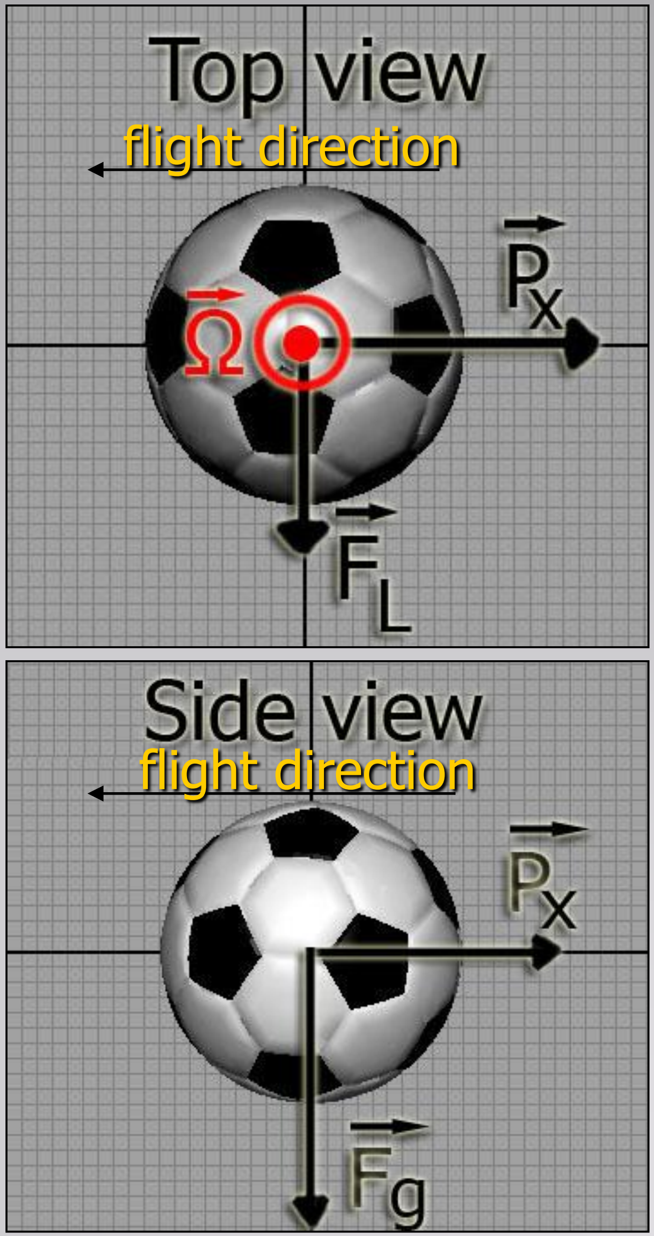
12. Ball spin

Spin can be used to alter the flight path of balls in sport. Investigate the motion of a spinning ball, for example a table-tennis or tennis ball, in order to determine the effect of the relevant parameters.

Influence of the rotary motion on the flight path

Forces, which act on the ball

- Gravity force - $\overrightarrow{F_g}$
- Drag force - $\overrightarrow{P_x}$
- Magnus force - $\overrightarrow{F_L}$



