Studying the Viscous Flow Around a Cylinder Using OpenFoam

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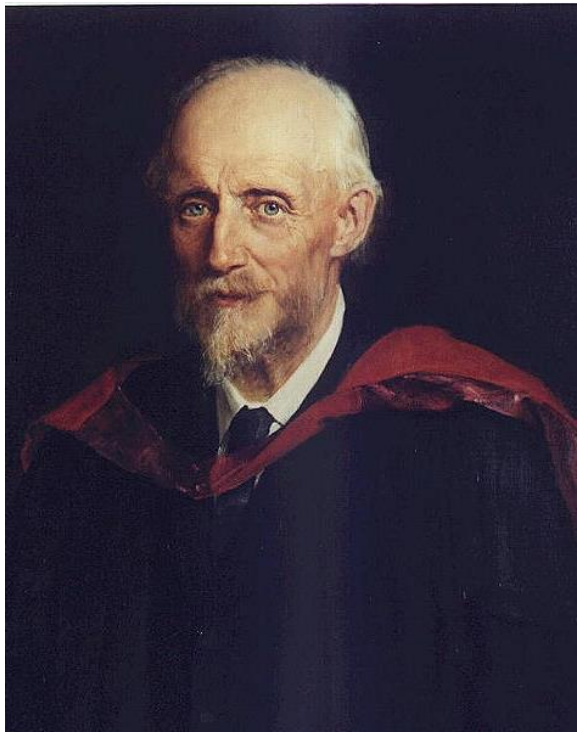
ME702

December 20, 2016

Motivation

- Flow around a cylinder is an essential topic in Fluids due to the simplicity of the geometry
  - Since it is a basic, foundational topic, important to be able to simulate
  - **Want to test capability of OpenFoam to accurately model an incompressible, viscous flow around a cylinder**

Overview



- Reynolds number (R)
  - Ratio of inertial forces to viscous forces
    - $R = \frac{\rho V L}{\mu} = \frac{LV}{\nu}$
      - L=length of object (i.e. cylinder)
      - V=fluid velocity
      - ρ=fluid density
      - μ=viscosity
  - Used to indicate when flow will become turbulent
- Law of similarity
  - Developed by Osborne Reynolds (1883)
  - If Reynolds number the same for two cases with different flows around similarly shaped objects, flow patterns should be the same

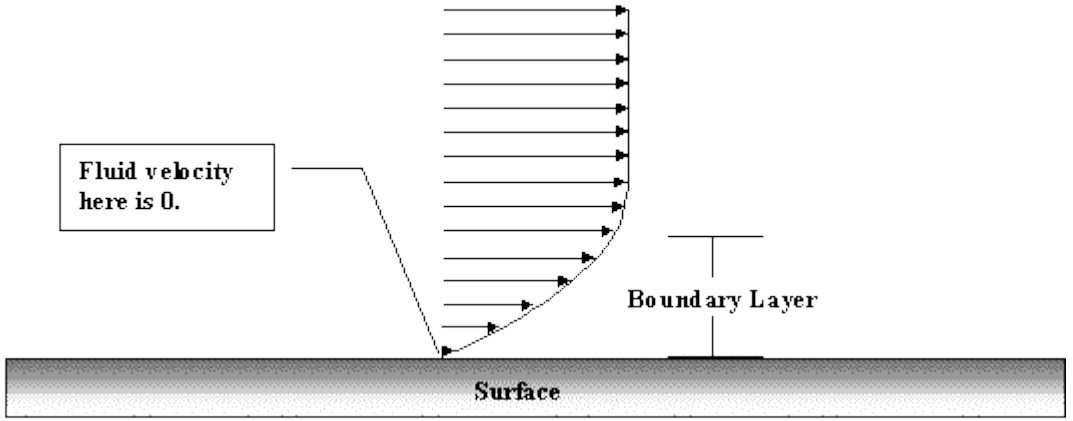
Overview

- For increasing Reynolds number, start to see the appearance of vortices in flow behind a cylinder
  - 20<R<60: begin to see the appearance of vortices behind the cylinder
  - 60<R<200: string of vortices develops behind cylinder
    - String called “Karman vortex sheet”
    - Studied by Theodore von Karman (1911)
  - R>200: turbulent wake develops behind the cylinder

Courtesy of Nasa

Overview

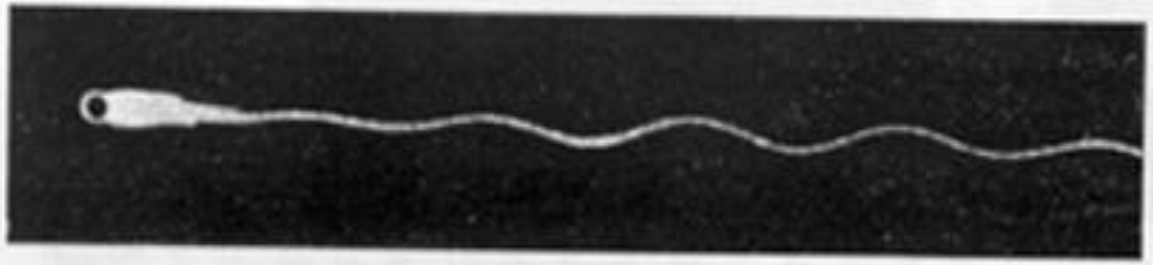
- Presence of vortices as R increases seems to violate Kelvin's vorticity theorem
  - Flux of vorticity is conserved (i.e. if no vortices initially, can't generate vortices)
- Vortices caused by thin boundary layer near cylinder where the gradient of velocity is very high
  - means $\mu\nabla^2\boldsymbol{v}$ term in Navier-Stokes equation cannot be neglected (i.e. viscosity important)
  - Presence of viscosity means fluid not ideal, so no longer holds to Kelvin's vorticity theorem



courtesy of rose-hulman.edu

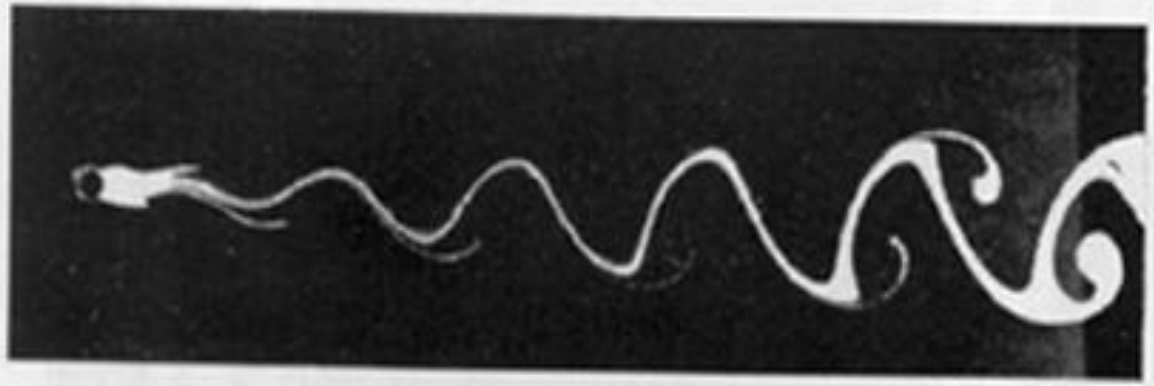
$R = 32$

$R = 73$

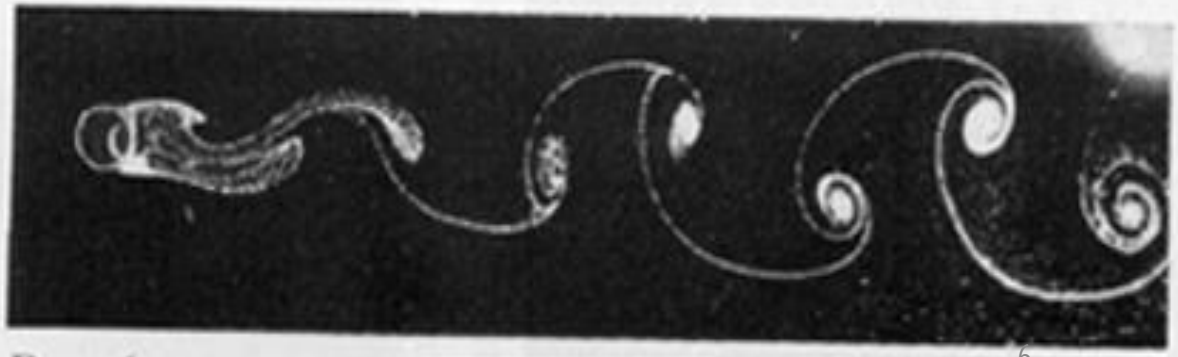


$R = 55$

$R = 102$



$R = 65$



$R = 161$

Originally from Homann (1936), reproduced from Batchelor (1967)

