

Energies, fluids & processes – Laboratory

HSLU, Semester 2

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1 Introduction to energies, fluids, and processes

Energy exists in different forms and can neither be destroyed nor generated, but only transformed.

1.1 Energy forms

- Potential energy: $E = mgh$
- Kinetic energy: $E = \frac{1}{2}mv^2$
- Thermal energy: $E = mc_p\Delta T$
- Light energy: $E = h\nu$

- Chemical energy: $E = mH$
- Electrical energy: $E = k\frac{q_1q_2}{r}$
- Nuclear energy: $E = \Delta mc^2$
- Pressure energy (acoustic): $E = \frac{mp}{\rho}$

2 Fluids as energy carriers

2.1 Fluid definition

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2.1.1 Properties of a fluid

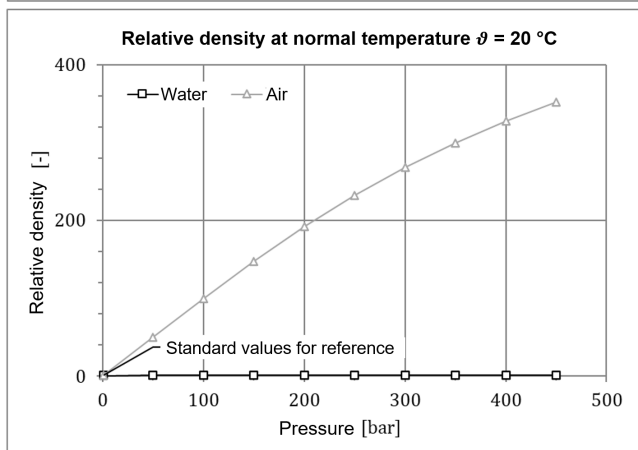
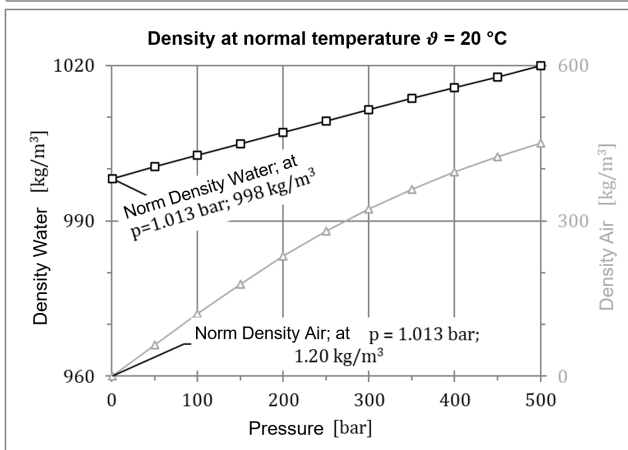
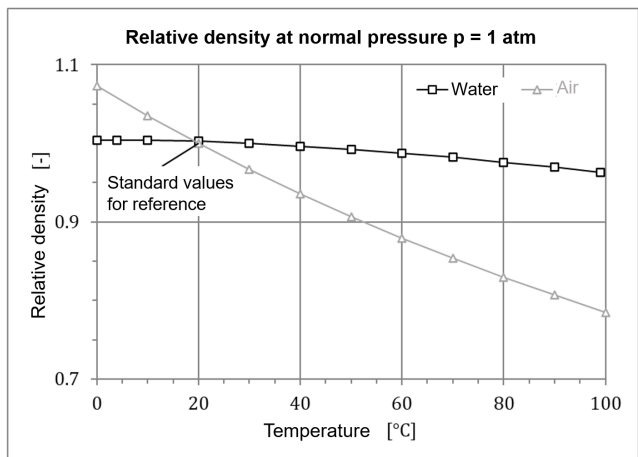
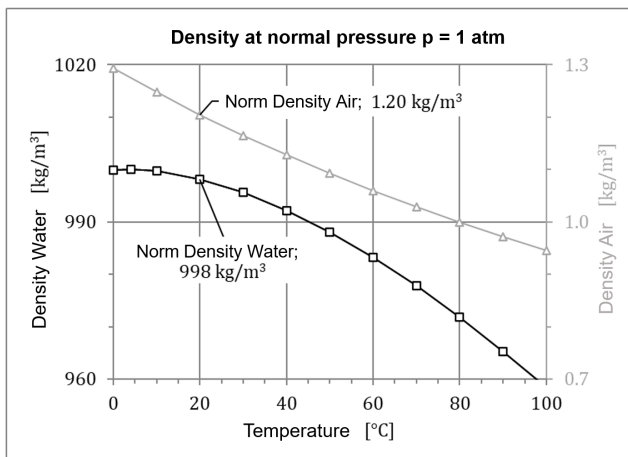
Density ρ

Density is a measure of working potential of a fluid:

$$\rho \triangleq \frac{m}{V} \left[\frac{\text{kg}}{\text{m}^3} \right]$$

where:

- m = mass;
- V = volume.



