Fluid Mechanics
Lecture 1 - Introduction

Fluid Mechanics or Liquid and Gas Mechanics

Fluid Mechanics - may be divided into three kinds:

- Experimental Fluid Mechanics
- Theoretical Fluid Mechanics
- Computational Fluid Mechanics

Experimental Fluid Mechanics

- Observation of physical phenomena in the fluid flows
- Inspiration for creation of the physical and mathematical models of these phenomena
- Model experiments as an element of the design process of the full scale objects
- Verification (validation) of the physical and mathematical models and also of the computational methods

Theoretical Fluid Mechanics

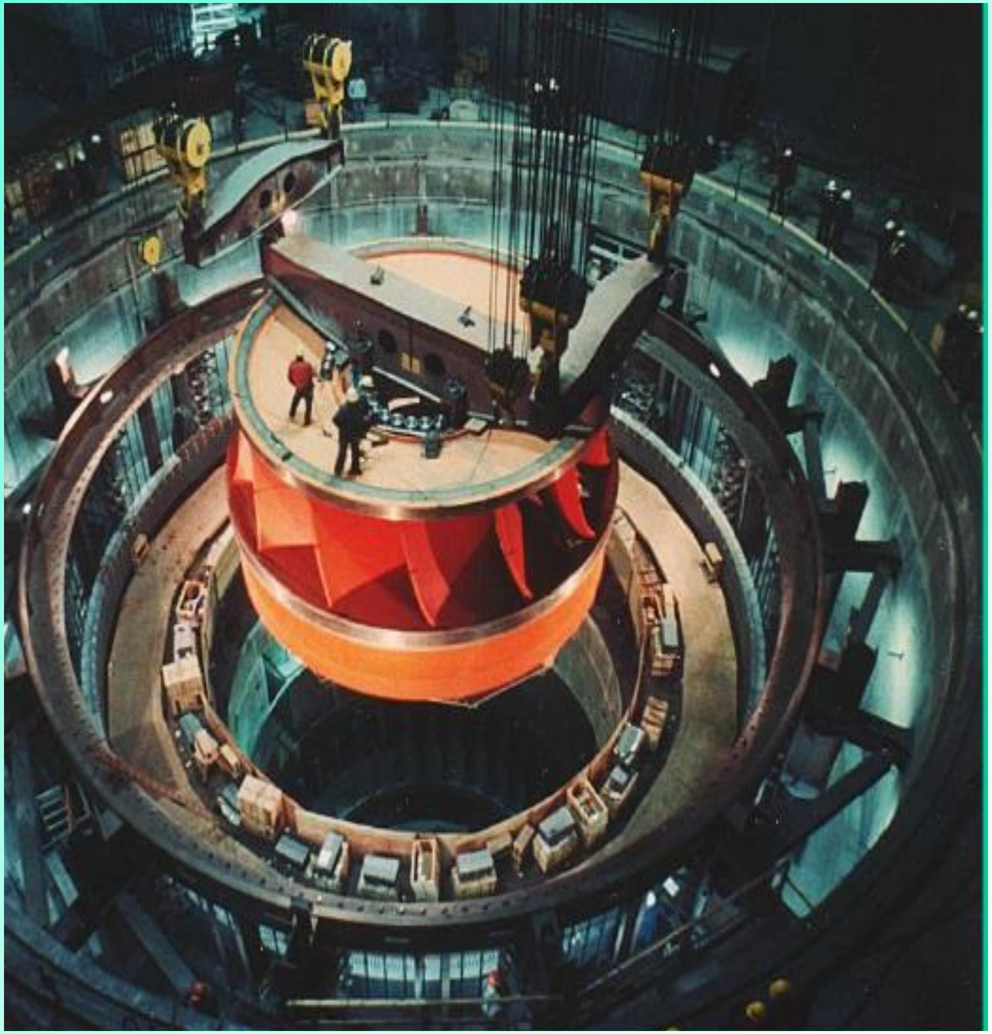
- Creation of the physical and mathematical models for the fluid flow phenomena
- Analytical solutions of the fluid flow equations for the simple flow cases
- Formulation of problems and tasks for the Experimental Fluid Mechanics

Computational Fluid Mechanics

- Development of numerical methods for solution of the complicated practical problems of the fluid mechanics
- Verification (validation) of the numerical methods
- Computational analyses of the fluid flow problems as an element of the design process of different engineering objects

Areas of practical application of fluid mechanics

- Pumps and water turbines
- Steam and gas turbines
- Ventilators, compressors and windmills
- Systems of pipelines and chemical equipment
- Ships, aircraft and surface vehicles
- Ports, canals and hydrotechnical structures
- Buildings and bridges
- Biomechanics and medical equipment
- Meteorology and climatology
- Ecoengineering and environment protection



