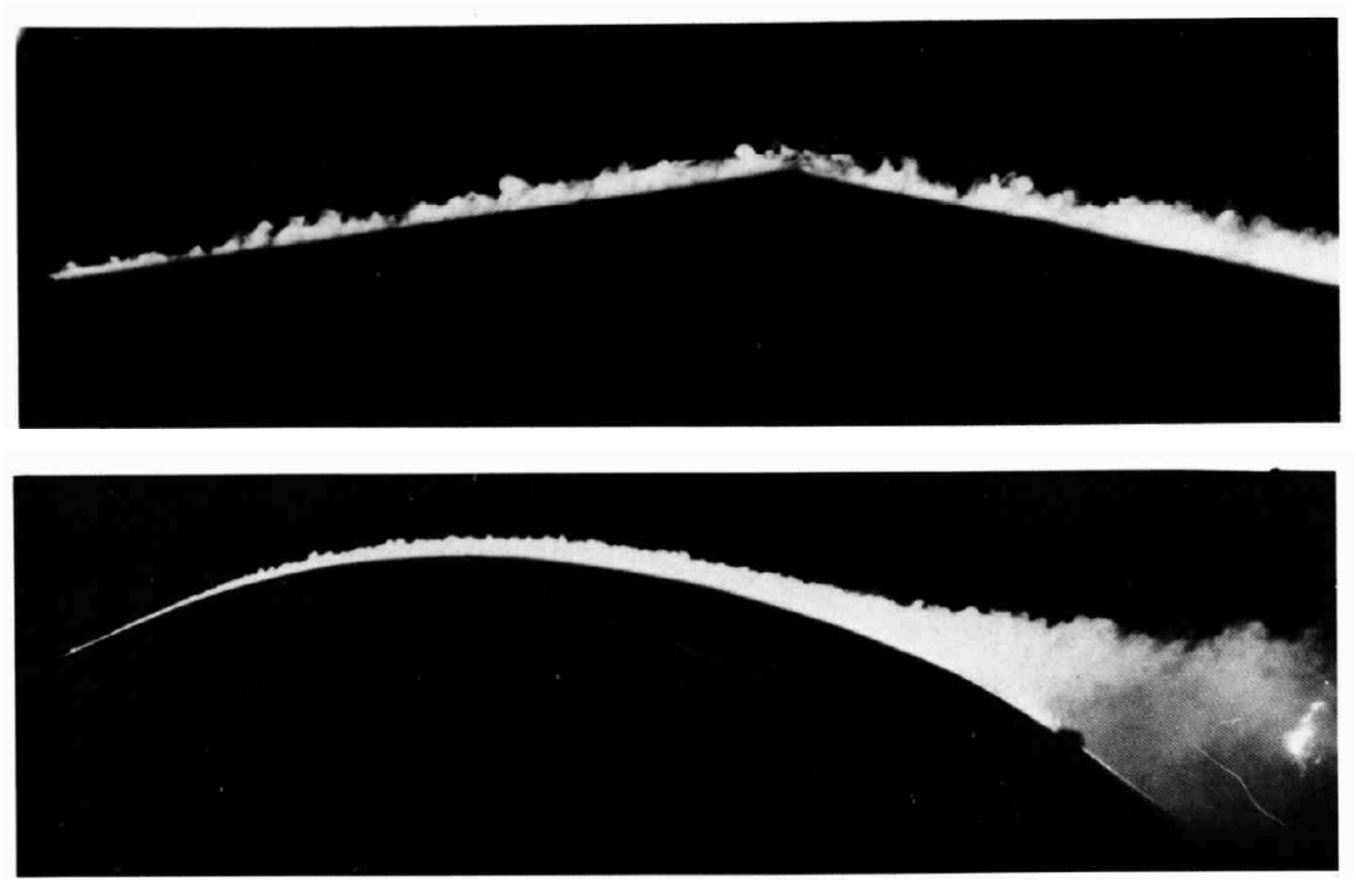
Roadmap to Lecture 0

1. ~~Quick review of solution methods in CFD~~
2. ~~What is Ansys Fluent? – Executive summary~~
3. **Turbulence in action**

