Hydromechanics, biophysics of blood and respiration

Properties of gas and liquid

- Mechanics of fluid
  - Aeromechanics
    - Aerostatics
    - Aerodynamics
  - Hydromechanics
    - Hydrostatics
    - hydrodynamics

Gas properties

- Do not have their own shape and volume
- Compressible
- $E_k > E_p$
- Convective heat transfer
- Gas leads electric current under certain conditions

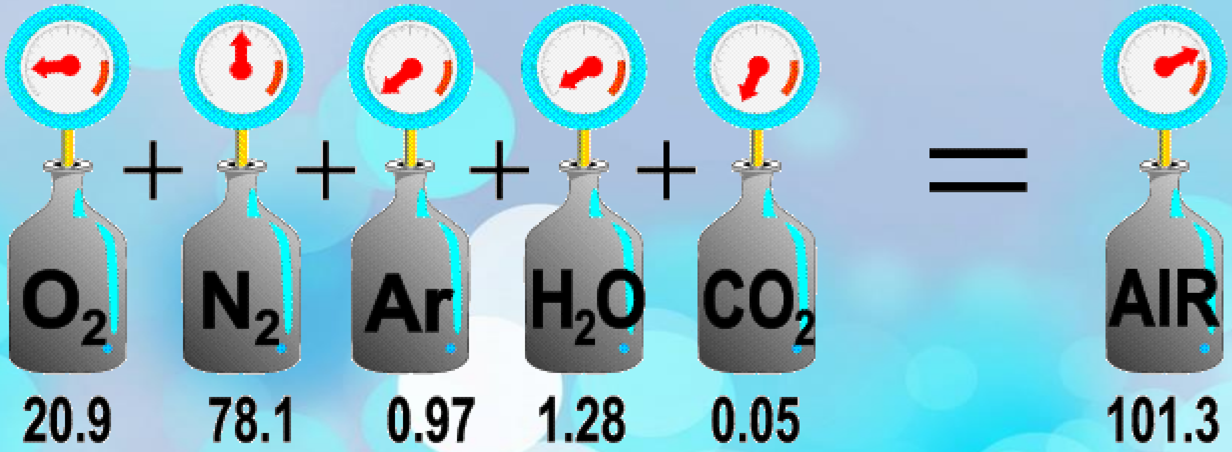
Gas properties

- Gas volume
  - At 0 °C and 101 325 Pa volume of 1 mol is equal to 22,414 dm^3
  - IUPAC conditions: at 0 °C and 100 000 Pa volume of 1 mol is equal to 22,71 dm^3

Gas properties

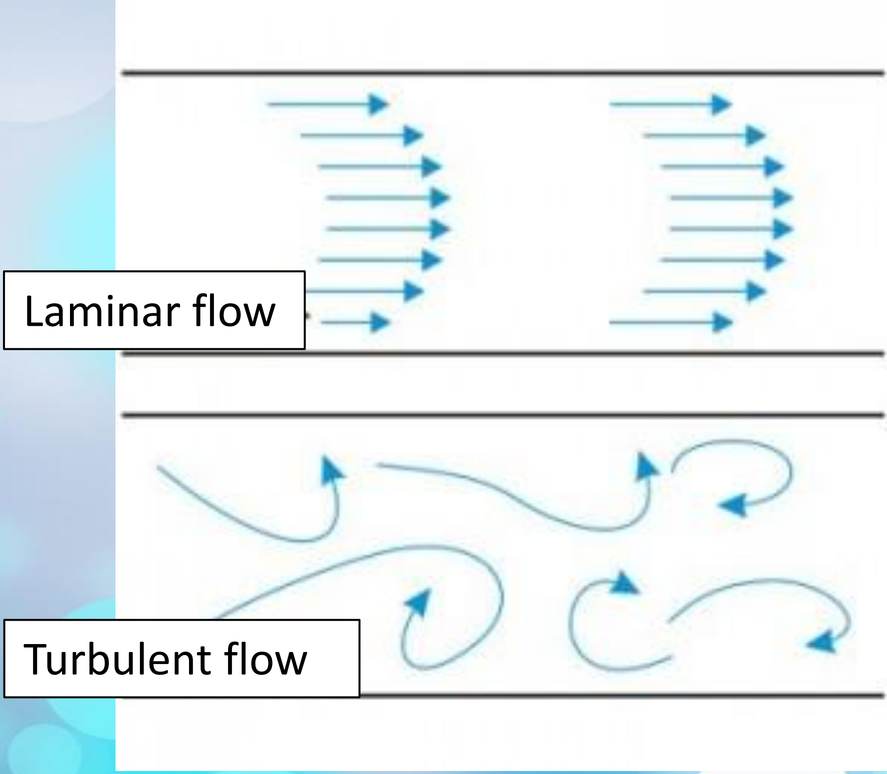
- Dalton‘s Law
  - In a mixture of non-reacting gases, total pressure of the gaseous mixture is equal to the sum of partial pressures of individual gases.

