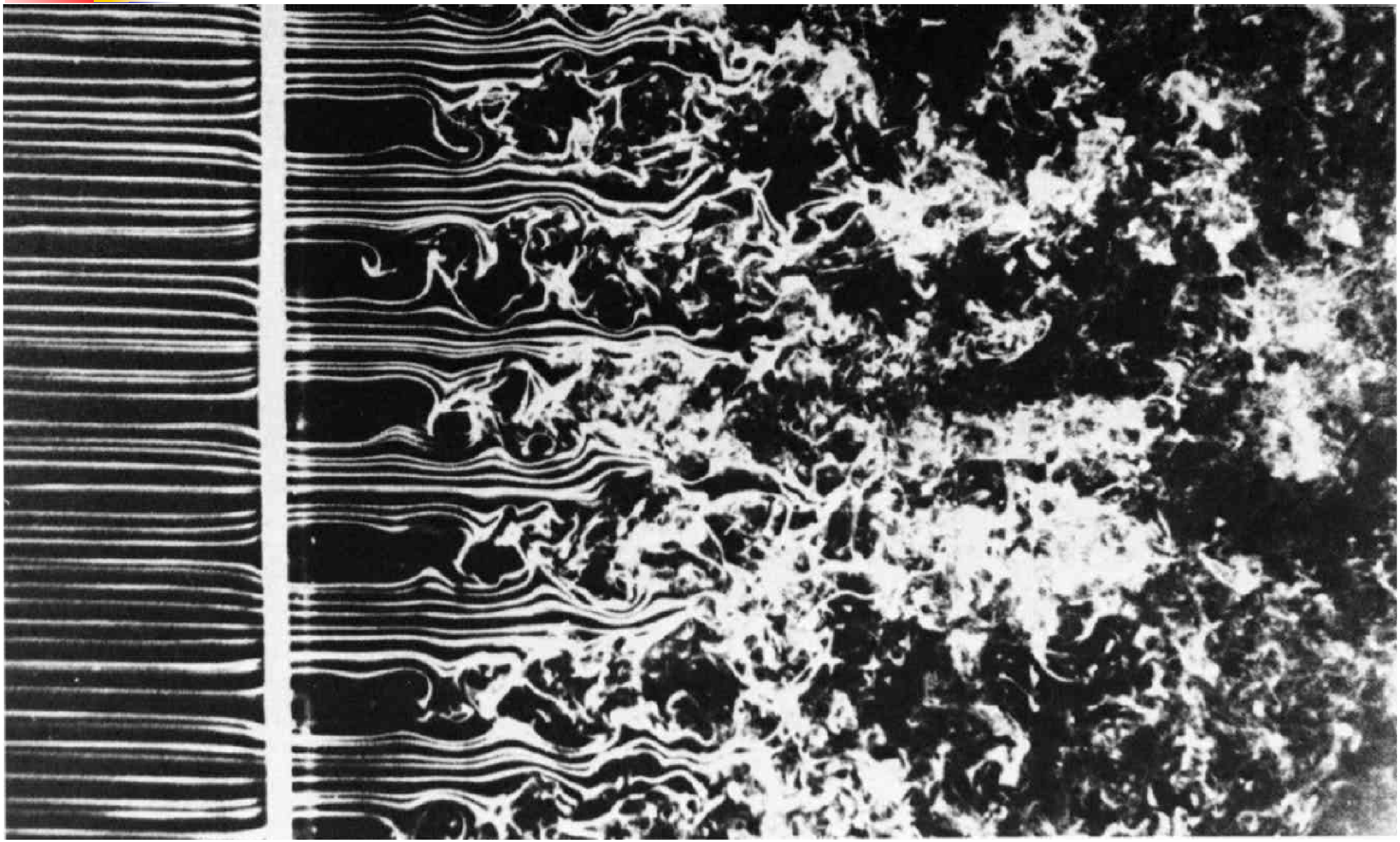



DNS Simulation. Contours of the kinetic energy on a plane in the flow created by an oscillating grid in a quiescent fluid; the grid is located at the top of the figure.

Source: Ferziger & Peric, Computational Methods for Fluid Dynamics, 2002

# Generation of turbulence by a grid

6 grid holes of ¾ inch (19.05 mm) can be seen at the left side



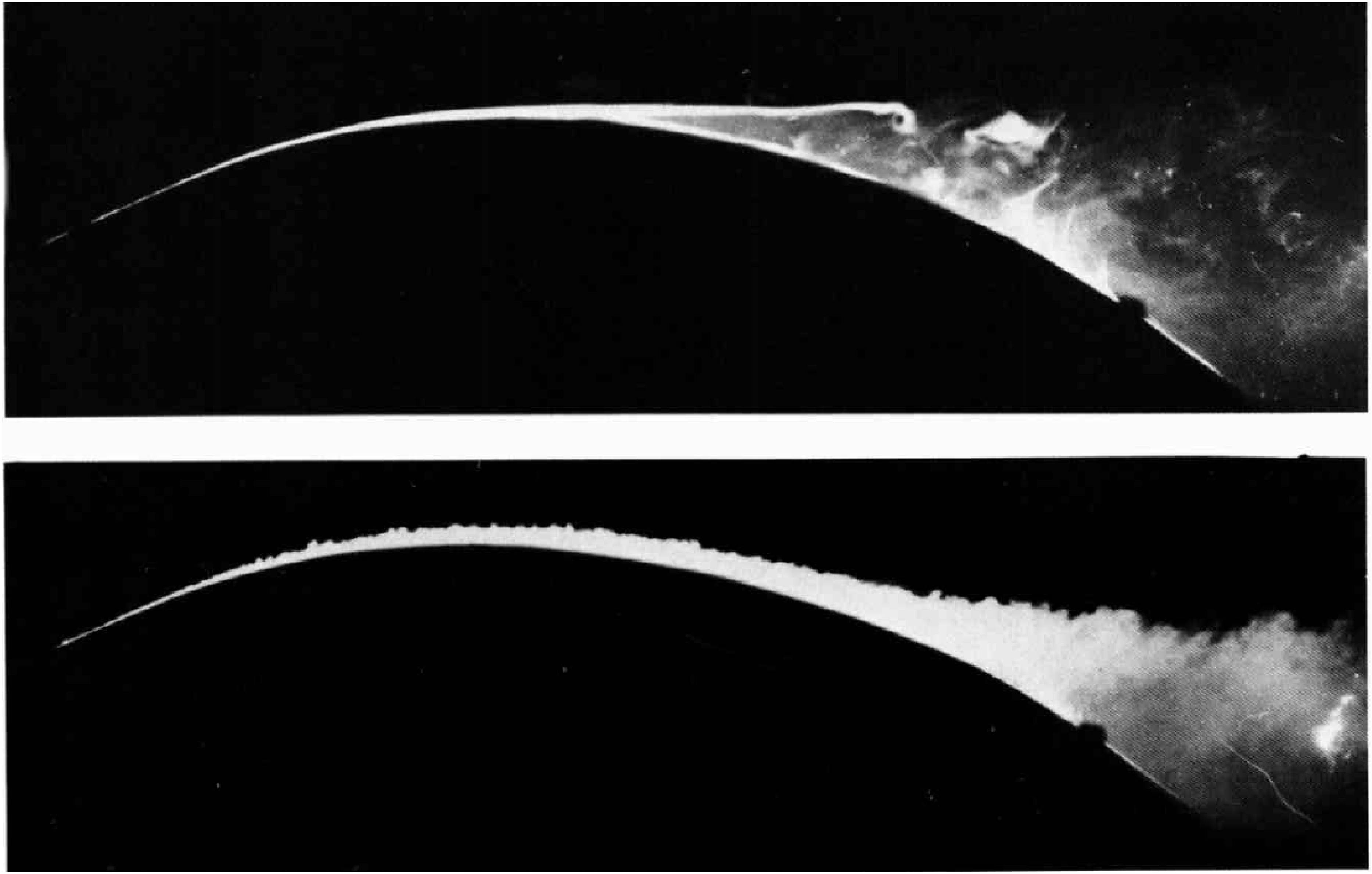
Source: Van Dyke, An Album of Fluid Motion, Stanford, 1982 (p. 89)

Turbulent water jet directed downward into water seen in the plane of symmetry. The jet is illuminated by using Laser-induced fluorescence (LIF).