Turbulence in action

Turbulence modeling – Wall bounded and shear free turbulence

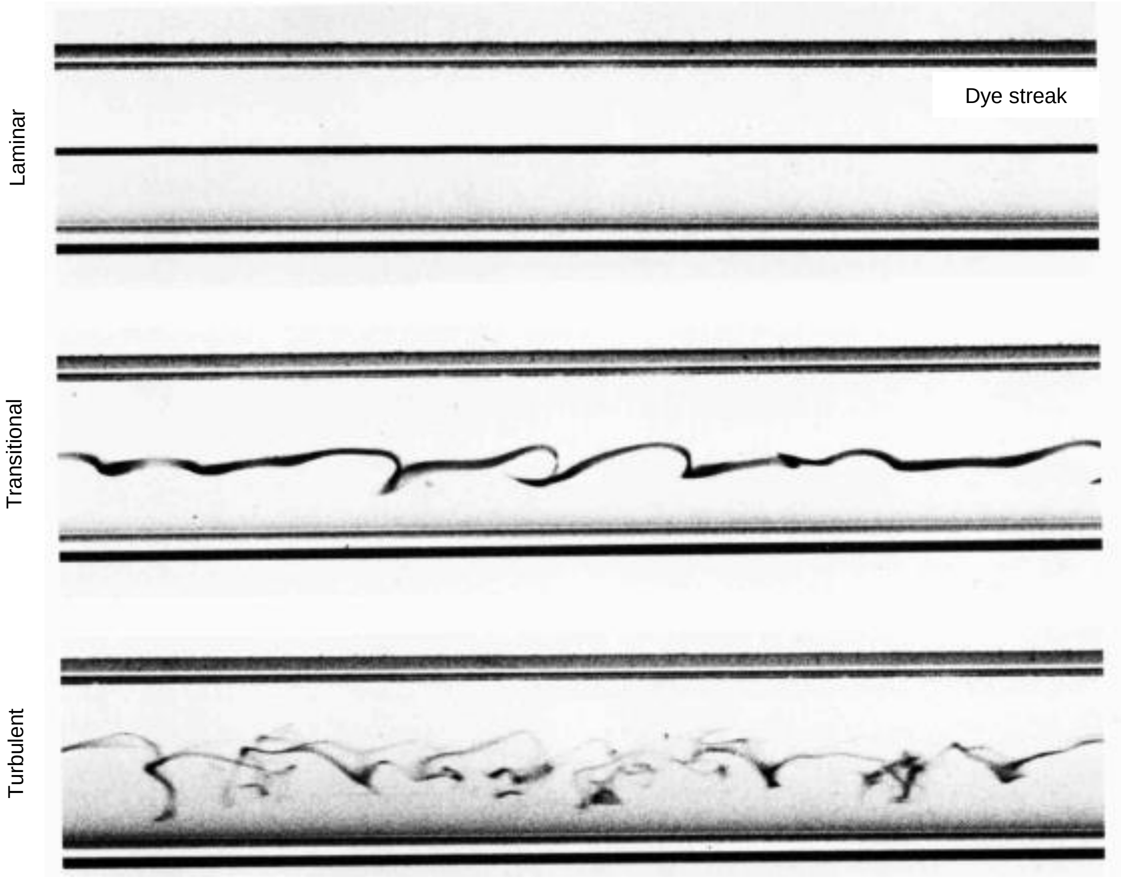


Wall bounded turbulence

- **Turbulent flows can originate at the walls.** When this is the case, we talk about wall bounded turbulence.

Turbulence in action

Turbulence modeling – Wall bounded and shear free turbulence

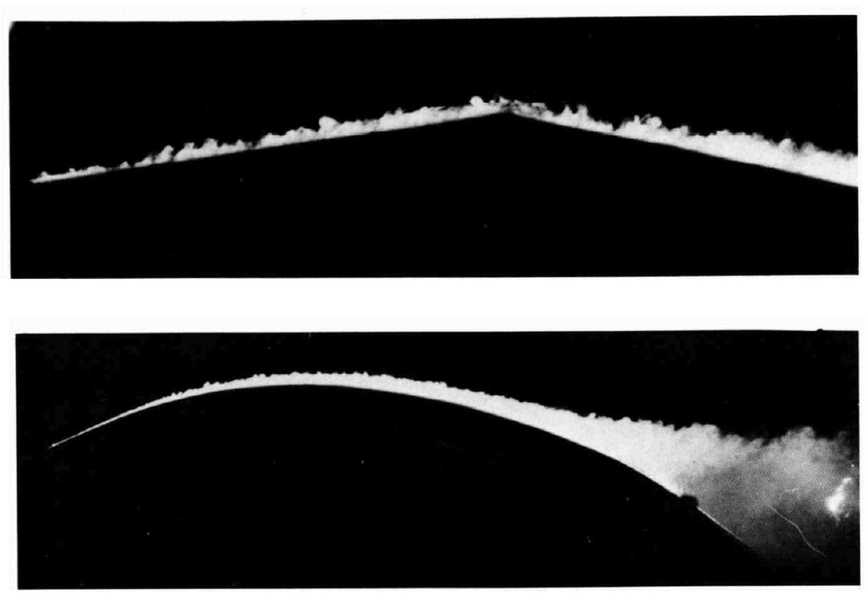


Shear free turbulence

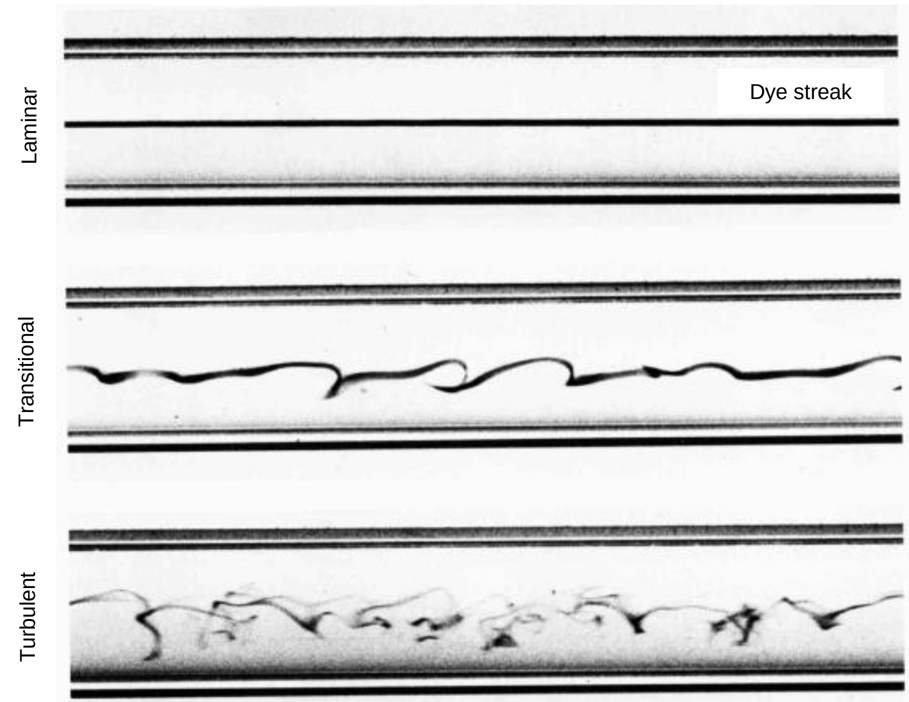
- **Turbulent flows can also originate in the absence of walls (or far from walls).** When this is the case, we talk about shear free turbulence (usually jets, heated walls, atmospheric flows).

