Fig. 4.1: Pressure and stress
Fig. 4.2: Telemetry of pressure by the communicating tube

- Pressure in pipe
- Measured pressure
- Level
- Fluid

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Fig. 4.3: Continuity

Density
Compressibility
Incompressible fluid
Law of conservation of mass
Fig. 4.4: Expression of Bernoulli

\[(1/2)\rho v^2 + p = \text{constant}\]  

(4.2)
Fig. 4.5: Head drop

Drop: $h \Rightarrow$ Pressure difference: $\rho gh$

Density: $\rho$

Gravitational acceleration: $g$
Fig. 4.6: Shunt

Flow path and control fluid path

Valve

Flow path
Fig. 4.7: Principle of siphon

Atmospheric pressure

\[ 1.0 \times 10^3 \text{ kg m}^{-3} \times 9.8 \text{ m s}^{-2} \times 10 \text{ m} = 98 \text{ kPa} \]  
\[ (4.4) \]

\[ 101.325 \text{ kPa} - 98 \text{ kPa} = 3.325 \text{ kPa} \]  
\[ (4.5) \]
Fig. 4.8: Collapse

(a) Vein collapse  (b) Blood removal cannula

Vein  

Blood  

Collapse  

Vessel wall  

Left atrium  

Removal cannula  

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Fig. 4.9: Hook elastic body

Stress: $\tau$

Strain: $\varepsilon$

Slope: 

elastic modulus: $E$
Fig. 4.10: Shear rate

\[ \gamma = \frac{\Delta v}{y} \]  

(4.6)
Fig. 4.11: Newtonian fluid

Shear stress: $\tau$

Slope: coefficient of viscosity: $\eta$

$\eta = \frac{\tau}{\gamma}$ (4.7)
Fig. 4.12: Viscosity with temperature

Easy to be shear

[Gas]

Molecular velocity

[Low temperature]

[High temperature]

Hard to be shear

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Fig. 4.13: Viscosity with shear rate

Viscosity: $\eta$, Pa s

Shear rate: $\gamma$, s$^{-1}$

Water: 293 K

Blood: $Ht = 40\%$, 310 K

Hematocrit: $Ht$

non-Newtonian fluid

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Fig. 4.14: Rouleau formation

Rouleau

Erythrocyte

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Fig. 4.15: Viscosity tracings with vibrating electrode
Fig. 4.16: Measurement of local viscosity with vibrating electrode

Vibrating electrode

Albumen

Yolk

Fixed electrode
Fig. 4.17: Maxwell model

Stress: $\tau$

Strain: $\varepsilon$

Elastic element

Viscosity element

Stress relaxation

Time: $t$

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Fig. 4.18: Kelvin-Voigt model

- **Elasticity element**
- **Viscosity element**

Stress: $\tau$

Strain: $\varepsilon$

Time: $t$

Creep deformation

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Fig. 4.19: Circulation resistance

Cardiac output: $Q$

Pulmonary artery pressure: $Pp$

Right atrial pressure: $Pr$

Pulmonary circulation resistance: $Rp$

(Bronchial circulation)

Left atrial pressure: $Pl$

Aortic pressure: $Pa$

[Systemic circulation resistance: $Rs$]
Fig. 4.20: Velocity distribution in pipe

(a) Plug flow

(b) Hagen-Poiseuille flow
Fig. 4.21: Force balance in cylinder in flow
Fig. 4.22: Cylinders of fluid in flow through pipe
Fig. 4.23: Distribution of velocity

(a) Plug flow

(b) Hagen-Poiseuille flow
Fig. 4.24: Inlet region

Distribution of velocity

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Fig. 4.25: Boundary layer

Main stream

Wall

Boundary layer
Fig. 4.26: Couette flow

\[ \gamma = \frac{v}{d} \quad (4.37) \]
Fig. 4.27: Flow between rotating cone and stationary plate

\[ \gamma = \frac{v}{d} = r \frac{\omega}{(r \theta)} = \frac{\omega}{\theta} \quad (4.40) \]
Fig. 4.28: Cone-plate viscometer