Source: Van Dyke, An Album of Fluid Motion, Stanford, 1982 (page 97)

# Comparison of laminar and turbulent boundary layer separation

Laminar at top separates and turbulent at bottom stays attached



Source: Van Dyke, An Album of Fluid Motion, Stanford, 1982 (page 91)

# Y+

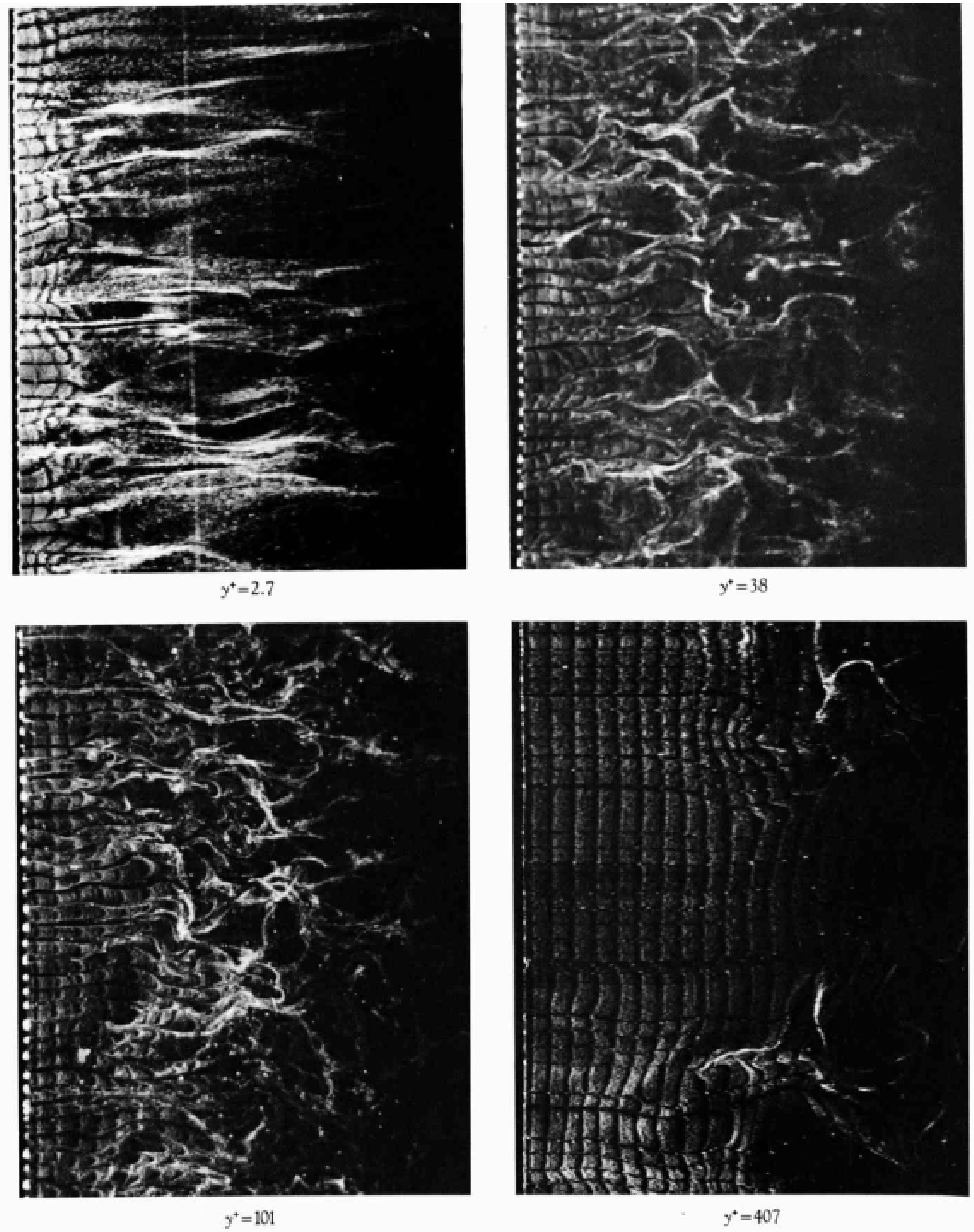
- Y+ is a ratio between turbulent and laminar influences in a cell, if Y+ is big then the cell is turbulent, if it is small it is laminar.

- This is from CFD online – a good forum.
- https://www.cfd-online.com/Forums/main/861-can-someone-explain-y-plus-value.html

Structure of a turbulent boundary layer near a flat plate

$y^+=2.7$

$y^+=38$




$y^+=101$

$y^+=407$

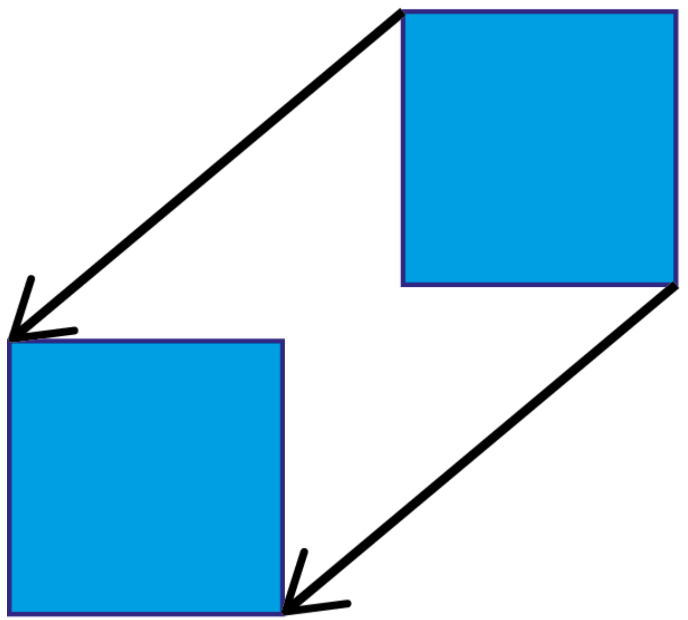
Source: Van Dyke, An Album of Fluid Motion, Stanford, 1982 (p. 94)

# Creation of instabilities
## (Kelvin–Helmholtz instability)

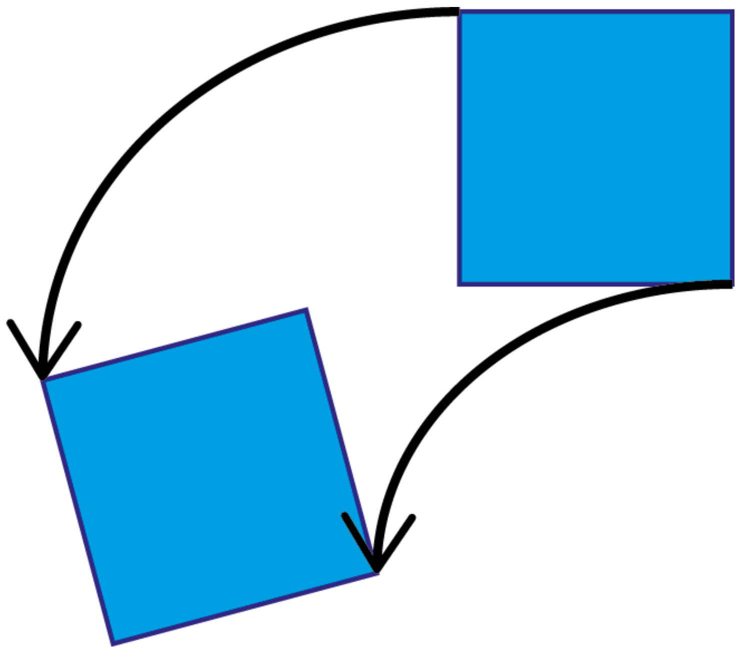
Source https://de.wikipedia.org/wiki/Kelvin-Helmholtz-Instabilit%C3%A4t