Turbulence in action

Turbulence modeling – Wall bounded and shear free turbulence



Wall bounded turbulence

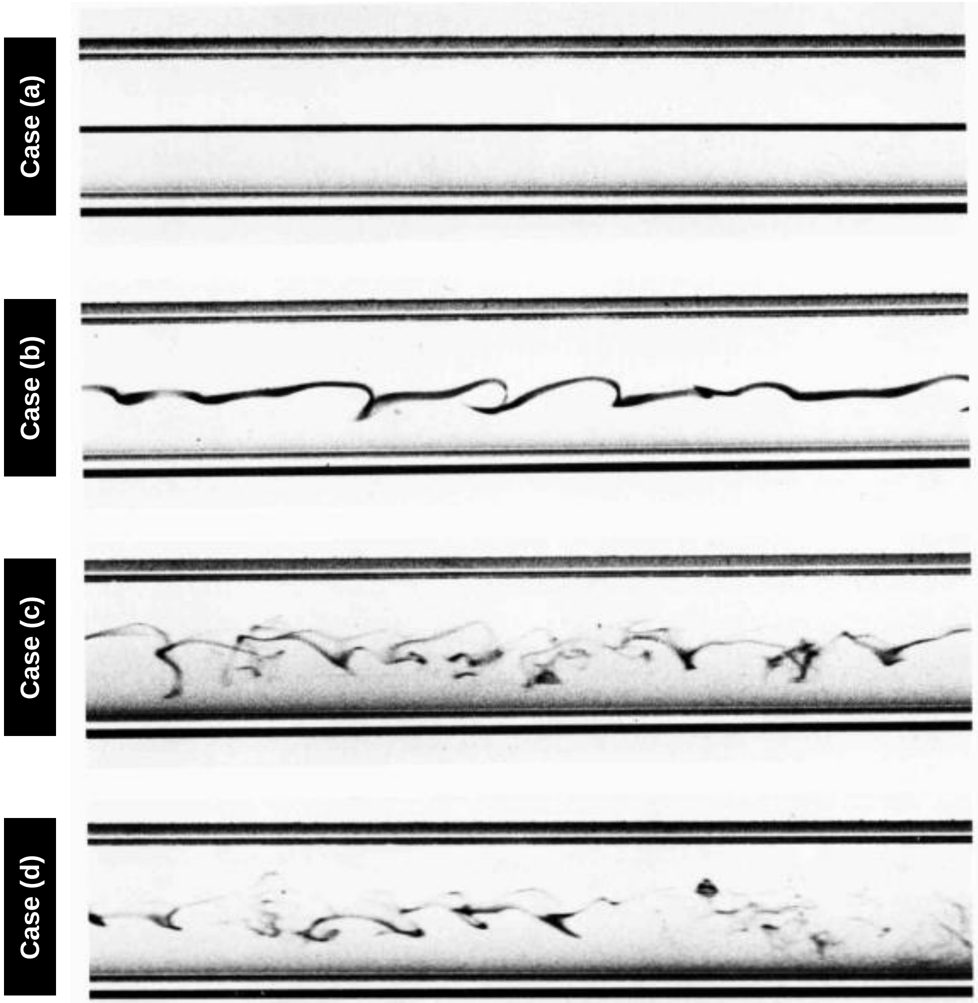


Shear free turbulence

- But indifferently of the type of turbulence, wall bounded or shear free, the turbulent motion has a direct effect on the velocity profiles, wall shear stresses, and mixing of transported quantities (heat transfer rate, species concentration, mass transfer, and so on).

Turbulence in action

Turbulence modeling – Wall bounded and shear free turbulence

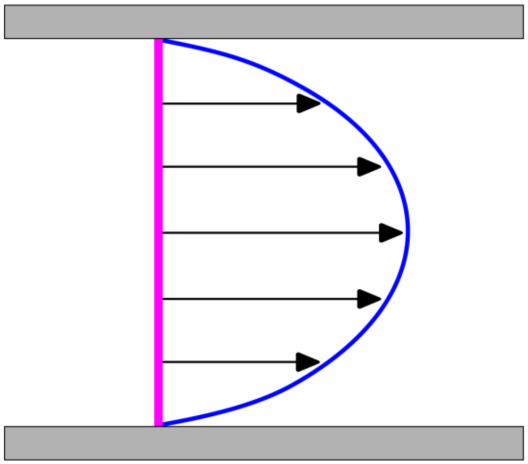


- Turbulence has a direct effect on the velocity profiles and mixing of transported quantities.
    - **Case (a)** corresponds to a laminar flow, where the dye do not show any oscillation and can mix with the main flow only via molecular diffusion, this kind of mixing can take very long times.
    - **Case (b)** shows a transitional state where the dye streak becomes wavy, but the main flow still is laminar.
    - **Case (c) and case (d)** show the turbulent state, where the dye streak changes direction erratically, and the dye has mixed significantly with the main flow due to the velocity fluctuations.
- In the figure, a filament of colored water injected into pipe flow (left to right), and the flow velocity is increased from top to bottom.
- This image give us an idea of what happens at the core of the flow, but what about the walls?

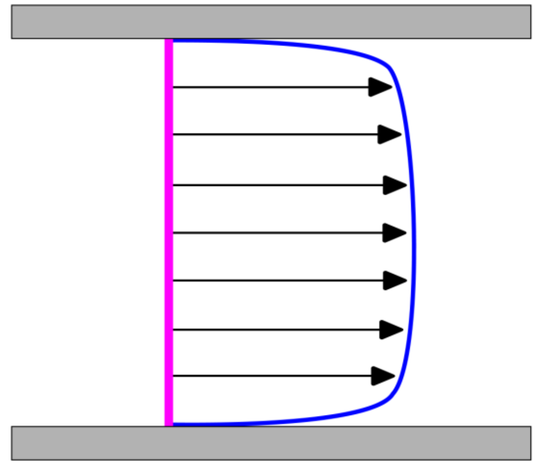
Repetition of Reynolds' dye experiment.
Photo credit: M. Van Dyke. An Album of Fluid Motion. The Parabolic Press, Stanford, California, 1982.

Turbulence in action

Turbulence modeling – Wall bounded and shear free turbulence



Laminar flow in a pipe

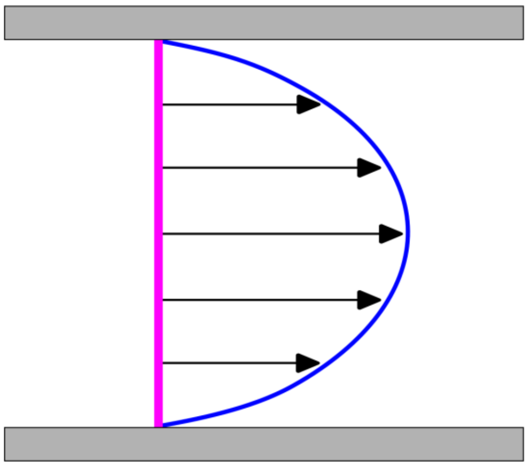


Turbulent flow in a pipe

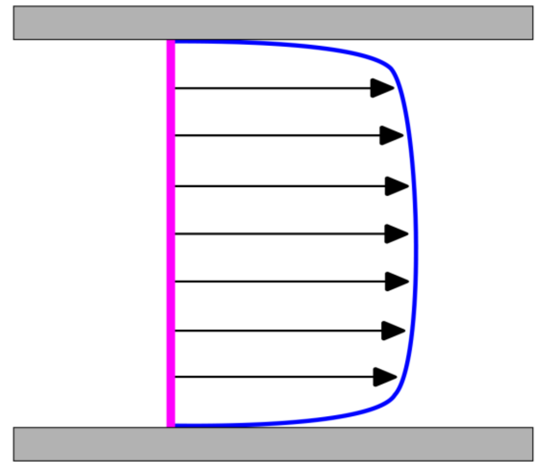
- Turbulence has a direct effect on the velocity profiles and mixing of transported quantities.
  - In the **laminar case**, the velocity gradient close to the walls is small (therefore the shear stresses are lower).
  - The **turbulent case** shows two regions.
    - One thin region close to the walls with very large velocity gradients (hence large shear stresses).
    - Another region far from the wall where the velocity profile is nearly uniform.
  - The larger the velocity gradient close to the walls, the larger the wall shear stresses will be.