$$P = p1 + p2 + p3 + \ldots + pn$$



Gas properties

- Air flow



Laminar flow

Turbulent flow

Respiration biophysics

Respiration

- Intake of O_2 to tissue and dispose of CO_2 from organism
- External respiration
  - Gas exchange between alveolar gas and blood
- Internal respiration
  - Gas exchange between blood and tissue

External respiration

1. Pulmonary ventilation
2. Distribution
3. Diffusion
4. Perfusion

1. Pulmonary ventilation

- Inspiration – active action; contraction of respiration muscles (diaphragm)
  - Pressure gradient to lungs; air is drawn in
  - Action happens against resistance
    - Elasticity of pulmonary tissue
    - Surface tension of alveoli (Laplace law)
    - Inelastic tissue resistance (= tissue viscous resistance) - friction of lung tissue, chest, respiratory muscles etc.
    - Flow resistance of the airways - a summary of several types of resistances, caused by the airways (turbulence, viscosity…)

1. Pulmonary ventilation

- Expiration – passive action
  - Pressure gradient from lungs to the outside; air is expelled
  - Happens spontaneously
    - Tissue flexibility
    - Muscle relaxation

  - Muscles work in forced expiratory

Respiration mechanics

- Lungs and chest elasticity
  - Creates retraction force = tendency to lower volume
  - Extension of lungs is conditioned with pressure increase
  - Lungs pliability – Lungs compliance
    - Static x dynamic (continual record)

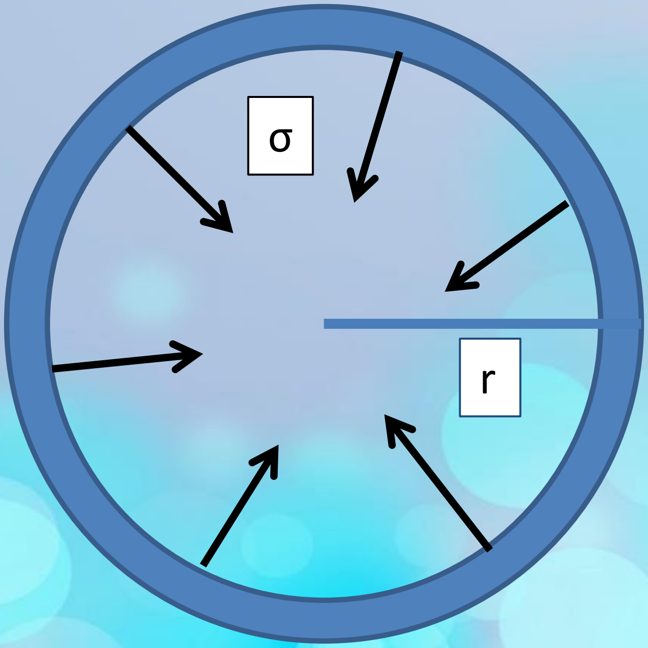
$$E = \frac{\Delta p}{\Delta V}$$

$$c = \frac{\Delta V}{\Delta p}$$

Respiration mechanics

- Retraction force of lungs
  - Its influence leads to decrease of alveoli diameter during expiration
  - Laplace’s law:

$$p = \frac{2\sigma}{r}$$



Respiration mechanics

- Negative pleural pressure
  - Pressure in area between pleuras
    - Inspiration: - 0,8kPa
    - Expiration: - 0,33 kPa
  - Lymphatic system constantly sucks in pleural liquid
  - Lungs are distended, they follow movement of respiration muscles
  - damage = pneumothorax – lung collapse

2. Distribution

- Intake of air to lungs and its mixing with air, which was left in lungs after last expiration

- Dead space – volume of airways, where exchange of gases is not happening (150 ml)

3. Diffusion

- movement of gases through alveolar membrane in the direction of concentration gradient (from location with high concentration to location with lower concentration)

- Description of diffusion: Adolf Fick -> Fick‘s diffusion laws

3. Diffusion

- 1. Fick‘s law
  - Diffusion flux is directly proportional to substance concentration (calm state)

$$J = -D \frac{\Delta C}{\Delta X}$$

$$\frac{n}{S.t} = -D \frac{\Delta C}{\Delta X}$$

J … diffusion flux [mol.m^{-2}.s^{-1}]
n … amount of substance[mol]
x … distance [m]
t … time [s]

D … diffusion coeficient [m^{2}.s^{-1}]
c … concentration [mol.m^{-3}]
S … cross-section area[m^{2}]

3. Diffusion

- Gas diffusion speed through alveocapillary membrane
  - derived from Fick‘s law

$$V / t = \frac{\left(P_1 - P_2\right).S.k}{d}$$

  - k = diffusion constant (directly proportional to solubility coefficient alpha, inversely proportional to square root of molecular weight)

$$k = \frac{\alpha}{\sqrt{m_h}}$$

3. Diffusion

- Amount of gas dissolved in liquid medium= Henry‘s law
  - Amount of dissolved gas is directly proportional to partial pressure of gas above the liquid medium and its solubility coefficient

$$V = \frac{\alpha . p_t . 1000}{P_B}$$

V … volume
P_t … partial gas pressure
α … solubility coefficient
P_B … total barometric pressure

3. Diffusion

- Solubility coefficient alpha
  - Gas amount dissolved in 1 ml of liquid at 0 °C temperature and pressure 101,3 kPa
  - Human body t = 37 °C

3. Diffusion

O_2
98.6% bound to hemoglobin
1.4% physically dissolved

CO_2
20 times more soluble than O_2; 46 times more soluble than N_2
94% chemically bound as HCO_3^- CO_3^{2-}
6% physically dissolved

N_2
100% physically dissolved (inert gas)
More soluble in adipose tissue

4. Perfusion

- Permanent perfusion of pulmonary tissue
  - Rich perfusion, including alveoli surrounded by capillaries, helps to maintain pressure gradient of gases

Decompression syndrome

- Equalization of partial pressures is performed by diffusion
- N_2 more soluble in fat tissue than in blood
- Equalization of N_2 pressures is slower
- During quick decompression diffusion is not enough to equalize
- Creation of air bubbles
- Bubbles can cause emboly

Decompression syndrome

- Pressure chamber (barochamber)
  - Oxygen overpressure
  - Burns
  - CO_2 poisoning
  - Shock state

Altitude sickness

Atmospheric pressure reduction

- at normal barometric pressure

  pi O_2 = 21.3 kPa

- at an altitude of 4,000 m

  pi O_2 = 13.3 kPa

- Reduction of oxygen saturation
- Altitude hypoxia
- Compensation

Properties of liquids

- Do not have a shape
- Do have a volume
- Form surface
- Hardly compressible
- Convective heat transfer
- With presence of ions = el. current conductive