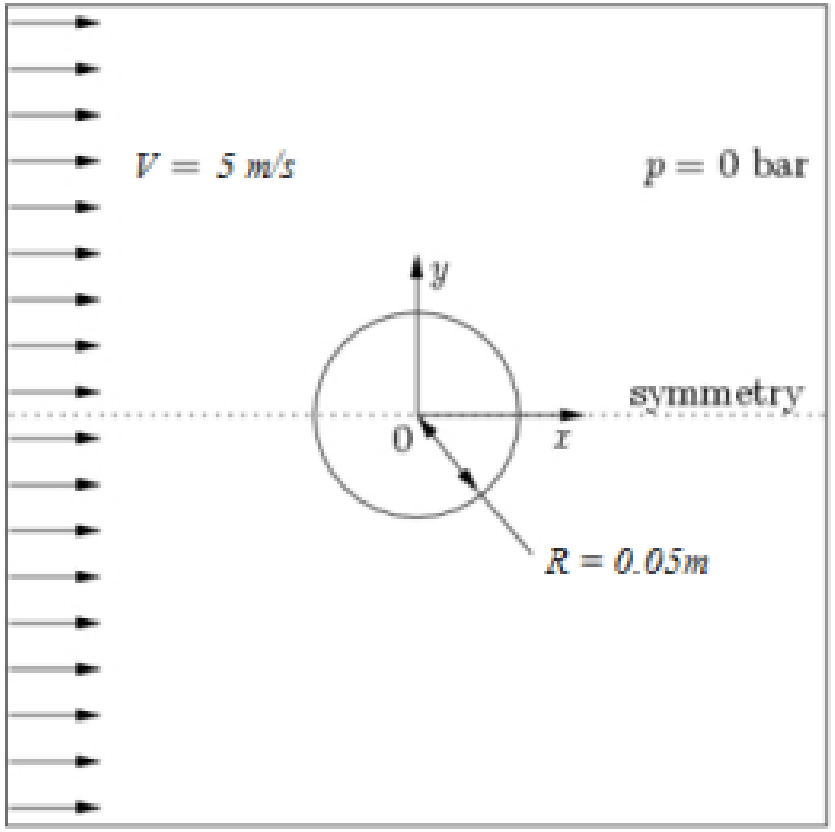
OpenFoam

- Using an incompressible, viscous fluid
- Use the icoFoam solver
- Solves the following equations:
  - $\boldsymbol{\nabla} \cdot \boldsymbol{v} = 0$
  - $\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v} \cdot \boldsymbol{\nabla v} = -\frac{1}{\rho}\boldsymbol{\nabla} p + \frac{\mu}{\rho}\boldsymbol{\nabla}^2 \boldsymbol{v}$
- Use laminar flow
- Created mesh via blockMesh

