Fluid Dynamics

Chapter 1

Introduction

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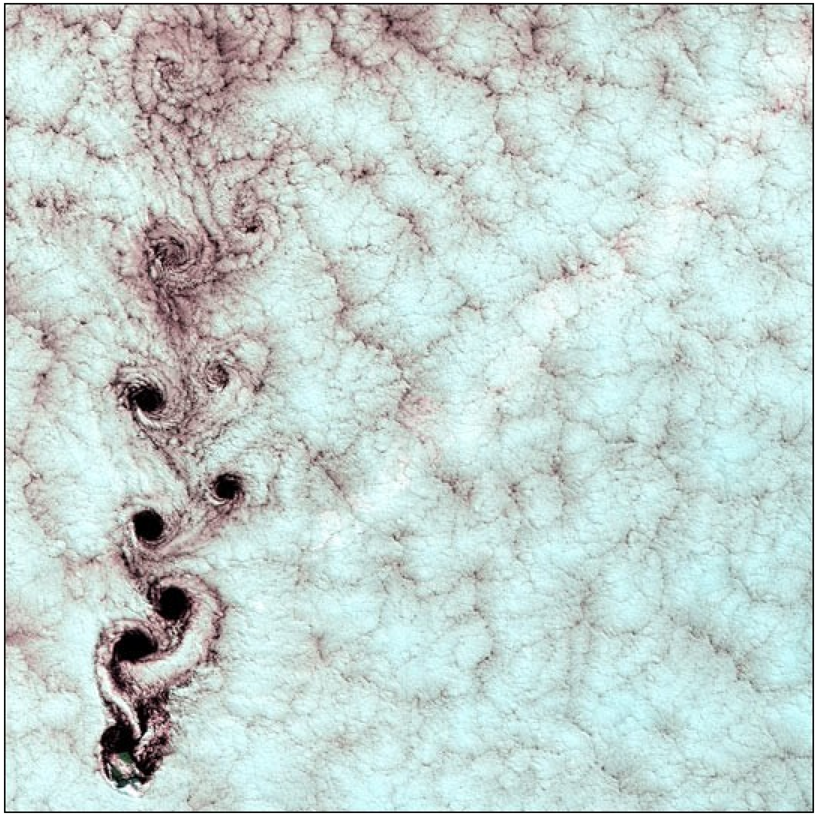
Why Fluid Dynamics?

- Watching a flow is fascinating:
  - clouds
  - smoke
  - water vortex

- Structures are formed, caused by the dynamic of a flow



[https://eros.usgs.gov/image-gallery/earth-as-art-1/karman-vortices]

Why Fluid Dynamics?

- It is fascinating to watch flows, even in big scales.

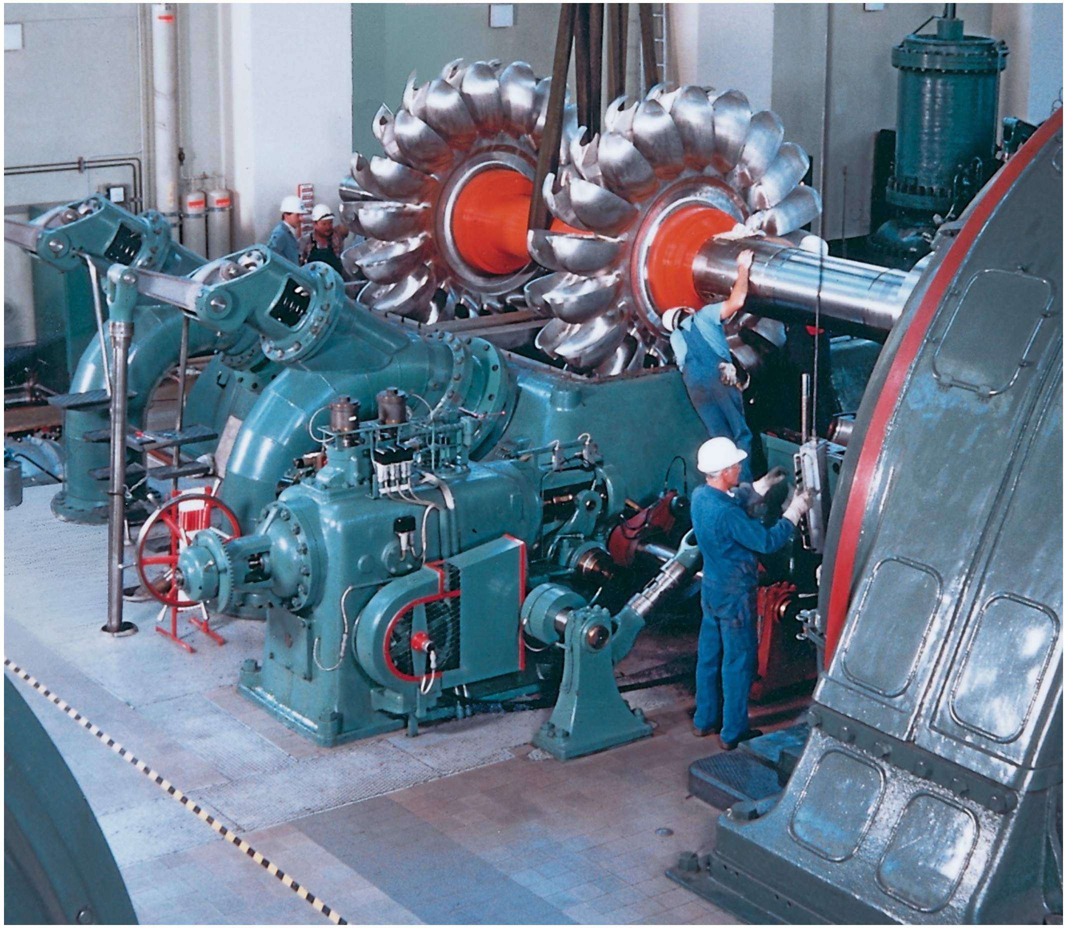
http://hubblesite.org/newscenter/archive/releases/2007/16/image/a/