Hydromechanics

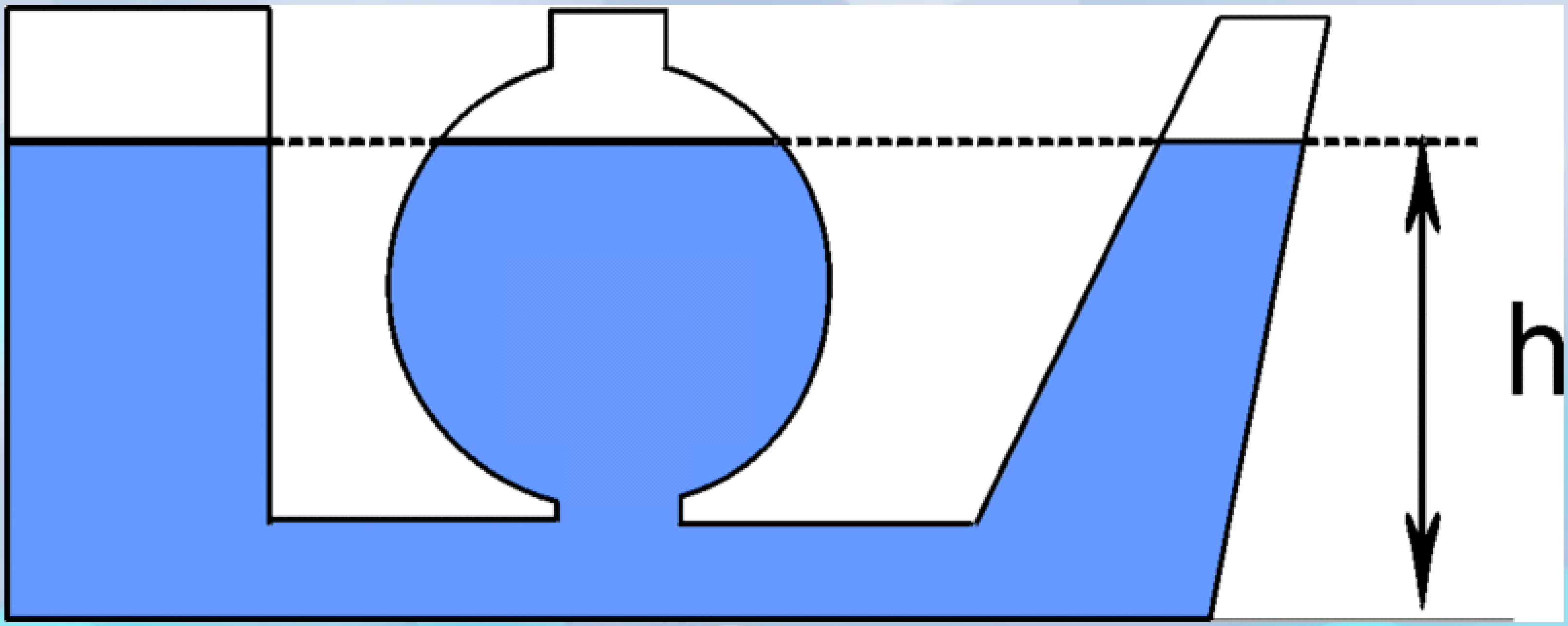
- Studies physical behavior of liquids
- a) hydrostatics – behavior of liquids at rest
- b) hydrodynamics - behavior of liquids in motion

Hydromechanics

- The hydrostatic pressure $p_h = h.\rho.g$
  the pressure caused by the weight of the liquid on a body immersed in a certain depth (or at the vessel wall, but also to itself); caused by the gravitational force

- Hydrostatic force $F_h = p_h S\ (h.\rho.g.S)$
  - compressive force by which the liquid pushes at the immersed body at a certain depth (or. at the vessel wall, but also to itself)