# Vorticity

Translation



Rotation



# Vortex stretching

- Youtube
  - http://youtu.be/JaABLY6E8HE
  - http://youtu.be/59LL_IRs1MQ
  - https://youtu.be/Tfi8BLca07M (5 min)

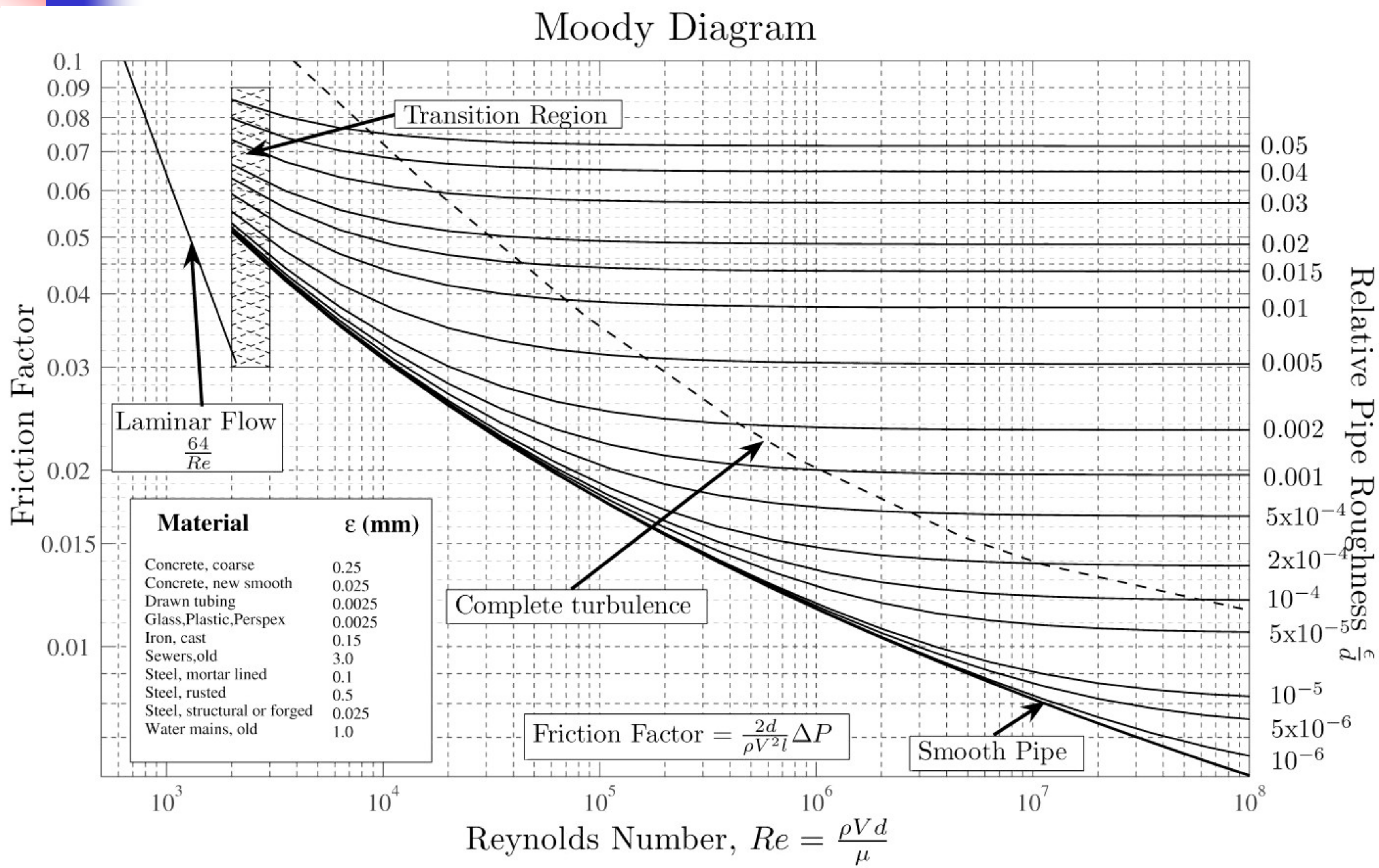
# Hierarchy of turbulence models

- Simple models (eg. Moody chart, heat transfer)
- 0. equation models (eg. Baldwin-Lomax for aerodynamic)
- RANS models
- LES models
- DNS

- Further down on list – longer time to calculate

# Turbulence in pipe flow

$$\Delta P = f\,\frac{\rho \cdot V^2 \cdot l}{2 \cdot d}$$

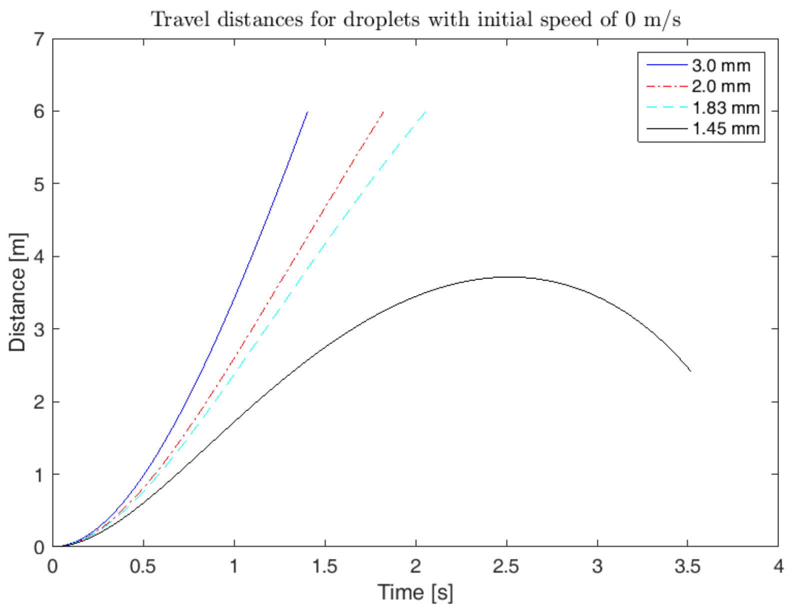


# Example with Nusselt number for a failing droplet in hot air

$$\frac{dd}{dt} = \frac{2 \cdot h \cdot \Delta T}{H_v \cdot \rho}$$

$$h = \frac{Nu \cdot k}{d}$$

$$Nu = 2 + 0.6 \cdot \mathrm{Re}^{0.5} \cdot \mathrm{Pr}^{0.33}$$



# Modelling of turbulence in CFD

- RANS (Reynolds Average Navier Stokes)
- LES (Large Eddy Simulation)
- DNS (Direct Numerical Simulation)