Water turbines

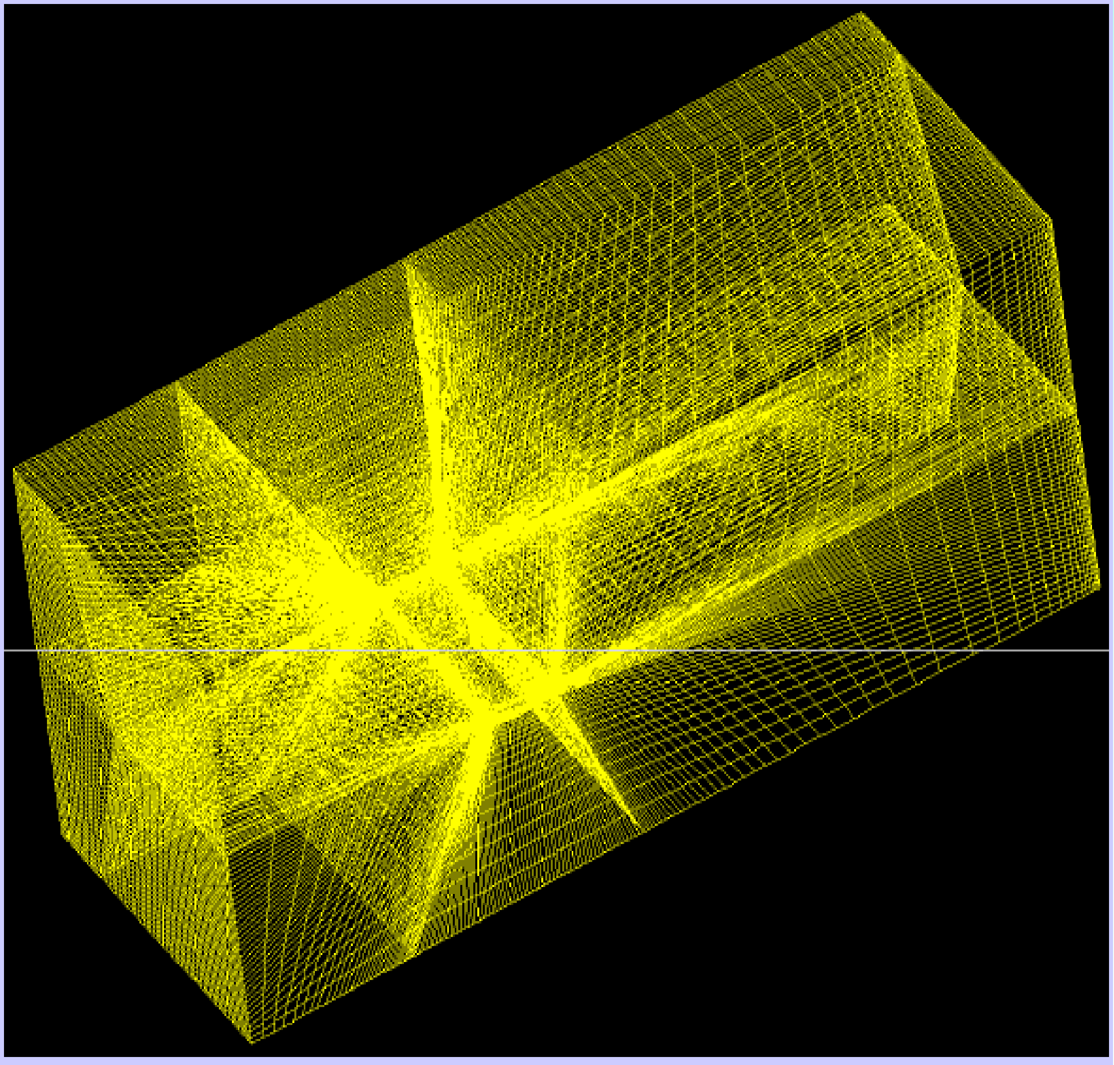
Steam and gas turbines

Wind turbines

Systems of pipelines and chemical installations

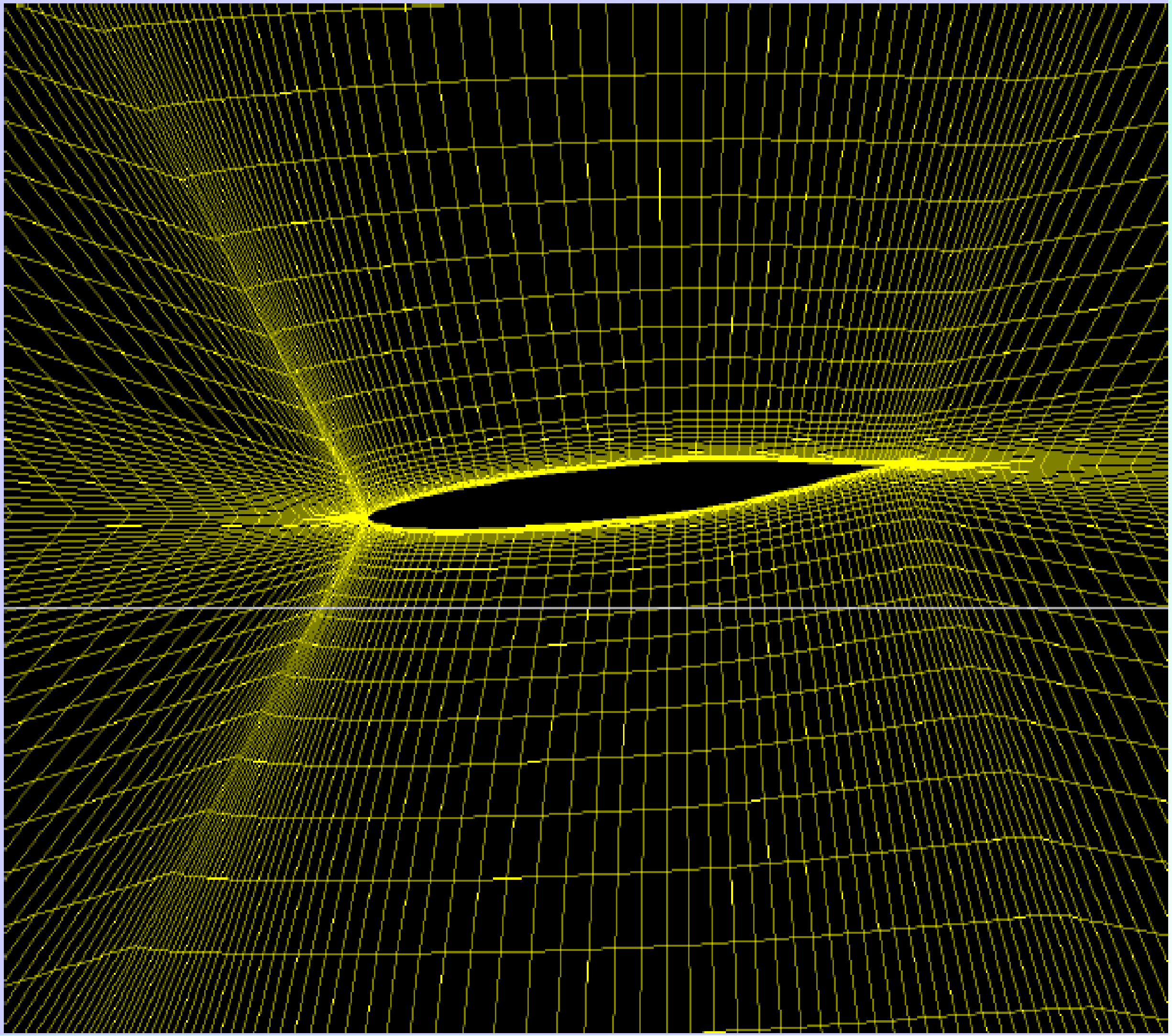
Ships

I will show examples of application of Fluid Mechanics

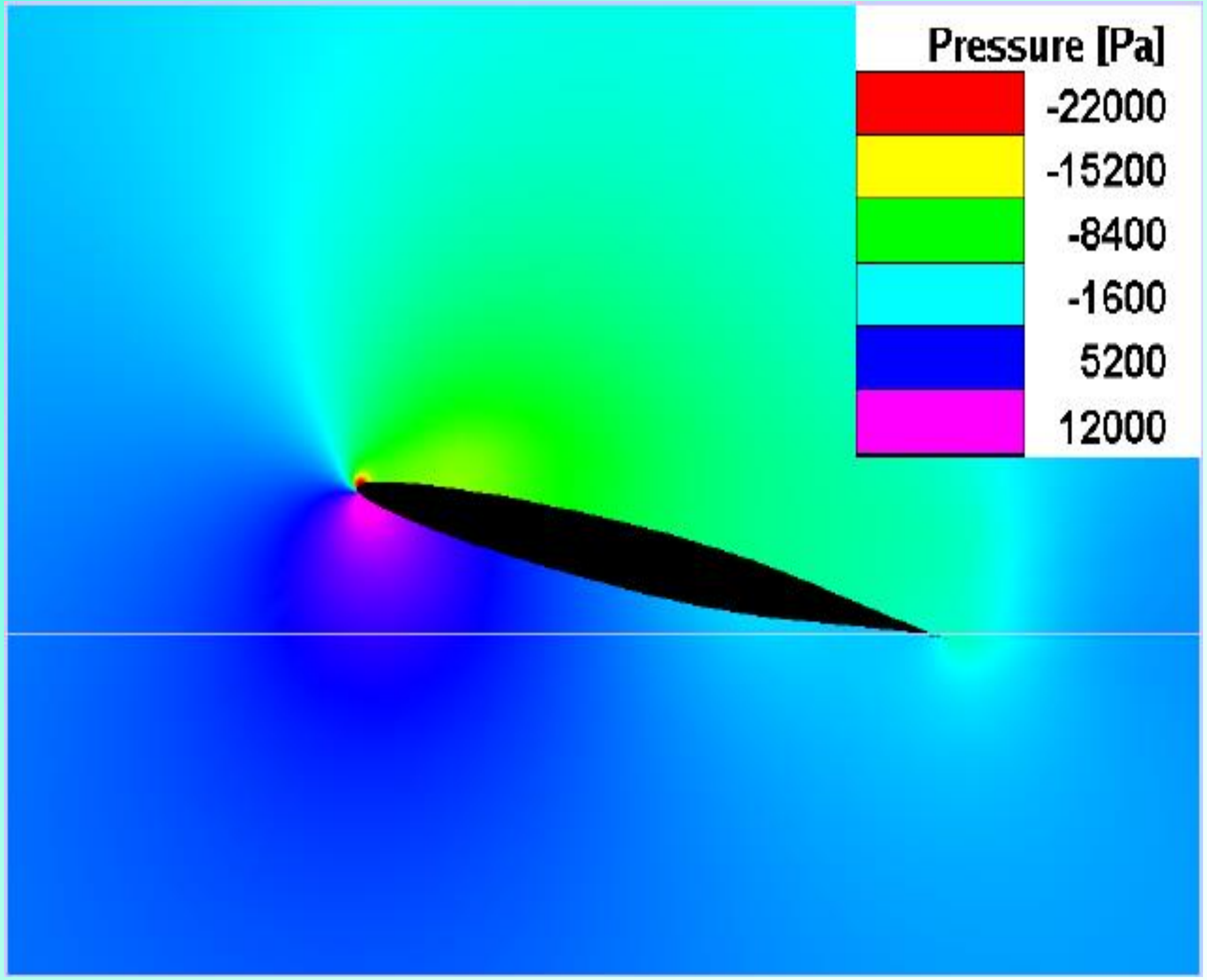


Discretization of the flow domain around a foil

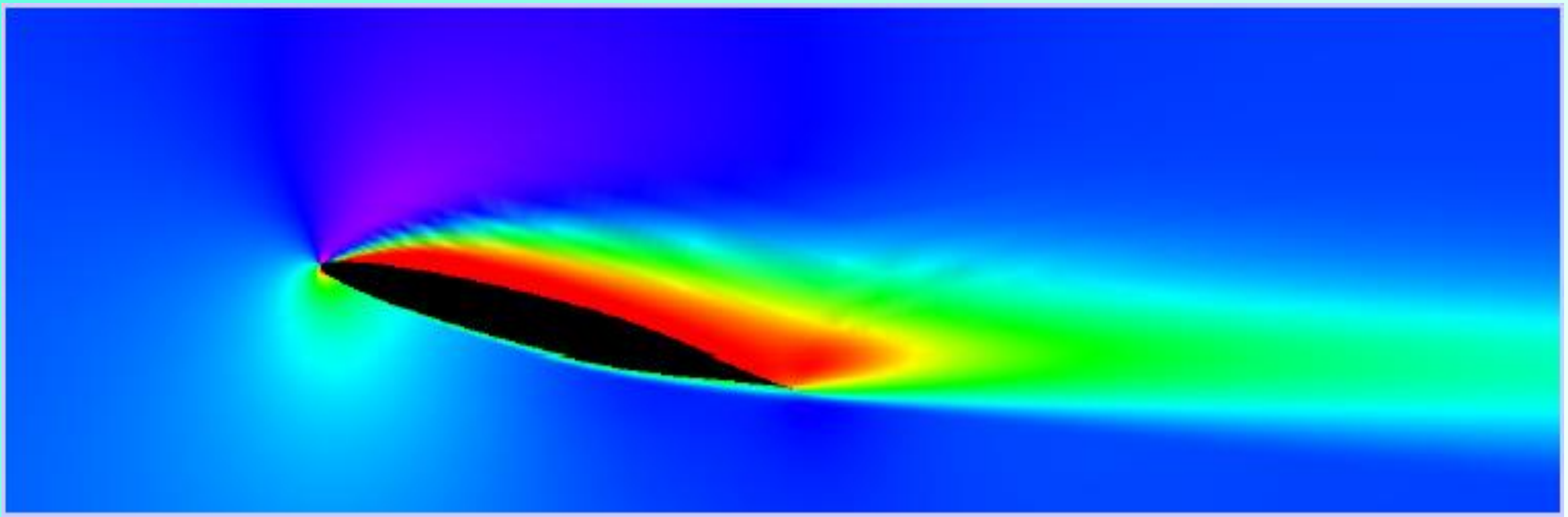
Foil model in the circulating water tunnel



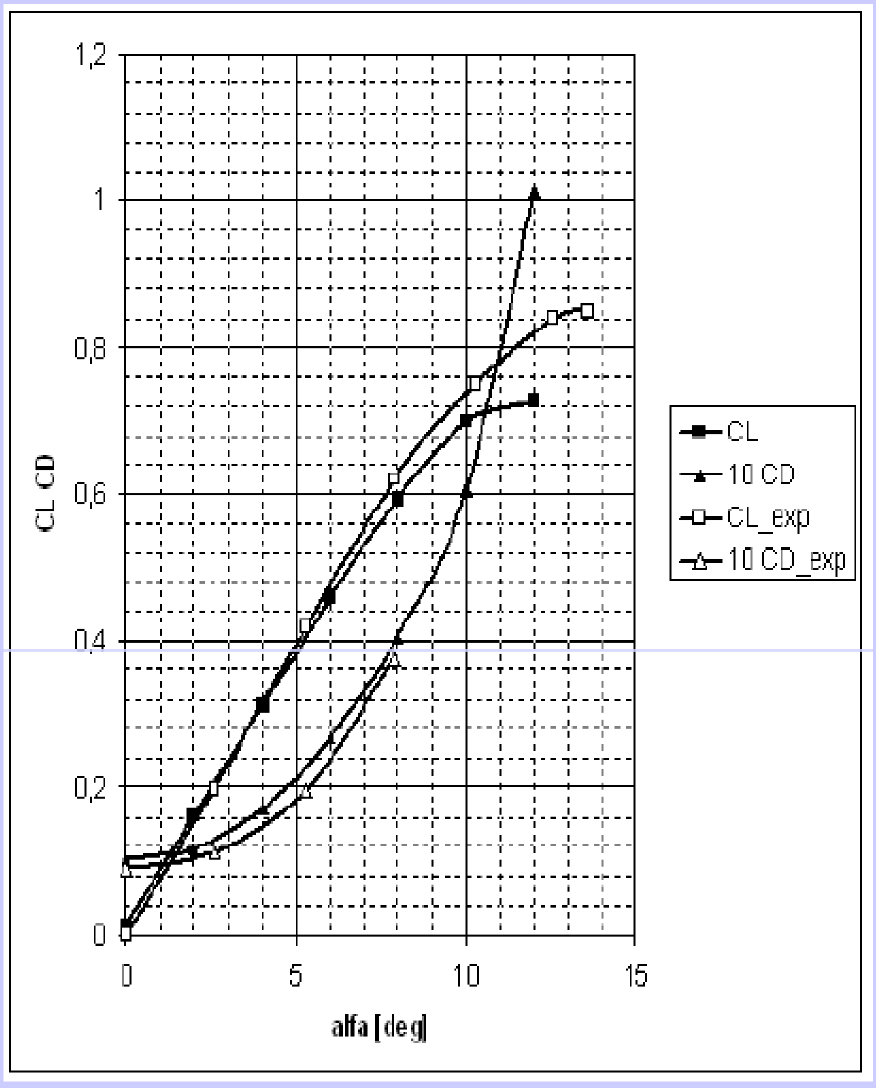
Details of the grid near the foil



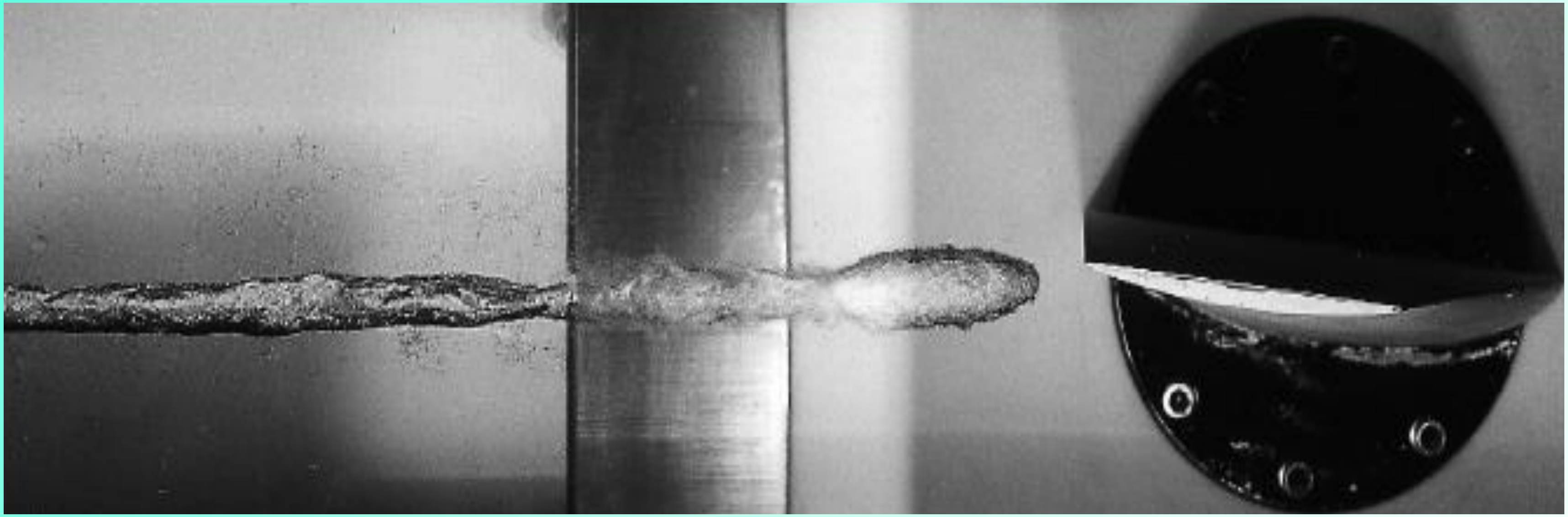
Calculated pressure field around an airfoil