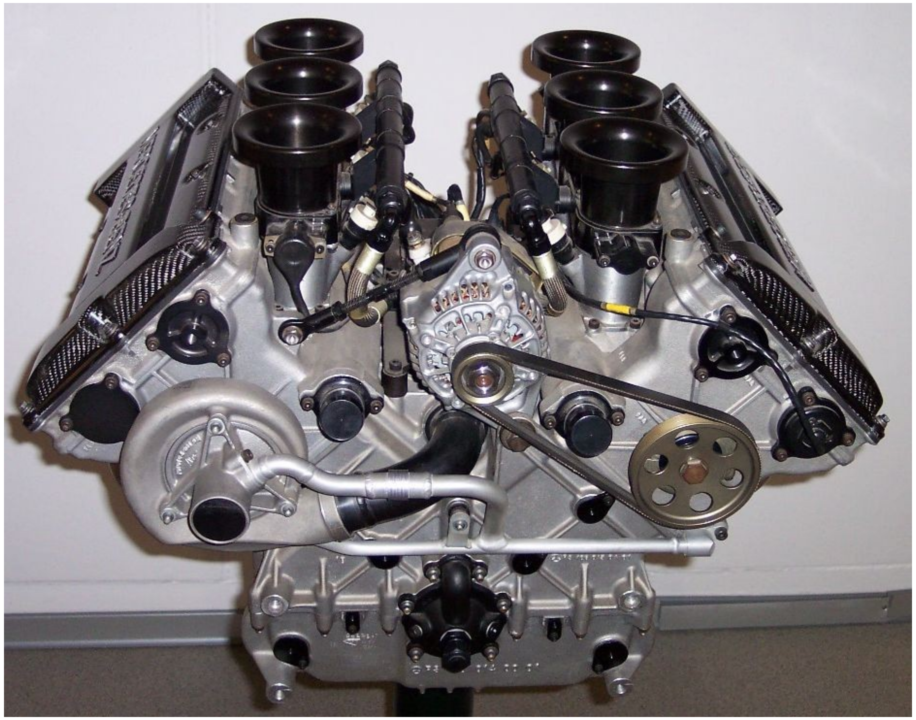
- dimensions from left to right: 50 light years

Why Fluid Dynamics?

- It is beneficial to understand fluid dynamics.
  - Engines
  - Power Plants
  - ...

https://de.wikipedia.org/wiki/Datei:Walchenseewerk_Pelton_120.jpg





https://de.wikipedia.org/wiki/Datei:Mercedes_V6_DTM_Rennmotor_1996.jpg

Why Fluid Dynamics?

– Wind Turbines

https://de.wikipedia.org/wiki/Datei:Windkraftanlage_Dimension.jpg

https://commons.wikimedia.org/wiki/File:Windpark_Berching01.JPG

Why Fluid Dynamics?