# RANS - Mean Values

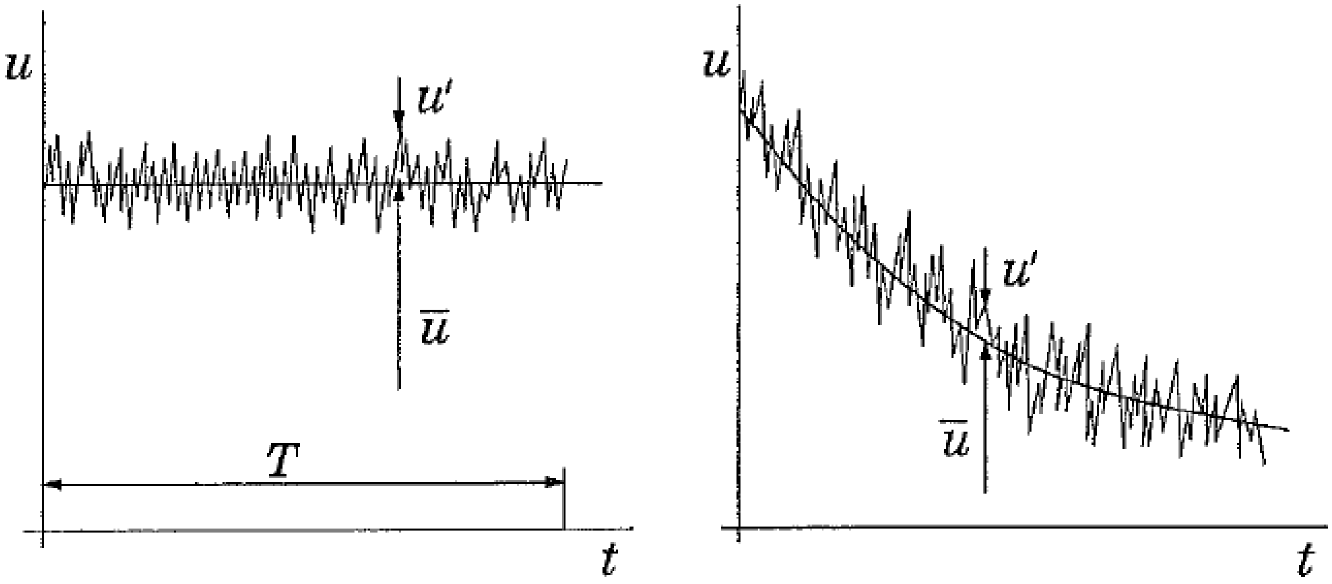



**Fig. 9.10.** Time averaging for a statistically steady flow (left) and ensemble averaging for an unsteady flow (right)

# Turbulent kinetic energy

- For a quasi steady state flow the instantaneous velocity is the mean velocity + a fluctuating component

$$u = \bar{u} + u'$$

- The turbulent kinetic energy k is defined as

$$k = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)$$

- The turbulent intensity is defined as

$$I = \frac{\sqrt{\frac{1}{3}\cdot\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)}}{\bar{u}}$$

# LES and DNS, Ferziger and Peric (2002)

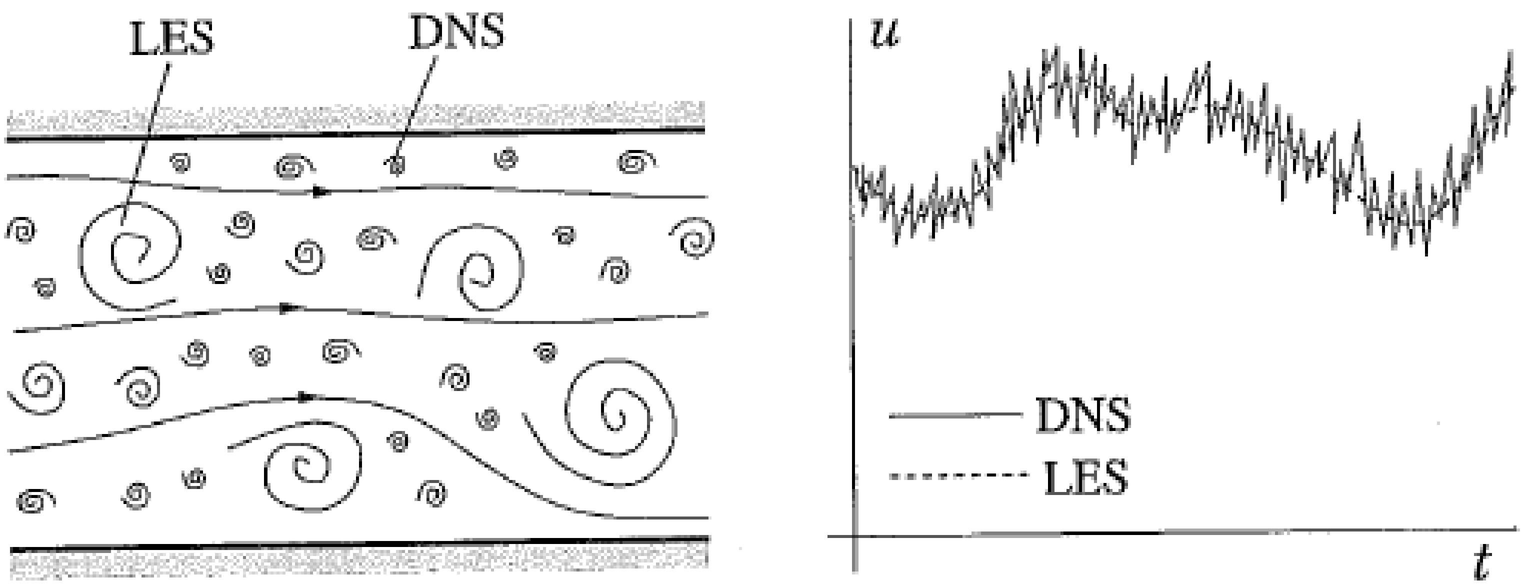
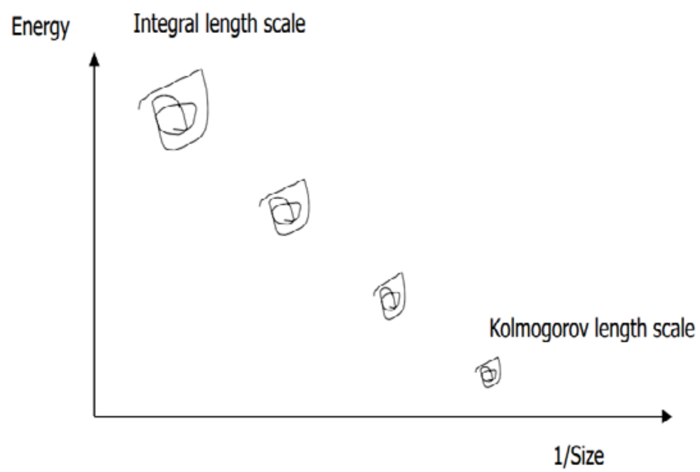


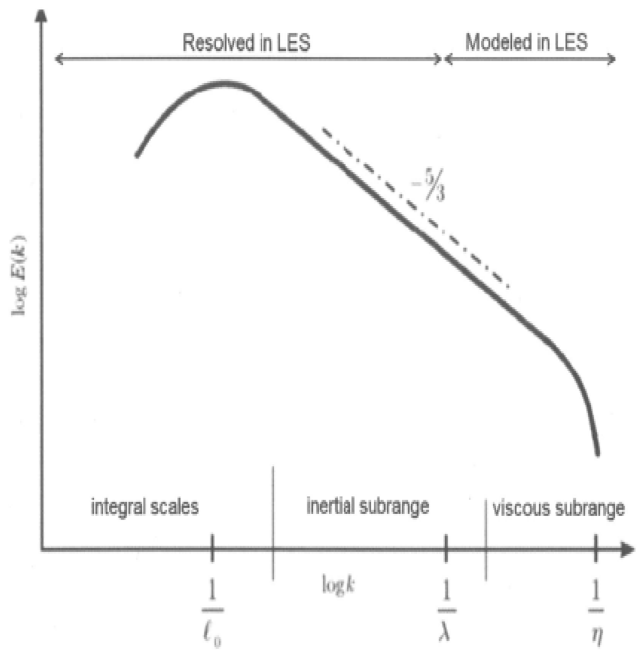

**Fig. 9.3.** Schematic representation of turbulent motion (left) and the time dependence of a velocity component at a point (right)

# Scales of turbulent structures

- Intergral scale – largest scale
- Taylor micro scale – Viscocity starts to become important
- Kolmogorov scale – smallest turbulent scale.