Turbulence in action

Turbulence modeling – Wall bounded and shear free turbulence



Laminar flow in a pipe



Turbulent flow in a pipe

- Turbulence has a direct effect on the velocity profiles and mixing of transported quantities.
  - In a laminar flow or in the viscous sub-layer*, the wall shear stress τ_{wall} can be approximated as follows,

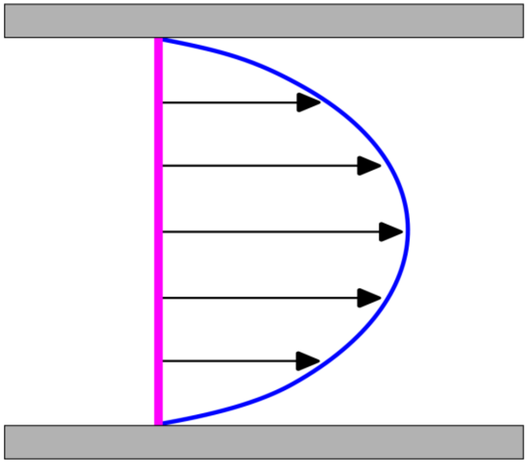
$$\tau_{wall} = \mu \frac{\partial u}{\partial y}$$

Note:
This approximation is valid for 2D boundary layers

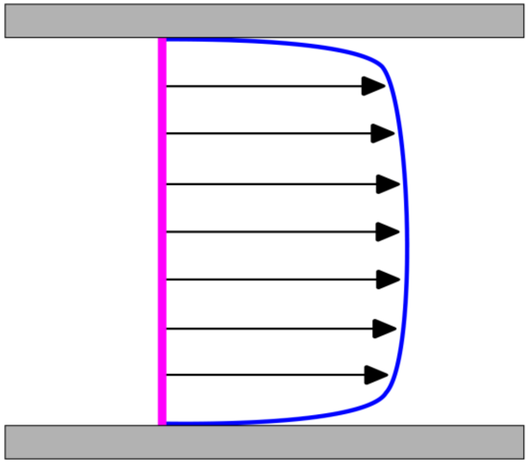
* The viscous sub-layer is the region of the turbulent boundary layer very close to the wall where the flow is laminar.

Turbulence in action

Turbulence modeling – Wall bounded and shear free turbulence



Laminar flow in a pipe



Turbulent flow in a pipe

- Turbulence has a direct effect on the velocity profiles and mixing of transported quantities.
  - In a turbulent flow, the wall shear stress τ_{wall} cannot be approximated using the same relation as for laminar flows.
  - We need to add a correction to take into account the effects of the increased mixing, randomness, or agitation of turbulence flows.

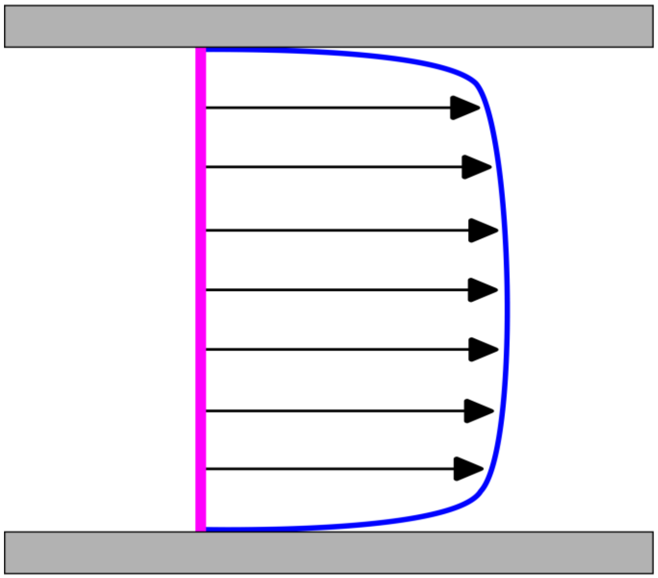
Turbulence modeling is about how to approximate/model this term

$$\tau_{wall} = \mu \frac{\partial u}{\partial y} + \tau^R$$

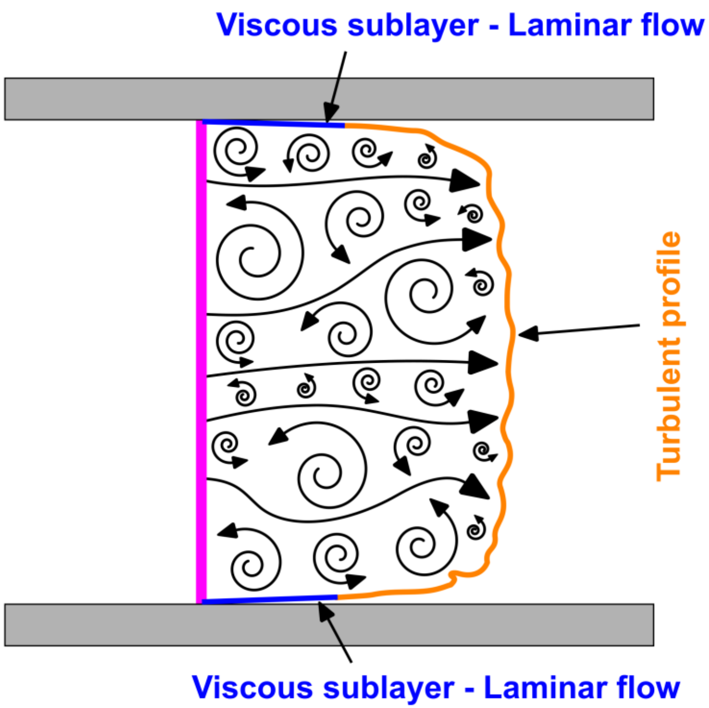
Note:
This approximation is valid for 2D boundary layers and where $\tau^R = \overline{u'v'}$

Turbulence in action

Turbulence modeling – Wall bounded and shear free turbulence



Averaged turbulent flow



Instantaneous turbulent flow

- In the left figure, the velocity profile has been averaged.
- In reality, the velocity profile fluctuates in time (right figure).
- The thin region close to the walls has very large velocity gradients and is laminar.
- Far from the flows, the flow becomes turbulent.
- Turbulence increases the wall shear stresses and enhances mixing.