- It is beneficial to understand fluid dynamics.
  - Aerodynamics

https://commons.wikimedia.org/wiki/File:Airbus_A380_inbound_ILA_2006.jpg

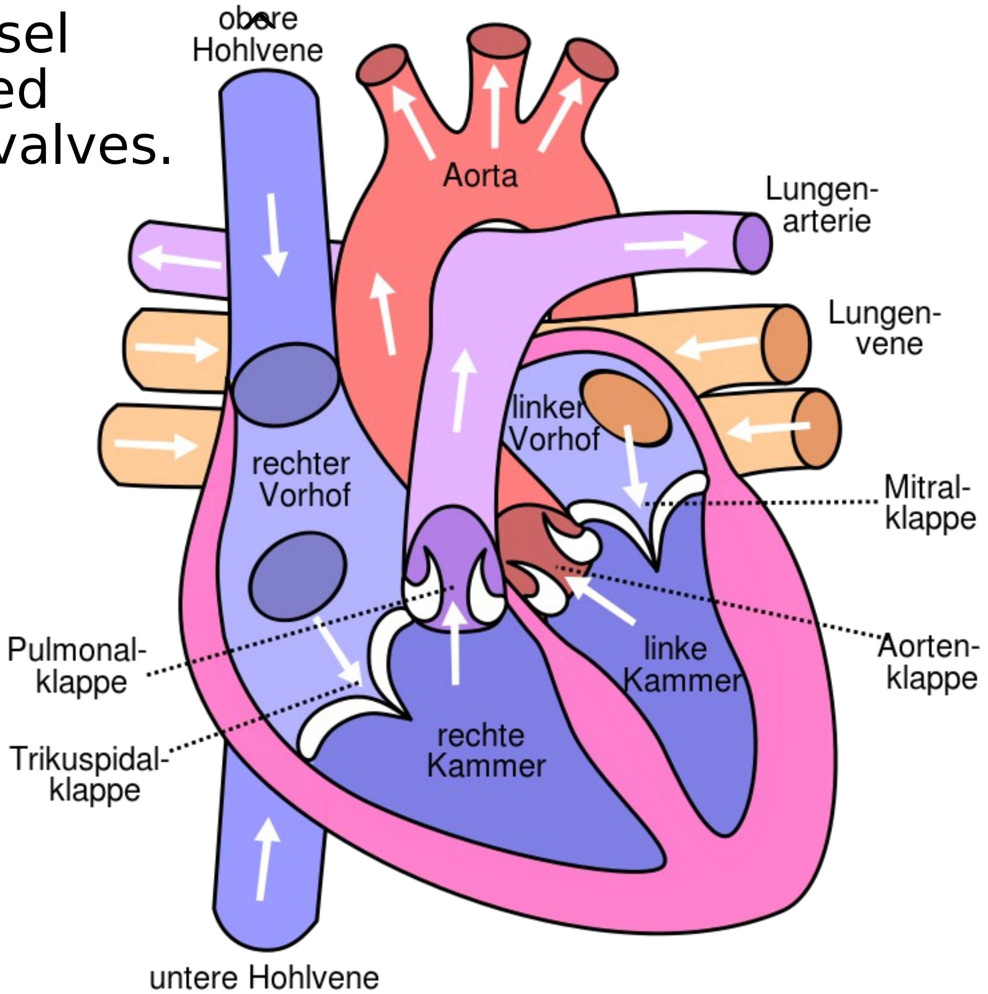
Why Fluid Dynamics?

- It is beneficial to understand fluid dynamics.
  - Aerodynamics

https://commons.wikimedia.org/wiki/File:Airplane_vortex_edit.jpg

Why Fluid Dynamics?

- It is beneficial to understand fluid dynamics.
  - Abrasion
  - Strong currents affect the vessel walls. This has to be considered when constructing e.g. heart valves.



https://commons.wikimedia.org/wiki/File:Diagram_of_the_human_heart_%28cropped%29_de.svg

Why Fluid Dynamics?

- It is beneficial to understand fluid dynamics.
  - combustion

https://commons.wikimedia.org/wiki/File:Fire02.jpg

Why Fluid Dynamics?

- It is beneficial to understand fluid dynamics.
  - chemistry

https://commons.wikimedia.org/wiki/File:Slovnaft_-_residual_hydrocracking_%28RHC%29.jpg

Definitions

- Fluid Dynamics
  Fluid Mechanics
  Flow Mechanics
  - mechanics of flowing matter, so called fluids, and the effecting forces
  - differentiation of:
    - stationary & static vs. streaming & dynamic
  - most important case: water as fluid
    - hydrostatics vs. hydrodynamics
- Compressible and incompressible flows
  - criteria: difference in density affects flow
  - compressible: e.g. rapid gas flows
  - incompressible: e.g. slow gas flows, flowing water

First Definition

- Fluid element
  - It is easier to understand flows, if you first observe a small partial volume.
  - It should be so small that physical variables can be assumed as constant (e.g. density, velocity, pressure).
  - But it needs to be very big in relation to atoms or molecules in order to be considered as continuum.
  - This is what we call a fluid element.

