北京航空航天大学
BEIHANG UNIVERSITY

Avionics Technology

B31353551

— *Airspeed*

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II. Airspeed

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Reference & further reading —

Chapter 7: Air data and air data systems & the first half of Chapter 3: Aerodynamics, *Introduction to Avionics Systems* (2nd Edition).

By measuring *on-coming air flow*, we can obtain the aircraft's *airspeed*

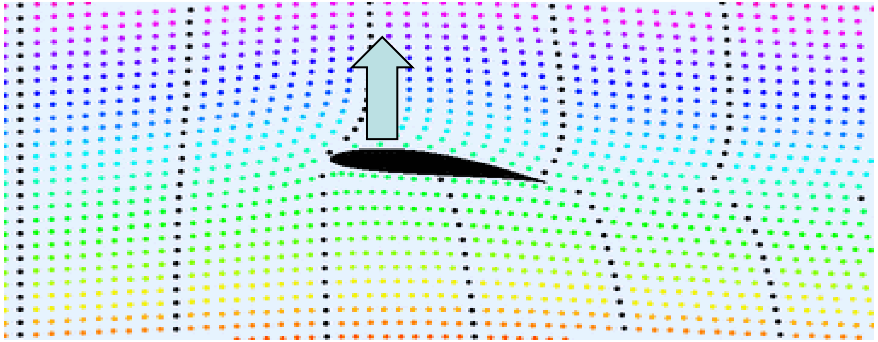
II. Airspeed

（1）Some concepts
（2）Types of airspeed
（3）Airspeed from air measurement

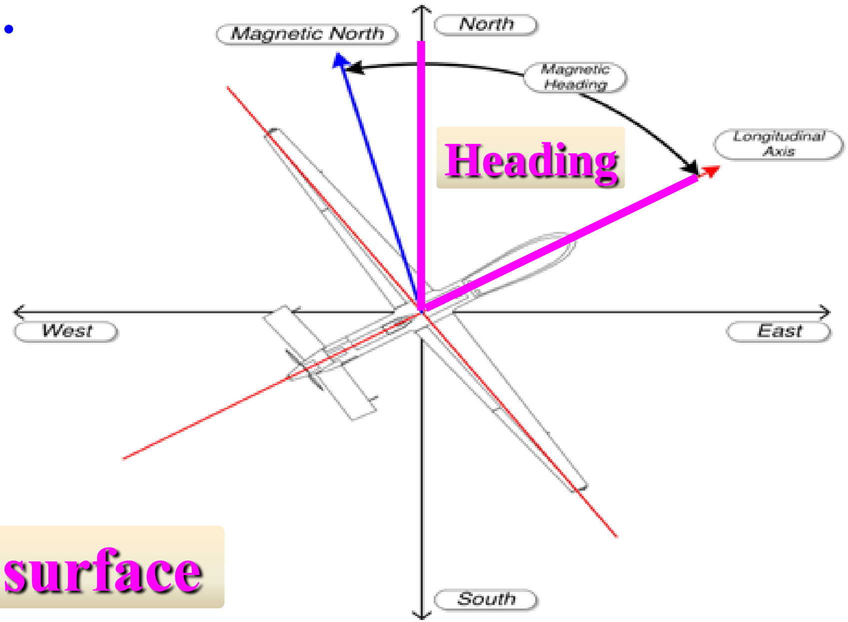
(1) Some concepts

- *Airspeed* is the speed of an aircraft relative to the air-mass in which it is flying through. This speed and heading of the aircraft constitute the *aircraft's velocity* relative to the atmosphere (air).