# Using Turbulence resolution (amount of unresolved turbulent kinetic energy)




Picture: Per Petersson

$$mtr = \frac{k_{subgrid}}{k_{LES} + k_{subgrid}}$$

# RANS

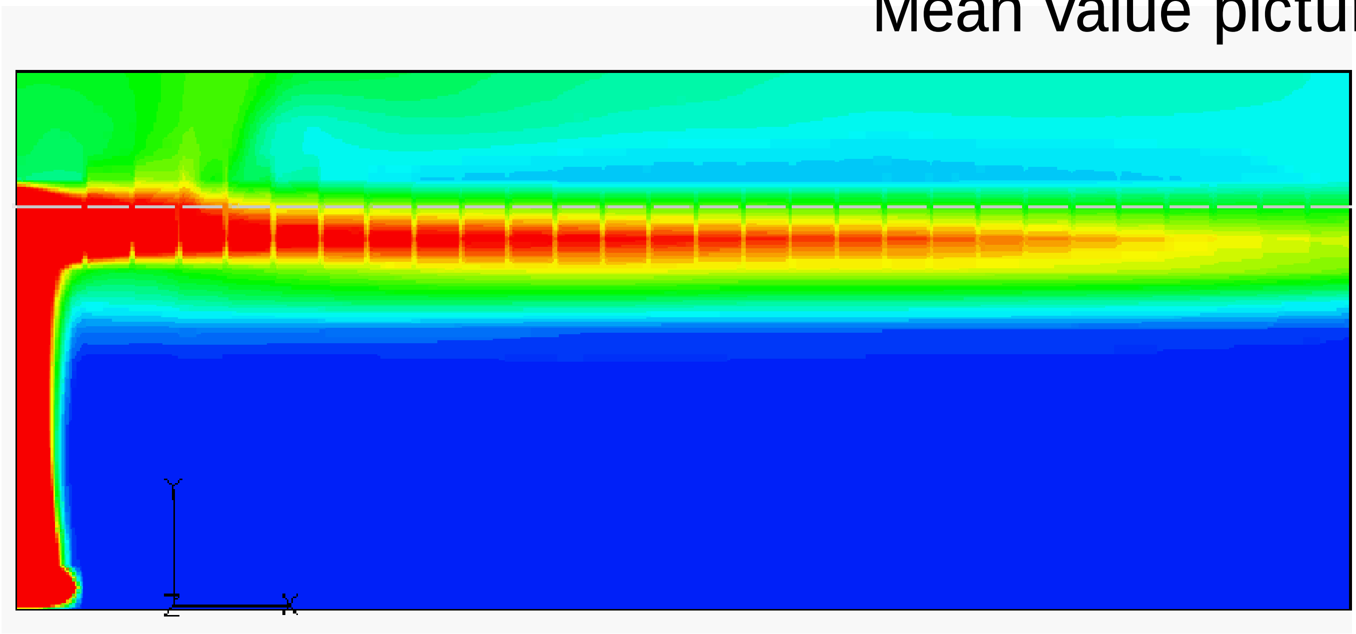
- Reynolds Average Navier Stokes

$$u = \overline{u} + u'$$ velocity

$$u' = \sqrt{\tfrac{1}{3}\left(u_x'^{\,2} + u_y'^{\,2} + u_z'^{\,2}\right)}$$ flutuatic velocity

$$I \equiv \frac{u'}{\overline{u}} \cdot 100\%$$ turbulent intensity

Mean value picture



# RANS 2

$$\tau_{i,j} = \rho\,\overline{u_i' u_j'} = \rho \begin{pmatrix} \overline{u_1' u_1'} & \overline{u_1' u_2'} & \overline{u_1' u_3'} \\ \overline{u_2' u_1'} & \overline{u_2' u_2'} & \overline{u_2' u_3'} \\ \overline{u_3' u_1'} & \overline{u_3' u_2'} & \overline{u_3' u_3'} \end{pmatrix}$$

- Turbulence models with RANS
  - Equations are averages
  - But there are too few equations to the number of unknown variables (this is called Closure)
  - Therefore additional equations are needed to close the system of equations

# RANS 3

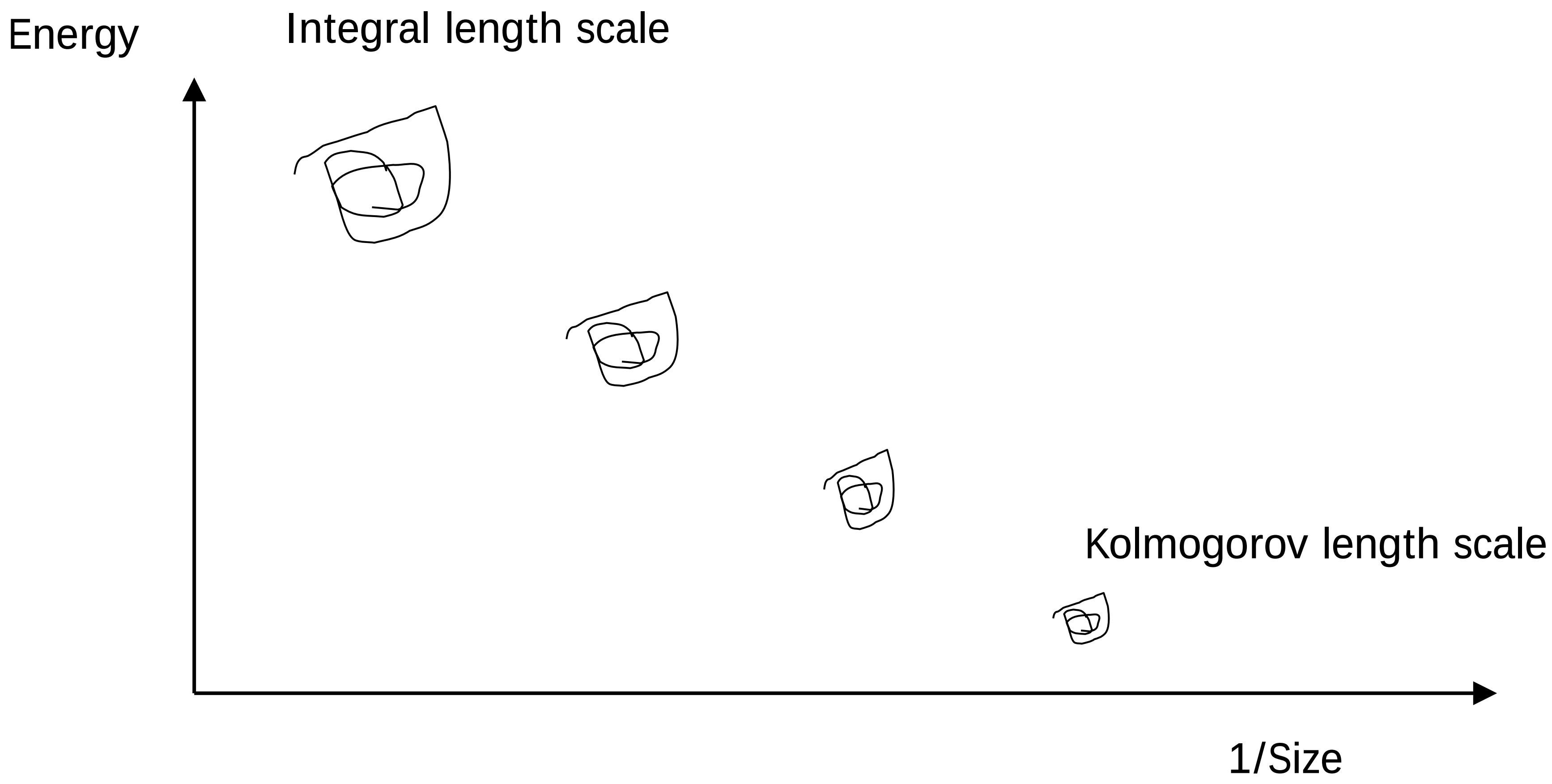
- Most well-known model to close the RANS equation is
  - k-$\varepsilon$ model
    - k is turbulent kinetic energy
    - $\varepsilon$ is the turbulent dissipation
    - Are used in industrial applications
  - Other models
    - k-$\omega$ model
    - Menter model

$$k = \frac{1}{2}\left(\overline{(u_1')^2} + \overline{(u_2')^2} + \overline{(u_3')^2}\right).$$