First Definition

- Inner friction of fluids
  - Differences in velocity cause shearing in fluids, to be more precise, the shear rate
  - The inner friction in fluids therefore causes shearig forces
  - In other words: friction forces in between the fluid elements
- Newtonian Fluids:
  shearing forces are proportional to the shear rate
  - gases
  - water
- Non-Newtonian Fluids:
  shearing forces are not proportional to the shear rate
  - paint
  - toothpaste
  - sand in water

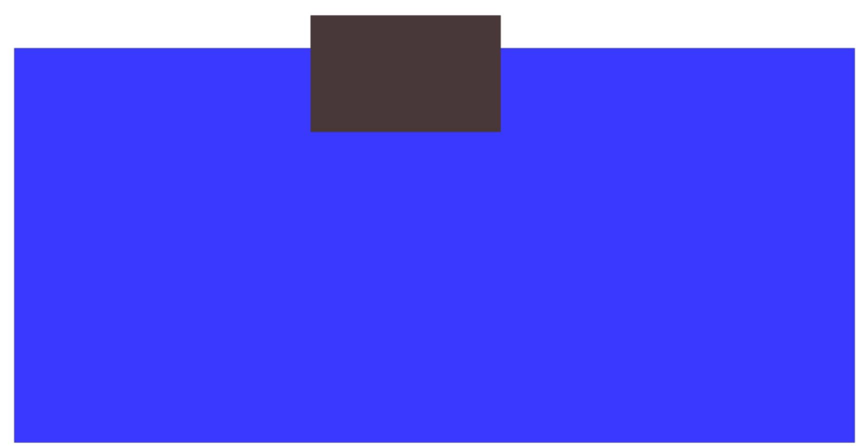
History

- Fluid Dynamics is a long existing science.

  Some historical examples:

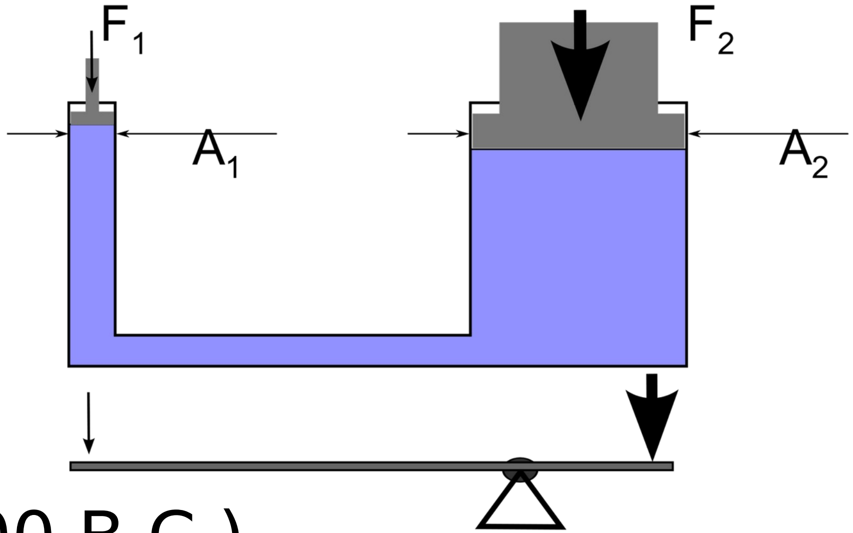
- Drainage and waste water-systems
  - Mohenjo-Daro (river Indus, Pakistan, ca. 2000 B.C.)
  - Cloaca Maxima (Rome ca. 600 B.C.)

- Archimedes of Syracuse (287-212 B.C.)
  - Fundamentals of hydrostatic and understanding of buoyancy