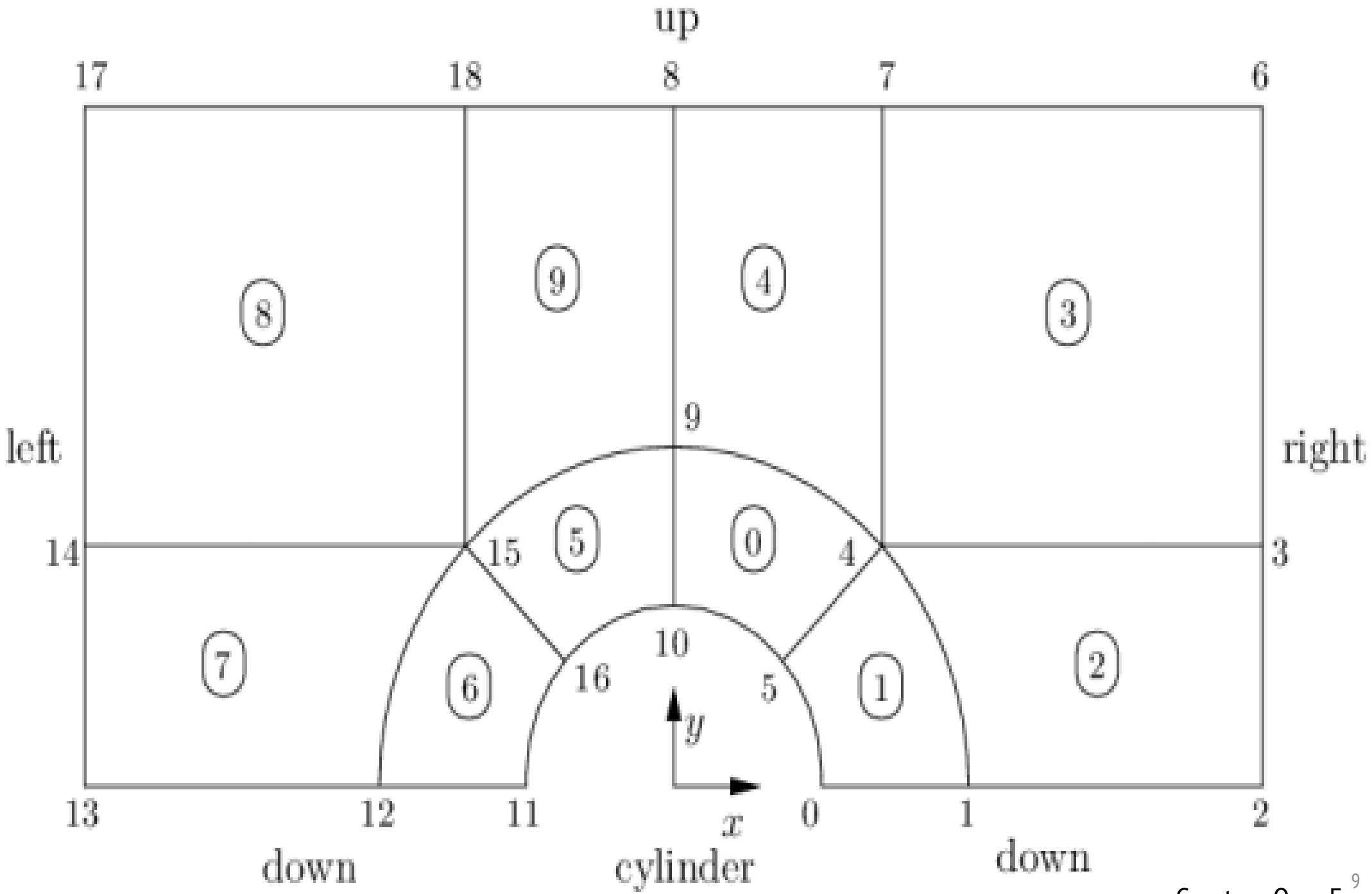
OpenFOAM

The Open Source CFD Toolbox

Basic Setup



Courtesy OpenFoam tutorial



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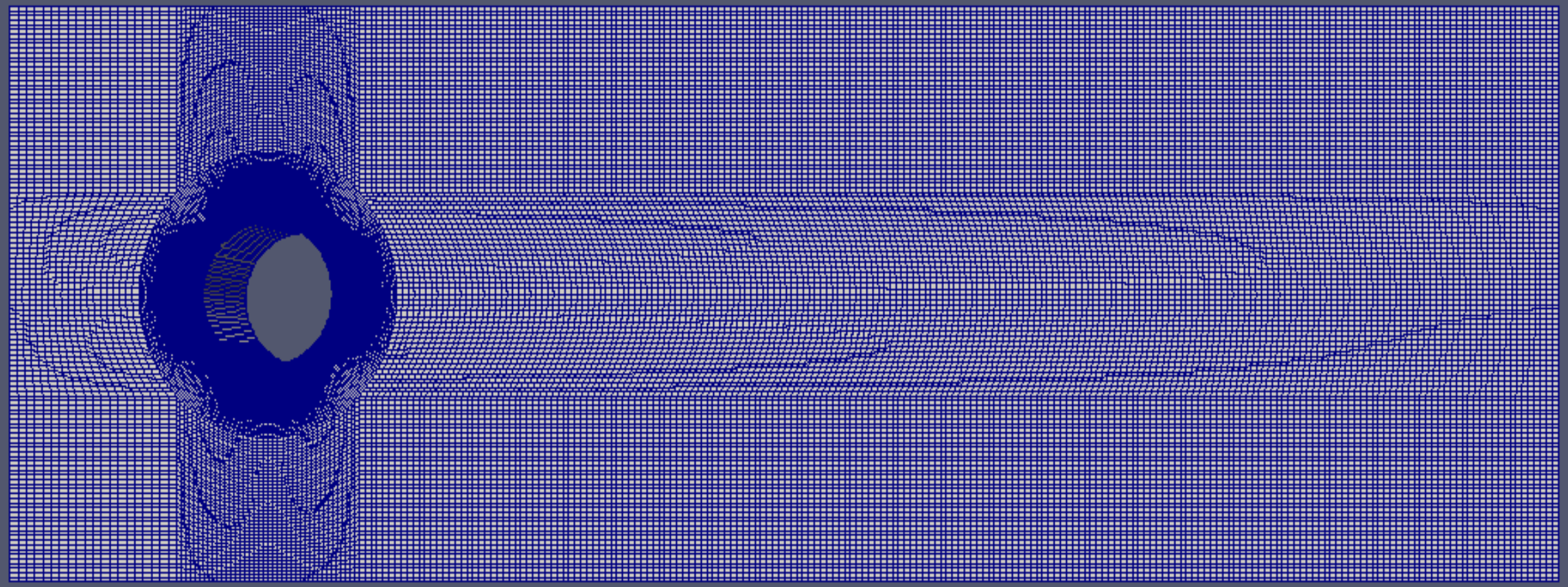
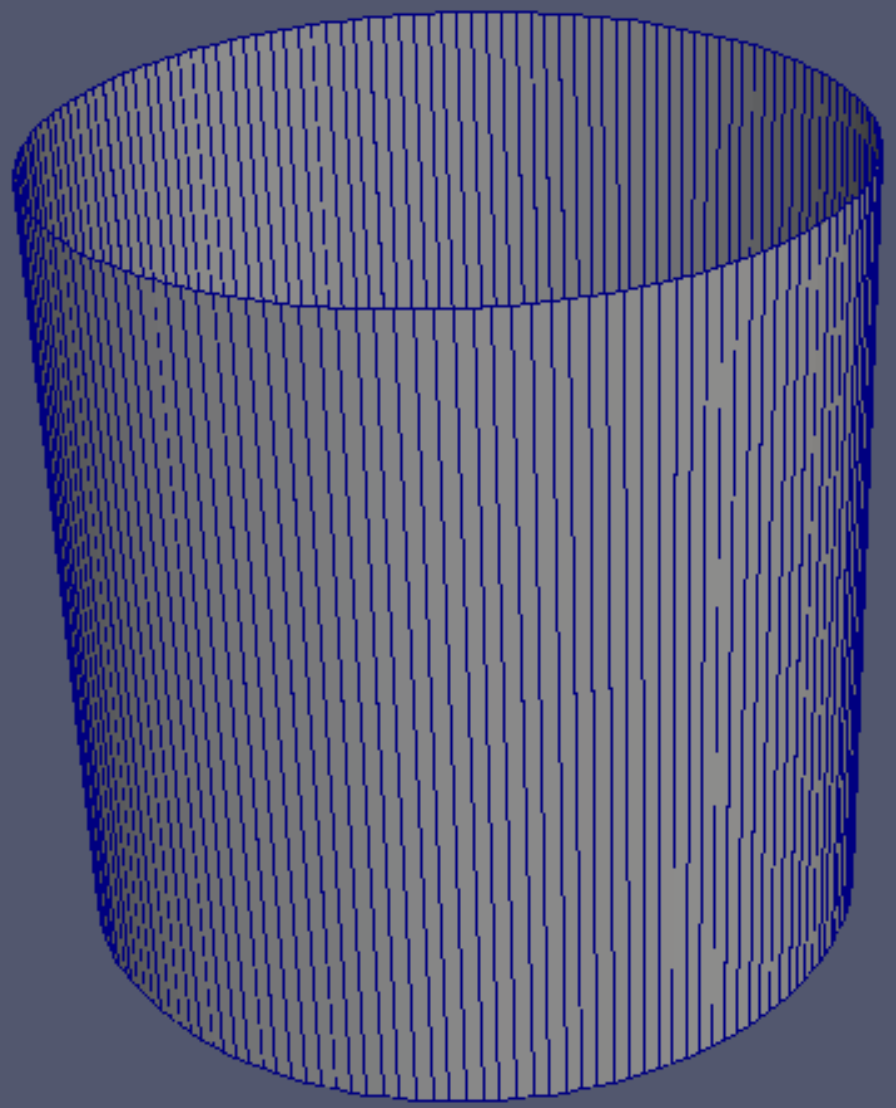
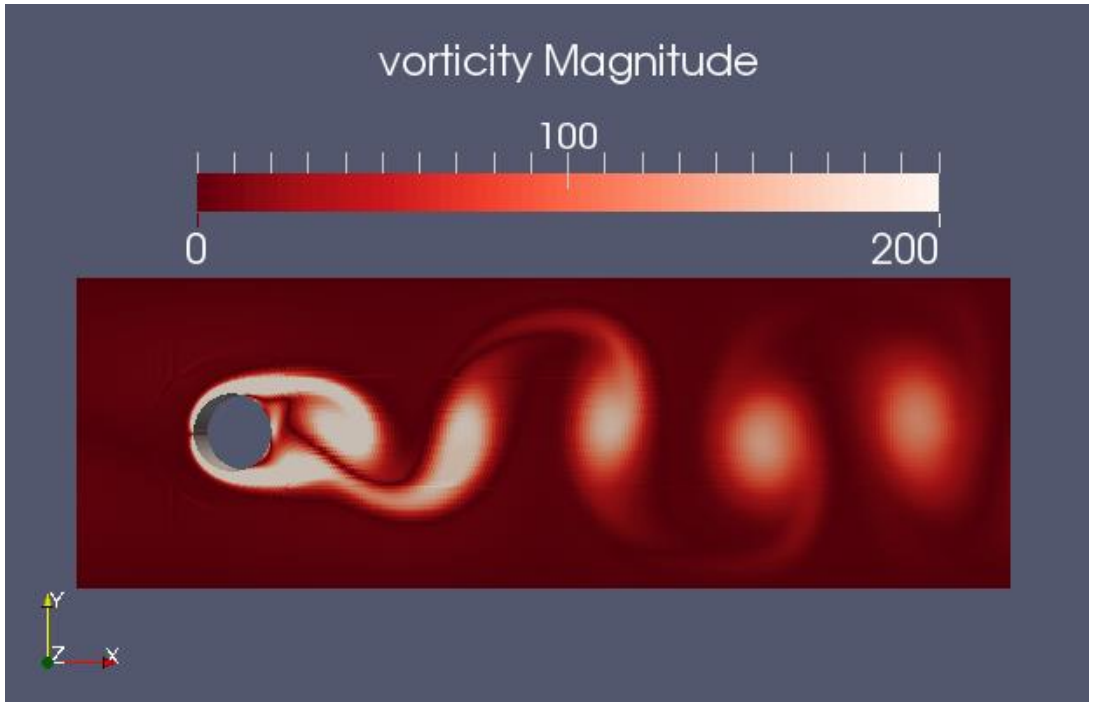

Y
Z
X

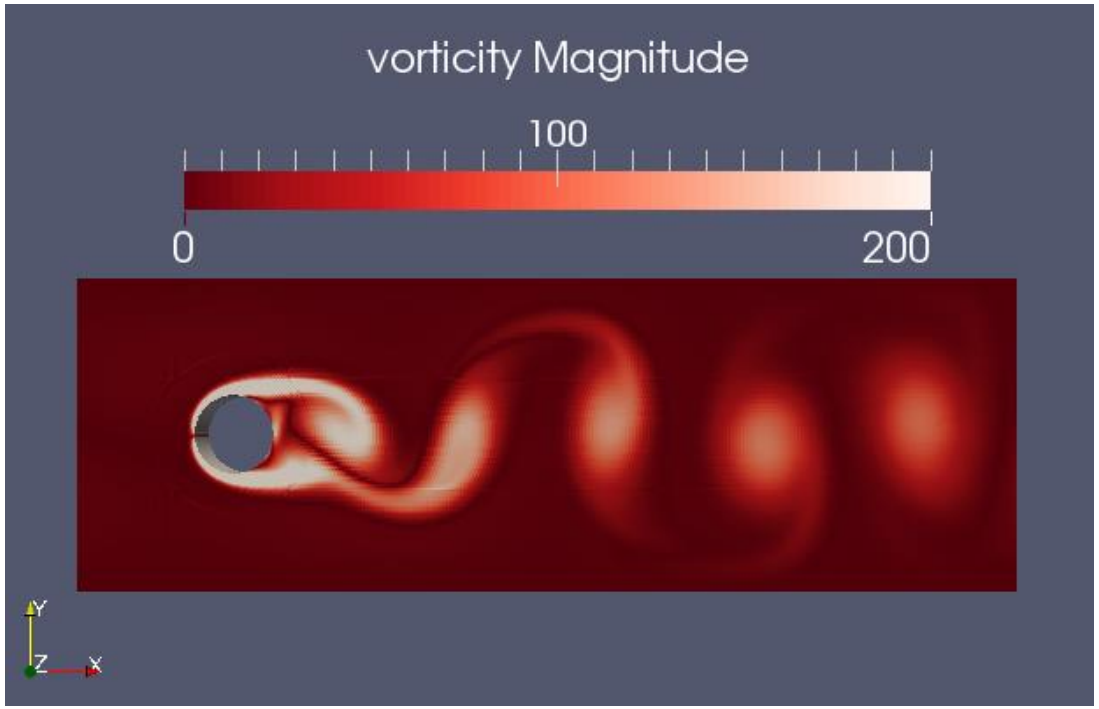


Law of Similarity (R=161)