Communicating vessels



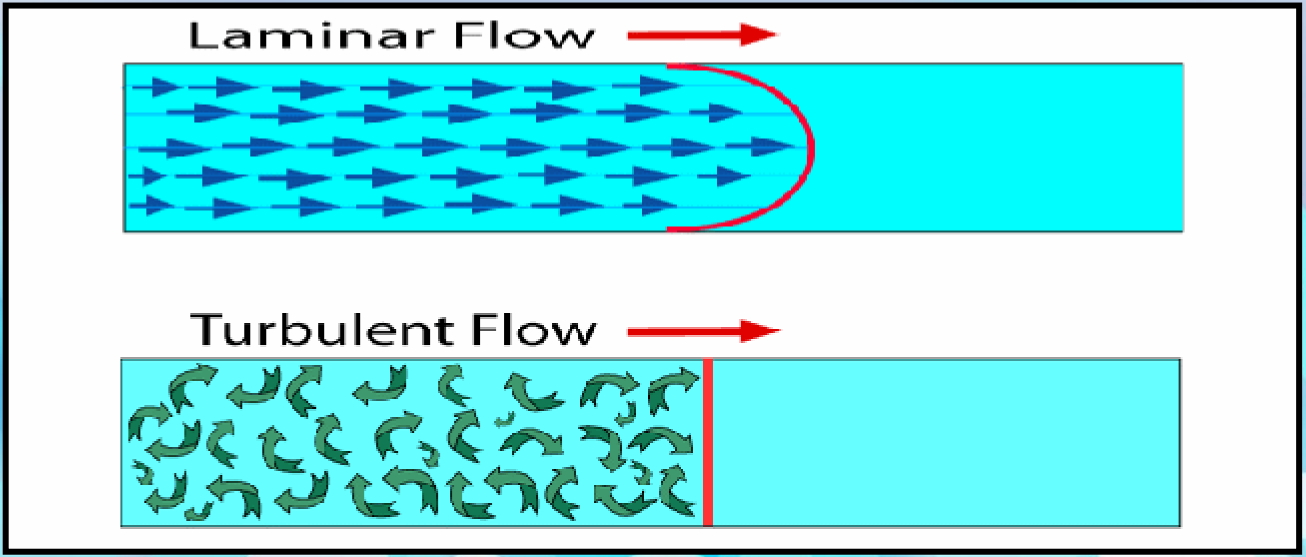
Hydrodynamics

Liquid flow

- Fluid movement, wherein the liquid particles move by disordered movement and by the movement in the flow direction
- Fluid flowing from higher pressure to areas of low pressure
- The trajectory of particles = streamline
  Stationary x nonstationary flow

Hydrodynamics

- The flow of viscous liquids
  - Laminar – streamlines are parallel
  - Turbulent – streamlines are random, mingled, nonstationary movement