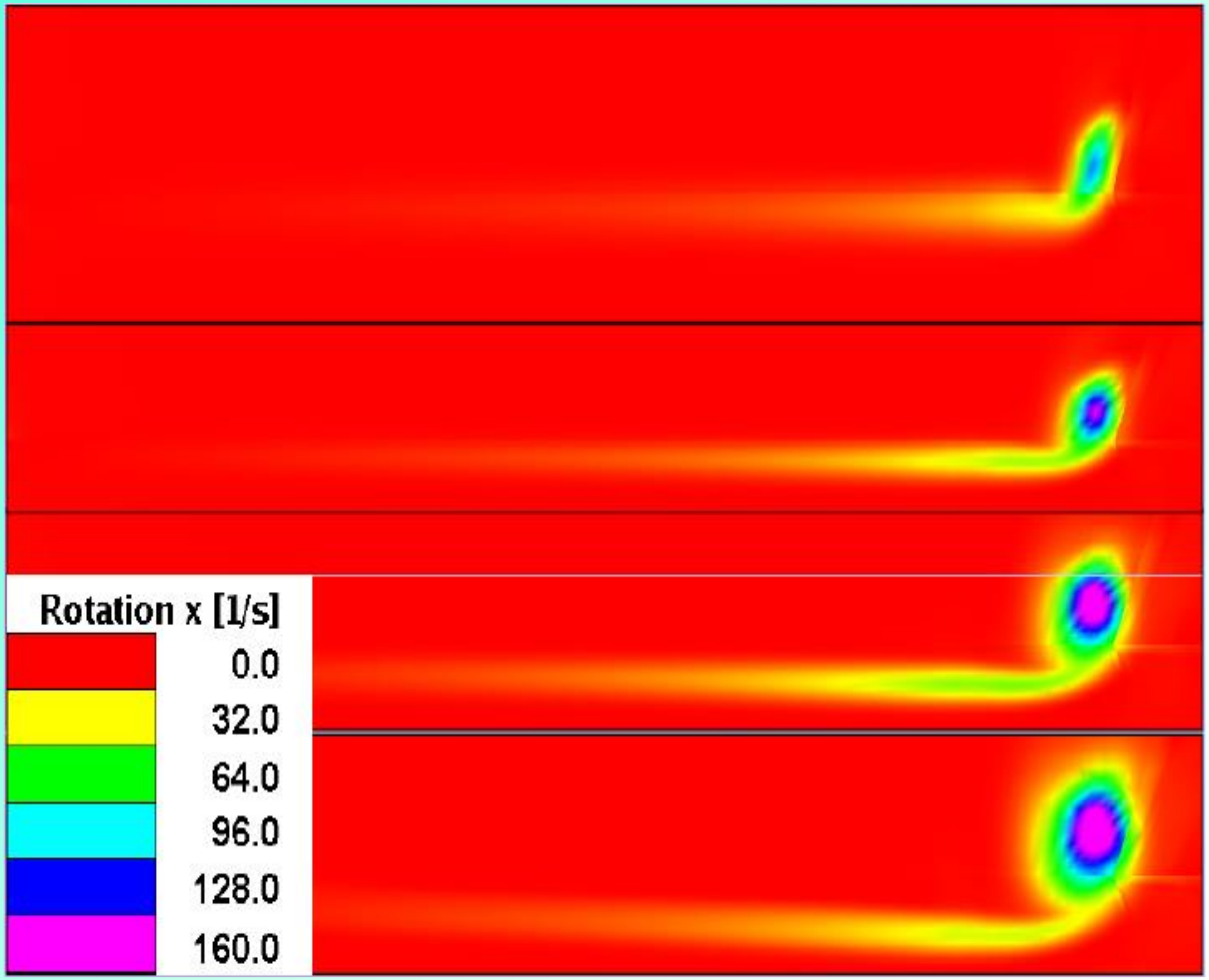
Calculated longitudinal velocity component near the foil



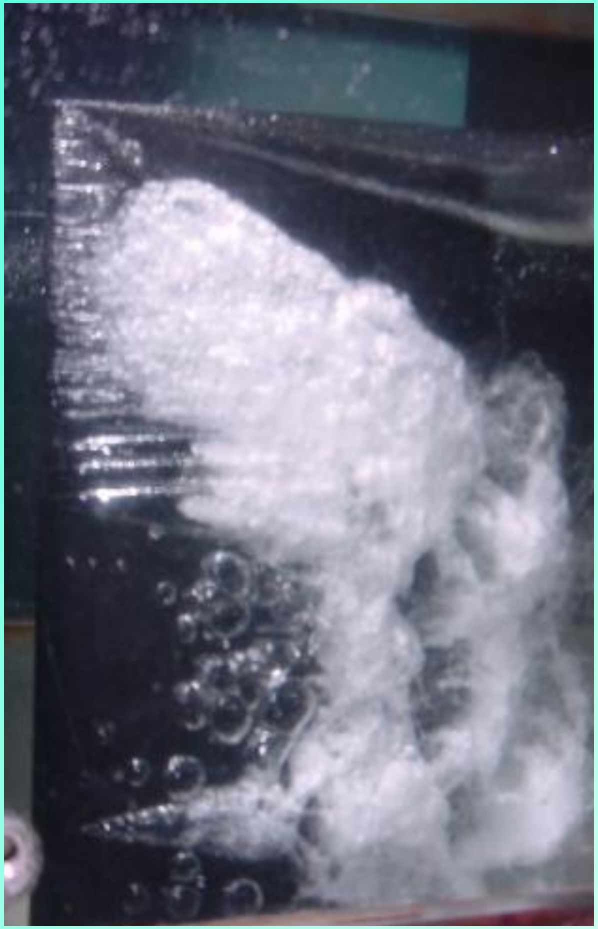
Comparison of calculated and measured foil characteristics

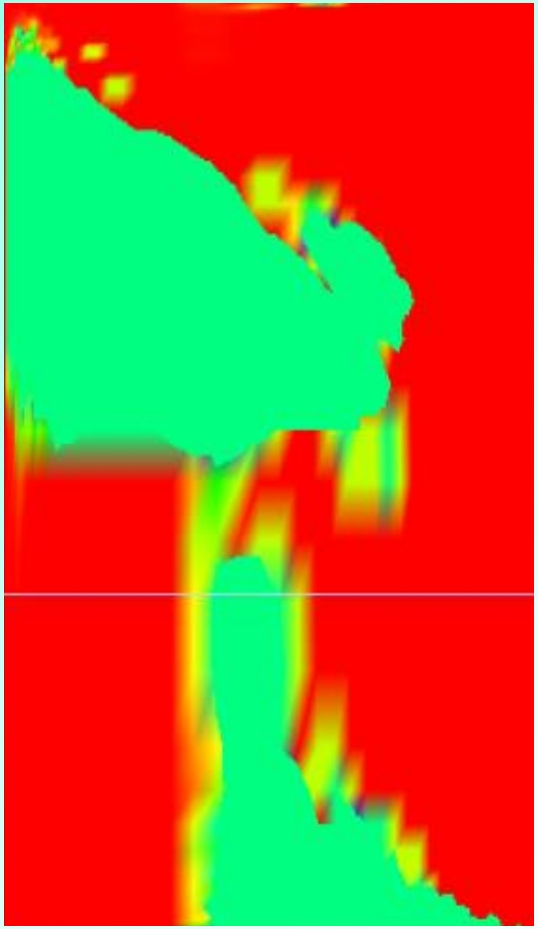


Vortex generated behind the foil tip



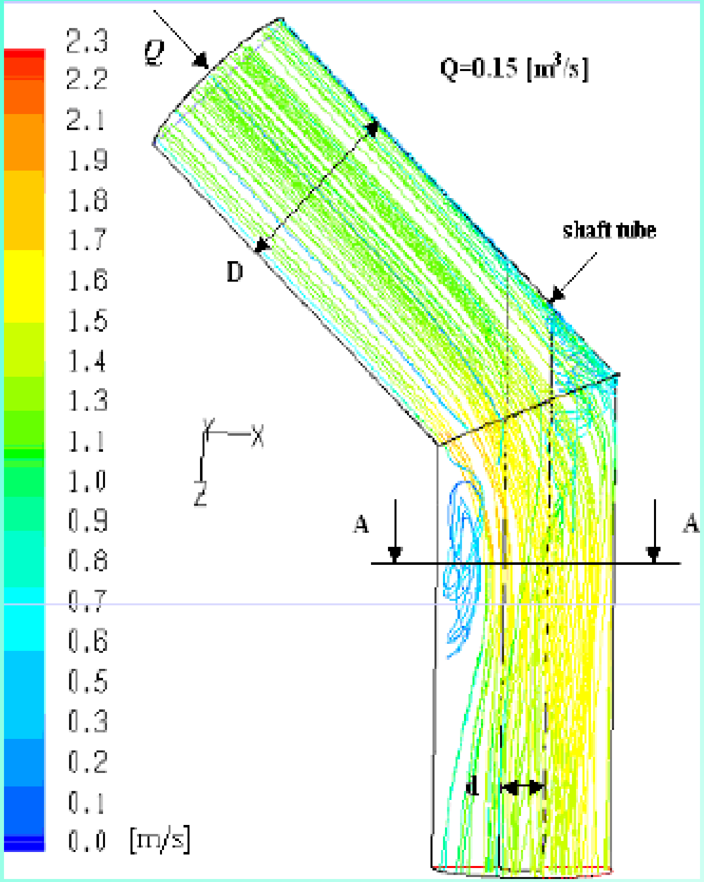
Calculated vortex formation behind the foil tip

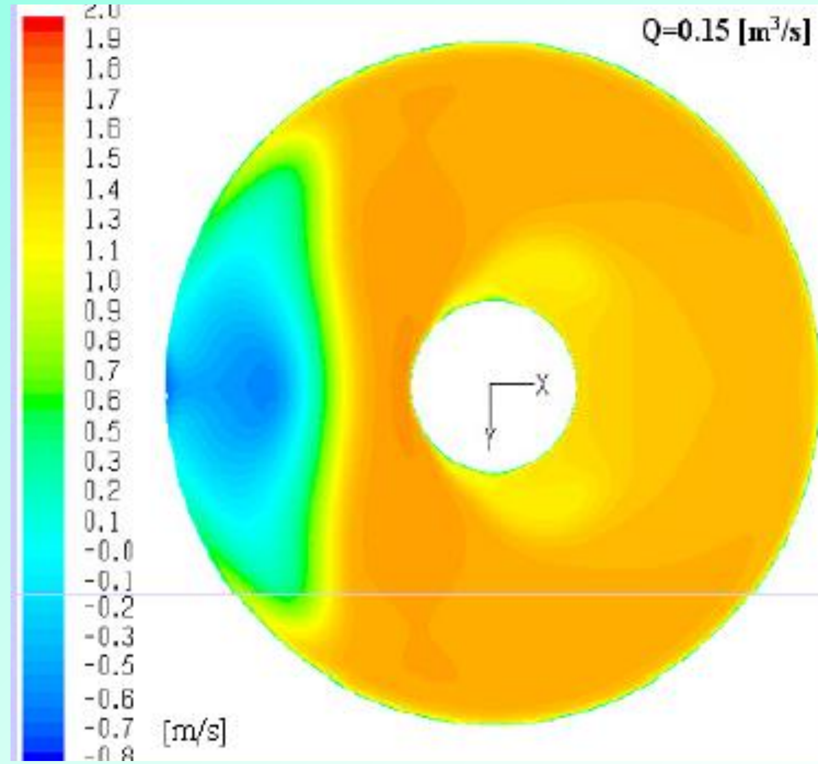




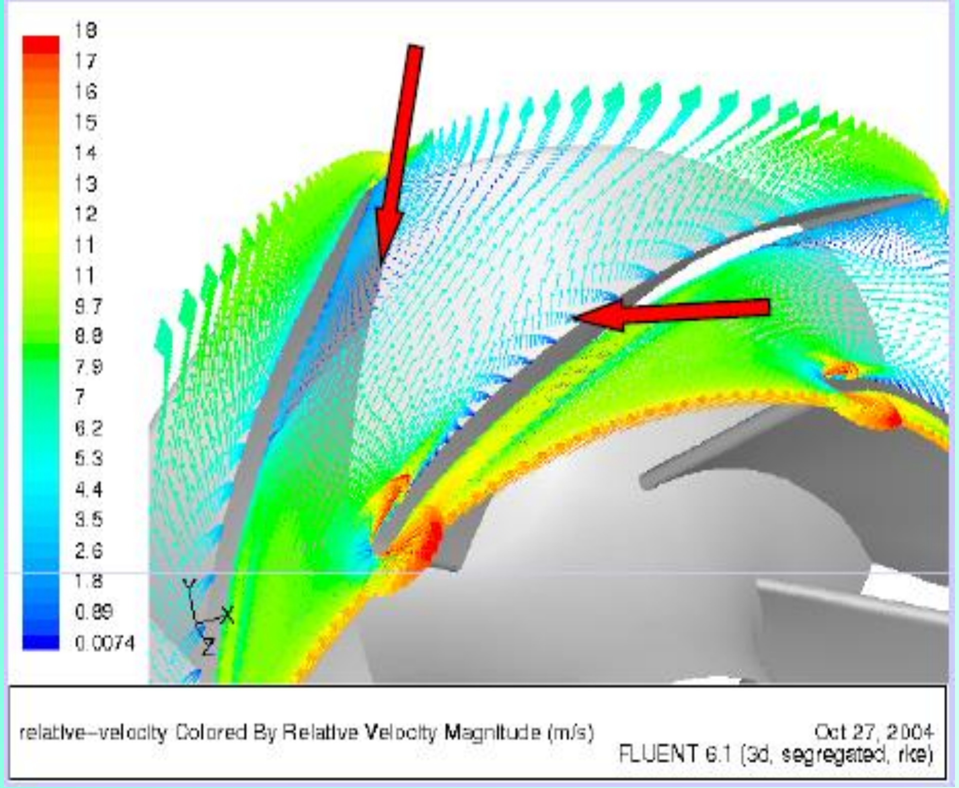
Comparison of observed and calculated extent of cavitation