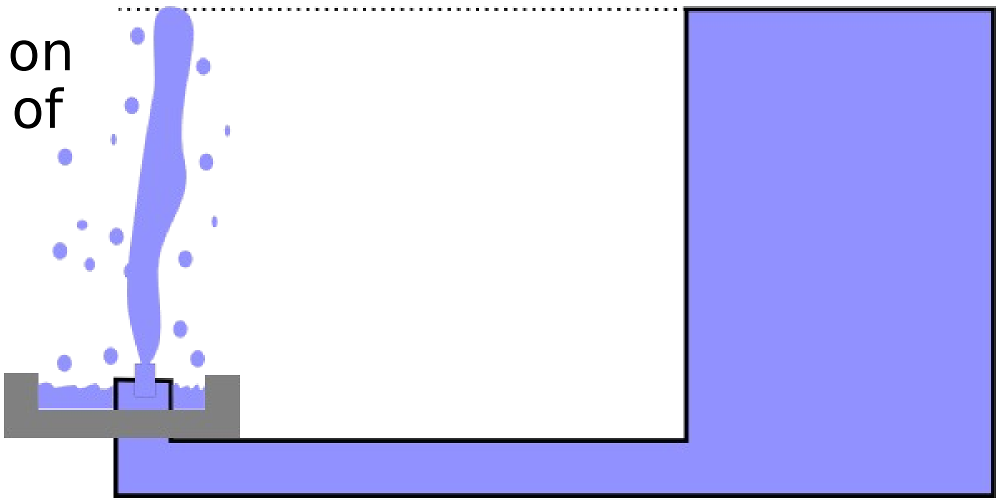


History

- School of Alexandria (ca. 120 B.C.)
  - construction of hydraulic machines



- Sextus Julius Frontinus (ca. 100 B.C.)
  - A stream coming from an opening doesn‘t only depend on the opening itself. The height of the water reservoir is an important parameter too.



History

- Islamic physicists
  - Abu Rayhan Biruni (973-1048) and Al-Khazini (1115-1130) determine specific masses with the help of mathematical theories of proportions an infinitesimal calculus.
- Leonardo da Vinci (1452-1519)
  - Redirection of rivers
  - Hydraulic pumps
  - Helix Pteron (helicopter)
- Benedetto Castelli (1577 - 1643)
  Evangelista Torricelli (1608 - 1647)
  - Students of Galileo
  - Applied the discoveries of Galileo on hydrodynamics. Invention of the barometer (among other things).

History

- Blaise Pascal (1623-1662)
  - fundamentals of hydrostatics
  - verification through experiments
  - Eponym of the unit of pressure
- Edme Mariotte (1620 – 1684)
  Domenico Guglielmini (1655 – 1710)
  - thorough experiments of flow mechanics
- Sir Isaac Newton (1643-1727)
  - description of effects of friction and viscosity
- Daniel Bernoulli (1700-1782)
  - Bernoulli principle for ideal fluids: Increase of velocity causes decrease of pressure or reduction of potential energy.

History

- Leonard Euler (1707-1783)
  - Mathematical equations for flow (differential equations, mathematical term of fields)
- Jean le Rond d’Alembert (1717-1783)
  - Research on equilibrium and movement of fluids; inertia
- Joseph-Louis Lagrange (1717-1783)
  - Research in the field of mathematics and mechanics. The lagrange principle of a continuum dates back to him
- Claude-Louis Navier (1785-1838)
  - Deduced the general equation of a three dimensional movement of Newtonian Fluids

History

- Hermann von Helmholtz (1821-1894)
  - Worked on field theories (fluids and electromagnetism) and formulated basic statements about vortexes
- Osborne Reynolds (1842-1912)
  - Studies about laminar and turbulent pipe flow

    → Reynolds-Number
- Ludwig Prandtl (1875-1953)
  - Pioneer in the development of a mathematically strict theory of the boundary layer of viscous fluids
- Theodore von Kármán (1875-1953)
  - Research on aerodynamics, especially on supersonic flows

Physical Quantities for the Description of Fluids

- Density ρ
  - Weight of a fluid per unit volume
  - Alternative: specific weight

$$\rho = \frac{m}{V}, \mathrm{in}\, \frac{\mathrm{kg}}{\mathrm{m}^3}$$

- Typical numbers in kg/m³:
  - Helium 0.179 (1 bar, 0°C)
  - H_2 0.089 (1 bar, 0°C)
  - Air 1.29 (1 bar, 0°C)
  - Water ca. 1000 (1 bar, 20°C)

Physical Quantities for the Description of Fluids

- Specific volume *v*
  - The volume required for a unit mass of a fluid
  - Reciprocal of density

$$v = \frac{1}{\rho} = \frac{V}{m} \quad \text{in} \quad \frac{\mathrm{m}^3}{\mathrm{kg}}$$

  - *v* usually used for velocity
  - This lecture will only use density!

Physical Quantities for the Description of Fluids

- Pressure p
  - Pressure in a fluid is a force per area, perpendicular to a imaginary or given area

$$p = \frac{F}{A} \quad \text{in} \frac{\mathrm{N}}{\mathrm{m}^2} = \mathrm{Pa}$$

  - Pressure in a fluid is a Scalar
  - Overpressure ≙ pressure relative to a reference value
  - Atmospherical pressure at sea level is a typical parameter

    (ca. 1 bar = 100.000 Pa)

Physical Quantities for the Description of Fluids

- Velocity ***v***
  - An objects rate of change of its position per time
  - **r** ≙ position of a fluid element. The velocity is the time derivation of the position:

$$\mathbf{v}=\frac{\mathrm{d}\,\mathbf{r}}{\mathrm{d}\,t}\quad \mathrm{in}\,\frac{\mathrm{m}}{s}$$

  - Velocity has an orientation → vector
  - In a three-dimensional Cartesian coordinate system, the components are often referred to as:

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix}=\frac{\mathrm{d}}{\mathrm{d}\,t}\begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

Physical Quantities for the Description of Fluids

- Flow without viscosity
  - In this lecture often *flow without friction is considered*
  - It is also called *ideal flow*
  - This is an assumption! It means:

    inertial forces $\ggg$ frictional forces

  - It makes calculations easier and mistakes unlikely
  - But this model does not work for real flow
  - Nevertheless, it is helpful for understanding basic flow phenomena

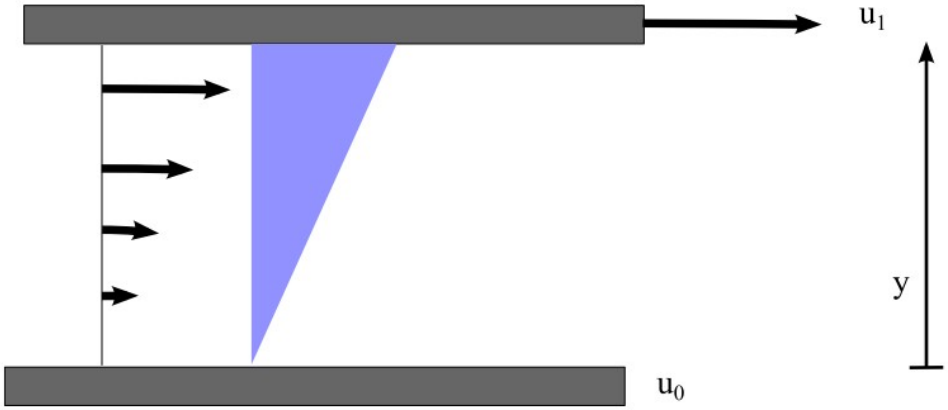
Physical Quantities for the Description of Fluids

- Viscosity
  - Inner friction: Resistance of a fluid against deformation due to shear movement
  - Difference in velocity causes a shear deformation rate
  - Shear deformation rate causes shear stress due to inner friction.
    - Note: the unit of stress is defined by force per area [N/m^2]
  - The relationship between the shear deformation rate and the shear stress is a material property, the viscosity
  - Before we take a look at the definition,

    a thought experiment …

Physical Quantities for the Description of Fluids

- Thought experiment about viscosity:
  Flow between two parallel plates



$$u_0 \neq u_1$$

  - Fluid elements in direct contact to the plates have the same velocity like the plates (no-slip condition)
  - If the distance between the plates is small, the velocity of the fluid between the plates is a linear function of *y*
  - Constant change of velocity in y-direction (*du/dy*)
  - The force required to move the plate can be measured
  - The shear stresses τ can be calculated based on the measured force (force/area).

Physical Quantities for the Description of Fluids

- For many important fluids, shear stress τ is proportional to the gradient of velocity *du/dy*.
- The proportionality factor μ is called *dynamic viscosity*.
  - equation:

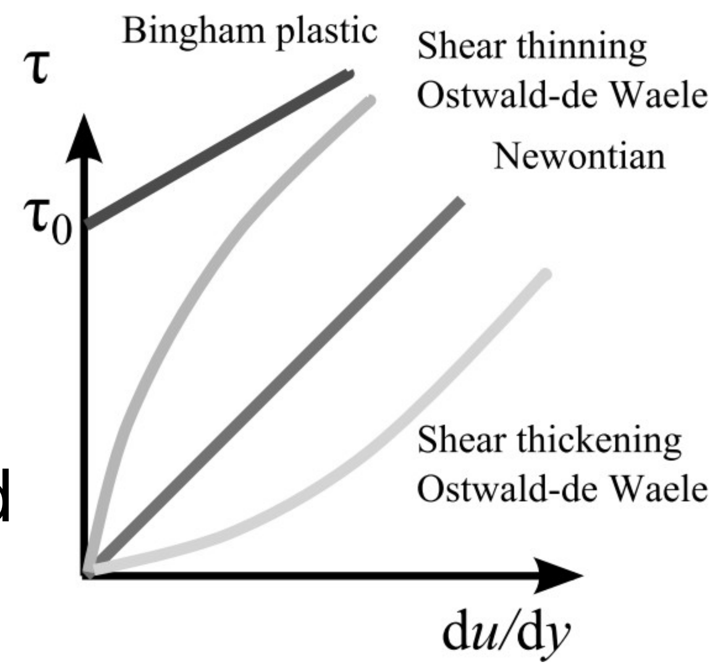
$$\tau = \mu \frac{\mathrm{d}u}{\mathrm{d}y} \quad \text{with } \mu \text{ in } \frac{\mathrm{kg}}{\mathrm{m \cdot s}} \text{ or } \mathrm{Pa \cdot s}$$