Static and dynamic pressure

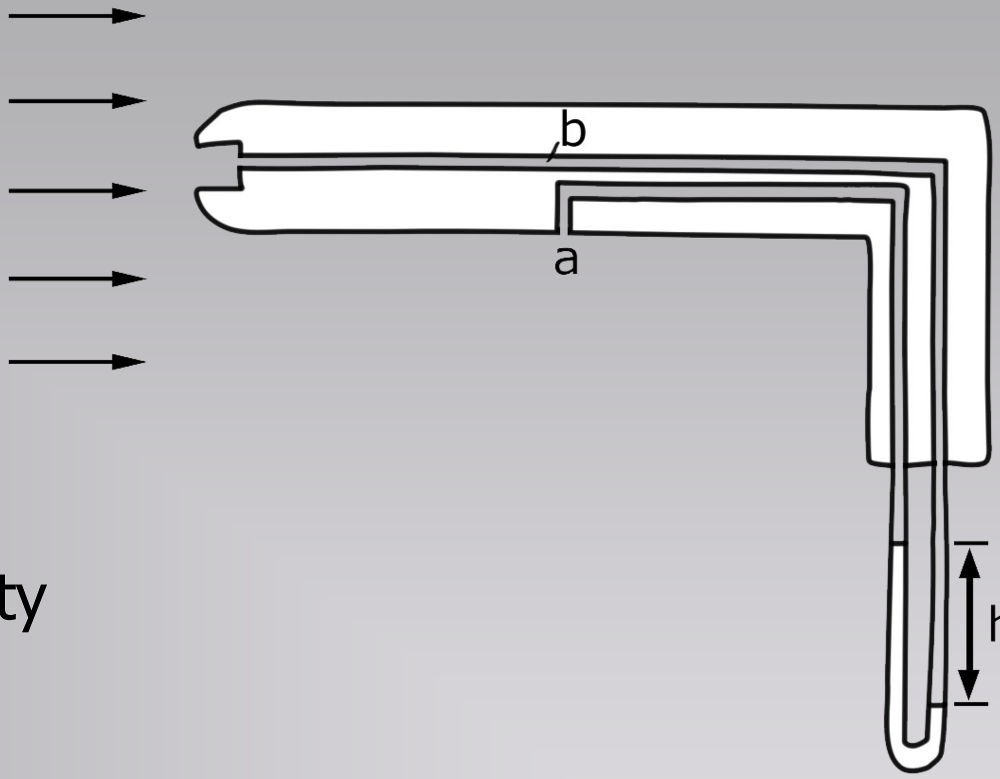
p_a - static pressure

$$p_b - p_a \Leftrightarrow q = \frac{\rho v^2}{2}$$

- dynamic pressure

where ρ - air density

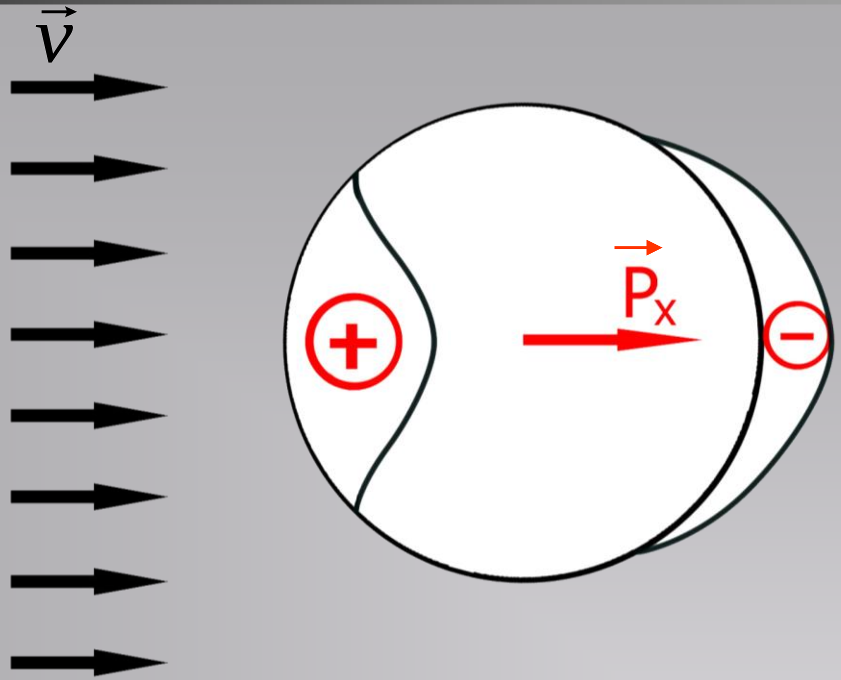
v - air stream velocity



$$p + \frac{\rho v^2}{2} = const.$$

- Bernoulli equation

Drag force

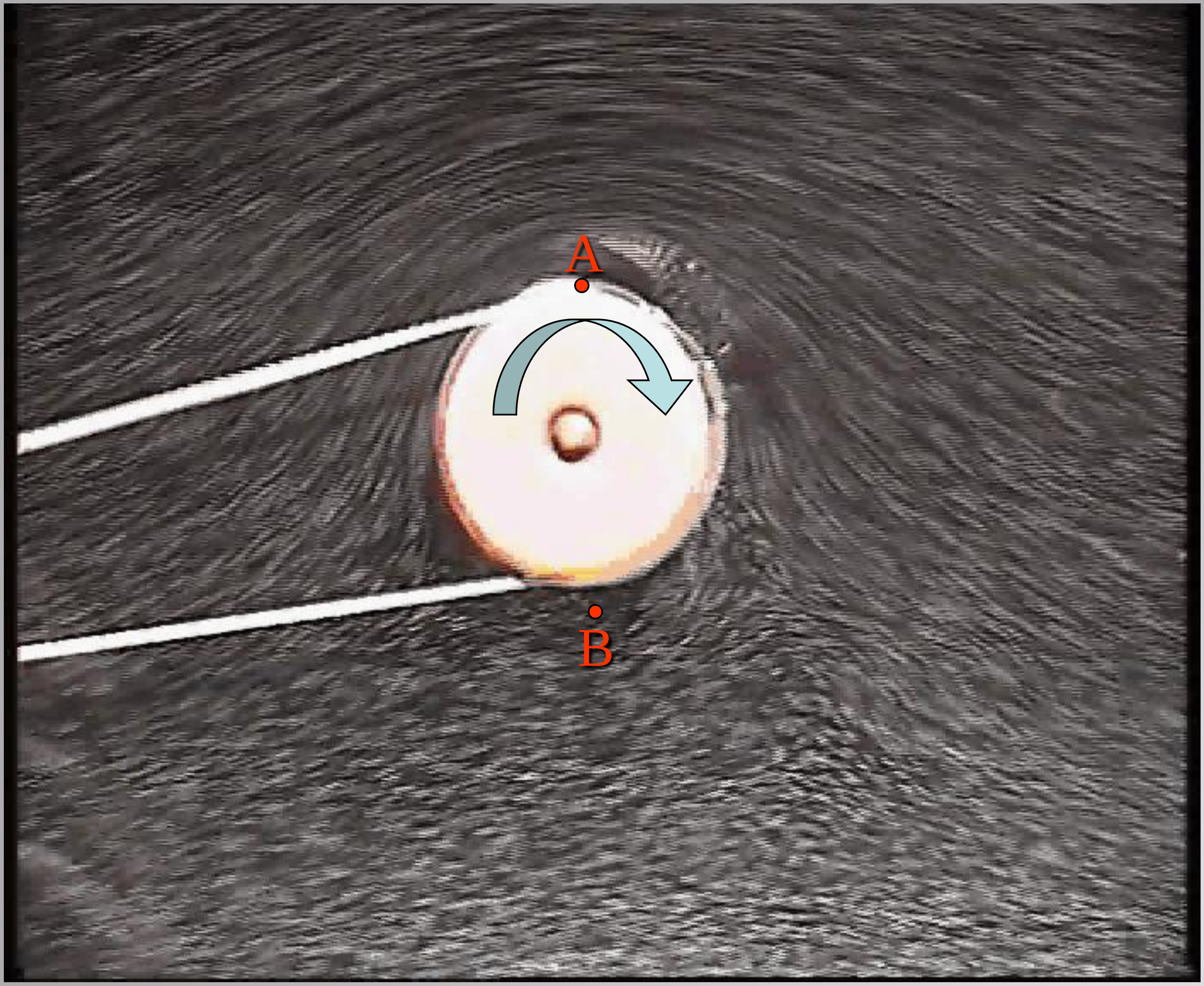


$$\vec{P}_x = c_x \cdot \frac{S\rho v^2}{2} \frac{\vec{v}}{|\vec{v}|}$$

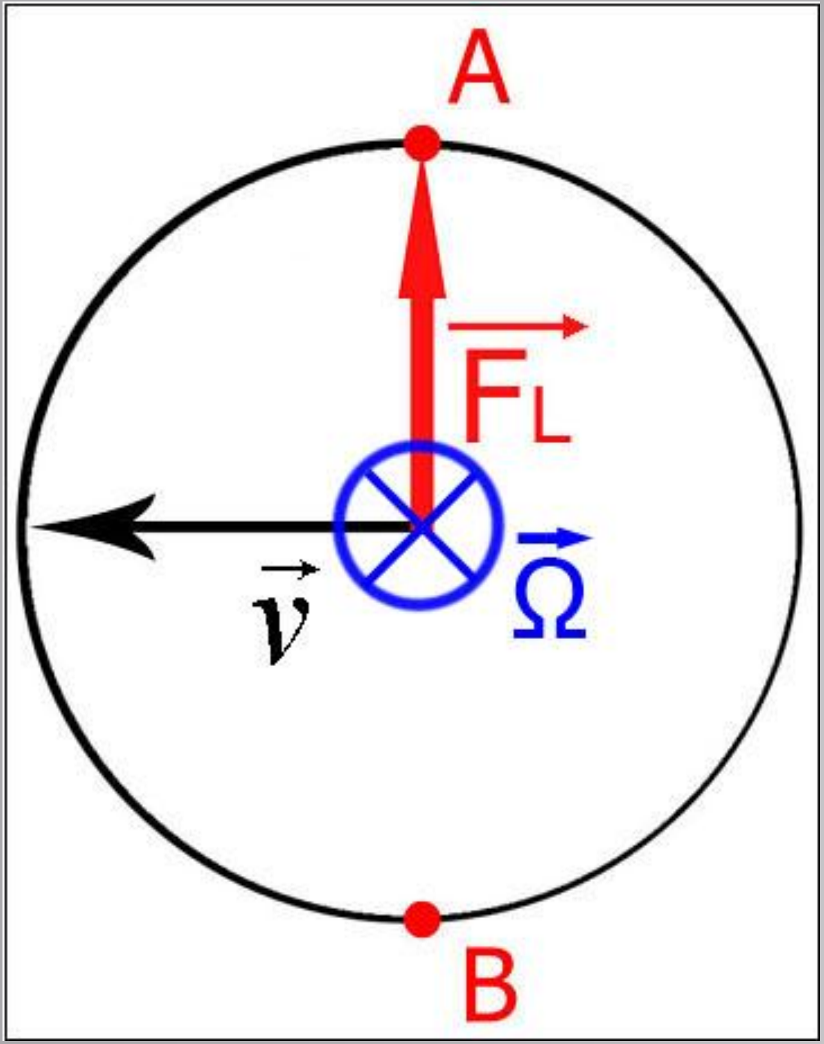
c_x - drag coefficient

S - cross-section of the ball

Magnus force formation mechanism



Magnus force



$$\vec{F}_L = \frac{\rho c_L A v^2}{2} \frac{\vec{\Omega} \times \vec{v}}{\left|\vec{\Omega} \times \vec{v}\right|}$$

where:

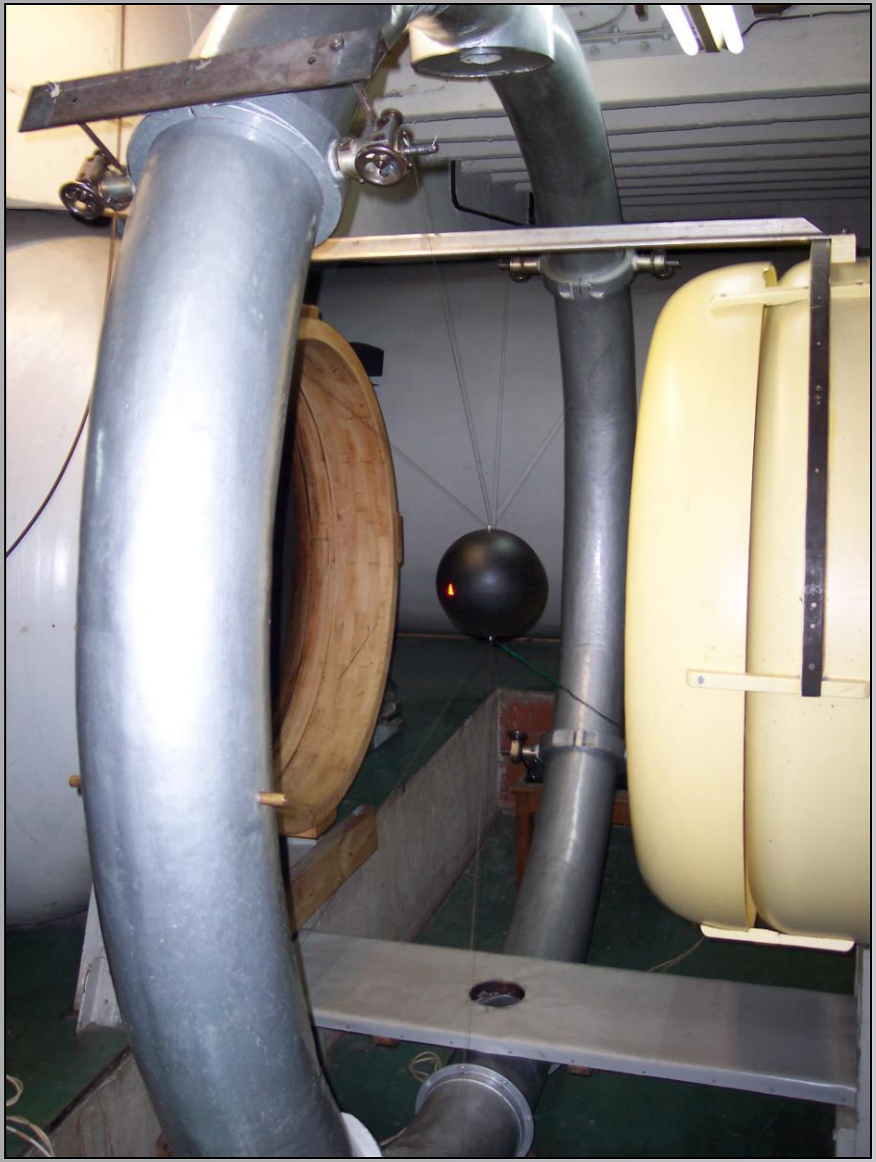
A - cross-section of the ball

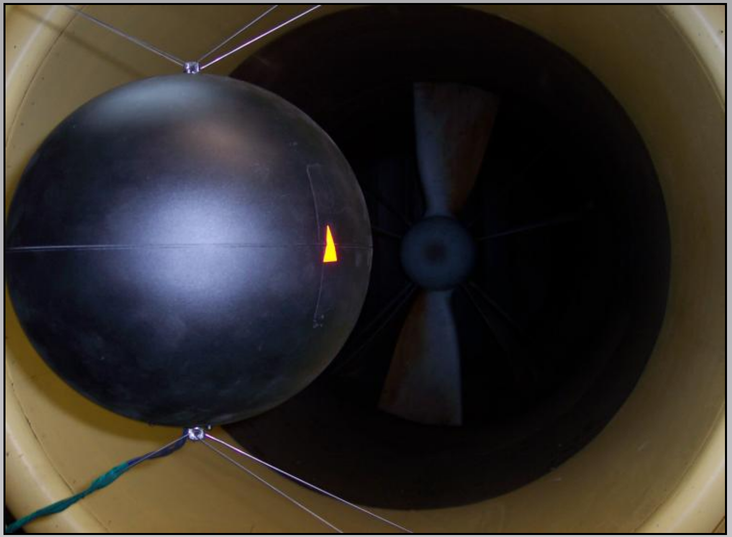
$\vec{v}$ - ball velocity

c_L - Magnus force coefficient

$\vec{\Omega}$ - angular velocity

Experimental system

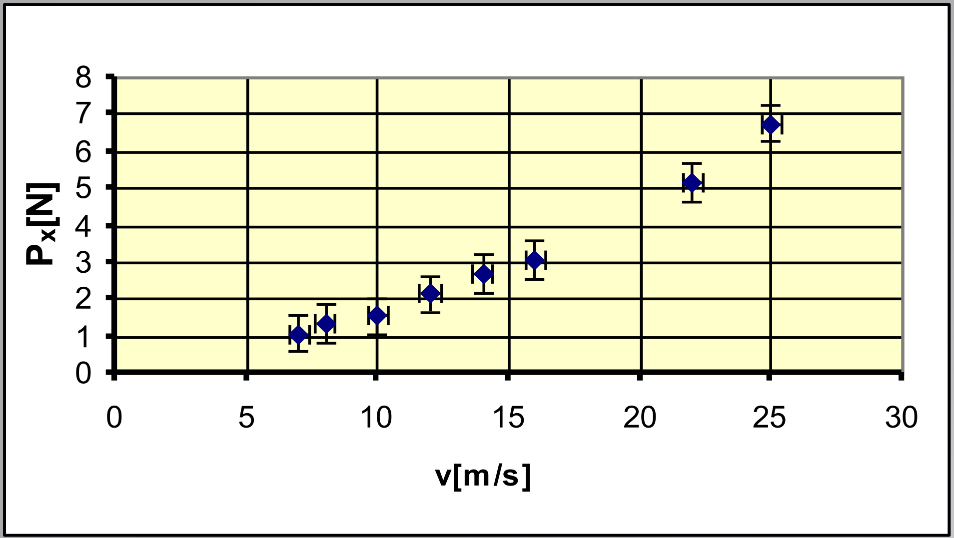


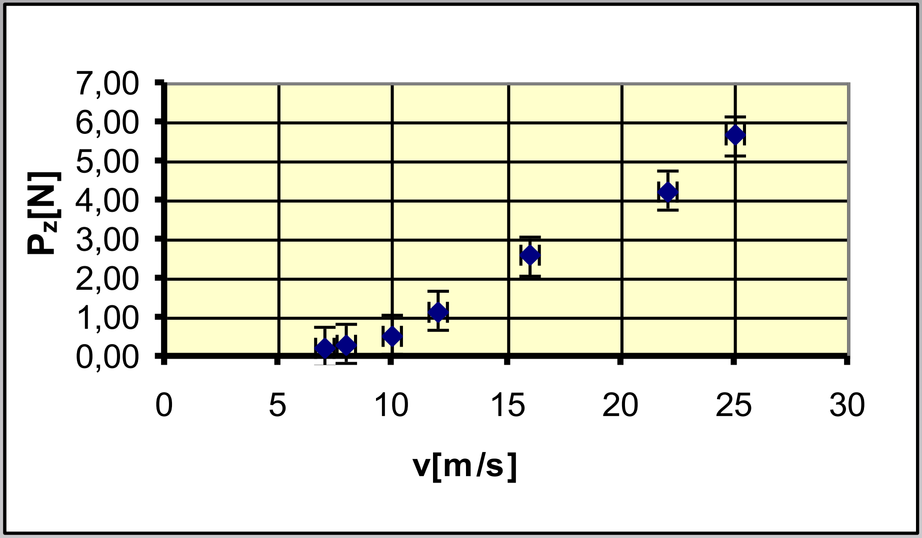


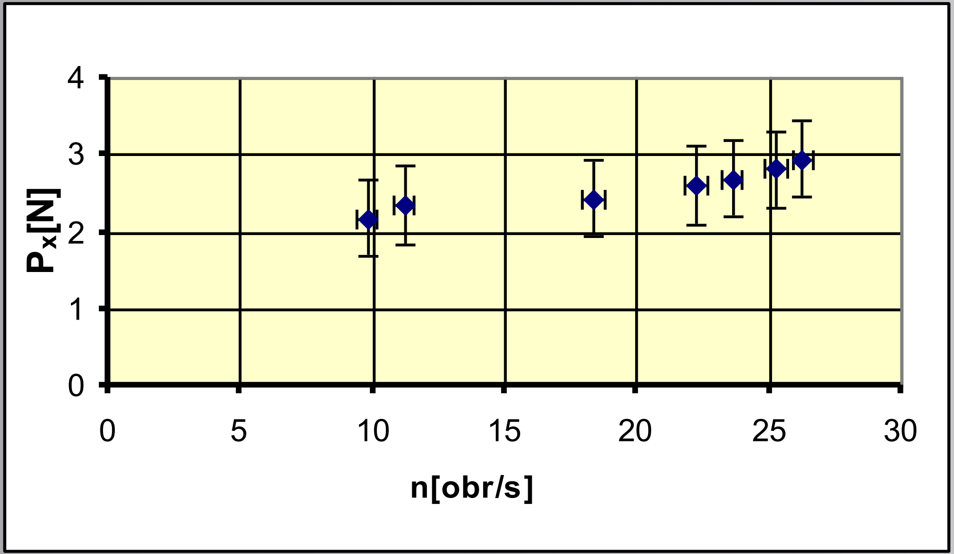
Results of experiment