U=5 m/s , ν=0.003106

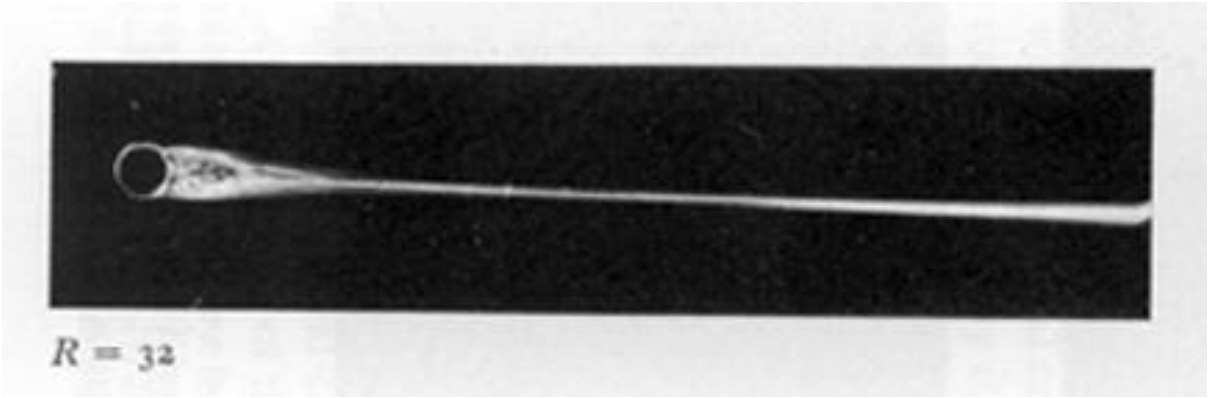


U=4.13 m/s, ν=0.002564

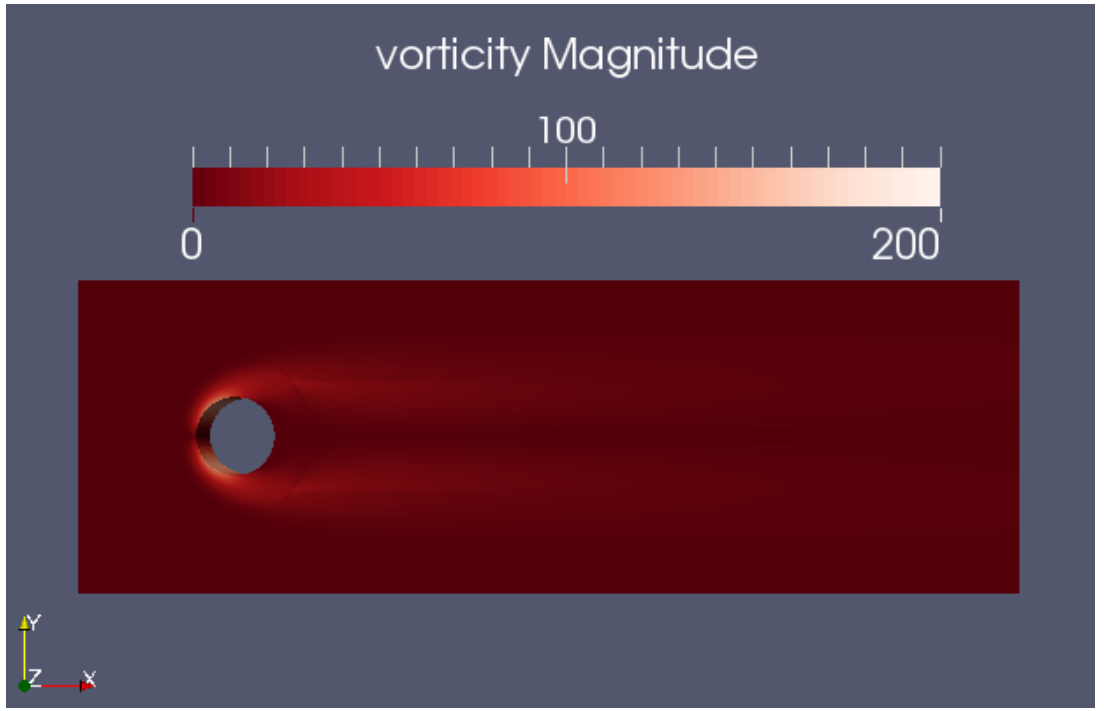


R=32

Observed

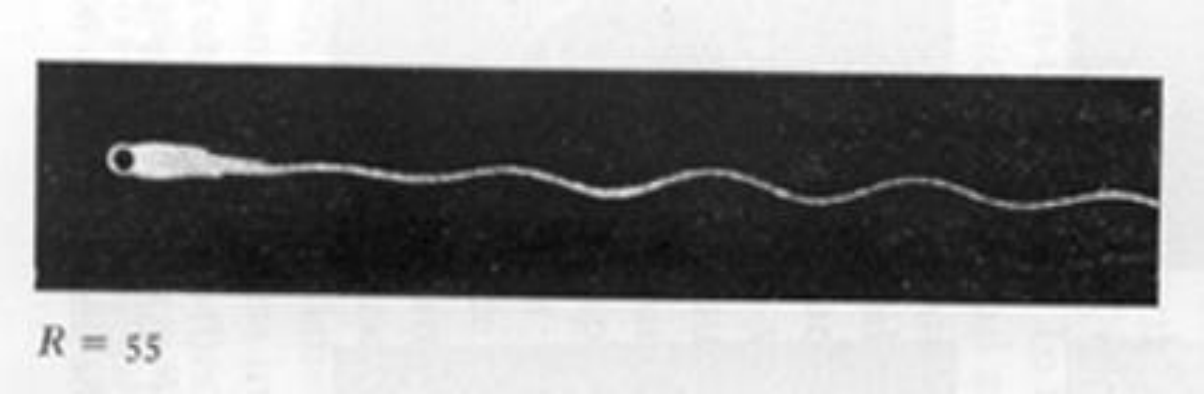


Simulated

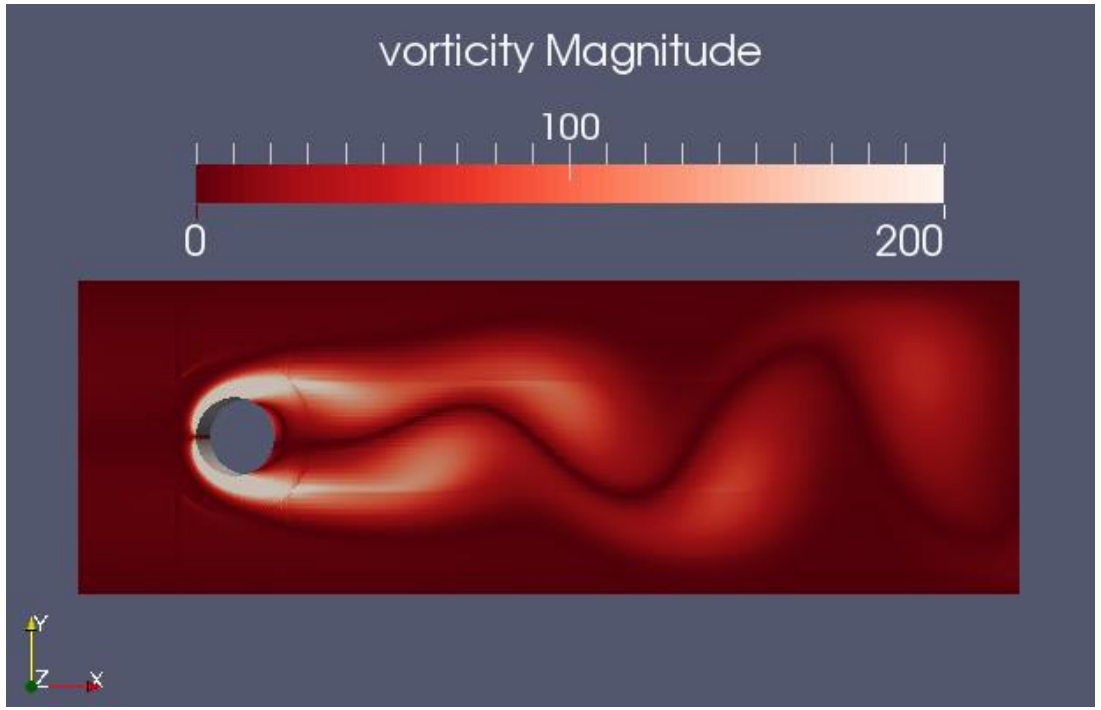


R=55

Observed

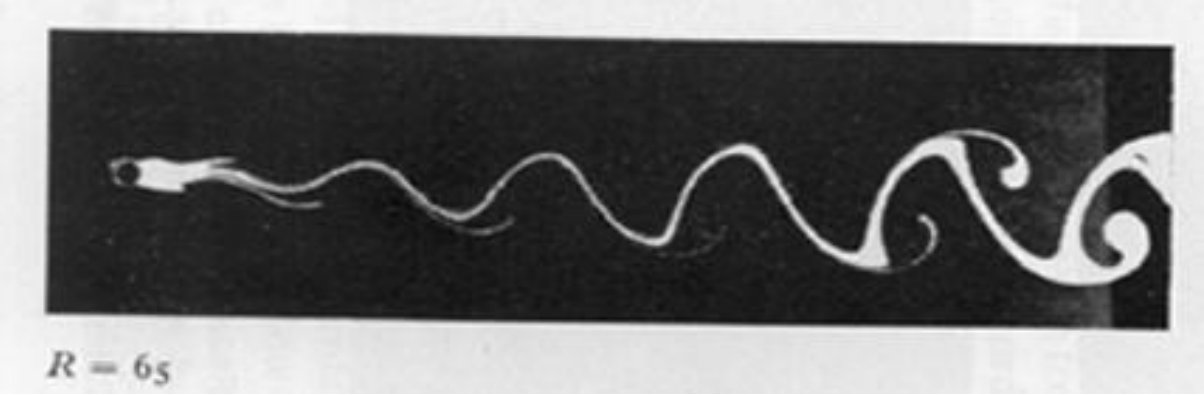


Simulated

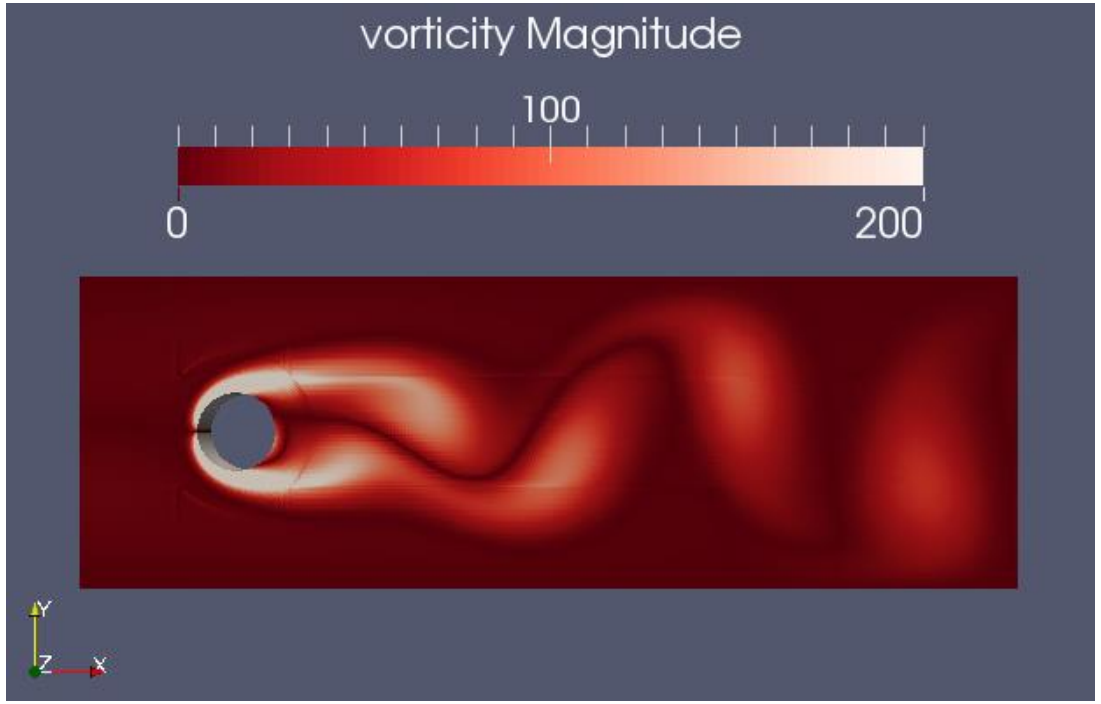


R=65

Observed



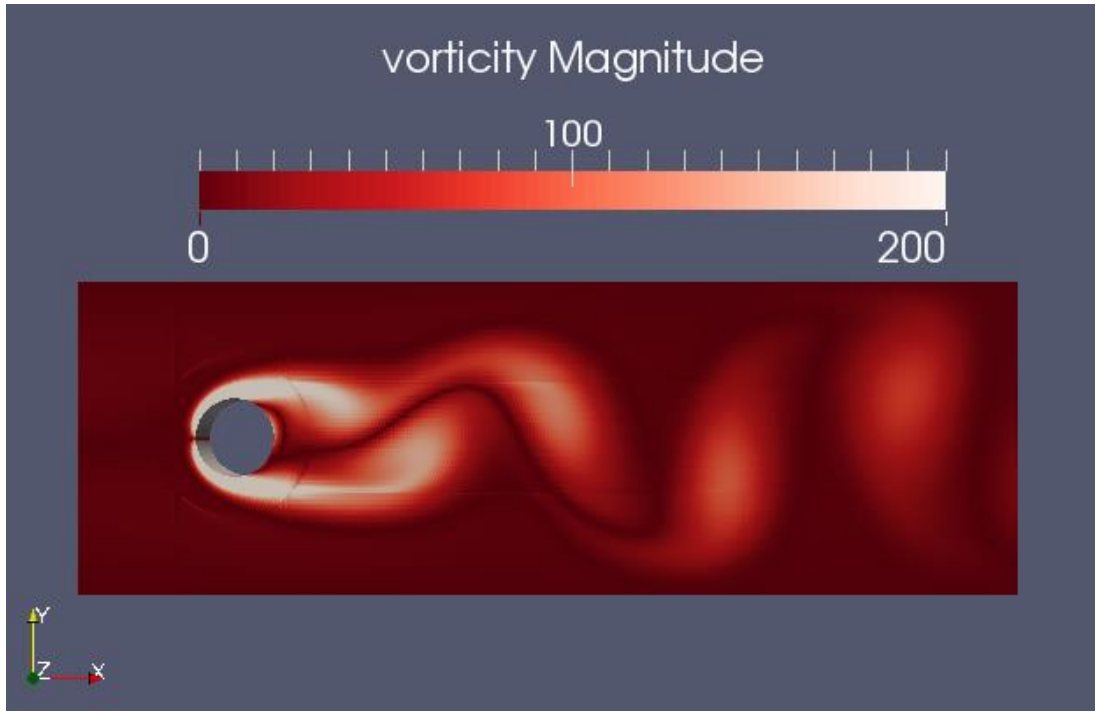
Simulated



R=73

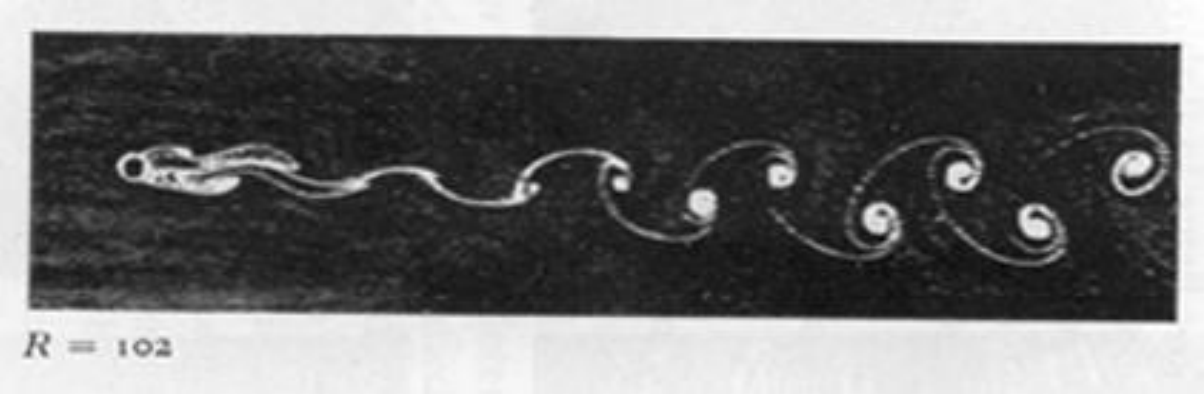
Observed

Simulated