- Fluids with these properties are called *Newtonian Fluids*
- Alternative: kinematic *viscosity* ν

$$\nu = \frac{\mu}{\rho} \quad \text{in} \quad \frac{\mathrm{m}^2}{\mathrm{s}}$$

Physical Quantities for the Description of Fluids

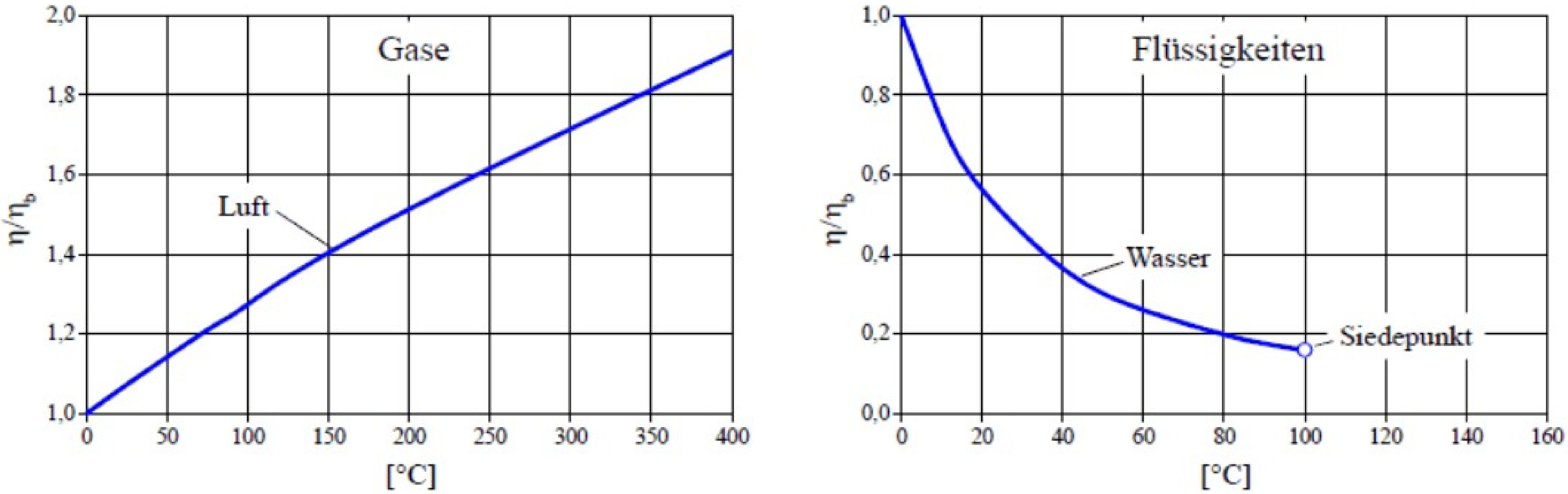
- Focus of this lecture: Newtonian Fluids
- Important Non-Newtonian Fluids
  - blood, paint, toothpaste
- There are lots of strange things!
  - Bingham-Fluids: Acts like a solid to the point it reaches a critical shear rate From then on it flows
- Viscosity is linked to pressure and especially to temperature:
  - Liquids:
    Viscosity <u>decreases</u> with an increase in temperature
  - Gases:
    Viscosity <u>increases</u> with an increase in temperature



Video – Non-Newtonian Fluid (Shear Thickening)