Consequences of cavitation

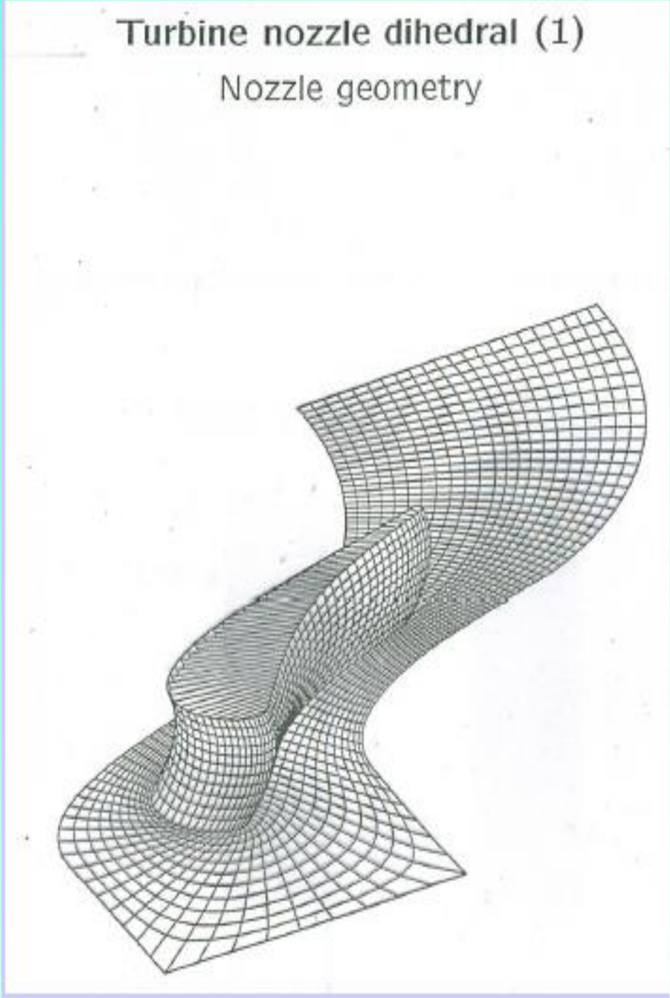




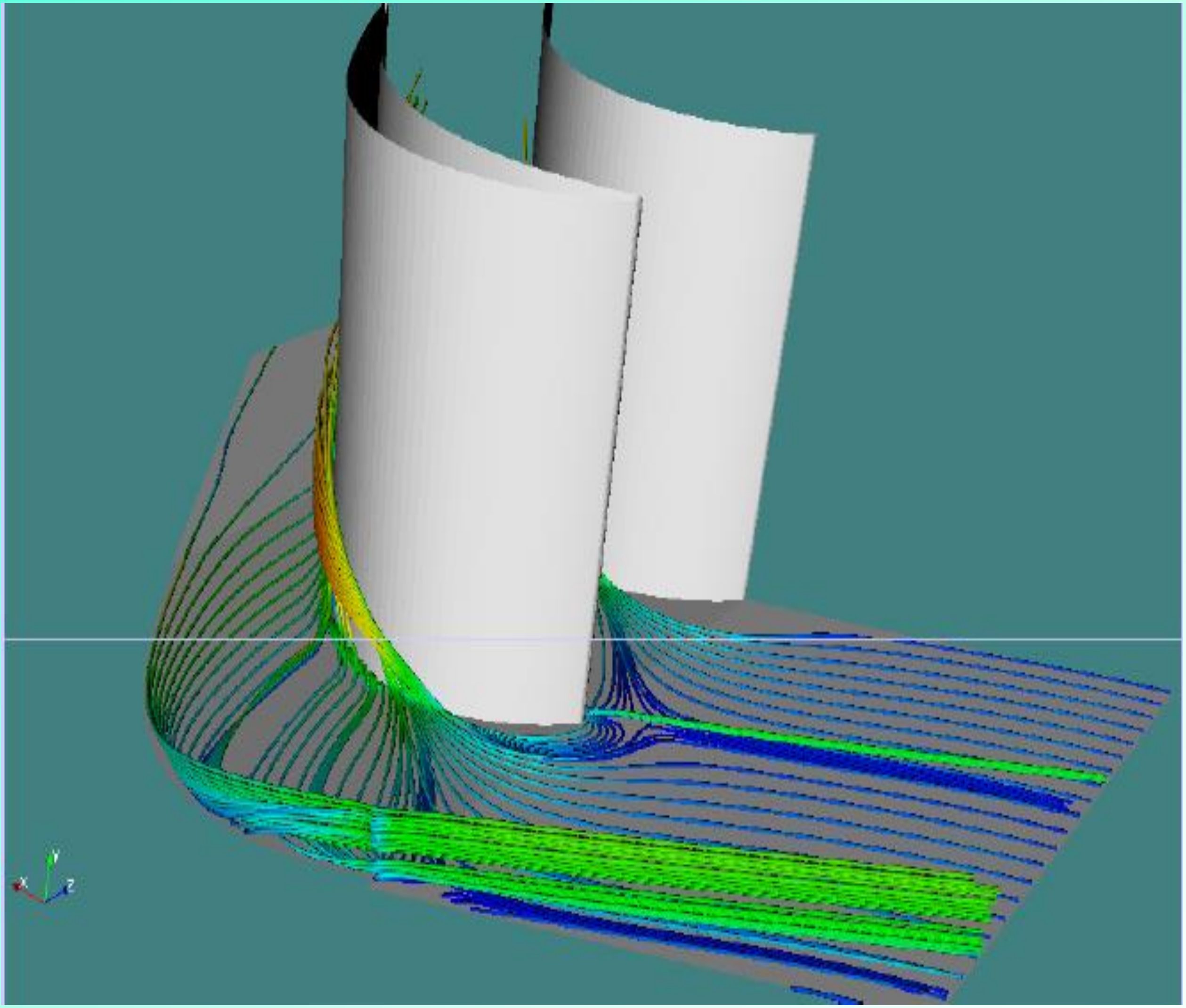
Detection of the flow separation in the inflow pipe of a water turbine



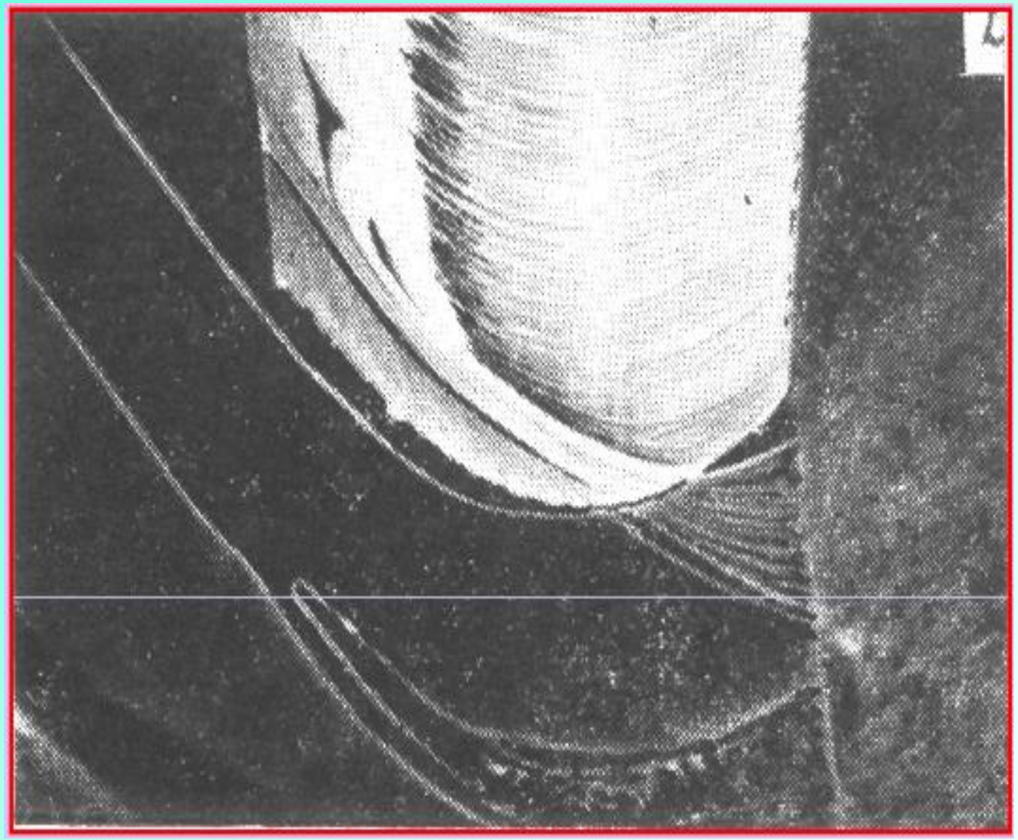
Detection of the flow separation in the impeller of the water pump