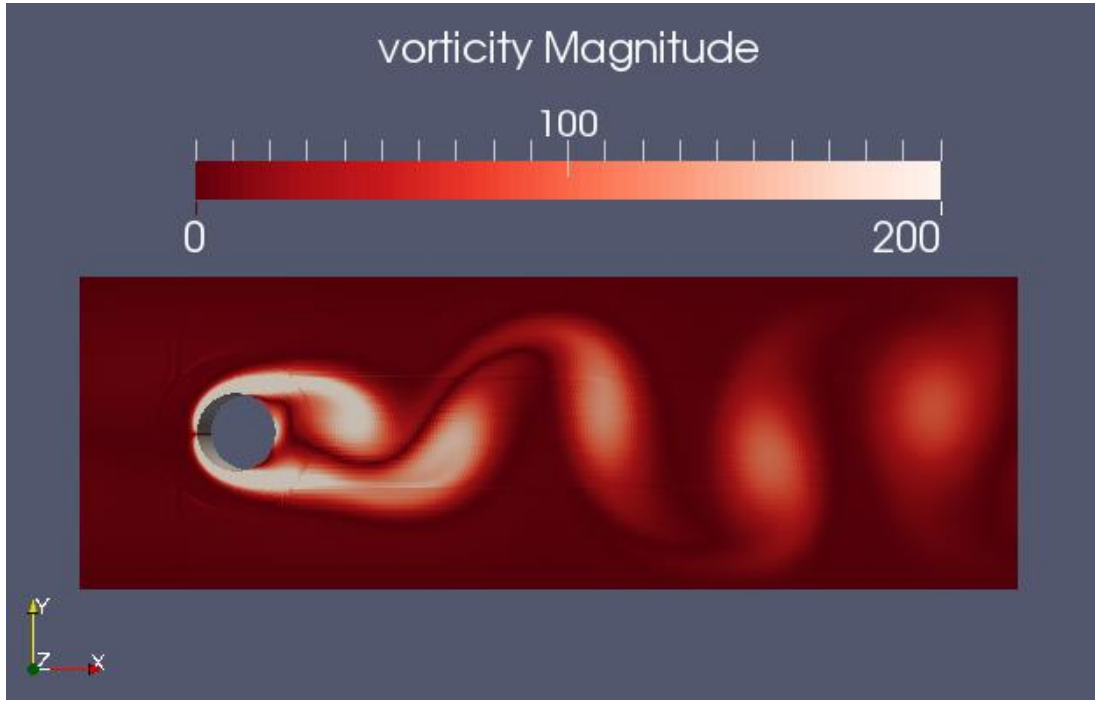


R=102

Observed

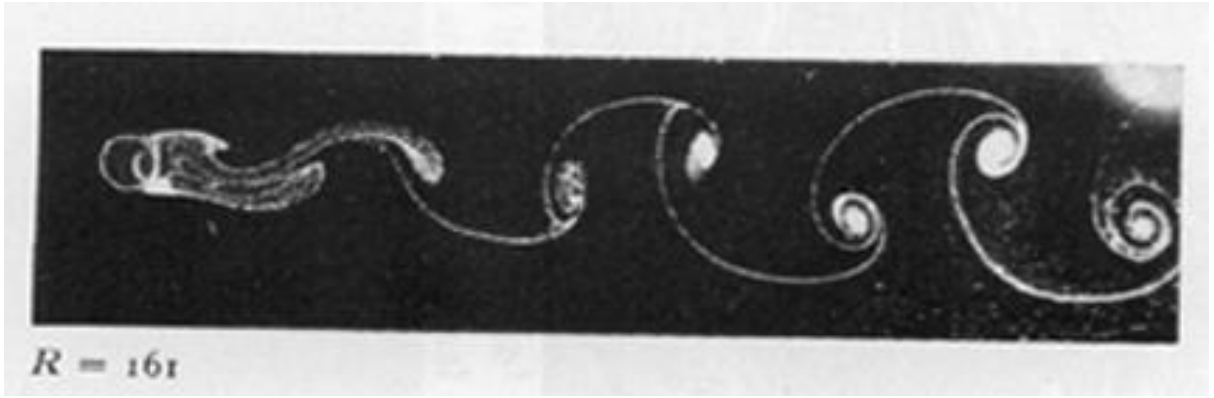


Simulated

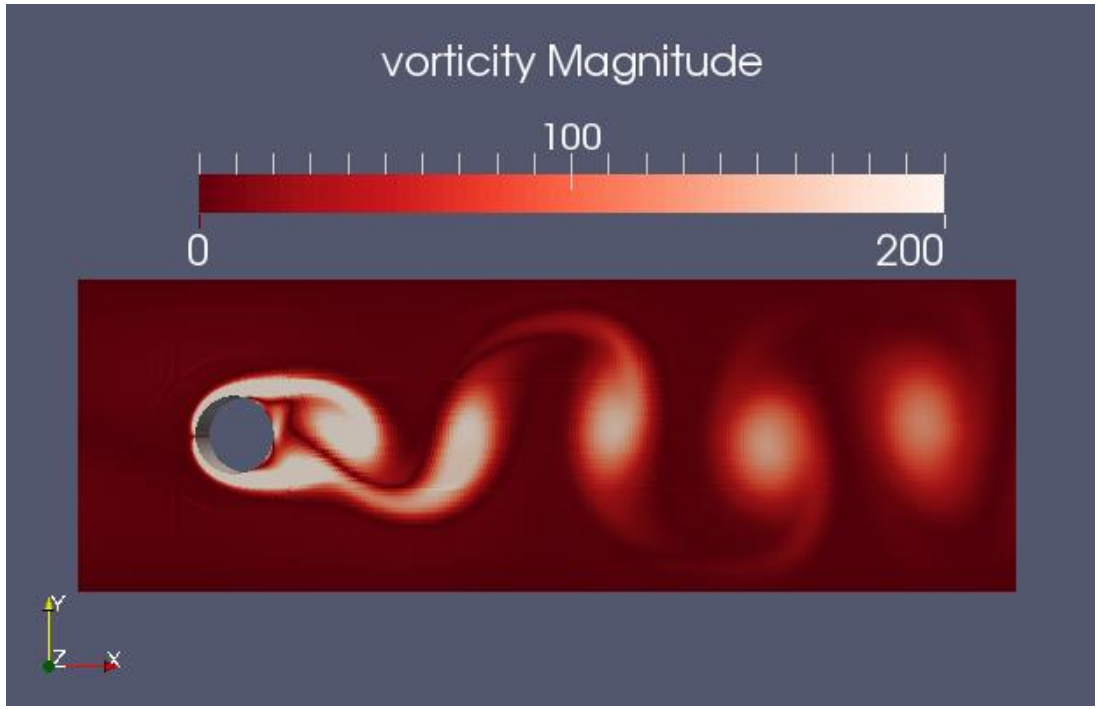


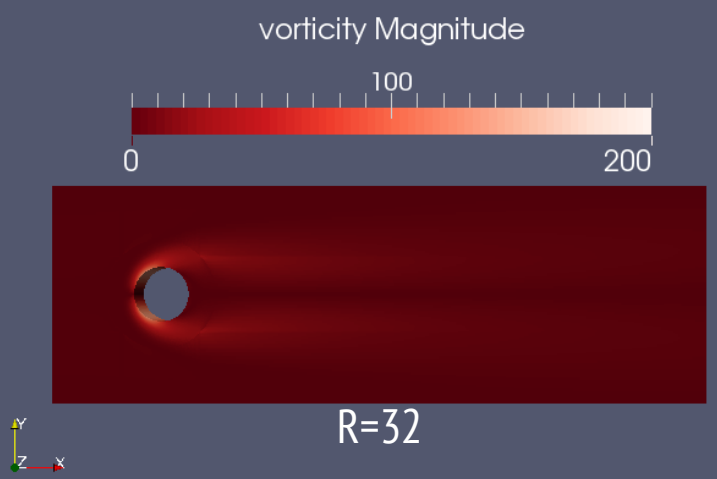
R=161

Observed

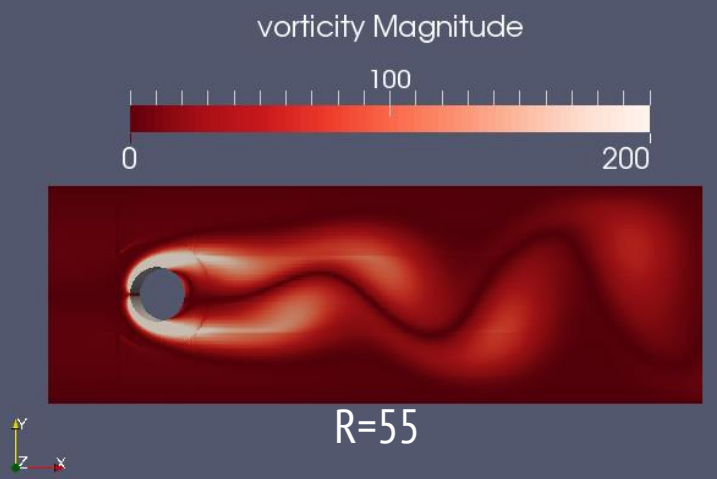


Simulated

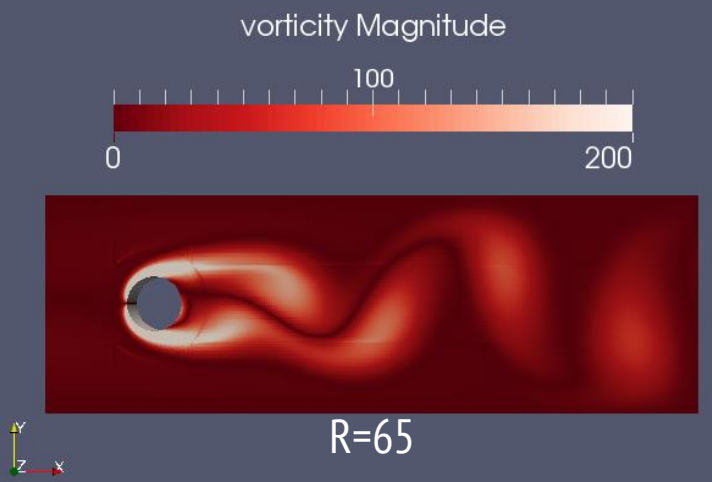




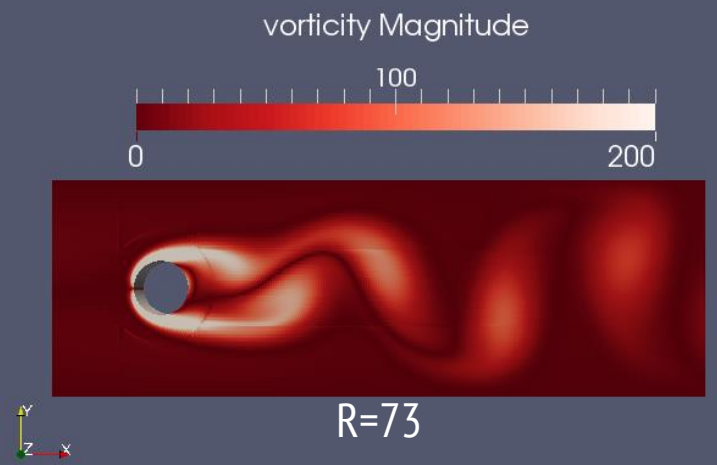
R=32



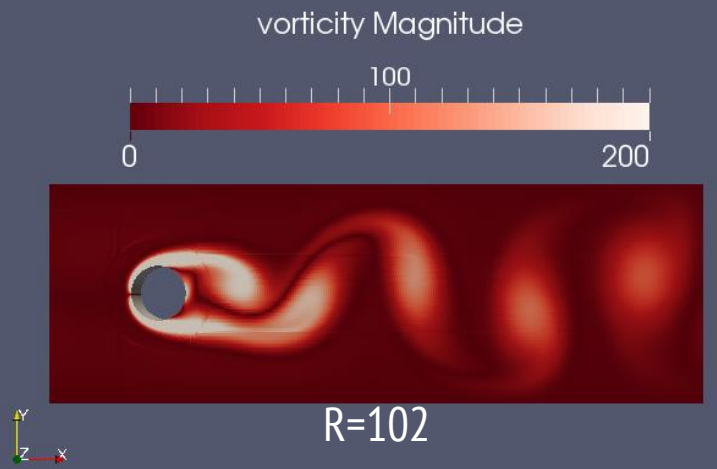
R=55



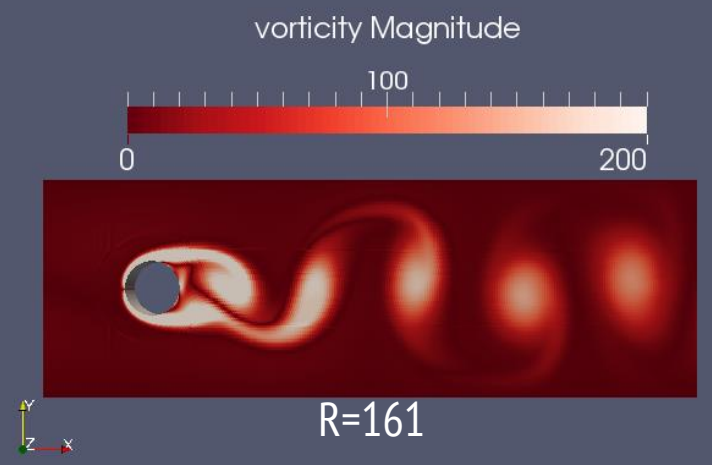
R=65



R=73



R=102