Turbulence in action

On the Reynolds number

- It is well known that the Reynolds number characterizes if the flow is laminar or turbulent.
- So before doing a simulation or experiment, check if the flow is turbulent.
- The Reynolds number is defined as follows,

Convective effects

Viscous effects

$$Re_L = \frac{\rho U L}{\mu} = \frac{U L}{\nu}$$

$$\nu = \frac{\mu}{\rho}$$

- Where *U* is a characteristic velocity, *e.g.*, free-stream velocity.
- And *L* is representative length scale, *e.g.*, length, height, diameter, etc.

Turbulence in action

On the Reynolds number

- Turbulent flow occurs at large Reynolds number.
  - For external flows,

$$Re_x \geq 500000$$ Around slender/streamlined bodies (surfaces)

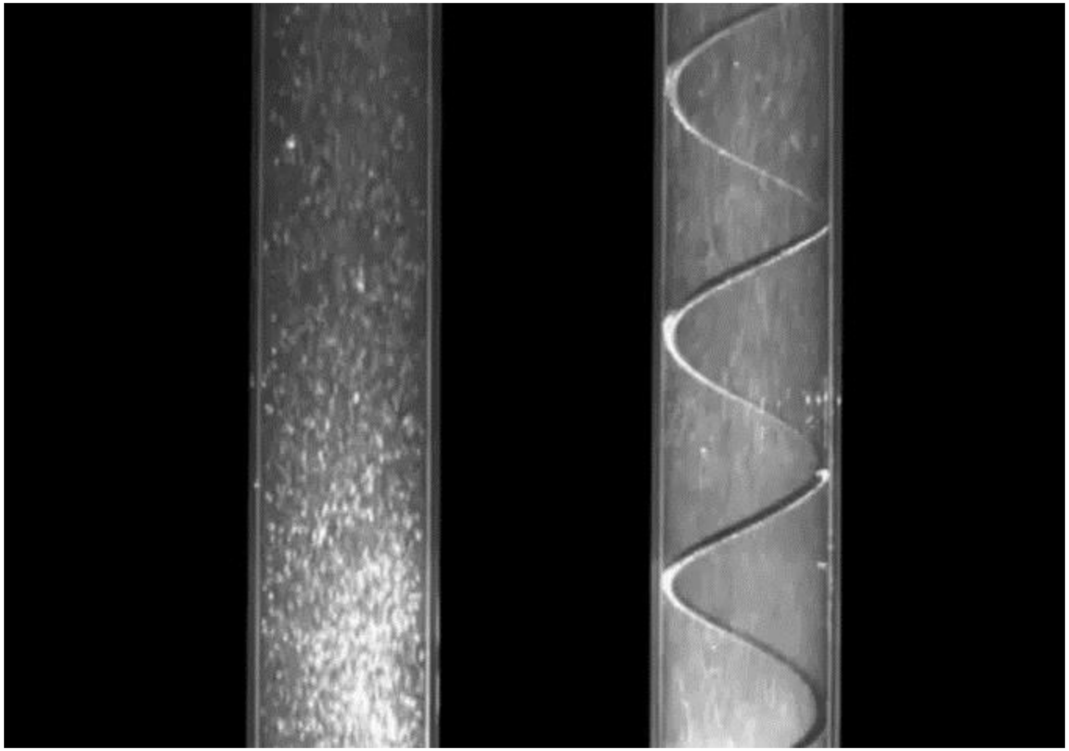
$$Re_d \geq 20000$$ Around an obstacle (bluff bodies)

  - For internal flows,

$$Re_{d_h} \geq 2300$$

- Notice that other factors such as free-stream turbulence, surface conditions, surface roughness and other disturbances, may cause transition to turbulence at lower Reynolds number.
- Turbulent and laminar flows have very different behaviors.
- Turbulent motion has a direct effect on the velocity profiles, wall shear stresses, and mixing of transported quantities (heat transfer rate, species concentration, mass transfer, and so on).