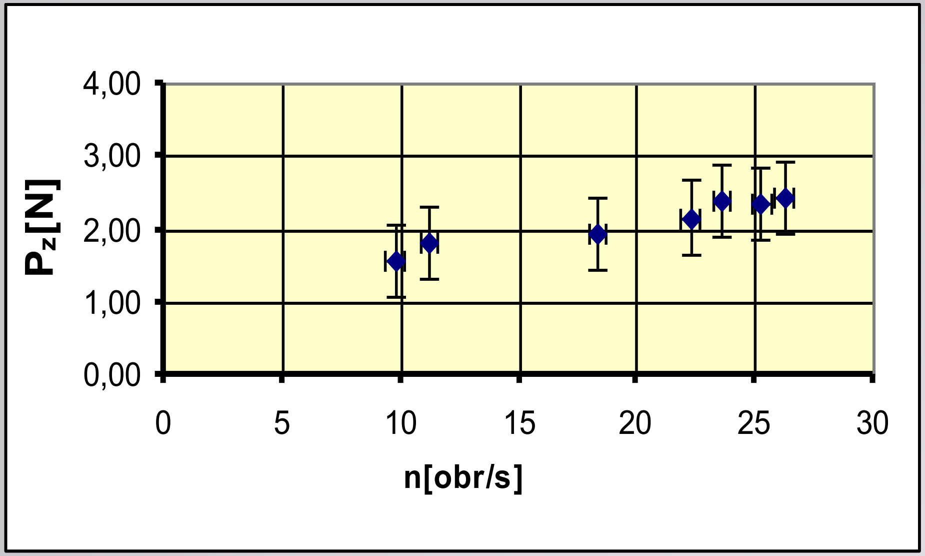
Drag force

Magnus force









Conclusions from experiment

- dynamism of the increase of the drag force decreases in a measured range of velocities

  - value of the drag coefficient depends on the air stream velocity

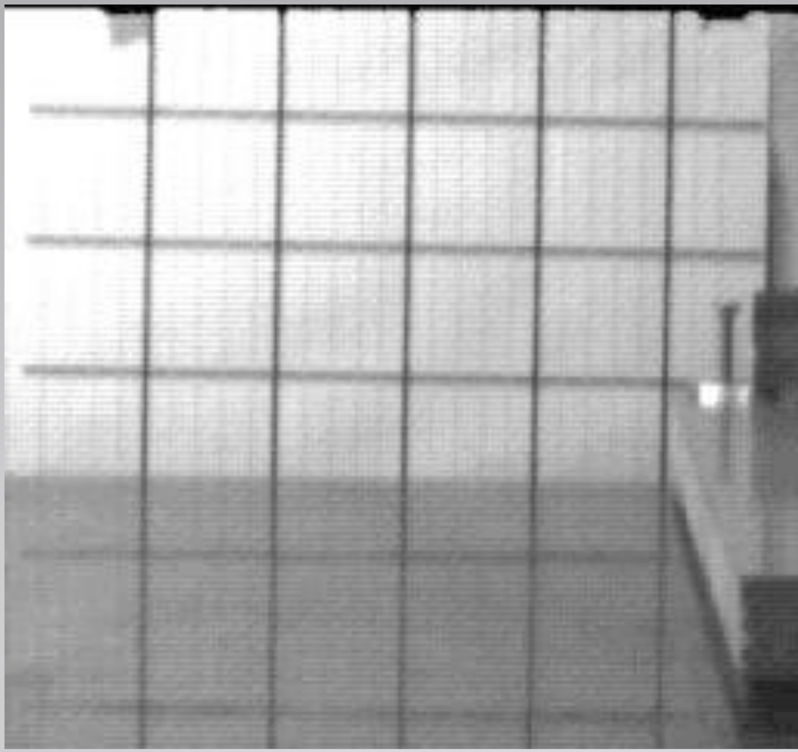
- when the air stream velocity increases the force which deflects the flight path drastically rises