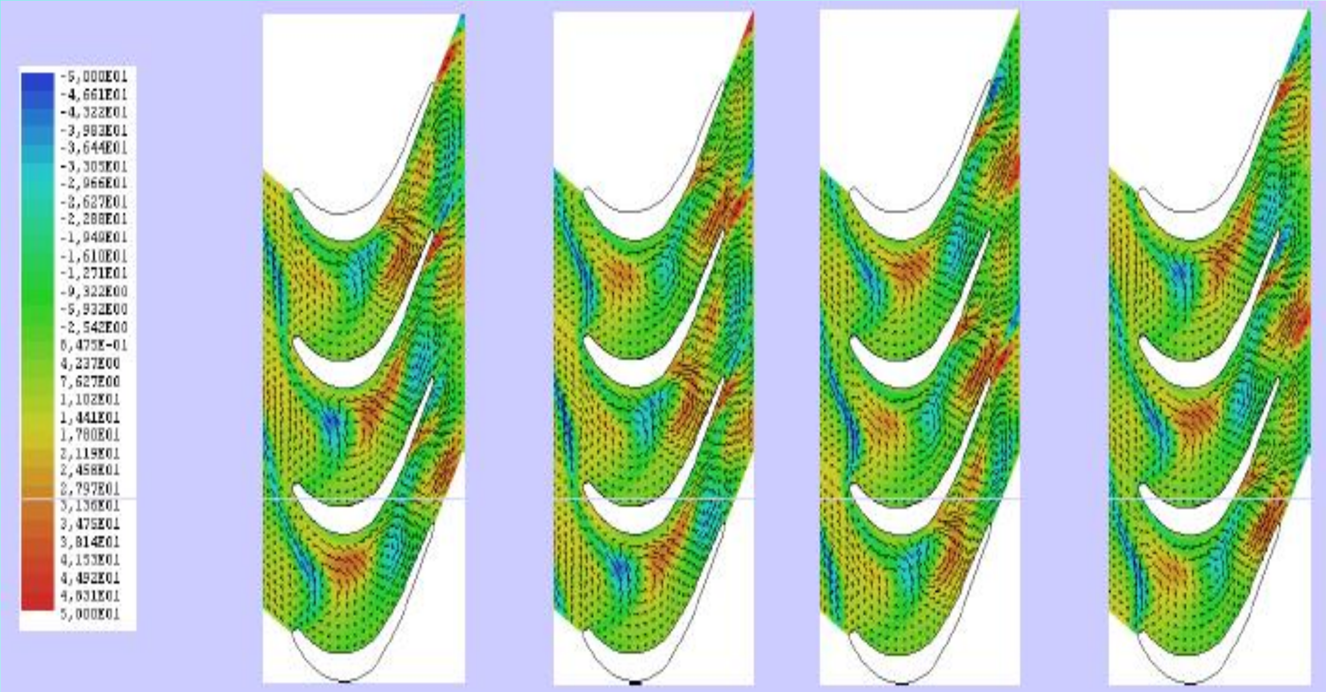
Discretization of a rotor element



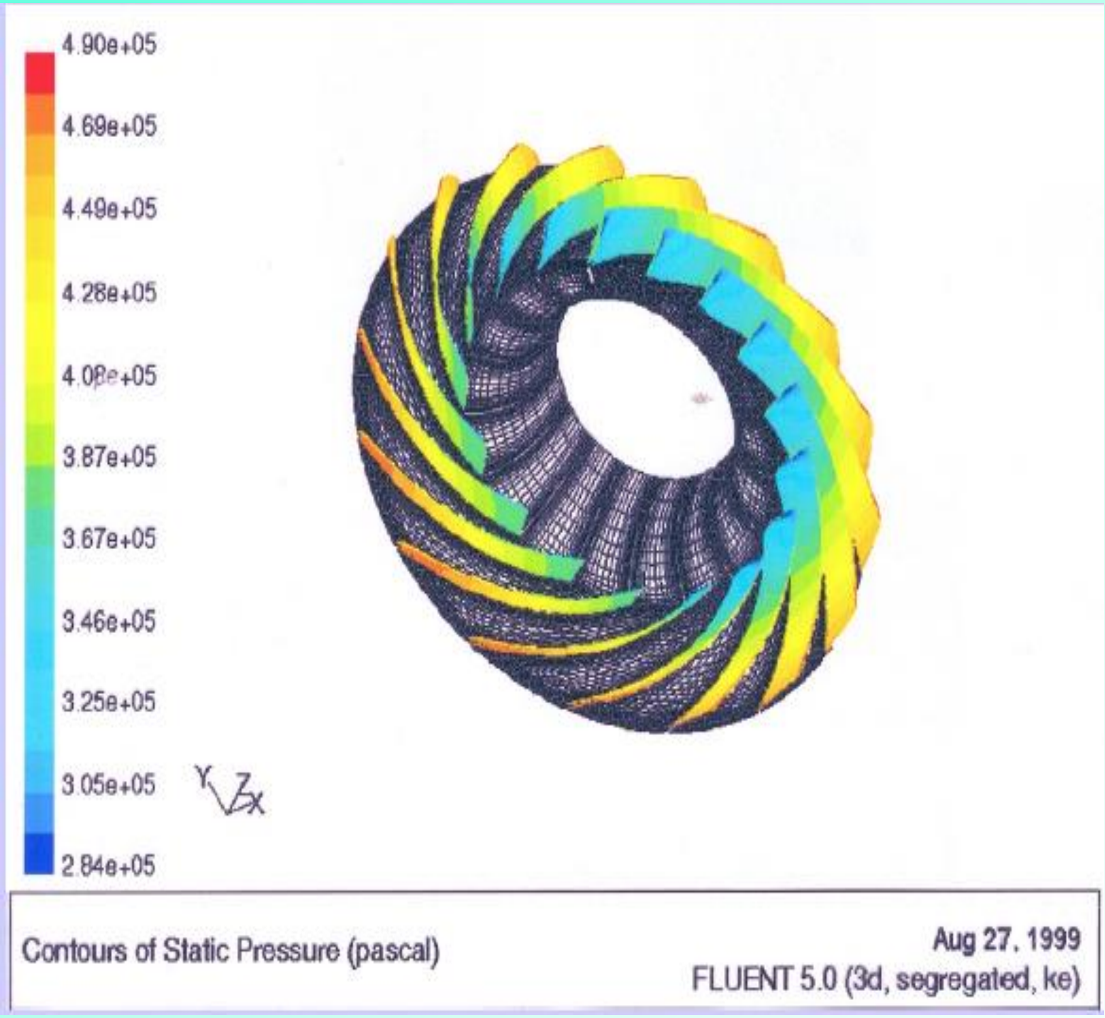
Calculated flow at the turbine blade root



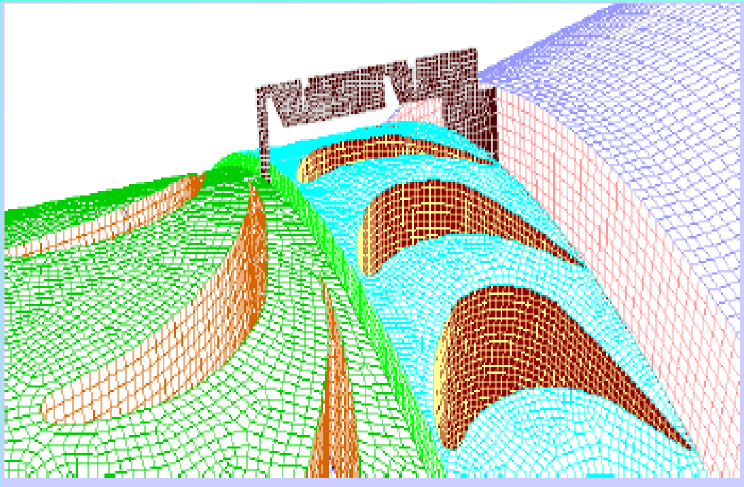
Experimental visualization of the flow around rotor blades

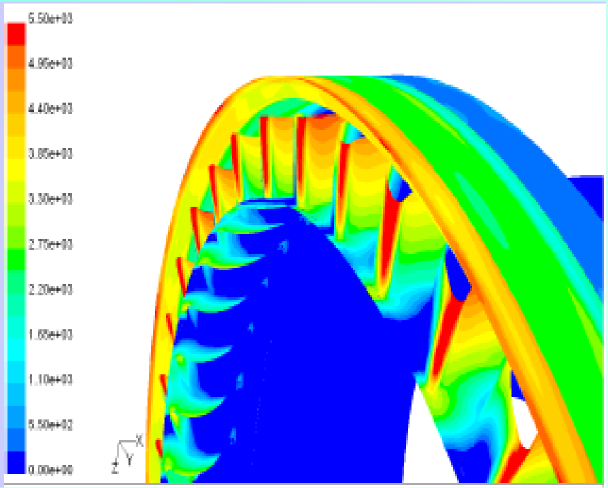


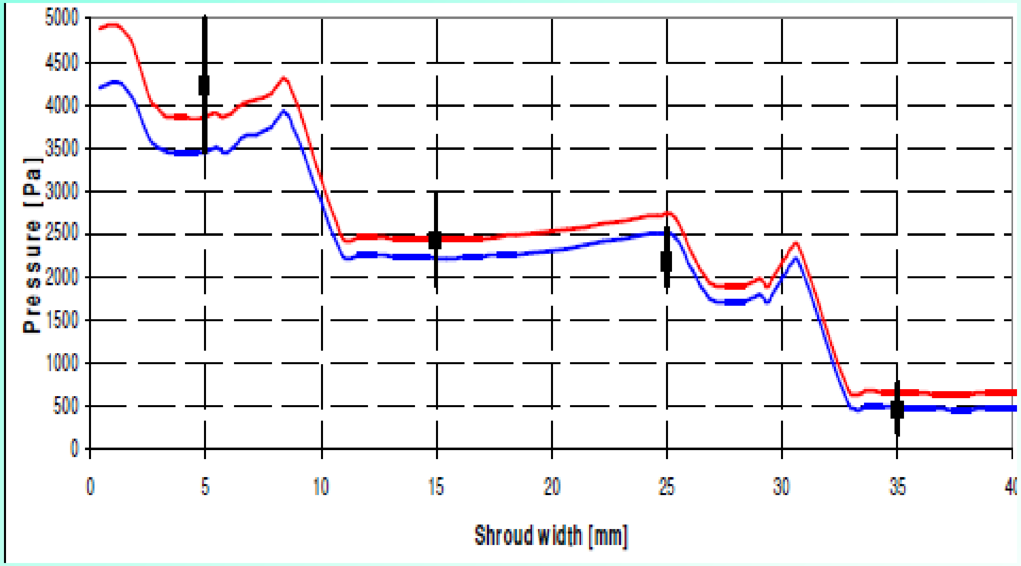
Calculation of the unsteady flow through a rotor



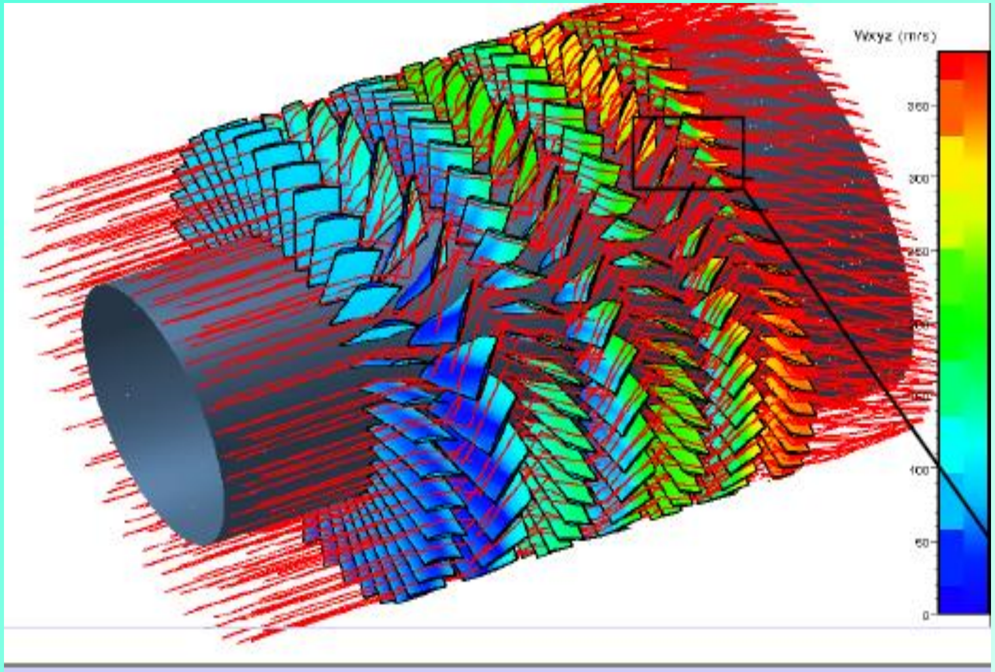
Calculated pressure distribution on a rotor