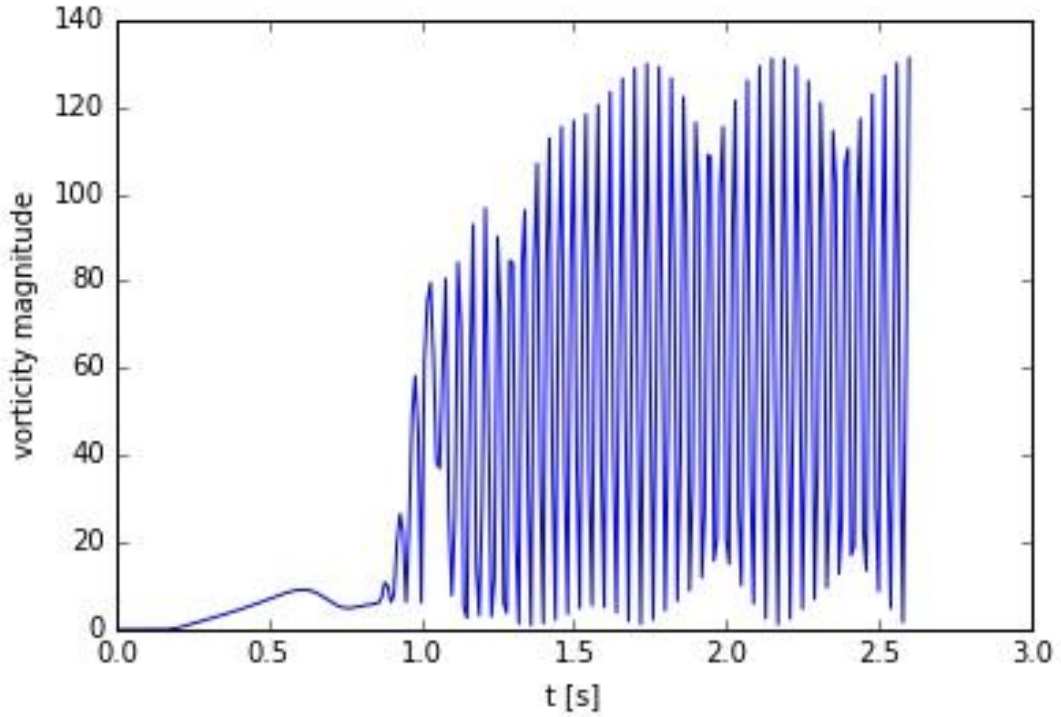


R=161

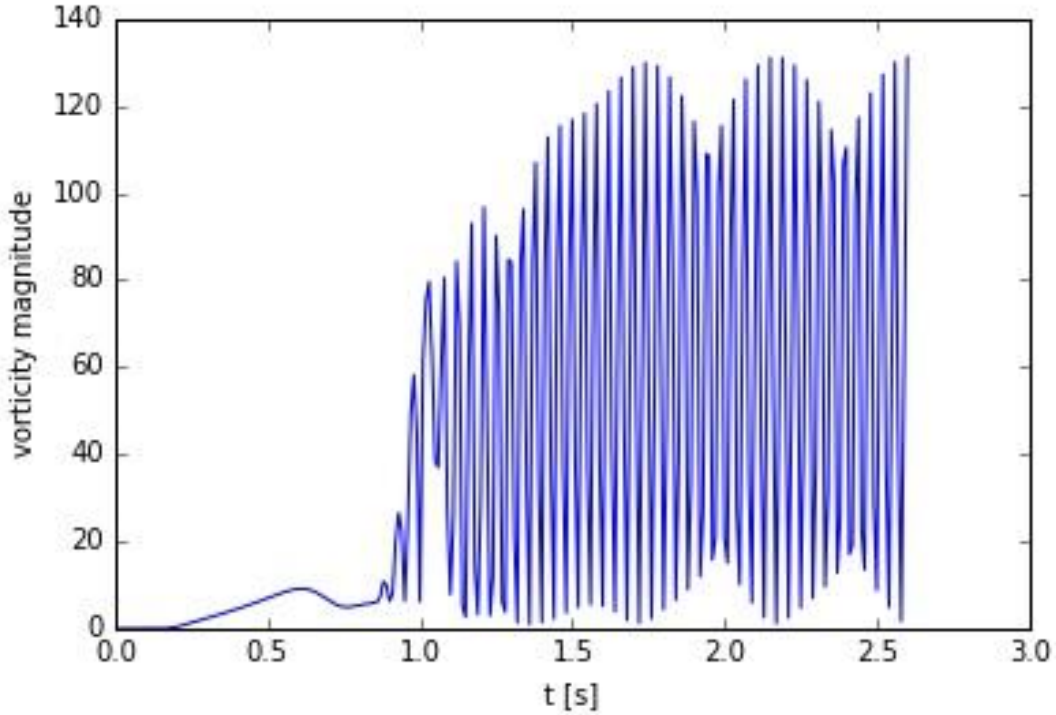
Strouhal Number

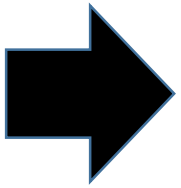
- Strouhal number describes shedding frequency of a fluid
- Mathematically: $S = \frac{fL}{V}$
  - f=shedding frequency
  - L=length of object (i.e. the cylinder)
  - V=fluid velocity
- Empirically: $S(R) = 0.2684 - \frac{1.0356}{\sqrt{R}}$ (Fey et al. 1998)

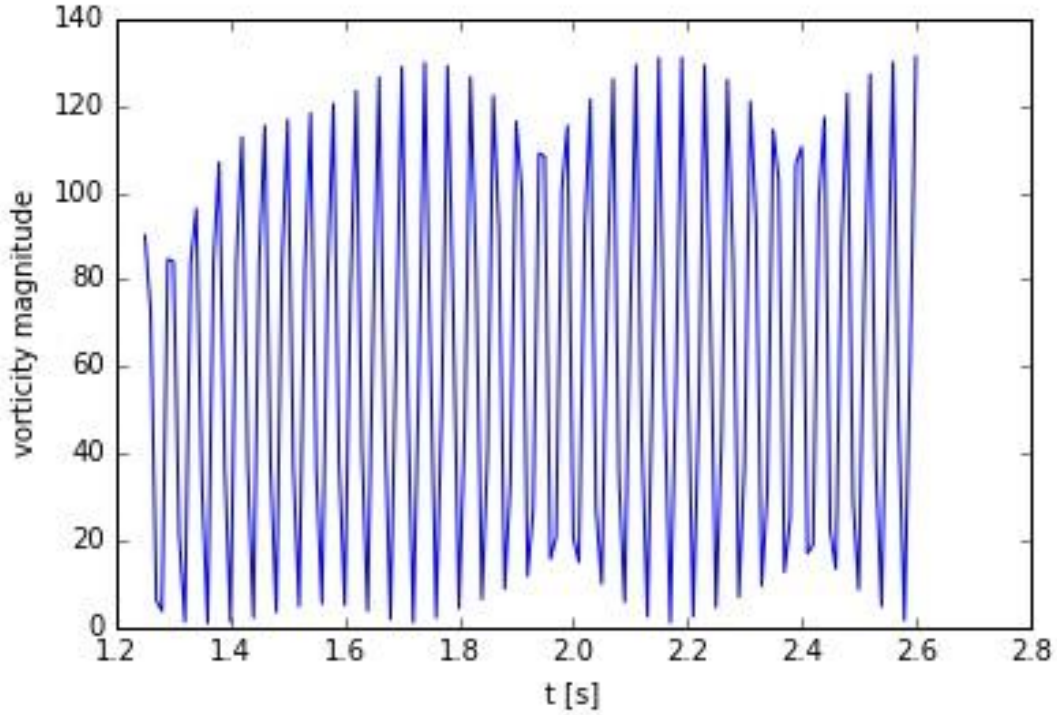
Strouhal Number



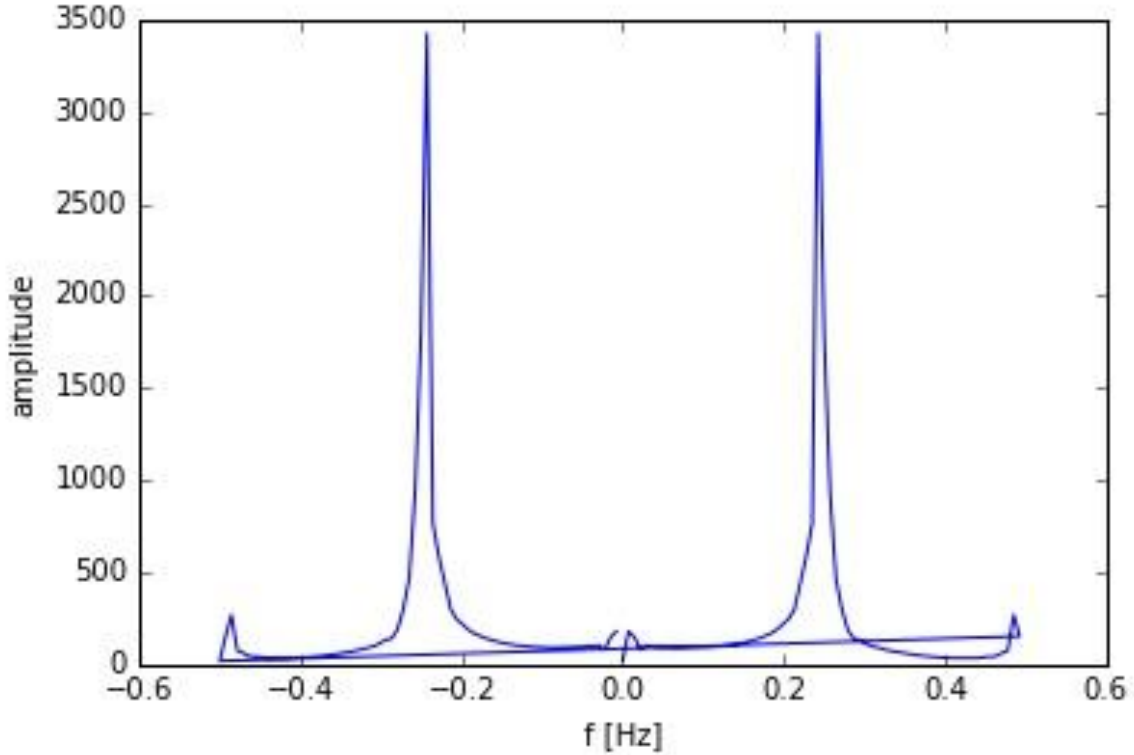