- increase of angular velocity induces increase of Magnus force

Computer simulation

SIMULATION

Experimental system



Comparision of results

Initial conditions:

$$v \approx 7{,}5\left[\frac{m}{s}\right]$$

$$\omega = 157\left[\frac{rad}{s}\right]$$

$$h = 0{,}794[m]$$

ω - angular velocity

v - initial velocity of the ball

x - range of ball's flight

z - path deflection

h - height of desk

Theoretical results:
(based on simulation)

$$x = 2,66 \pm 0,005[m]$$

$$z = 0,29 \pm 0,005[m]$$

Experimental data:

$$x = 2{,}6 \pm 0{,}1[m]$$

$$z = 0{,}32 \pm 0{,}05[m]$$

Different ball comparision

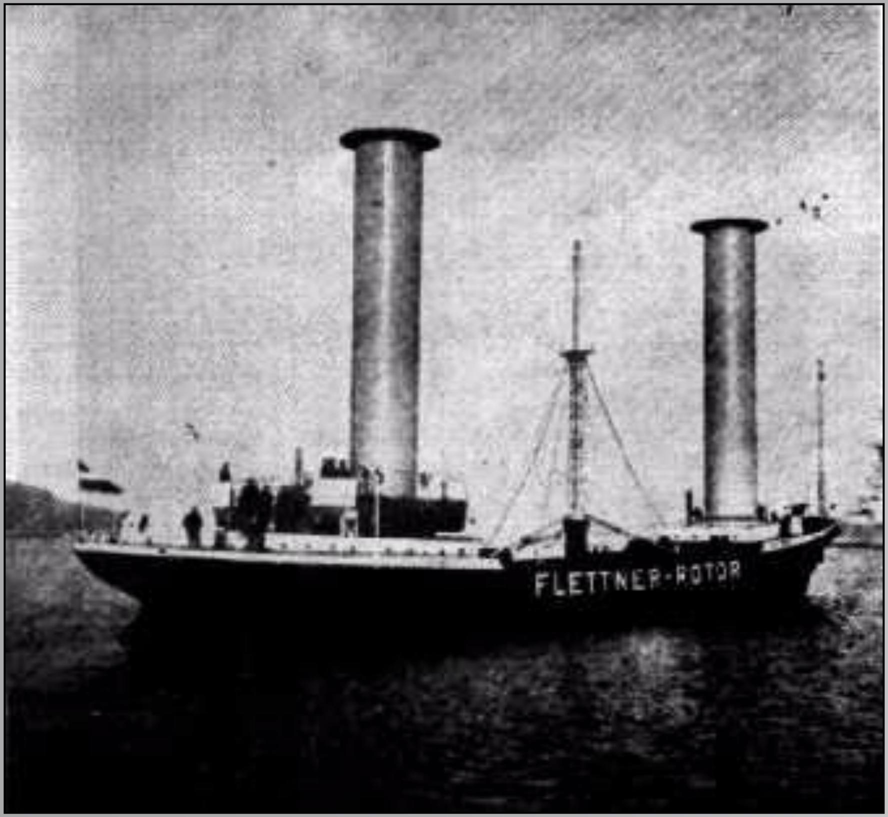
SIMULATION

Conclusions

- parameters which have influence on the flight path of the ball:

1. velocity
2. mass
3. angular velocity
4. roughness of the surface
5. density of the air
6. size of the ball
7. viscosity of the air

Magnus effect applications



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Flow similarity

$$\mathrm{Re} = \frac{\rho v L}{\mu}$$

where ρ - density of the fluid

L - linear size e.g.diameter of the ball

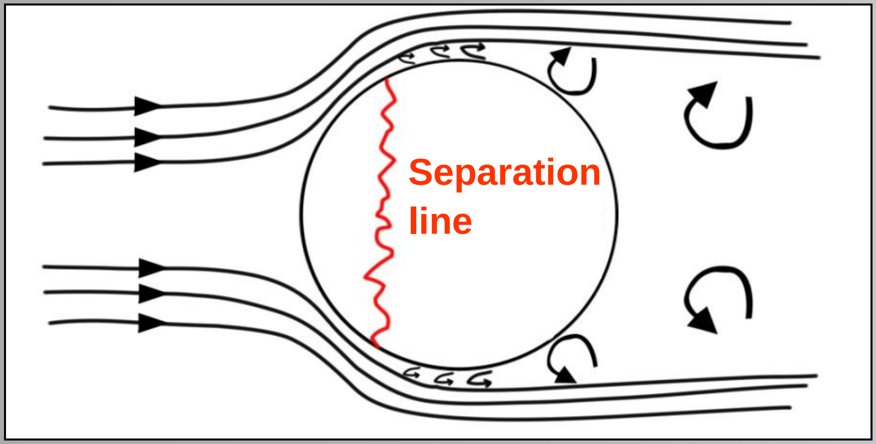
μ - dynamic viscosity

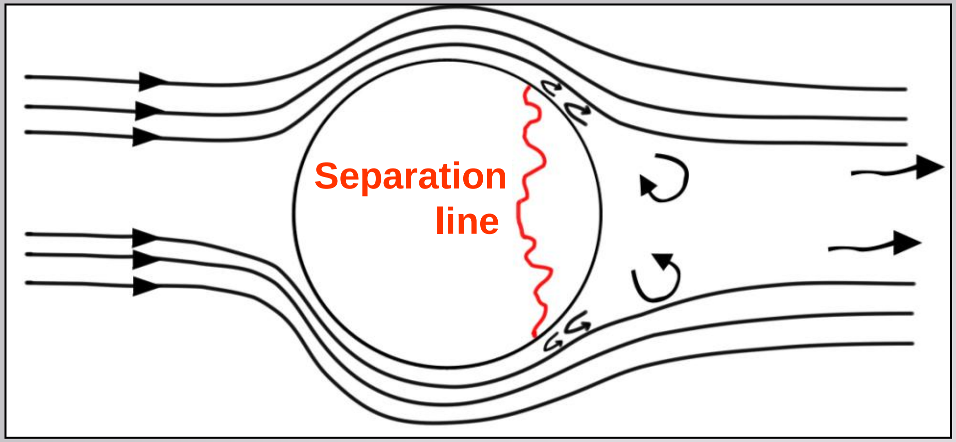
Value of the air's dynamic viscosity:

$$1{,}7064 \cdot 10^{-5} \left[\frac{kg \cdot s}{m^2} \right]$$

Drag crisis

- It occurs when the character of the boundary layer changes



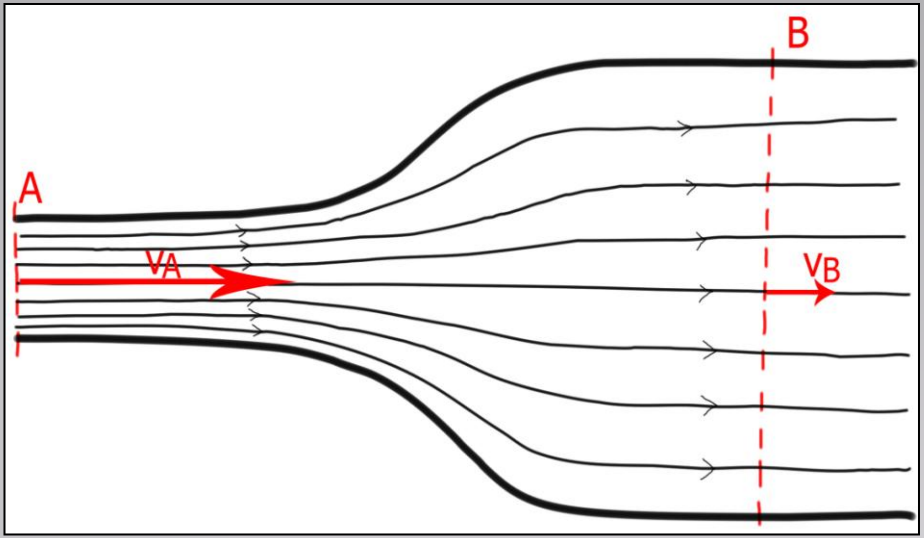


Continuity principle

$$m_A = m_B$$

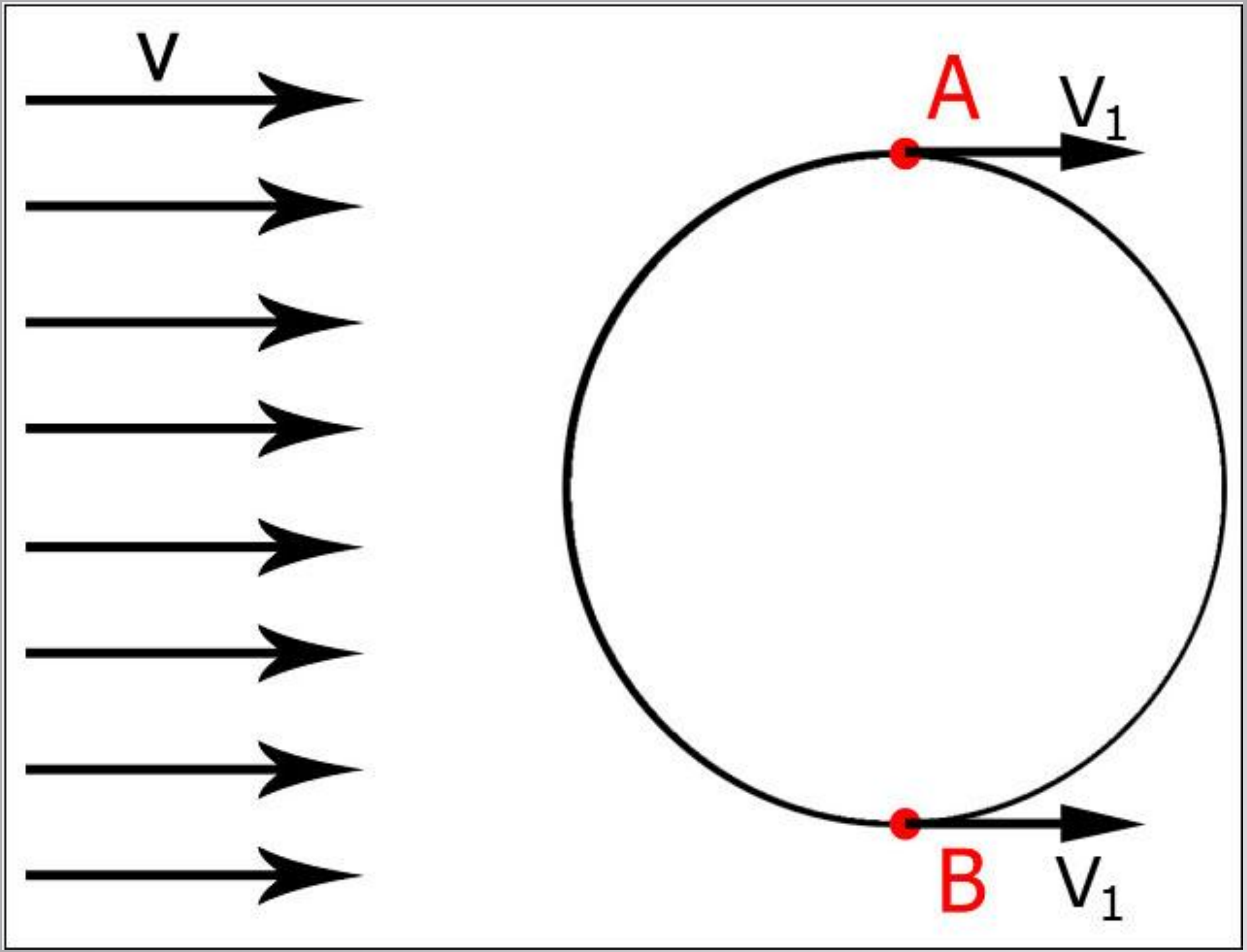
$$\rho_A \cdot S_A \cdot v_A = \rho_B \cdot S_B \cdot v_B$$