Force of lift



Air flowing around an aircraft's wing surface



(1) Some concepts

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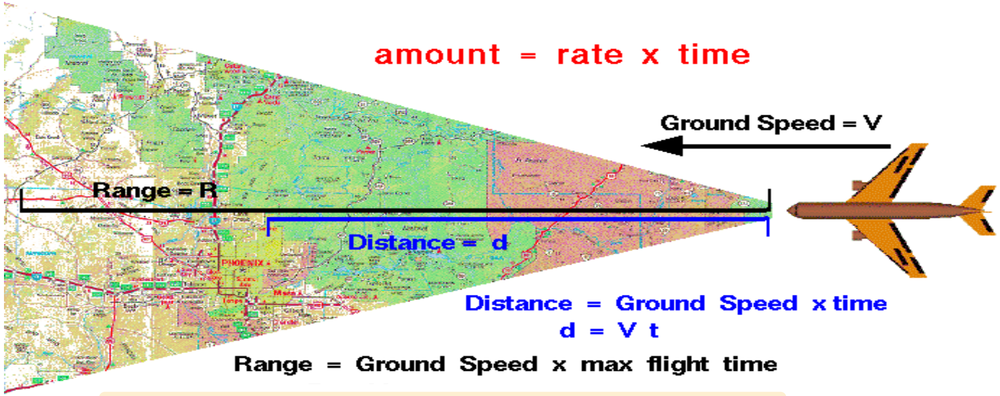
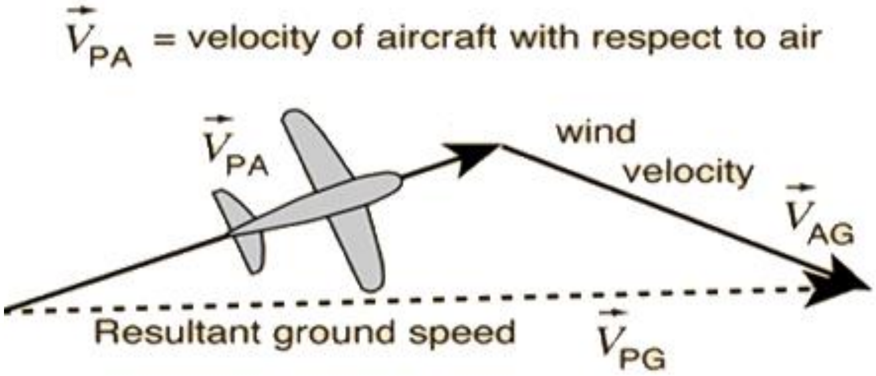
- From velocity of aircraft and wind velocity, *ground speed* (i.e. the speed of the aircraft relative to the ground) can be determined, which has nothing to do with atmospheric conditions (altitude, temperature, air density or pressure) and is for navigation purposes.



A example of navigation

Forward velocity triangle



（1）Some concepts

- At the cruise stage of a flight, the civil aircraft's airspeed can be up to 800 ~ 1,000 km/h (*subsonic speeds*, speed of sound at sea level is 340.294m/s or 1,225km/h).