Turbulent flows videos



Laminar-Turbulent flow in a pipe
Smooth vs corrugated tube

Video credit: https://www.youtube.com/watch?v=WG-YCpAGgQQ

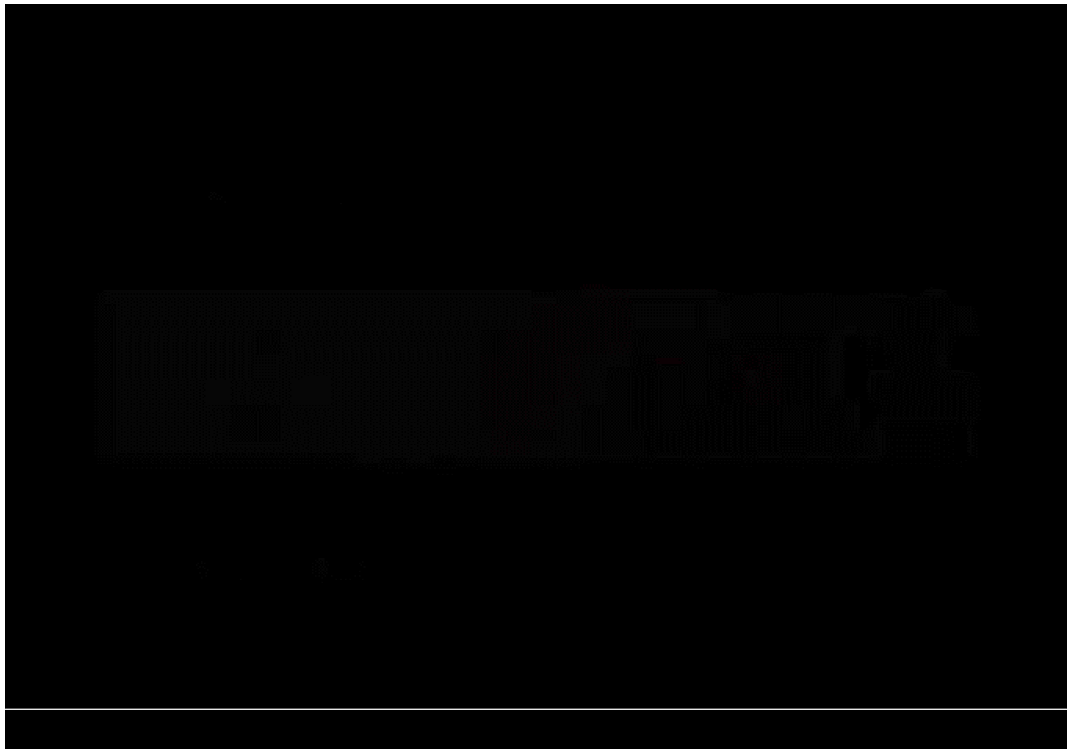
Turbulent flows videos

Reynolds' dye experiment
Various types of flow - Laminar-Transitional-Turbulent

Video credit: https://www.youtube.com/watch?v=ontHCuI6eB4

Turbulence in action

Turbulent flows videos



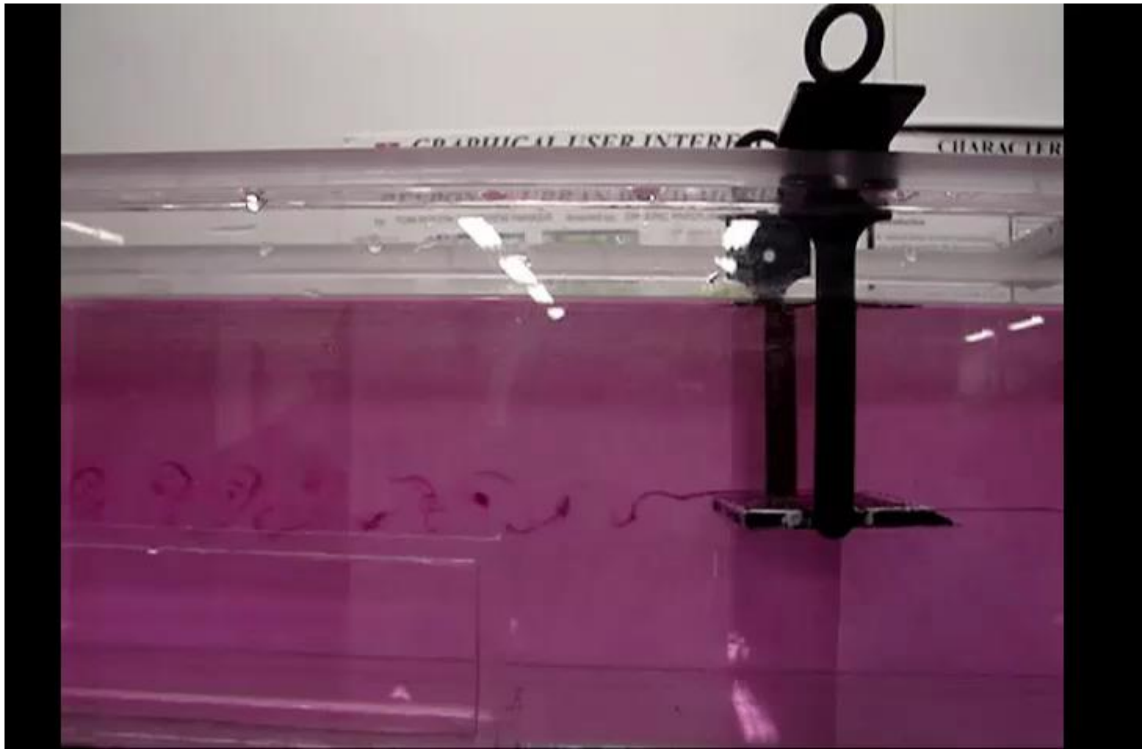
Laminar-Turbulent vortex shedding

Video credit: https://www.youtube.com/watch?v=JI0M1gVNhbw

This video has been edited to fit this presentation.

Turbulence in action

Turbulent flows videos



Flow over a flat plate
Attached and separated boundary layer

Video credit: https://www.youtube.com/watch?v=zsO5BQA_CZk

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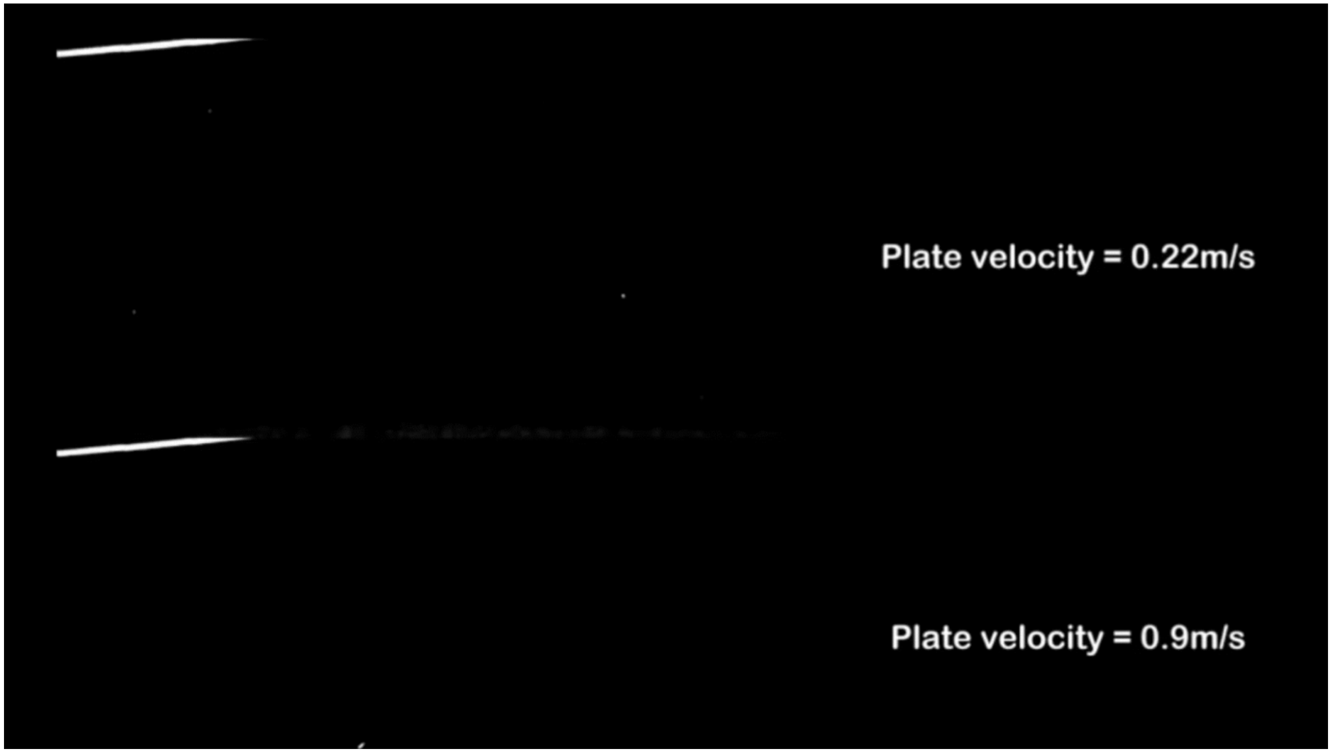
Turbulence in action