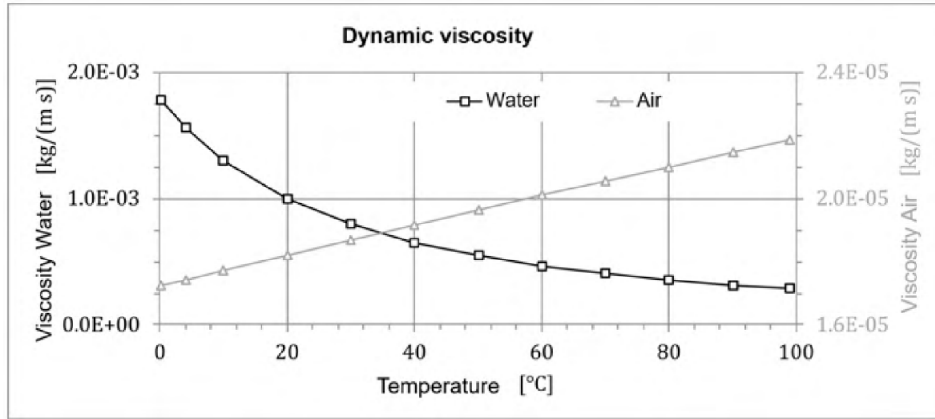
Kinematic viscosity ν

Viscosity is a measure of the specific loss capacity of a fluid:

$$\nu \triangleq \frac{\mu}{\rho} \left[\frac{N \cdot s}{m^2} = Pa \cdot s \right]$$

where:

- μ = dynamic viscosity
- ρ = density



Viscosity of a liquid fluid **decreases** with increasing temperature, while viscosity of a gaseous fluid **increases** with increasing temperature.

Remark: $\nu \propto \frac{1}{T}$

Compressibility

An increase in pressure on a given fluid mass causes compression and thus lead to a reduction in volume.

Mach number is a non-dimensional number that relates the fluid velocity to the sound velocity (in air):

$$M = \frac{u}{c}$$

Note: Since Mach number normally is very small, it can be neglected from calculations.

2.2 Real and ideal fluids

2.2.1 Real fluid

All fluids are real fluids and have real fluid properties. This means that they are compressible and exhibit frictional losses during the flow process. Physically, this means they have a viscosity $\nu > 0$.

2.2.2 Ideal fluid

A fluid can be simplified as an ideal fluid assuming a constant density (incompressible) and a viscosity $\nu = 0$ (frictionless).

2.3 Technical application flows

2.3.1 Internal flow (flow through)

Fluids that flow through a body (pipes, ducts, machines, ...).

Internal losses (such as friction, pressure, and fluid force) are relevant for the calculation of internal flows.

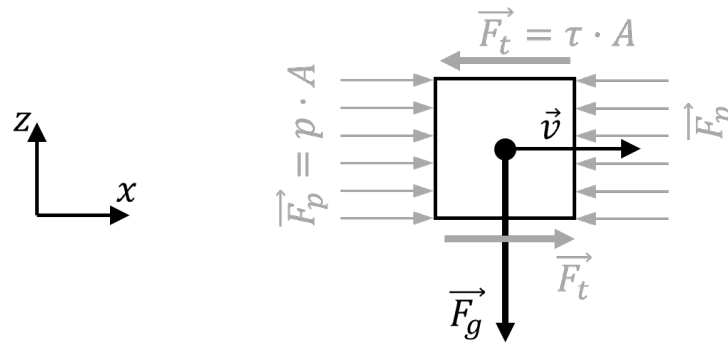
2.3.2 External flow (flow around)

Fluids that flow around bodies (motor vehicles, aircraft, buildings, ...).

External losses (such as velocity, pressure, density, and temperature near and far from bodies) are relevant for the calculation of external flows and aerodynamics.

2.4 Forces for fluid motion

2.4.1 1D flow in x direction



Surface forces act on the interfaces of a fluid body and are introduced by direct contact of the environment. Fluids also cause surface forces on their surroundings.