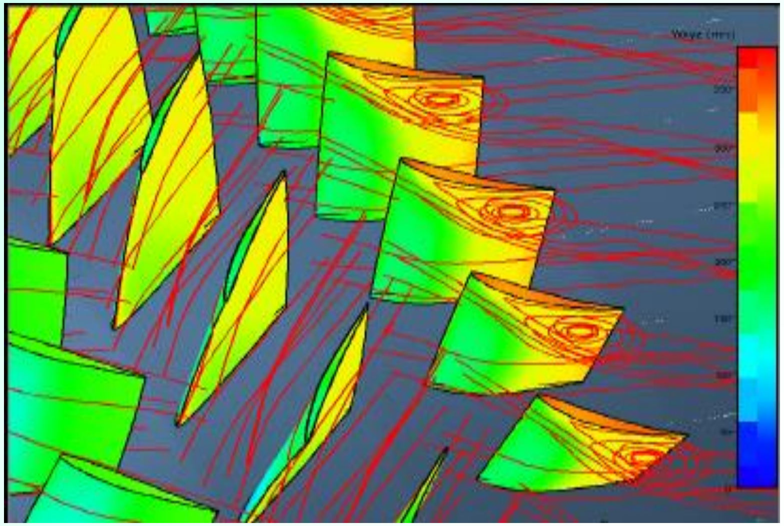




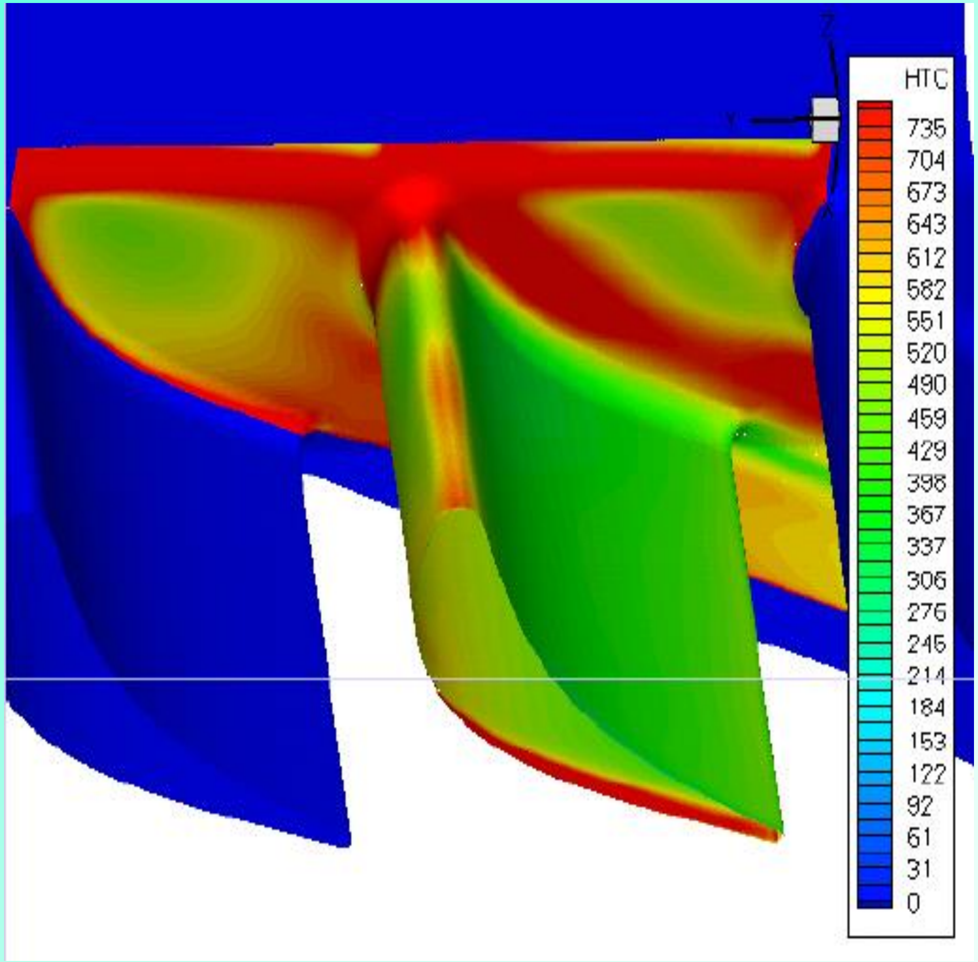


Calculation of the pressure inside tip clearance of the gas turbine rotor

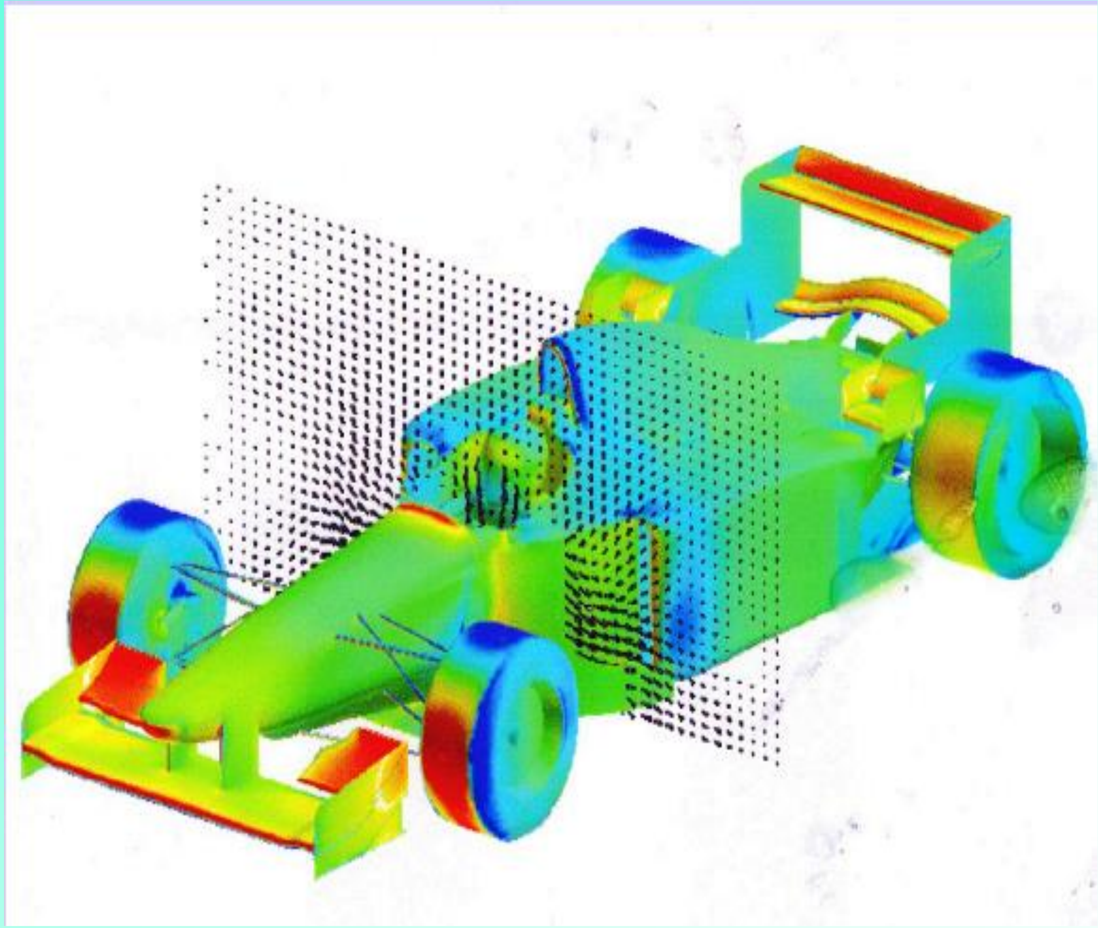




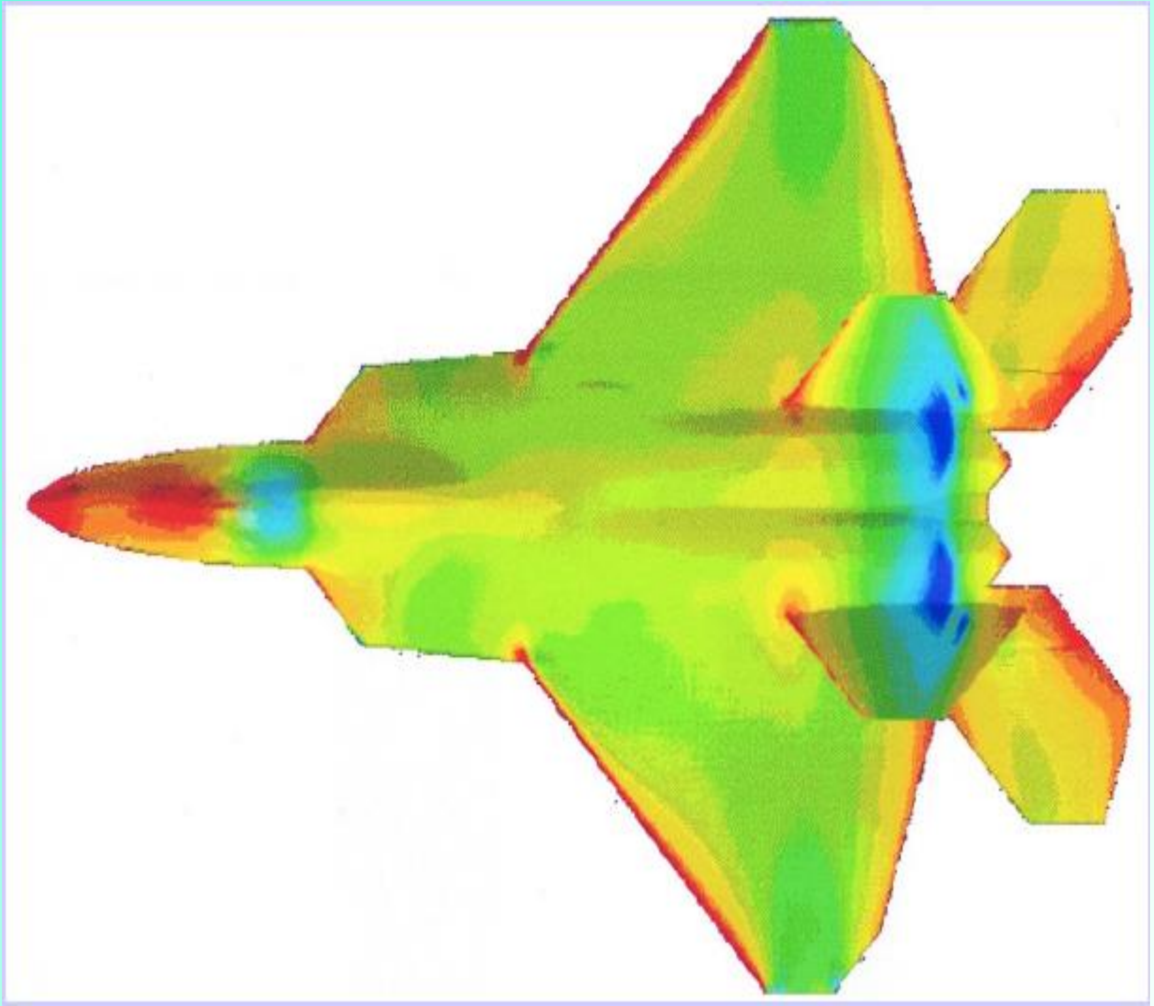
Streamlines and pressure distribution in the multistage compressor rotor



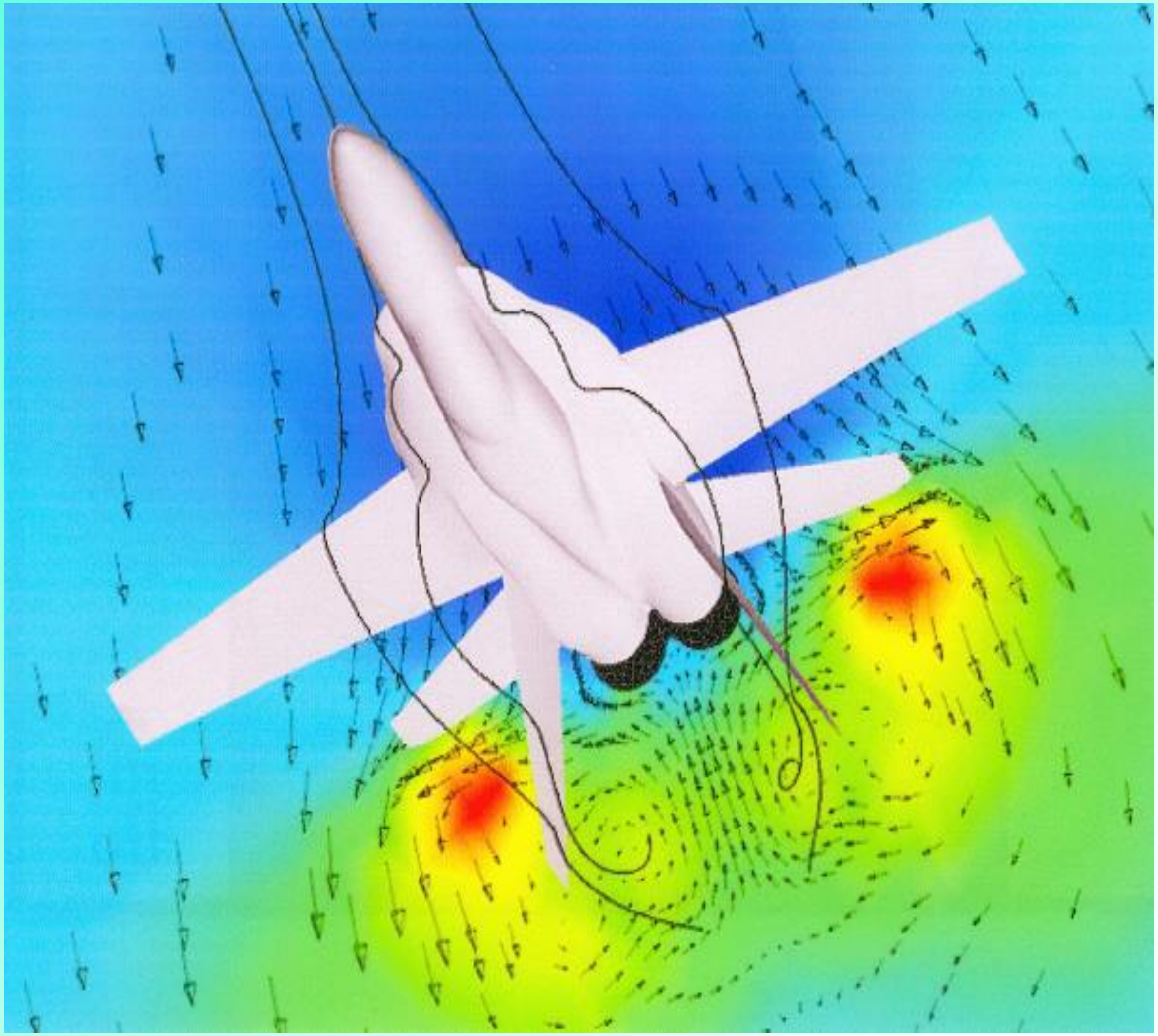
Determination of the heat exchange coefficient on the gas turbine rotor blade