# RANS 4

- The most time consuming closure for RANS is:
  - The Reynolds stress model
    - Gives 7 extra partial differential equations
    - Difficult to get to converge (solve)
    - It is maybe then better to use LES instead (see Versteeg, page 109)

# Turbulence cascade



# LES 1

- Filtering of the equations
  - Eddies below are given size $\Delta$ are handled by the ”sub grid” model
    - $\Delta > h$ , h is the grid size
  - Model to handle the ”small” eddies, turbulent viscosity
    - Constant Smagorinsky
    - Dynamic Smagorinsky
    - Deardorff (Default in FDS 6)
    - Vreman

# LES 2

- Energy on sub-grid
  - 90 % of the eddies should be resolved in the large grid, (se Combustion af Warnatz, Maas og Dibble)
    - The is rarely the case when using FDS
    - Use Measurement of turbulent resolution

# LES 3 Turbulent viscosity

- Smagorinsky

$$\mu_t = \rho\,(C_s\,\Delta)^2\,|S| \quad ; \quad |S| = \left(2S_{ij}S_{ij} - \frac{2}{3}(\nabla\cdot\mathbf{u})^2\right)^{\frac{1}{2}}$$

- Deardorff

$$\mu_t = \rho\,C_v\,\Delta\,\sqrt{k_{sgs}} \quad ; \quad k_{sgs} = \frac{1}{2}\left((\bar{u}-\hat{\bar{u}})^2 + (\bar{v}-\hat{\bar{v}})^2 + (\bar{w}-\hat{\bar{w}})^2\right)$$

# LES 4

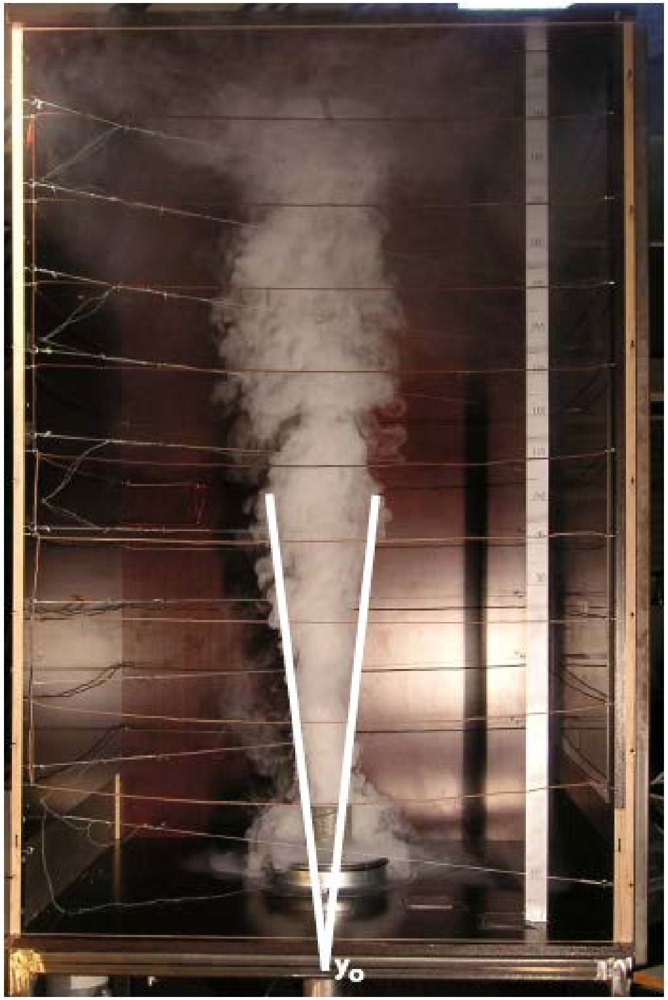
- Setting turbulence model in FDS

| TURBULENCE_MODEL | Description | Coefficient(s) |
|---|---|---|
| 'CONSTANT SMAGORINSKY' | Constant coefficient Smagorinsky model [11] | C_SMAGORINSKY |
| 'DYNAMIC SMAGORINSKY' | Dynamic Smagorinsky model [12, 13] | None |
| 'DEARDORFF' | Deardorff model [9, 10] | C_DEARDORFF |
| 'VREMAN' | Vreman's eddy viscosity model [14] | C_VREMAN |
| 'RNG' | Renormalization group eddy viscosity model [15] | C_RNG, C_RNG_CUTOFF |

# Smagorinsky constant (Cs)

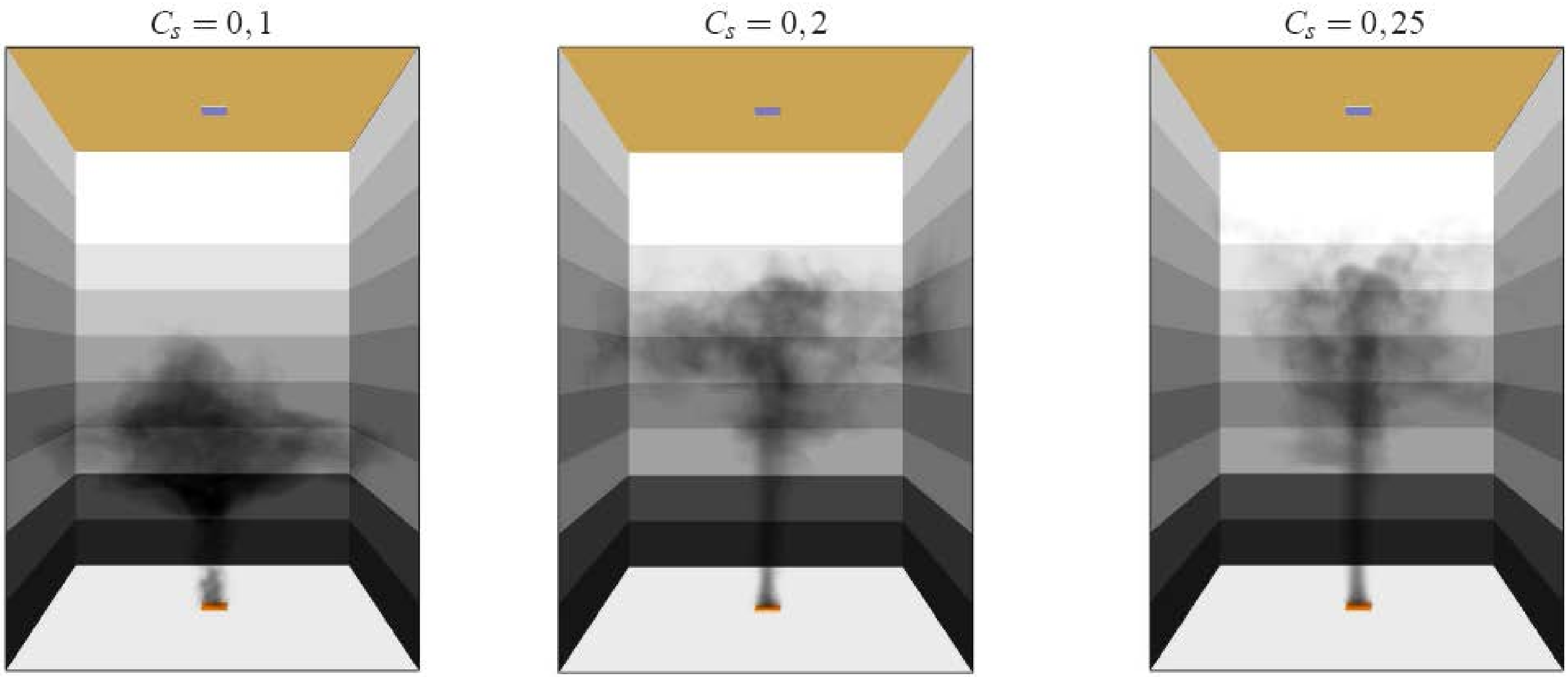
- What should it be  (FDS 5)
  - It is set to 0.20, but is depends on the geometry
- Example from Sommerlund-Larsen and Petersen's,  M.Sc. Thesis
- FDS 6 uses a dynamic Smagorinsky model