Turbulent flows videos



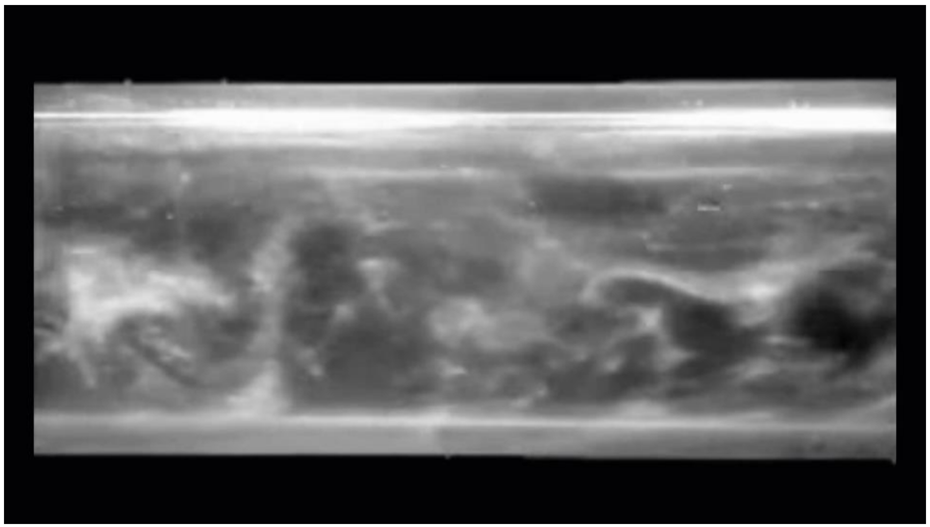
Turbulent boundary layer on a flat plate

Video credit: https://www.youtube.com/watch?v=e1TbkLIDWys
arXiv: https://arxiv.org/abs/1210.3881

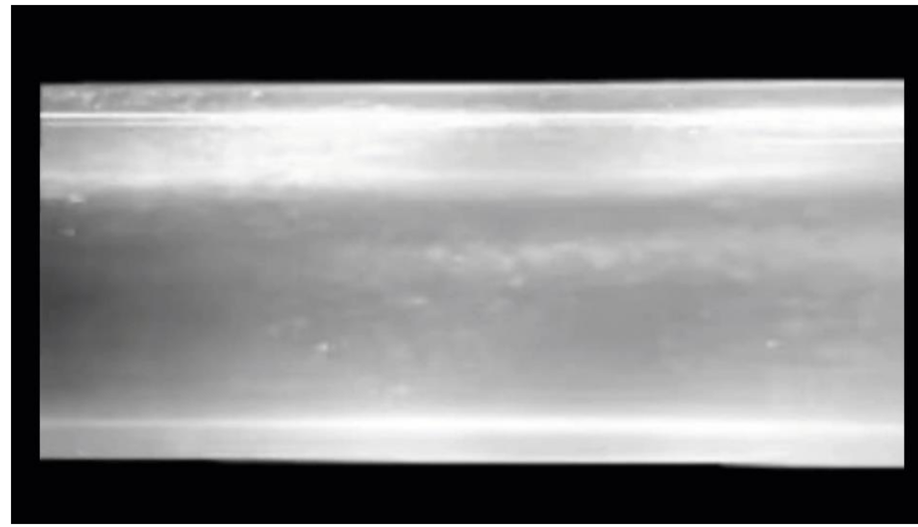
This video has been edited to fit this presentation.

Turbulence in action

Turbulent flows videos



Turbulent flow in a pipe
www.wolfdynamics.com/training/turbulence/video-pipe1.gif



Laminar flow in a pipe
www.wolfdynamics.com/training/turbulence/video-pipe2.gif

Video credit: https://gfm.aps.org/meetings/dfd-2017/59997842b8ac316d3884197e
DOI: https://doi.org/10.1103/APS.DFD.2017.GFM.V0013

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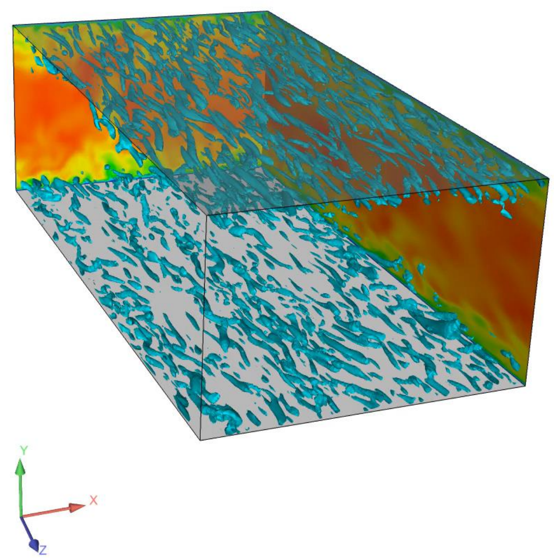
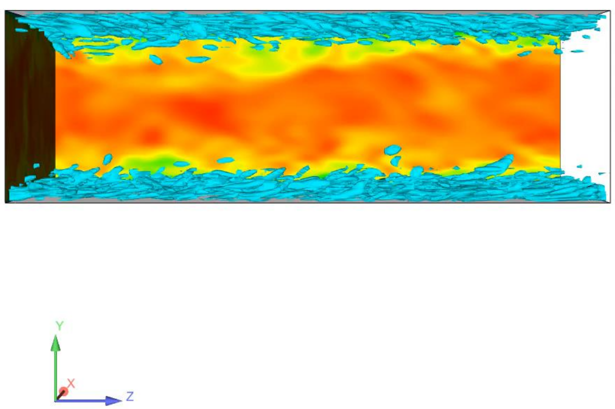
Turbulent flows simulations