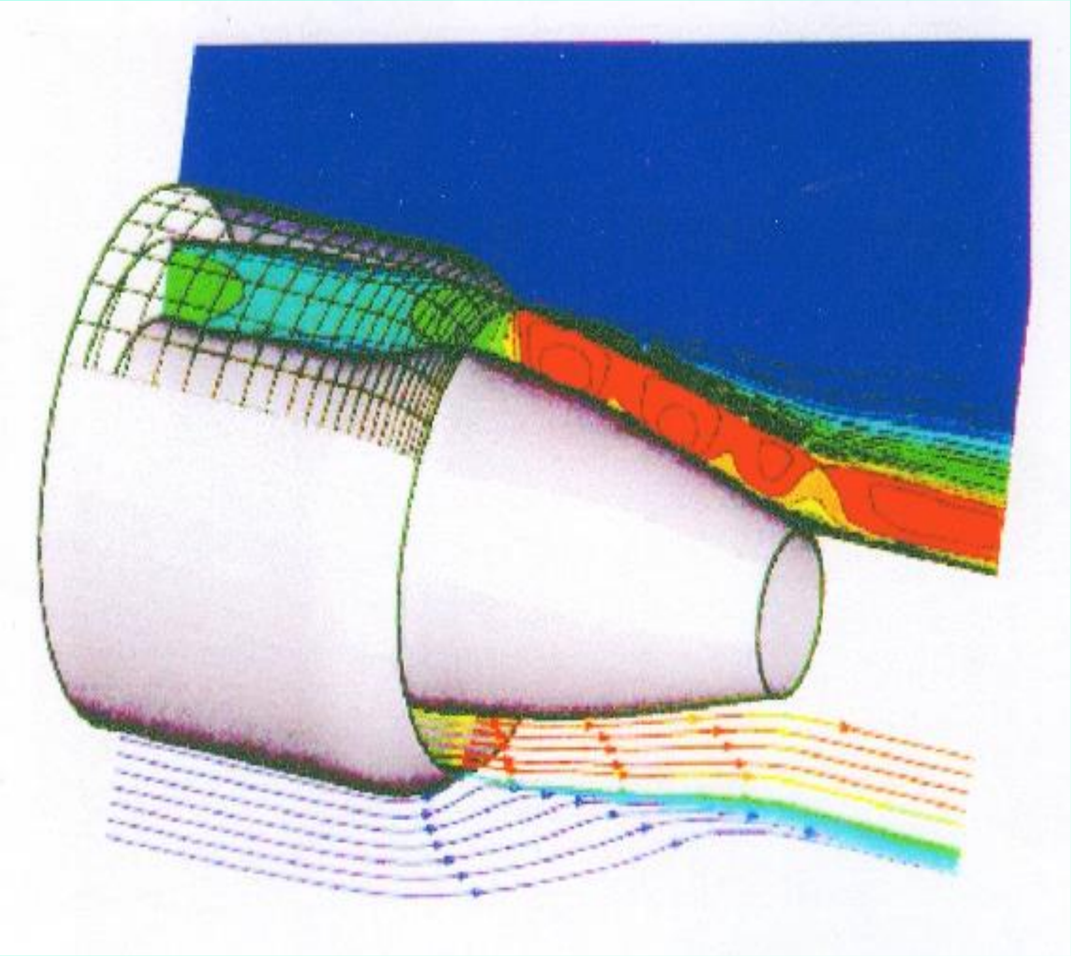
Calculated flow around a racing car



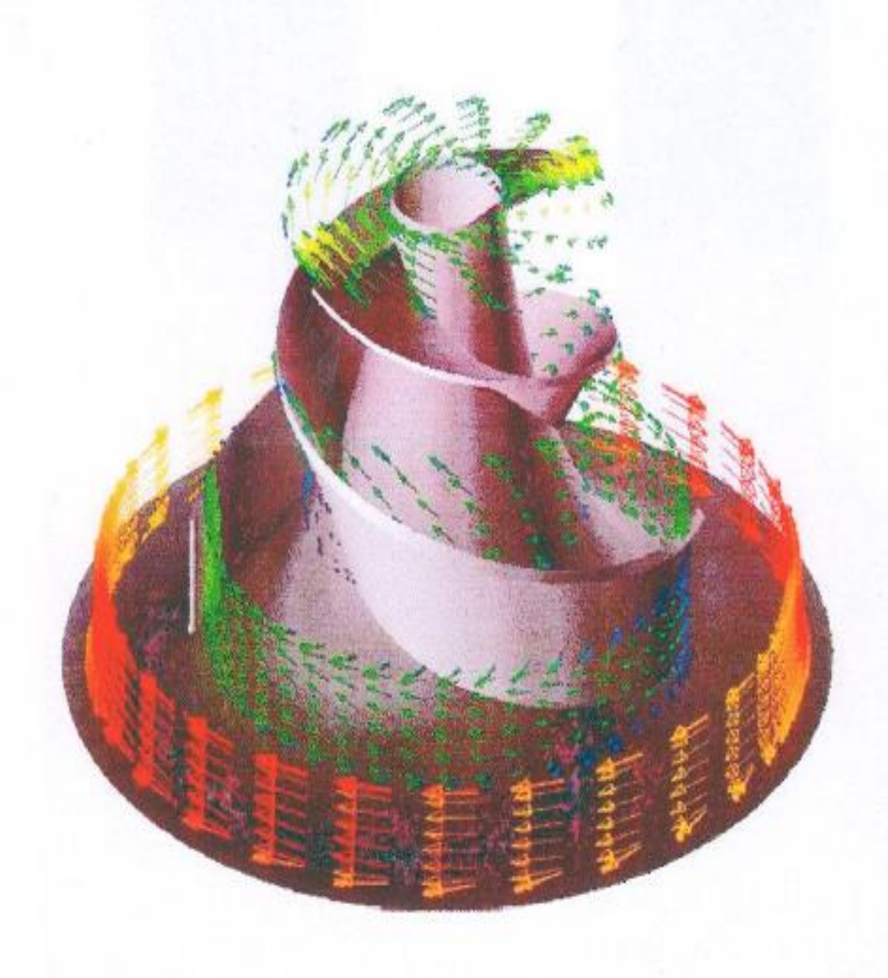
Calculated pressure distribution on an aircraft



Calculated velocity vectors and streamlines on an aircraft



Calculated outflow from an aircraft jet engine

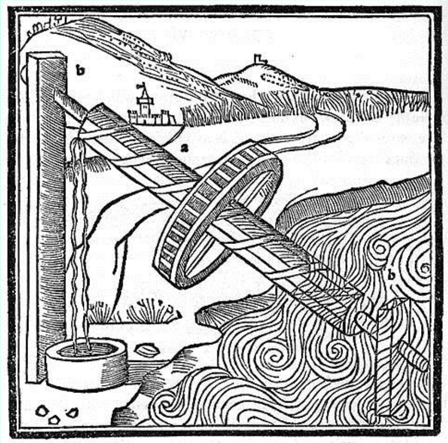


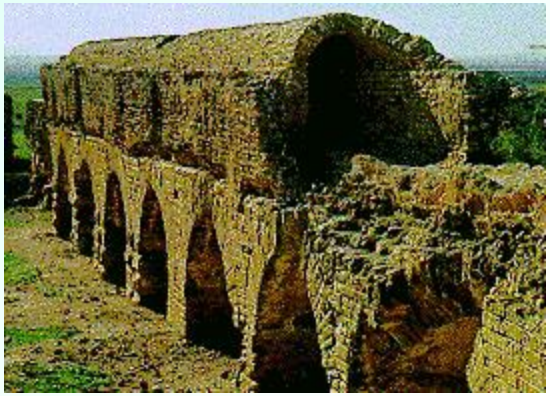
Calculated velocity vectors of the flow through the turbine rotor

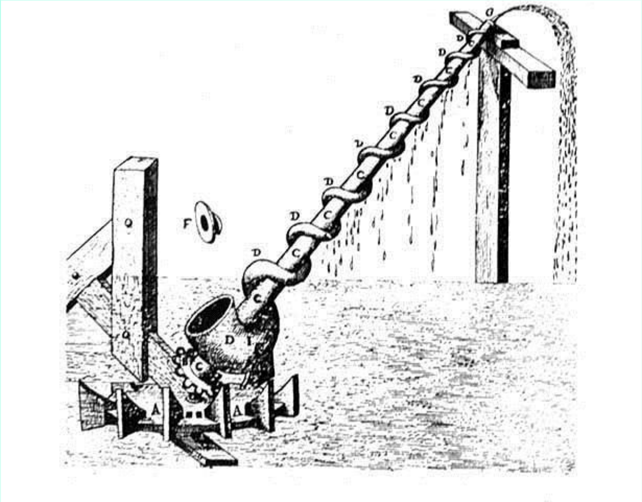
Review of the history of fluid dynamics

Antiquity

- Focus on waterworks: aqueducts, canals, harbors, bathhouses.
- One key figure was Archimedes - Greece (287-212 BC). He initiated the fields of static mechanics, hydrostatics, and pycnometry (how to measure densities and volumes of objects).
- One of Archimedes' inventions is the water screw, which can be used to lift and transport water and granular materials.

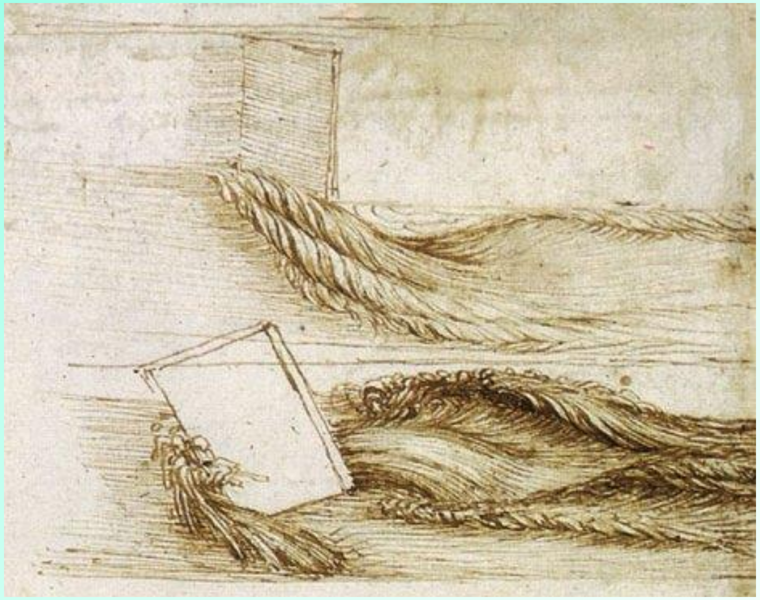






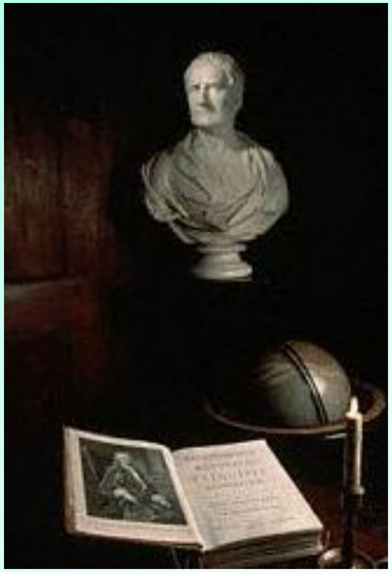
Leonardo da Vinci - Italy (1452-1519)

- Leonardo set out to observe all natural phenomena in the visible world, recognizing their form and structure, and describing them pictorially exactly as they are.
- He planned and supervised canal and harbor works over a large part of middle Italy. In France he designed a canal that connected the Loire and Saone.
- His contributions to fluid mechanics are presented in a nine part treatise (*Del moto e misura dell'acqua*) that covers the water surface, movement of water, water waves, eddies, falling water, free jets, interference of waves, and many other newly observed phenomena.