# Experiment – Sommerlund-Larsen and Petersen



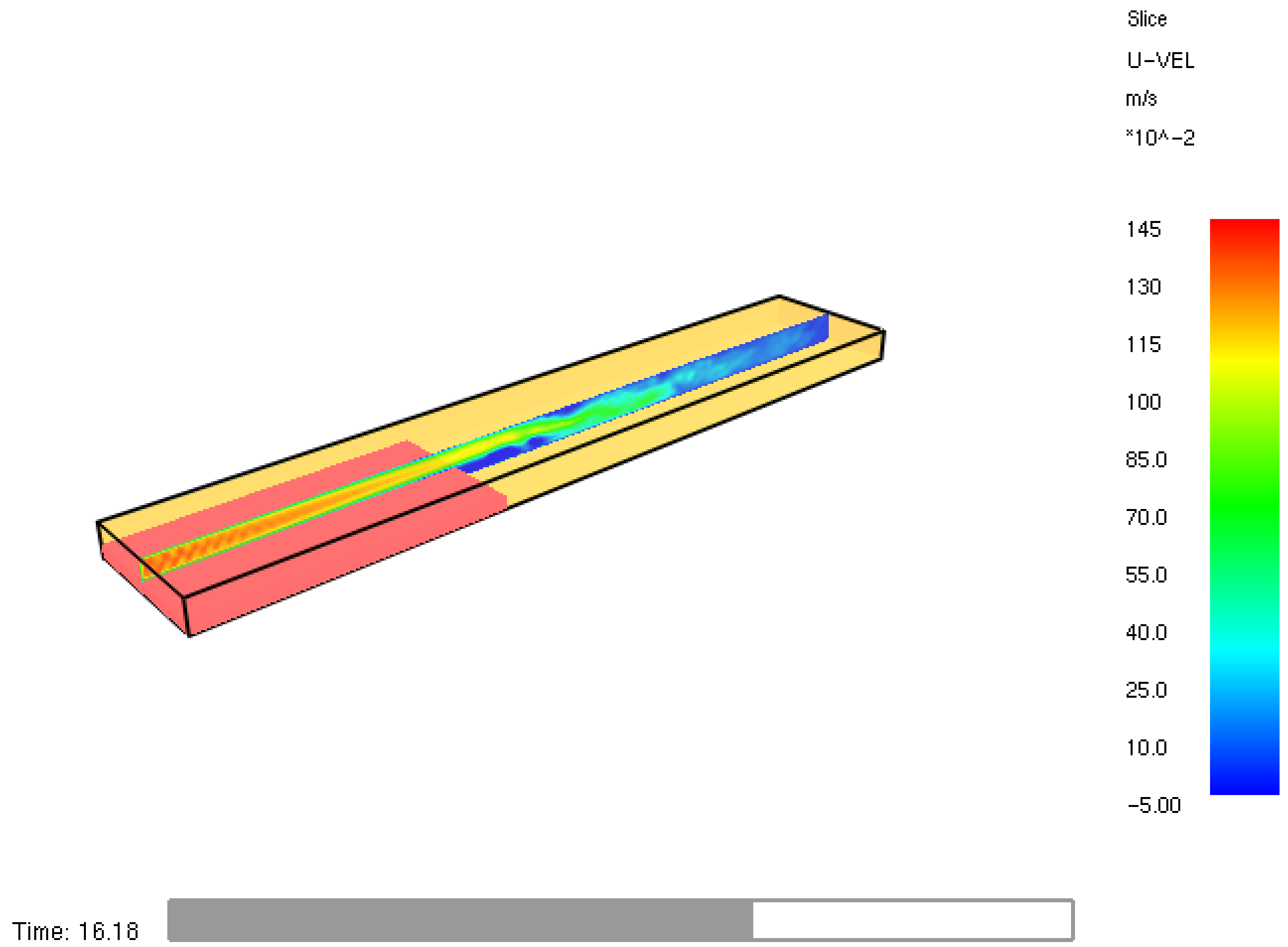

*Plumen under forsøg med opdriftsneutralt røglag, hvor spredningsvinklen er fundet til 14°.*