Strouhal Number







Strouhal Number



Strouhal Number

R	$f_{emp}\ [Hz]$	S_{emp}	$f_{OF}\ [Hz]$	S_{OF}
55	6.440	0.1288	19.61	0.3922
65	6.995	0.1399	21.31	0.4262
73	7.36	0.1472	22.09	0.4418
102	8.295	0.1659	22.52	0.4504
161	9.340	0.1868	24.26	0.4852

Strouhal Ratios

R_i	R_{i+1}	$(S_{i+1}/S_i)_{OF}$	$(S_{i+1}/S_i)_{emp}$	$\frac{(S_{i+1}/S_i)_{OF}}{(S_{i+1}/S_i)_{emp}}$
55	65	1.087	1.087	1.000
65	73	1.037	1.052	0.9857
73	102	1.019	1.127	0.9042
102	161	1.077	1.126	0.9565

Summary

- Modeled incompressible, viscous flow around a cylinder using OpenFoam
- Found decent qualitative agreement at lower Reynolds number, better qualitative agreement at higher Reynolds numbers
- Quantitatively, the shedding frequencies of the OpenFoam simulations are much higher than the observed cases (~factor of 3)
  - Despite higher shedding frequencies, by modeling the Strouhal ratios at different Reynolds numbers, can see the progression of the shedding is accurately modeled by OpenFoam