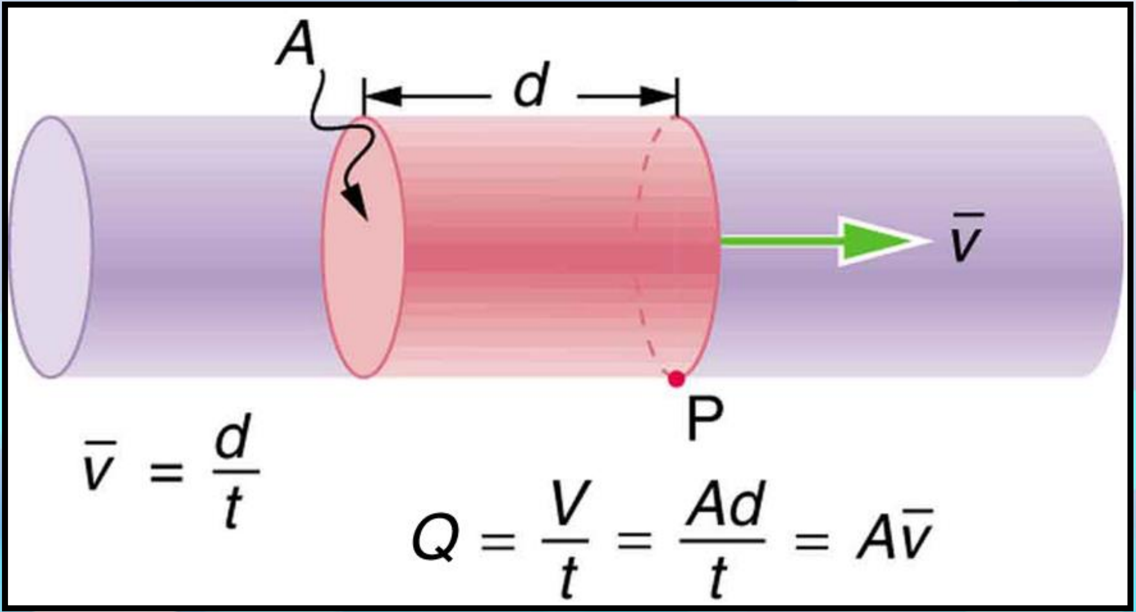


Volume flow rate

- Liquid volume, which flows through cross-section per time unit

$$Q_v = \frac{\Delta V}{\Delta t}$$

$$Q_v = S.v$$



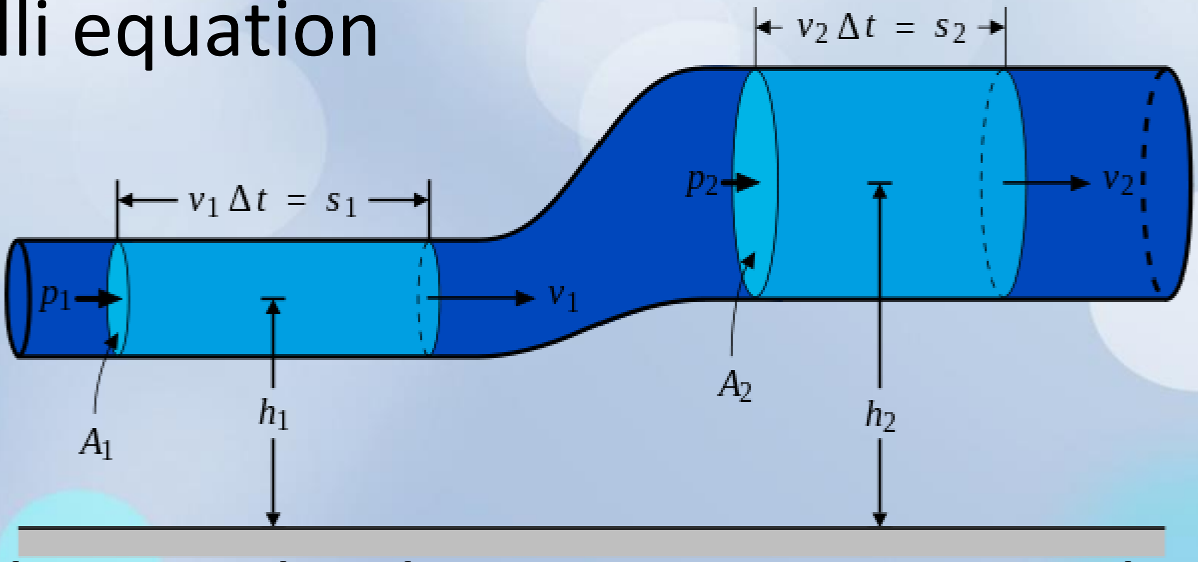
Hydrodynamics

- Bernoulli equation
- The law of energy conservation for a stable flow of ideal fluid
  - The sum of the potential pressure energy, kinetic energy, and potential energy is constant

$$\frac{1}{2}.\rho.v^2 + h.\rho.g + P = const.$$

Hydrodynamics

- Bernoulli equation



- In the place with a larger cross-section the flowing liquid has higher pressure, but lower speed, in a place with a smaller cross-sectional area has a smaller pressure but greater speed = pressure decreases with increasing speed