# Different value of Cs (Fixed Smagorinsky constant)



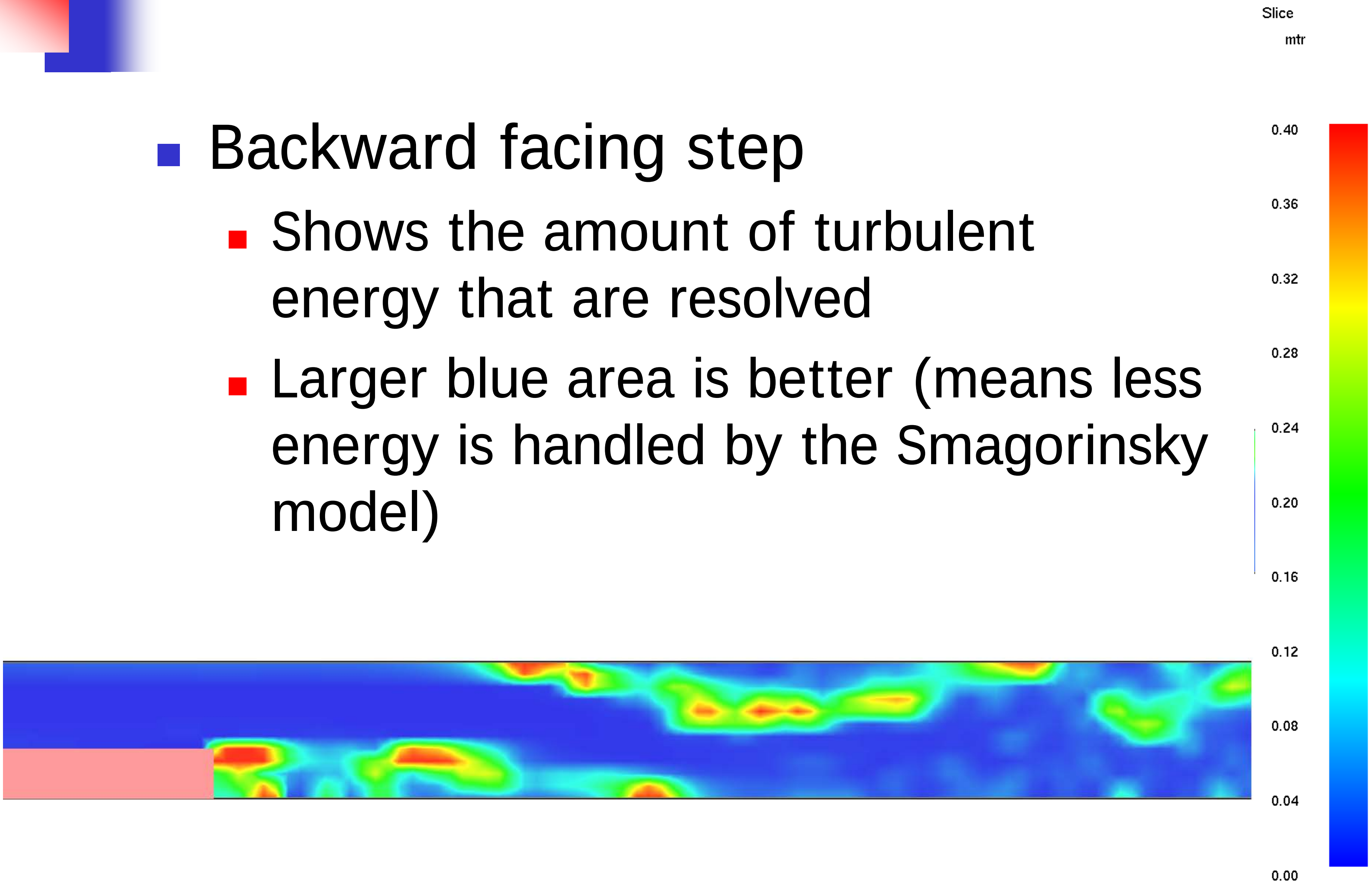

**Figur M.11:** *Røglagets udvikling efter 40 sekunders 14x14 cm 50 W brand. De tre brande har forskellige Smagorinsky konstanter, og fra venstre af, antager de værdierne 0,1, 0,2 og 0,25.*

# Backward facing step



# Dynamic Smagorinsky constant

- Backward facing step
  - Shows the amount of turbulent energy that are resolved
  - Larger blue area is better (means less energy is handled by the Smagorinsky model)



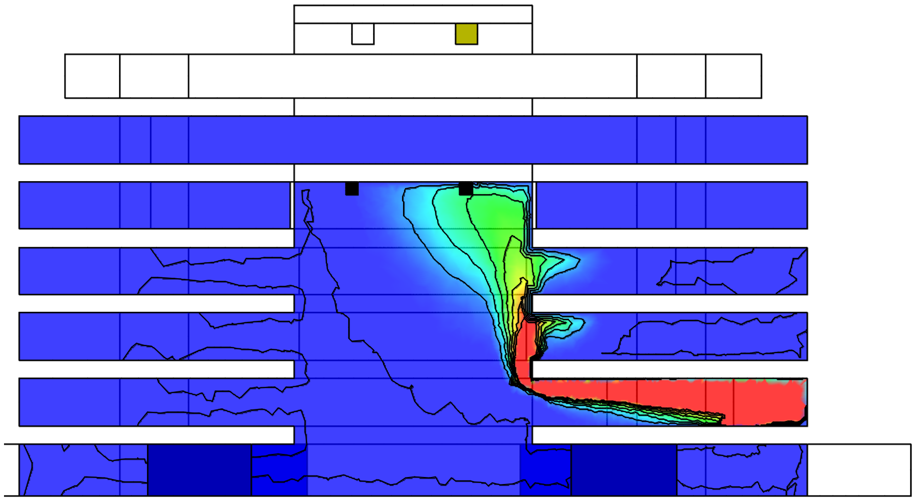
# RANS versus LES

Kontorhus med atrium

1 MW fast brand – mekanisk udsugning

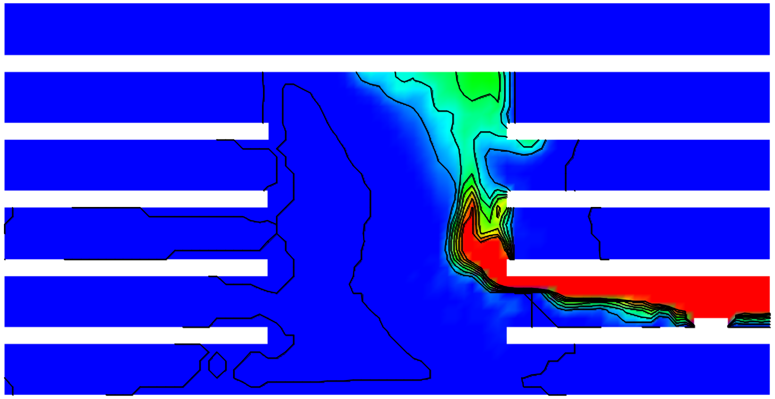
90 sekunder

RANS model

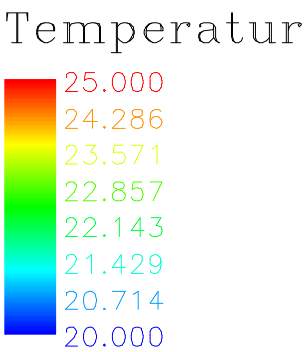


CFX 5.7

LES model



FDS 4.03




DBI 2004

# Pope's questions

- 1. Is LES the right approach?
- 2. Can the resolution of all scales be made tractable?
- 3. Do we have sufficient computer power for LES?
- 4. Is LES a physical model, a numerical procedure or a combination of both?
- 5. How can LES be made complete? (MTR)
- 6. What is the relationship between $U$ and $W$?
- 7. How do predicted flow statistics depend on ?
- 8. What is the goal of an LES calculation?
- 9. How are different LES models to be appraised?
- 10. Why is the dynamic procedure successful?

# Statistic, question 7

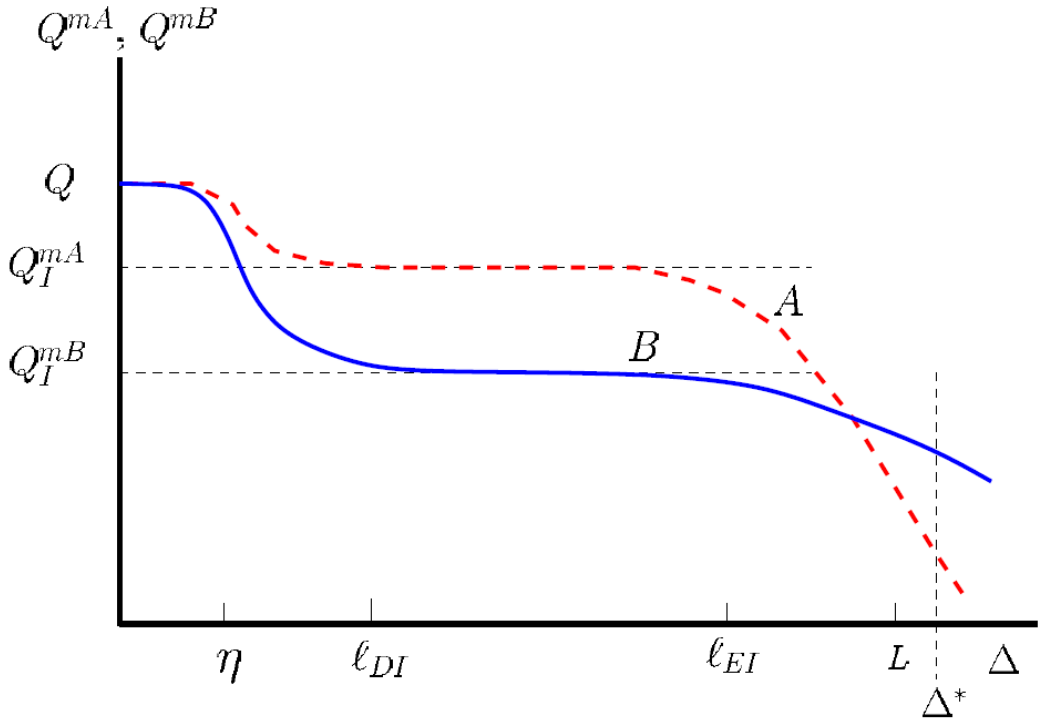



**Figure 5.** The predictions $Q^{mA}(\Delta)$ and $Q^{mB}(\Delta)$ of the statistic $Q$ obtained from LES models A and B as functions of the turbulence resolution length scale $\Delta$ for the case in which $Q$ has contributions from both energy-containing and dissipative scales.