Forces decomposition

Surface forces:

- $F_t = \tau \cdot A$: shear force (tangential to the surface);
- $F_p = p \cdot A$: fluid pressure force.

Body forces:

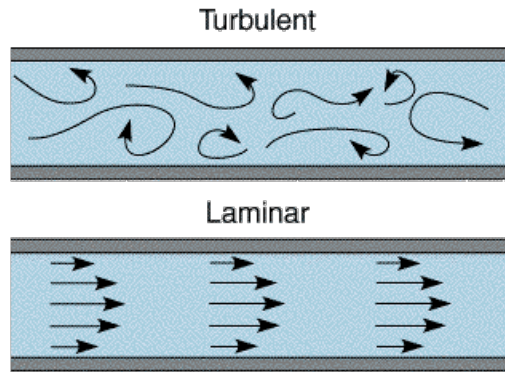
- $F_g = F \cdot g \cdot \cos \theta$: gravitational force (perpendicular to the surface);
- $F_n = -F \cdot g \cdot \cos \theta$: normal force (perpendicular to the surface);
- F_v : inertial force.

Inertial forces will always destabilize the flow field.

Viscous forces will always stabilize the flow field.

2.5 Laminar and turbulent flow

A flow that flows in an orderly manner is called laminar flow. In contrast, flows with vortices are called turbulent flow.



2.5.1 Reynolds number

Reynolds number is a non-dimensional number that makes the distinction between laminar and turbulent flows possible. The Reynolds number is given by the relation between inertial forces and viscous forces:

$$Re = \frac{v \cdot L}{\nu}$$

where:

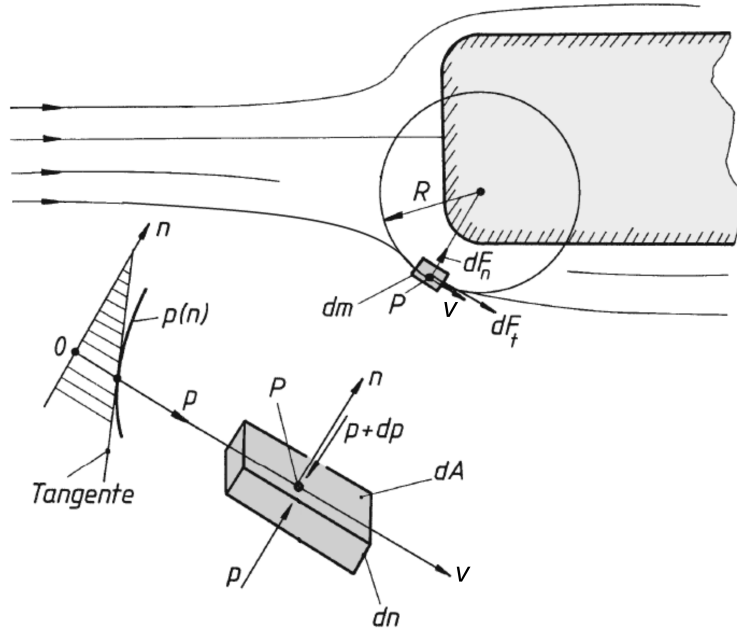
- v : velocity $\left[\frac{\text{m}}{\text{s}}\right]$;
- L : characteristic length [m];
- ν : kinematic viscosity $\left[\frac{\text{m}^2}{\text{s}}\right]$.

2.5.2 Critical Reynolds number

The transition from laminar to turbulent flow and it's determined by the critical Reynolds number:

$$\begin{array}{l} Re > 2300 \Rightarrow \text{turbulent flow} \\ Re = 2300 \Rightarrow \text{critical point} \\ Re < 2300 \Rightarrow \text{laminar flow} \end{array}$$

2.5.3 Flow pressure in curvatures



Force balance of the system:

$$dF_n = -dA ((p + dp) - p) = dm \cdot a_n$$

where:

- R : radius of the curvature
- $a_n = \frac{v^2}{R}$
- $dm = \rho \cdot dA \cdot dn$

Pressure in the curvature formulation:

$$\frac{dp}{dn} = -\rho \cdot \frac{v^2}{R}$$

2.6 Compressible and incompressible flow

2.6.1 Compressible flow

In compressible flows, the density of the fluid changes so much that the density change cannot be neglected.