Biophysics of blood circulation

Biophysics of blood circulation

- Circulatory system
  - Heart
  - Vessels
  - Blood
- Vessels – arteries, capillaries, veins

They have the possibility of some volumetric expansion (of elasticity), which is given by the coefficient of volumetric expansion E:

$$E = \frac{\Delta p}{\Delta V} \qquad c = \frac{\Delta V}{\Delta p}$$

Biophysics of blood circulation

Vascular system

Arterial part

- Arteries, arterioles, metarterioles
- The aorta and arteries have great content of elastic tissue => elastic effect => pulse

- The heart works discontinuously, but pulsation is unsuitable for proper diffusion in tissues
  - elastic arterioles - similar to arteries and aorta = high content of elastic fibers - expand in systole
  - muscular arterioles - a high content of smooth muscle fibers - maintain pressure during diastole

  = alternating both types of arterioles removes or at least minimizes the effect of pulsation in the capillaries, where a pressure of a constant value is then present

Biophysics of blood circulation

Capillary part

- It provides exchange between the arterial circulation and tissues
- Diffusion - is carried out through the pores of the capillary membranes (water-soluble substances) or whole capillary membrane (lipid-soluble substances; phenomenon describes the first Fick law)

$$\boxed{J = -D\frac{\Delta c}{\Delta x}}$$

$$\boxed{\frac{\Delta n}{S.\Delta t} = -D\frac{\Delta c}{\Delta x}}$$

J … diffusion flux [mol.m^{-2}.s^{-1}]

n … amount of substance[mol]

x … distance [m]

t … time [s]

D … diffusion coeficient [m^{2}.s^{-1}]

c … concentration [mol.m^{-3}]

S … cross-section area[m^{2}]

Biophysics of blood circulation

Capillary part

- It provides exchange happening between the arterial circulation and tissues
  - Filtration – depends on hydrostatic and colloid osmotic pressure; filtered volume is given by formula:

$$V = K.\left(p_k - \pi_k + \pi_{iF} - p_{iF}\right)$$

K… filtration coefficient
p_k…blood pressure
p_{iF}…intersticial fluid pressure

π_k…col. osm. blood press.
π_{iF}…col. osm. int. fl. press.

Biophysics of blood circulation

- Venous part
  - Less elastic, less muscle
  - In venous return: valves, the muscles of the lower limbs, the negative pressure in the pleural cavity are involved

Blood

- Blood plasma – a colloidal solution; viscoelastic fluid
- Blood cells
  - Red blood cells - adhesion at a slower flow rate

= suspension system

Blood

- Blood viscosity – viscosity characterizes internal friction in liquid, it depends on the attractive forces between the particles, viscosity indicates the ratio between shear stress and speed in dependency on the distance between adjacent layers
  - Dynamic viscosity