https://www.youtube.com/watch?v=G1Op_1yG6lQ

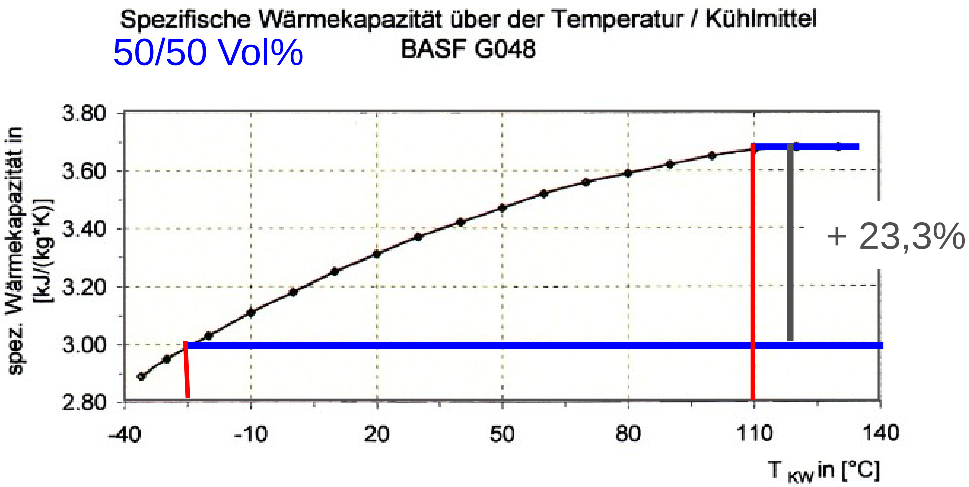
Viscosity of Fluids vs. temperature

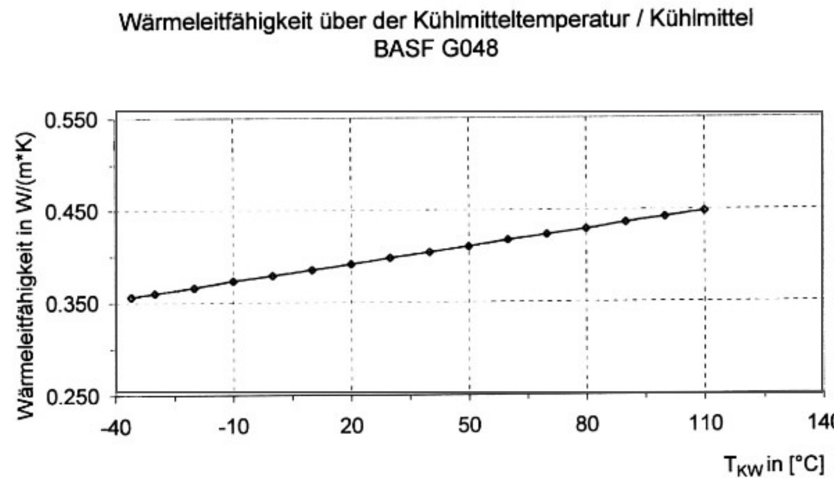


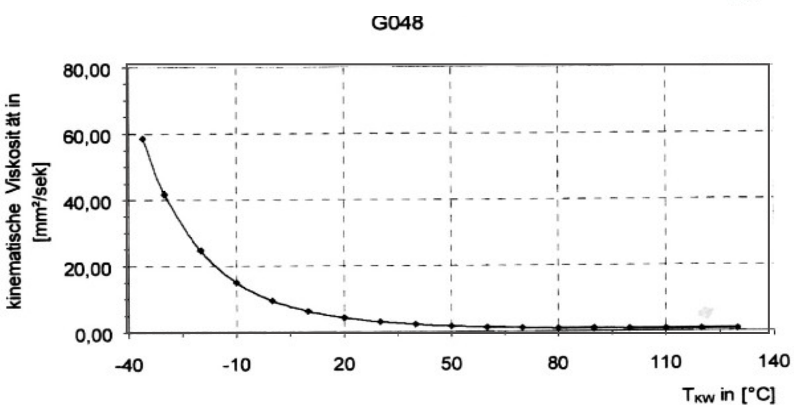
Stroemung-berechnen.de

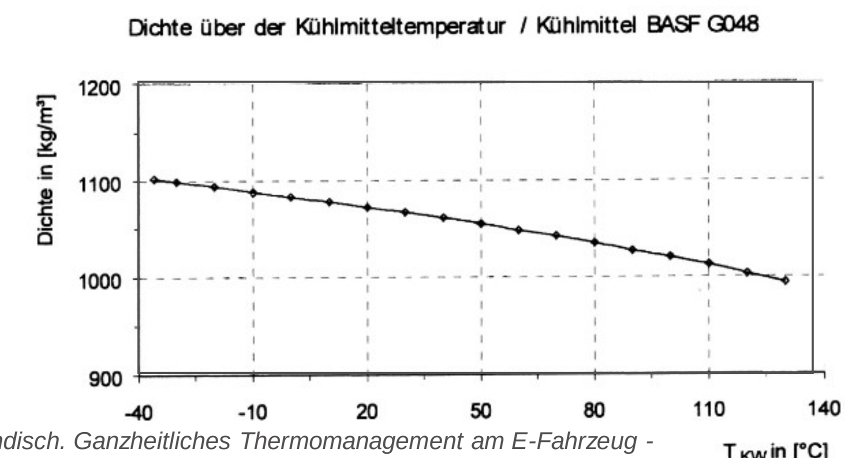
Physical Properties – Impact of Temperature

Bedenken sie bei genauen Berechnungen, dass alle Stoffgrößen temperaturabhängig sind.
z.B. für Frostschutz/Wasser-Gemische









Herbert Windisch. Ganzheitliches Thermomanagement am E-Fahrzeug - Inhouse-Seminar für die Technik-Akademie der Daimler AG. 2019

Video – High and Low Viscous Fluids

https://en.wikipedia.org/wiki/Viscosity#/media/File:Viscosities.gif