because $\rho_A = \rho_B$



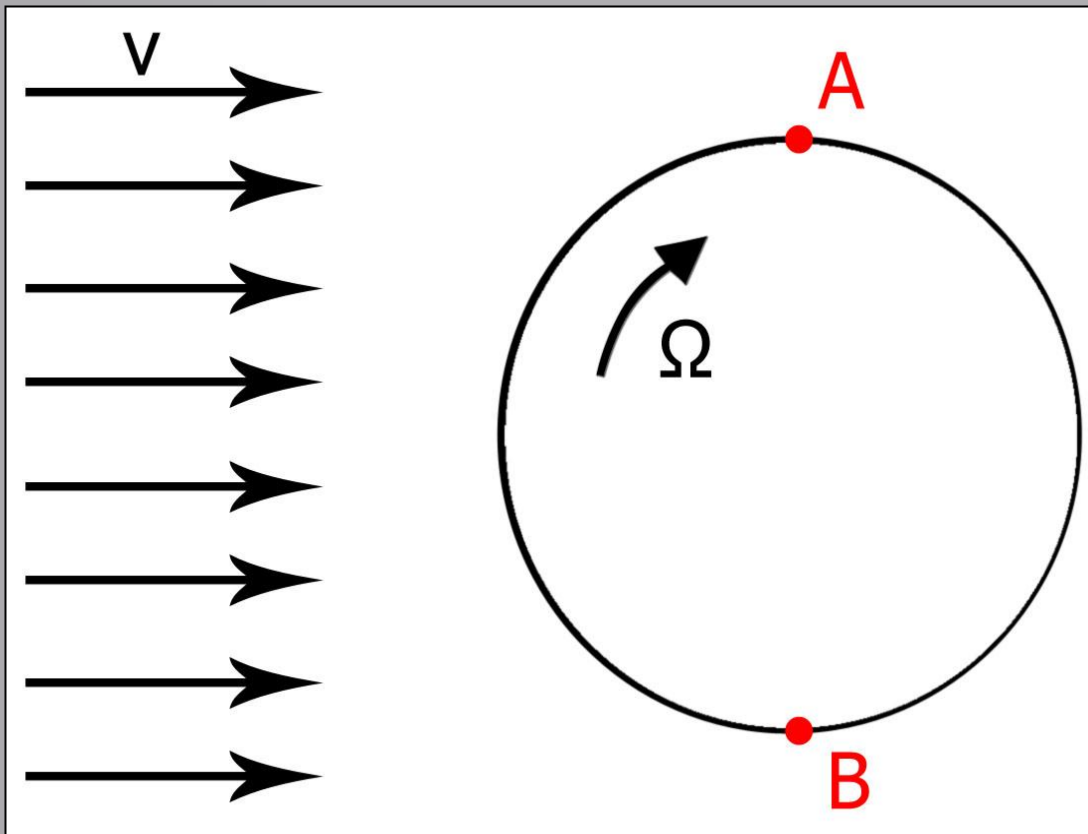
$$S_A \cdot v_A = S_B \cdot v_B$$

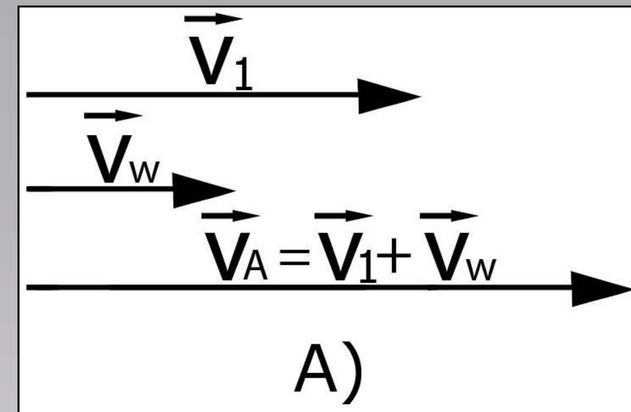
Velocities on a non-rotating ball

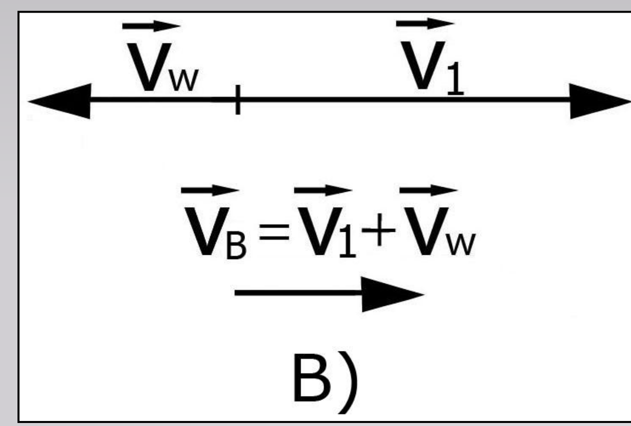


$$v < v_1$$

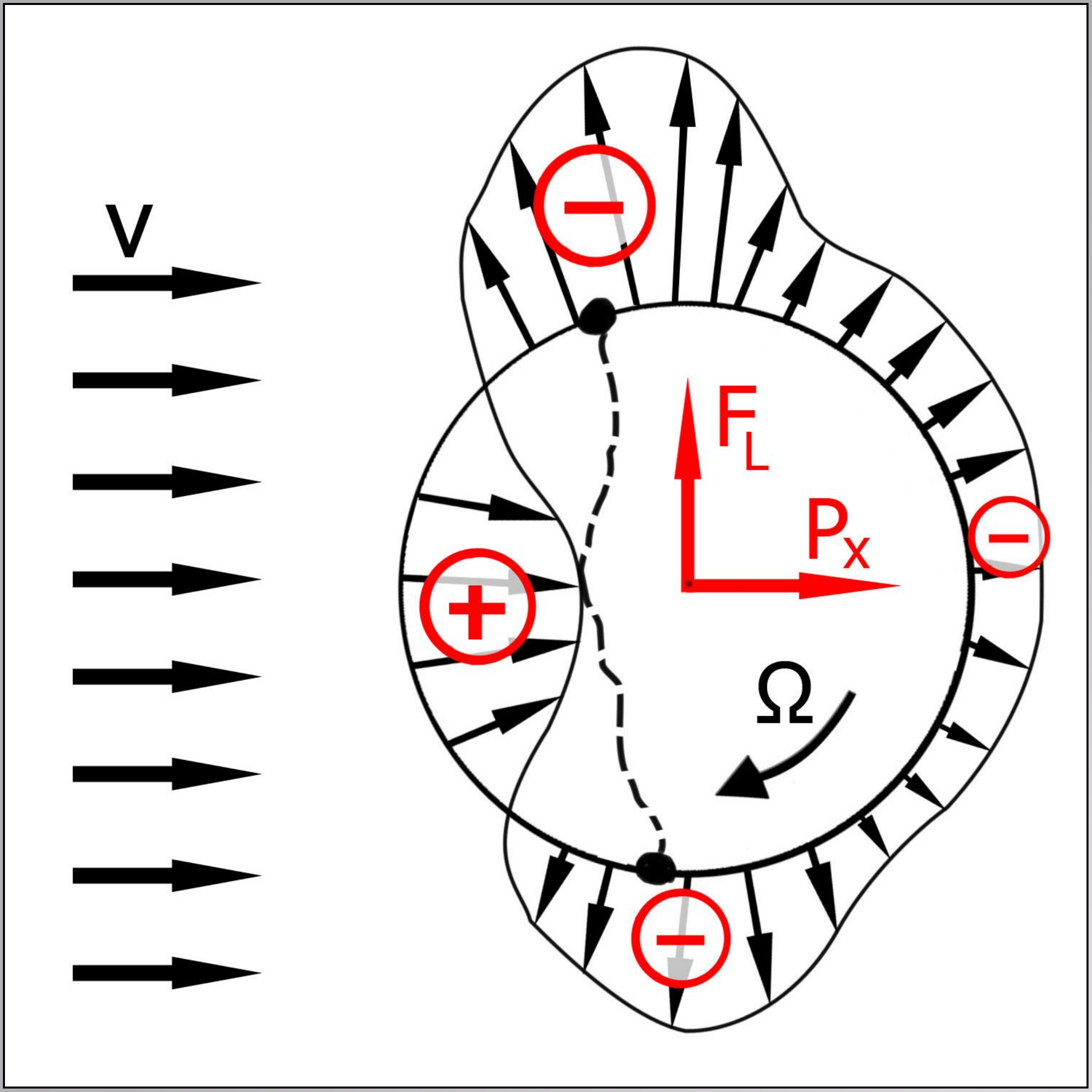
Velocities on a rotating ball



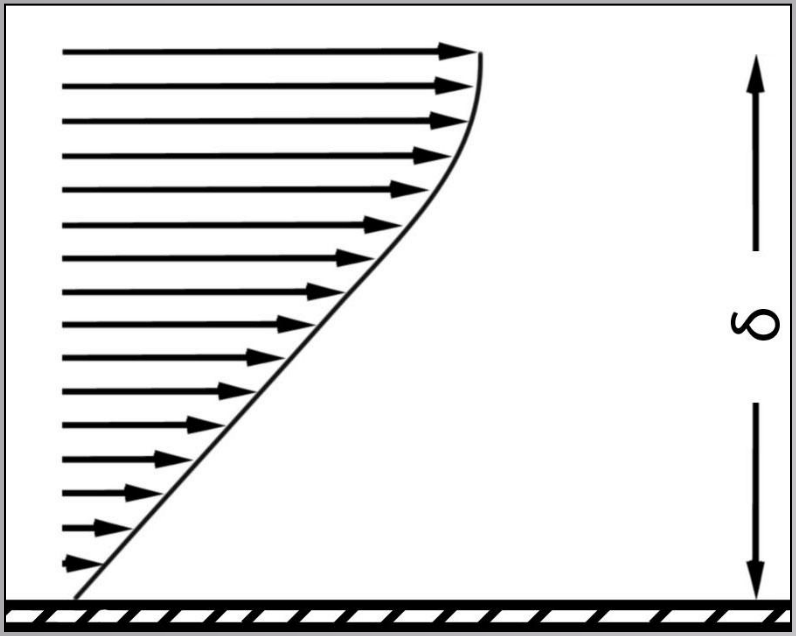




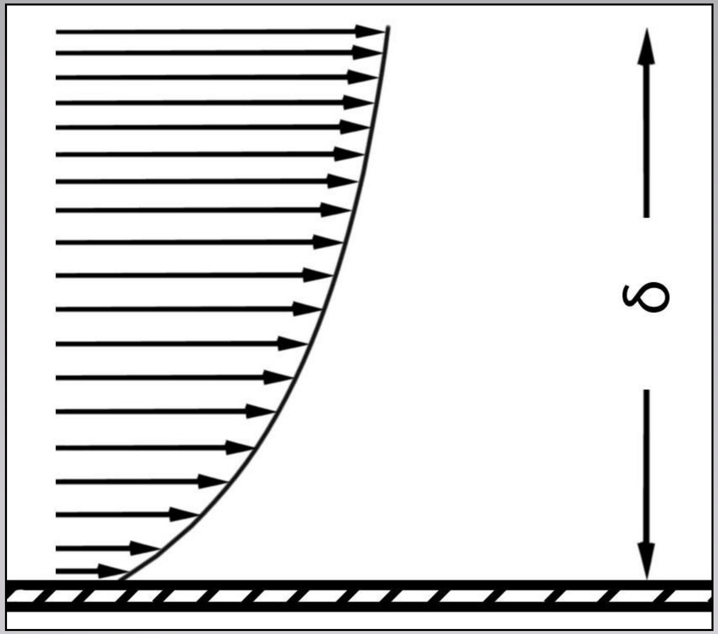
Pressure disposition on the ball



Boundary layer



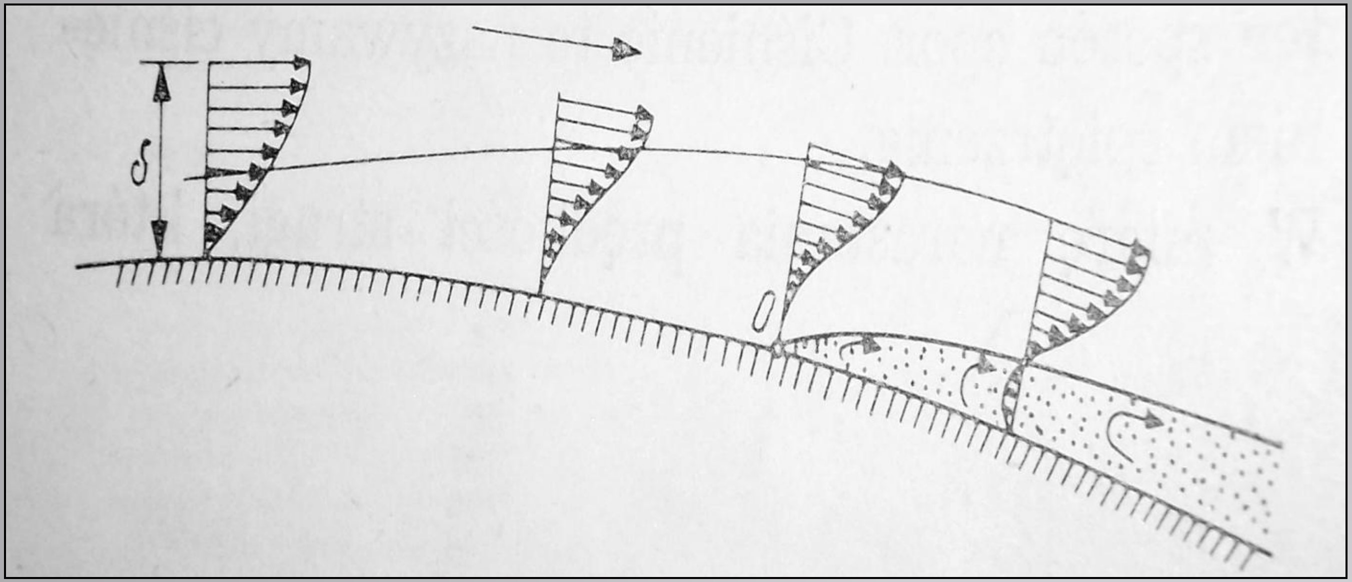
Laminar boundary layer



Turbulent boundary layer

δ - size of boundary layer

Boundary layer separation



Consequences:

- changes in pressures' disposition
- source of the drag force

Magnus force - equation

$$c_L = kZ$$

$$Z = \frac{\omega R}{v}$$

$$\vec{F}_L = \frac{kR^3 \pi \rho \omega v \sin\varphi}{2} \frac{\vec{\omega} \times \vec{v}}{\left|\vec{\omega} \times \vec{v}\right|}$$

$$\left|\vec{\omega} \times \vec{v}\right| = \omega v \sin\varphi$$

$$\vec{F}_L = \frac{kR^3 \pi \rho}{2} \vec{\omega} \times \vec{v}$$