Isaac Newton - England (1643-1727)

- One of the most important figures in science.
- Most well known for his three laws of motion.
- His key contributions to fluid mechanics include:
  - The second law: F=m.a.
  - The concept of Newtonian viscosity in which stress and the rate of strain vary linearly.
  - The reciprocity principle: the force applied upon a stationary object by a moving fluid is equal to the change in momentum of the fluid as it deflects around the front of the object.
  - Relationship between the speed of waves at a liquid surface and the wavelength.

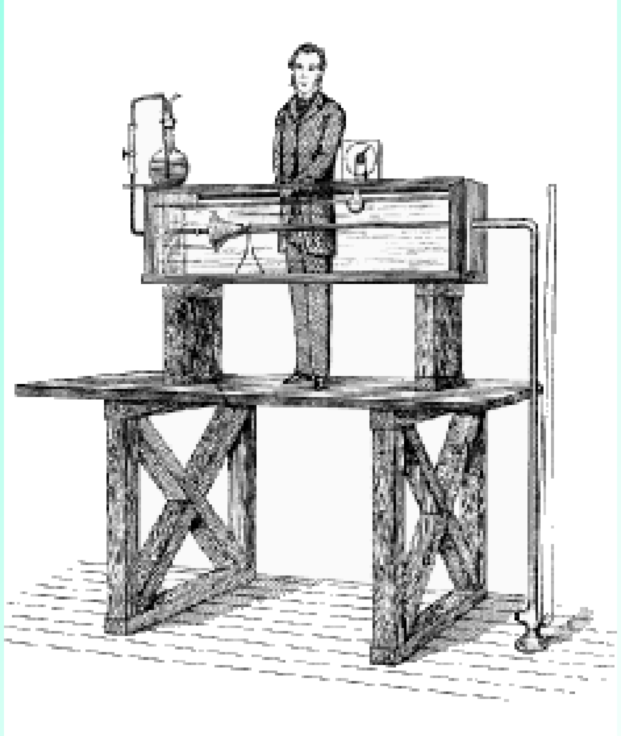


18th and 19th century

- During this period, significant work was done trying to mathematically describe the motion of fluids.
- Daniel Bernoulli (1700-1782) derived Bernoulli’s equation.
- Leonhard Euler (1707-1783) proposed the Euler equations, which describe conservation of momentum for an inviscid fluid, and conservation of mass. He also proposed the velocity potential theory.
- Claude Louis Marie Henry Navier (1785-1836) and George Gabriel Stokes (1819-1903) introduced viscous transport into the Euler equations, which resulted in the Navier-Stokes equation. This forms the basis of modern day fluid dynamics.
- Other key figures were Jean Le Rond d’Alembert, Siméon-Denis Poisson, Joseph Louis Lagrange, Jean Louis Marie Poiseuille, John William Rayleigh, M. Maurice Couette, and Pierre Simon de Laplace.

Osborne Reynolds - England (1842-1912)

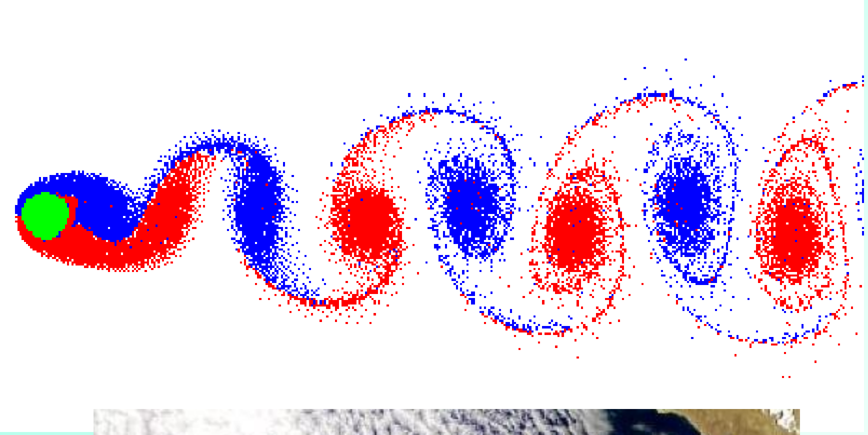
- Reynolds was a prolific writer who published almost 70 papers during his lifetime on a wide variety of science and engineering related topics.
- He is most well-known for the Reynolds number, which is the ratio between inertial and viscous forces in a fluid. This governs the transition from laminar to turbulent flow.

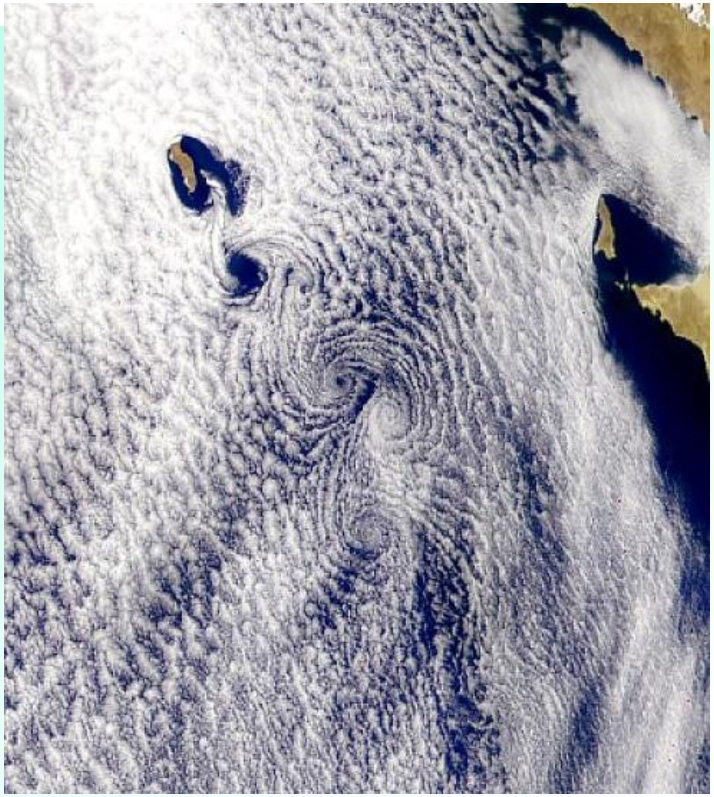


- Reynolds' apparatus consisted of a long glass pipe through which water could flow at different rates, controlled by a valve at the pipe exit. The state of the flow was visualized by a streak of dye injected at the entrance to the pipe. The flow rate was monitored by measuring the rate at which the free surface of the tank fell during draining. The immersion of the pipe in the tank provided temperature control due to the large thermal mass of the fluid.

First part of the 20th century

- Much work was done on refining theories of boundary layers and turbulence.
- Ludwig Prandtl (1875-1953): boundary layer theory, the mixing length concept, compressible flows, the Prandtl number, and more.
- Theodore von Karman (1881-1963) analyzed what is now known as the von Karman vortex street.
- Geoffrey Ingram Taylor (1886-1975): statistical theory of turbulence and the Taylor microscale.
- Andrey Nikolaevich Kolmogorov (1903-1987): the Kolmogorov scales and the universal energy spectrum.
- George Keith Batchelor (1920-2000): contributions to the theory of homogeneous turbulence.



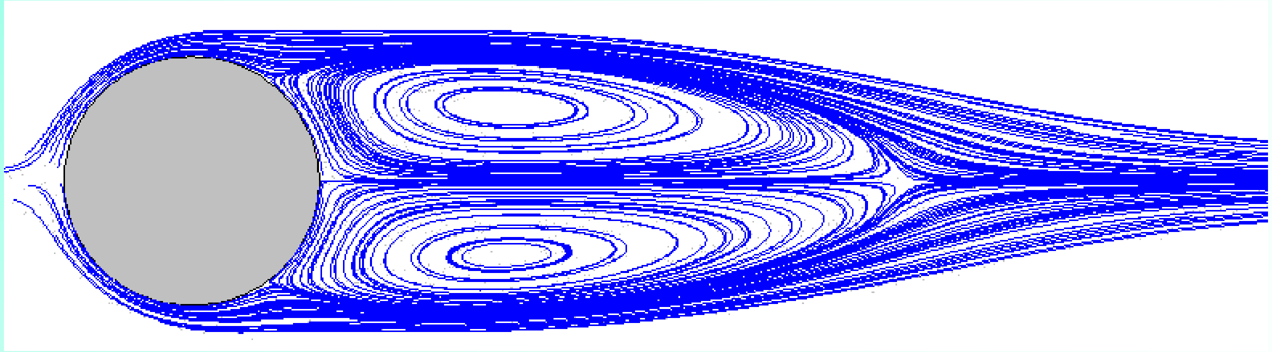


Lewis Fry Richardson (1881-1953)

- In 1922, Lewis Fry Richardson developed the first numerical weather prediction system.
  - Division of space into grid cells and the finite difference approximations of Bjerknes's "primitive differential equations."
  - His own attempt to calculate weather for a single eight-hour period took six weeks and ended in failure.
- His model's enormous calculation requirements led Richardson to propose a solution he called the “forecast-factory.”
  - The "factory" would have filled a vast stadium with 64,000 people.
  - Each one, armed with a mechanical calculator, would perform part of the calculation.
  - A leader in the center, using colored signal lights and telegraph communication, would coordinate the forecast.

1930s to 1950s

- Earliest numerical solution: for flow past a cylinder (1933).
    - A.Thom, ‘The Flow Past Circular Cylinders at Low Speeds’, Proc. Royal Society, A141, pp. 651-666, London, 1933
- Kawaguti obtains a solution for flow around a cylinder, in 1953 by using a mechanical desk calculator, working 20 hours per week for 18 months.
    - M. Kawaguti, ‘Numerical Solution of the NS Equations for the Flow Around a Circular Cylinder at Reynolds Number 40’, Journal of Phy. Soc. Japan, vol. 8, pp. 747-757, 1953.



1960s and 1970s

- During the 1960s the theoretical division at Los Alamos contributed many numerical methods that are still in use today, such as the following methods:
  - Particle-In-Cell (PIC).
  - Marker-and-Cell (MAC).
  - Vorticity-Streamfunction Methods.
  - Arbitrary Lagrangian-Eulerian (ALE).
  - k-ε turbulence model.
- During the 1970s a group working under D. Brian Spalding, at Imperial College, London, develop:
  - Parabolic flow codes (GENMIX).
  - Vorticity-Streamfunction based codes.
  - The SIMPLE algorithm and the TEACH code.
  - The form of the k-ε equations that are used today.
  - Upwind differencing.
  - ‘Eddy break-up’ and ‘presumed pdf’ combustion models.
- In 1980 Suhas V. Patankar publishes *Numerical Heat Transfer and Fluid Flow*, probably the most influential book on CFD to date.

1980s and 1990s

- Previously, CFD was performed using academic, research and in-house codes. When one wanted to perform a CFD calculation, one had to write a program.
- This is the period during which most commercial CFD codes originated that are available today:
  - Fluent (UK and US).
  - Fidap (US).
  - Polyflow (Belgium).
  - Phoenix (UK).
  - Star CD (UK).
  - Ansys/CFX (UK).
  - Flow 3d (US).
  - ESI/CFDRC (US).
  - SCRYU (Japan).
  - and more, see www.cfdreview.com.

Plan of the lectures

- **Introduction**: models of fluids, mathematical tools
- **Statics of fluids:** equilibrium of
fluid, hydrostatic force, floating and stability
- **Kinematics of flows**: general motion of a fluid element
- Mass conservation equation
- **Dynamics of flows:** momentum conservation equation.
- State of stress in the fluid
- Energy conservation equation. Balance of entropy
equation. Dissipation of mechanical energy
- Closed system of conservation equations for the
compressible and incompressible fluids. Initial and
boundary conditions
- Bernoulli equation
- **Similarity of flows**: dimensional analysis,
criteria of similarity

Plan of the lectures - **continued**

- **Laminar and turbulent flows**
- Boundary layers and wakes
- Aerodynamics of lifting foils
- **Cavitation** – physical principles, hydrodynamic consequences
- **Potential flows** – flow around a cylinder, Joukovsky theorem, modeling of potential flows
- Flows in closed channels
- Flows in open channels
- Gas dynamics: speed of sound, shock waves, flow through the de Laval nozzle
- Written final test