2.6.2 Incompressible flow

Fluid flows can be considered incompressible at sufficiently low velocities. For ideal gases, the speed of sound can be calculated from the state variables and the fluid properties to:

$$c = \sqrt{\kappa \cdot R_i \cdot T}$$

If the Mach number is below 0.3, the gas flow can be considered incompressible.

$$Ma = \frac{v}{c} = \frac{v}{\sqrt{\kappa \cdot R_i \cdot T}}$$

where:

- v : fluid velocity $\left[\frac{m}{s}\right]$;
- c : speed of sound $\left[\frac{m}{s}\right]$;

- κ : isentropic exponent $[-]$;
- R_i : individual gas constant $\left[\frac{J}{kg \cdot K} \right]$;
- T : temperature $[K]$.

3 Mass conservation

4 Energy conservation

$$\frac{dE}{dt} = \underbrace{\sum P + \sum \dot{Q}}_{\text{Energy flow across system boundary}} + \underbrace{\sum_{in} \left[\dot{m}^{\swarrow} \cdot \left(h^{\swarrow} + \frac{v^{2\swarrow}}{2} + g \cdot z^{\swarrow} \right) \right]}_{\text{Energy transfer mass}} - \underbrace{\sum_{out} \left[\dot{m}^{\nearrow} \cdot \left(h^{\nearrow} + \frac{v^{2\nearrow}}{2} + g \cdot z^{\nearrow} \right) \right]}_{\text{Energy transfer escaping mass}}$$

where:

- E : total energy of the system;
- P : power;
- \dot{Q} : heat flow;
- \dot{m} : mass flow entering/leaving the system;
- h : enthalpy of the entering/leaving mass flow;
- v : velocity of the entering/leaving mass flow;
- z : height of the entering/leaving mass flow.

4.1 Bernoulli equations

4.1.1 Energy conservation

$$0 = \sum_{in} \left[\dot{m}^{\swarrow} \cdot \left(h^{\swarrow} + \frac{v^{2\swarrow}}{2} + g \cdot z^{\swarrow} \right) \right] - \sum_{out} \left[\dot{m}^{\nearrow} \cdot \left(h^{\nearrow} + \frac{v^{2\nearrow}}{2} + g \cdot z^{\nearrow} \right) \right]$$

4.1.2 ...

4.2 1st law of thermodynamics: General energy conservation equation

In the case of stationary flow:

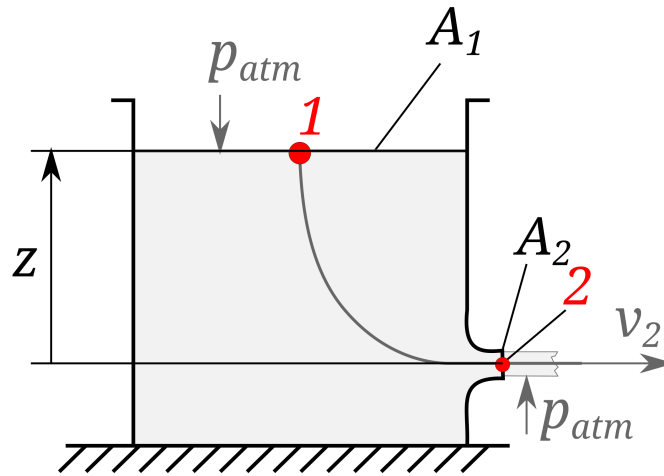
4.3 Examples of Bernoulli equation

4.3.1 Horizontal streamtube

Since the pipe is horizontal, $z_1 = z_2$, and since point ② is a stagnation point, we have $\frac{v_2^2}{2} = 0$, then the specific form of Bernoulli can be simplified to:

$$p_1 + g \cdot \frac{v_1^2}{2} = p_2$$

4.3.2 Flow out of a tank



Setting the reference point at the top of the tank, we have $z_1 = 0$ and $z_2 = z$, which brings the velocity at the top of the tank to be zero, so $\frac{v_1^2}{2} = 0$. Since $p_1 = p_2 = p_{atm}$, the specific form of Bernoulli can be simplified to:

$$g \cdot z = \frac{v_2^2}{2} \Rightarrow v_2 = \sqrt{2gz}$$

The difference between the pressure p_2 at the exit of the tank and the atmospheric pressure p_{atm} changes because of the contraction number α :

$$\alpha = \frac{A_2^*}{A_2} \dots\dots$$

4.4 Hydrostatic equation

The hydrostatic equation is a special case of the Bernoulli equation, where the velocity is zero:

$$p_2 = p_1 + \rho g z_1$$

5 Energy grade line diagram