Incoming flow



Incoming flow

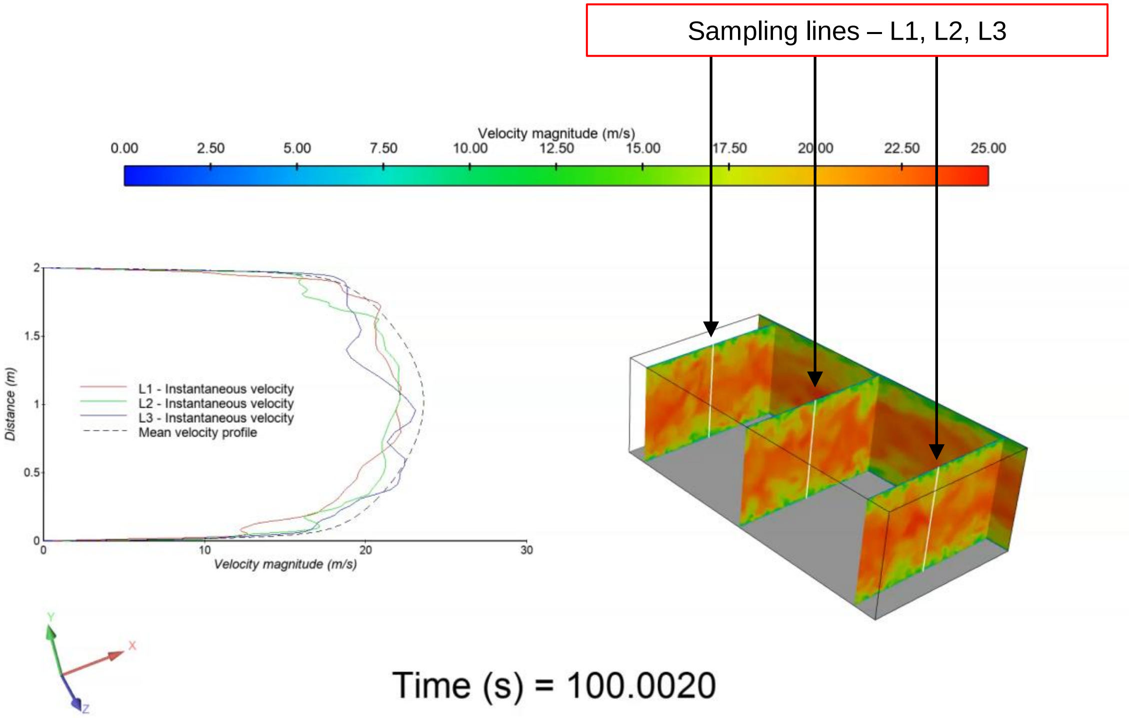


Wall bounded flow – Channel flow

Video credit: http://www.wolfdynamics.com/training/turbulence/channel1.mp4

This video has been edited to fit this presentation.

Turbulent flows simulations



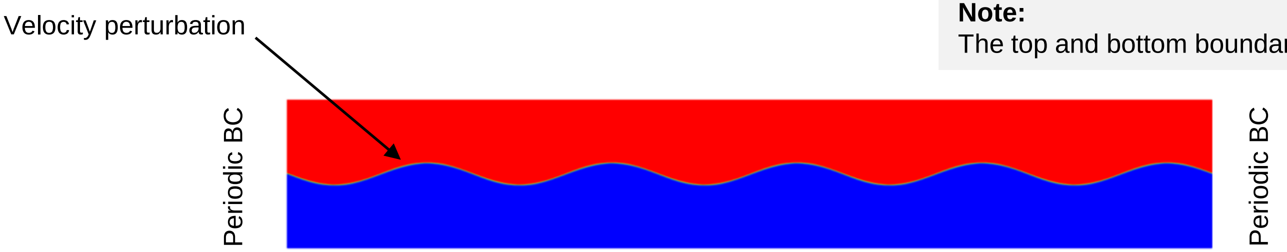
Wall bounded flow – Channel flow

Video credit: http://www.wolfdynamics.com/training/turbulence/channel2.mp4

Turbulent flows simulations

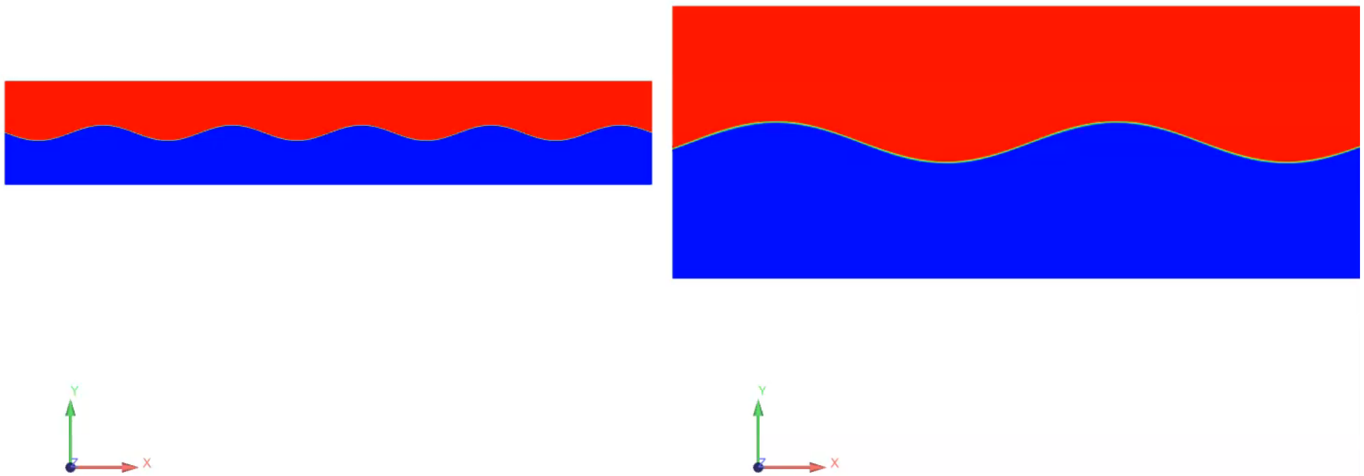
Kelvin Helmholtz Clouds
Photo credit: **https://www.deviantart.com/yenom/art/Kelvin-Helmholtz-Clouds-5368556**

Note:
The top and bottom boundaries are slip walls



Shear free flow – Kelvin-Helmholtz instability – Initialization for the numerical simulation

Turbulent flows simulations



Numerical simulation of the Kelvin-Helmholtz instability – Shear free flow

Video credit: www.wolfdynamics.com/training/turbulence/KH.mp4