$$\eta = \frac{F}{S} \cdot \frac{\Delta x}{\Delta v}$$

Pa.s

Kinematic viscosity

$$v = \frac{\eta}{\rho}$$

Stokes

Blood

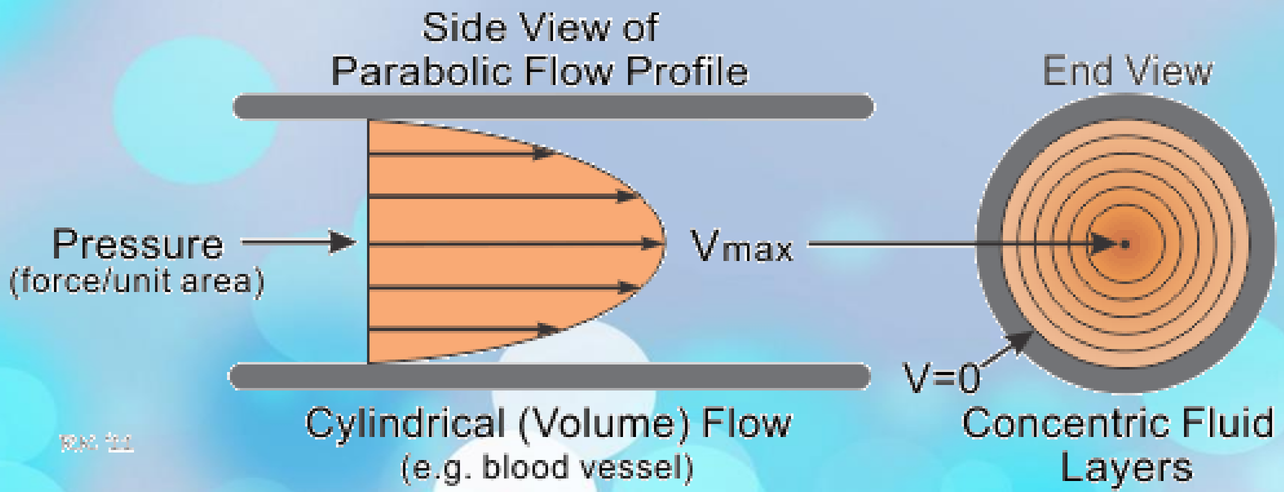
Blood viscosity: $\eta_s = \eta \,.\, (1 + k \,.\, c)$
(suspension)

η is fluid viscosity without solid phase, **k** is a constant characterizing solid particles properties, **c** is volume concentration of particles

Blood viscosity depends on temperature:
for 37 °C approx $3 – 3{,}5 \,.\, 10^{-3}$ Pa . s
Clinically = blood sedimentation

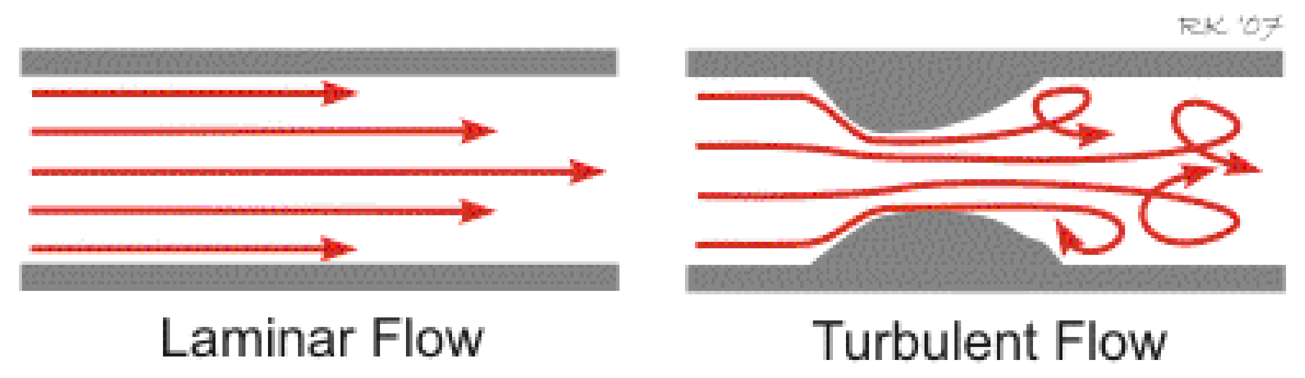
Blood flow

- Physiologically, blood flow is laminar flow, liquid layer at vessel wall is the slowest moving layer, speed of blood flow is increasing in direction towards the center of the vessel



Blood flow

- Patophysiologically, turbulent flow is formed in places, where vessels are obstructed, or in vessel with lowered lumen – increase of flowing speed => creation of turbulent flow; heart murmur



Reynolds number

- Flow of liquid is laminar just to a certain value of speed – critical speed – then the flow becomes turbulent; treshold is determined by Reynolds number

$$R = \frac{\rho d v}{\eta}$$

- Laminar/turbulent borderline
- 2320 < R < 4000
- Blood = 1000