- Rotation
- Torque
- Viscosity
- Rotating cone
- Fluid
- Stationary plate

Couette flow
Fig. 4.29: Clotting between rotating cone and stationary plate

(a) Blood between rotating cone and stationary plate

(b) Torque tracings during clot formation

\[ Rc = \frac{(T_1 - T_0)}{T_1} \]  

\( t_0 \)
Fig. 4.29: Clot formation between rotating cone and stationary plate

(c) Clot; cone (left), plate (right)

\[ \gamma = 430 \text{ s}^{-1} \quad \text{Shear rate} \]
\[ Rc = 0.45 \quad \text{Clotting ratio} \]

\[ \gamma = 43 \text{ s}^{-1} \]
\[ Rc = 0.70 \]

\[ \gamma = 4.3 \text{ s}^{-1} \]
\[ Rc = 0.90 \]
Fig. 4.29: Clot formation between rotating cone and stationary plate

(d) Shear rate $\gamma$ and Clotting ratio $R_c$

\[ R_c \]

\[ \gamma, \text{ s}^{-1} \]
Fig. 4.30(a): Counter rotating rheoscope

[Rotating disc]
[Fluid]
Stationary plane
(observations)
Erythrocyte

Microscope

Velocity

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Fig. 4.30(b): Counter rotating rheoscope
Fig. 4.31(a): Velocity distribution in flow between parallel walls

\[ \gamma_w = \frac{6Q}{bd^2} \]  \hspace{1cm} (4.62)
Fig. 4.31(b): Force balance in flow between parallel walls

\[ dF = b \ dy \ \Delta P \]  

(4.46)
Fig. 4.32: Deformation and exfoliation of cell in flow

(1)

(2) Deformation

(3) Exfoliation

Flow

0.2 mm

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Fig. 4.33: Flow channel between parallel walls

Microscope

Flow channel
Fig. 4.34: Flow channel system with parallel wall for microscopic observation
Fig. 4.35: Extension of cell
Fig. 4.36: Movement, deformation, proliferation, orientation, and differentiation of cell
Fig. 4.37: Falling sphere

\[ \eta \propto d^2 \frac{(\rho_1 - \rho_2)}{v} \]  

(4.63)
Fig. 4.38: Magnus effect
Fig. 4.39: Axis concentration?
Fig. 4.40: Secondary flow in bend tube

Main flow

Secondary flow component in the cross section
Fig. 4.41: Secondary flow between cylinder (Taylor vortex)

- Rotating inner cylinder
- Main flow
- Secondary flow
- Stationary outer cylinder
Fig. 4.42: Secondary flow between rotating cone and stationary plate
Fig. 4.43: Flow between rotating outer cylinder and stationary inner cylinder

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Fig. 4.44: Flow between stationary convex cone and rotating concave cone

(a) Stationary convex cone

(b) Concave and convex cones

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Fig. 4.45: Pressure in pulsatile flow

- Pressure
- Time
- Acceleration
- Deceleration
- Systole
- Diastole
- Aortic pressure
- Left ventricular pressure
Fig. 4.46: Compliance of tube wall

Deformation with compliance of wall

Low compliance  High compliance

Pulsatile flow

Low compliance  High compliance

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Fig. 4.47: Clot formation and hemolysis with shear rate
Fig. 4.48: Tracing

(a) Laminar flow

(b) Turbulent flow

\[ Re = \frac{\rho v x}{\eta} \]  

(4.64)
Fig. 4.49: Streamline

Streamline

Flow vector
Fig. 4.50: Vortex

(a) Low Reynolds number

(b) High Reynolds number

Wall

Exfoliation

Vortex
Fig. 4.51: Artificial ventricle
Fig. 4.52: Clot in artificial ventricle