1 knots (nautical miles per hour) = 1.852km/h

Aircraft have *Pitot tubes* for measuring airspeed

Airspeed indicator

(1) Some concepts

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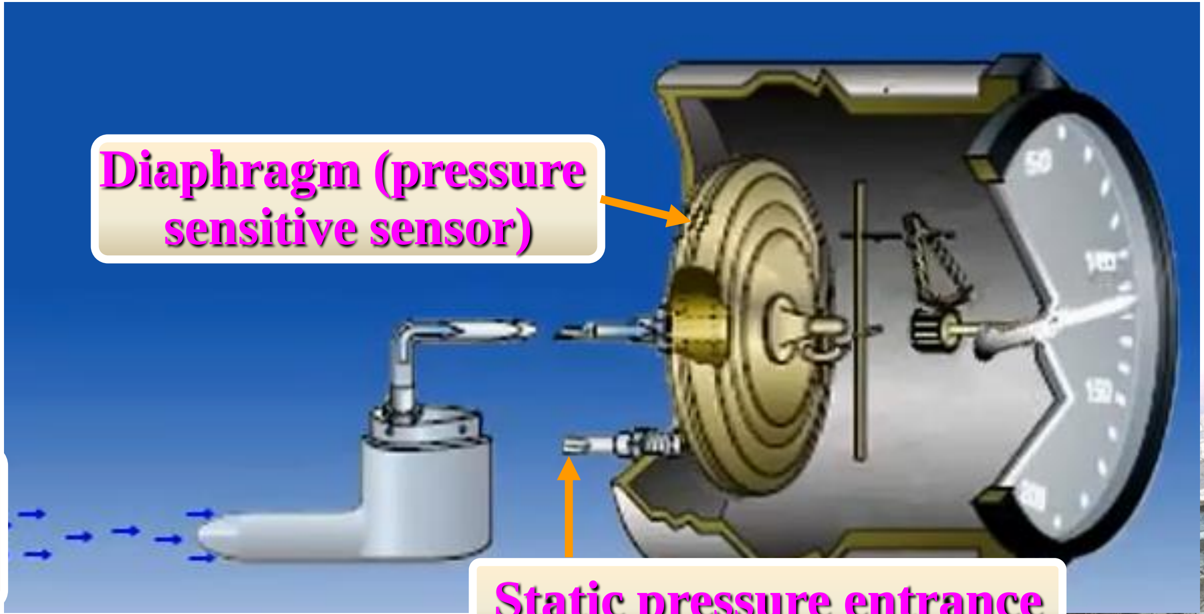
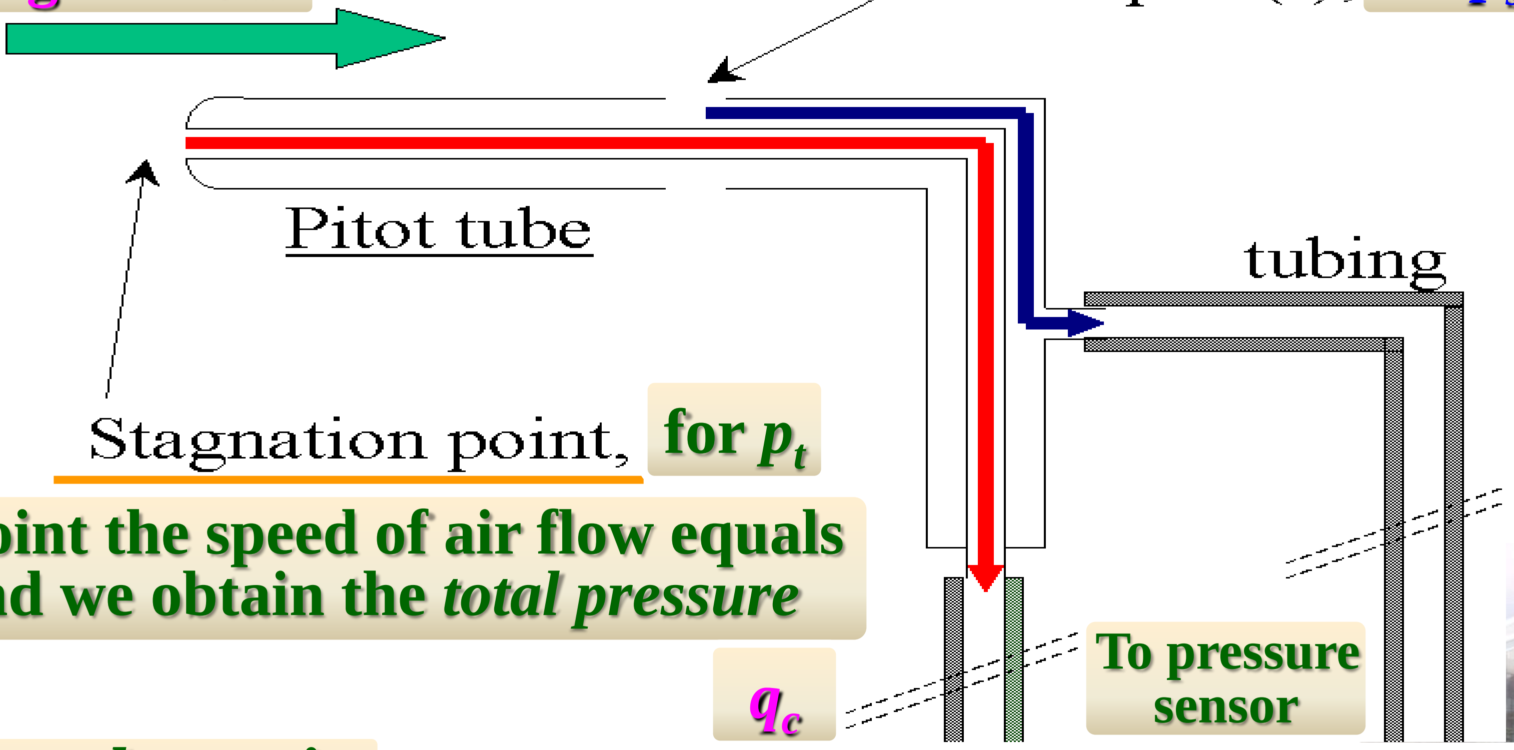
- The Pitot tube faces the on-coming air flow and measures airspeed using the pressure of the air. While this pressure differs from the static (atmospheric) pressure of the free airstream, and is known as the *dynamic* (*impact*) *pressure*.



The moving airstream enters the Pitot tube

(1) Some concepts

On-coming air flow

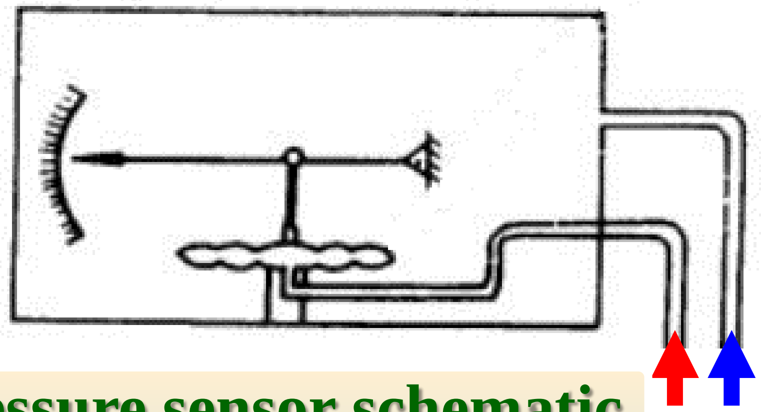


At this point the speed of air flow equals to 0, and we obtain the *total pressure*

Pitot tube schematic

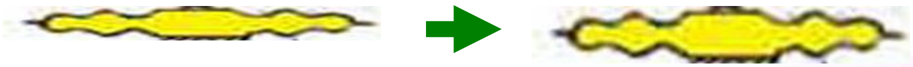
(1) Some concepts

- Dynamic pressure is the pressure exerted to bring the moving airstream to rest relative to the Pitot tube.
- The pressure sensitive sensor is used to measure dynamic pressure $(p_t - p_s)$,i.e. difference between the total pressure and static pressure.



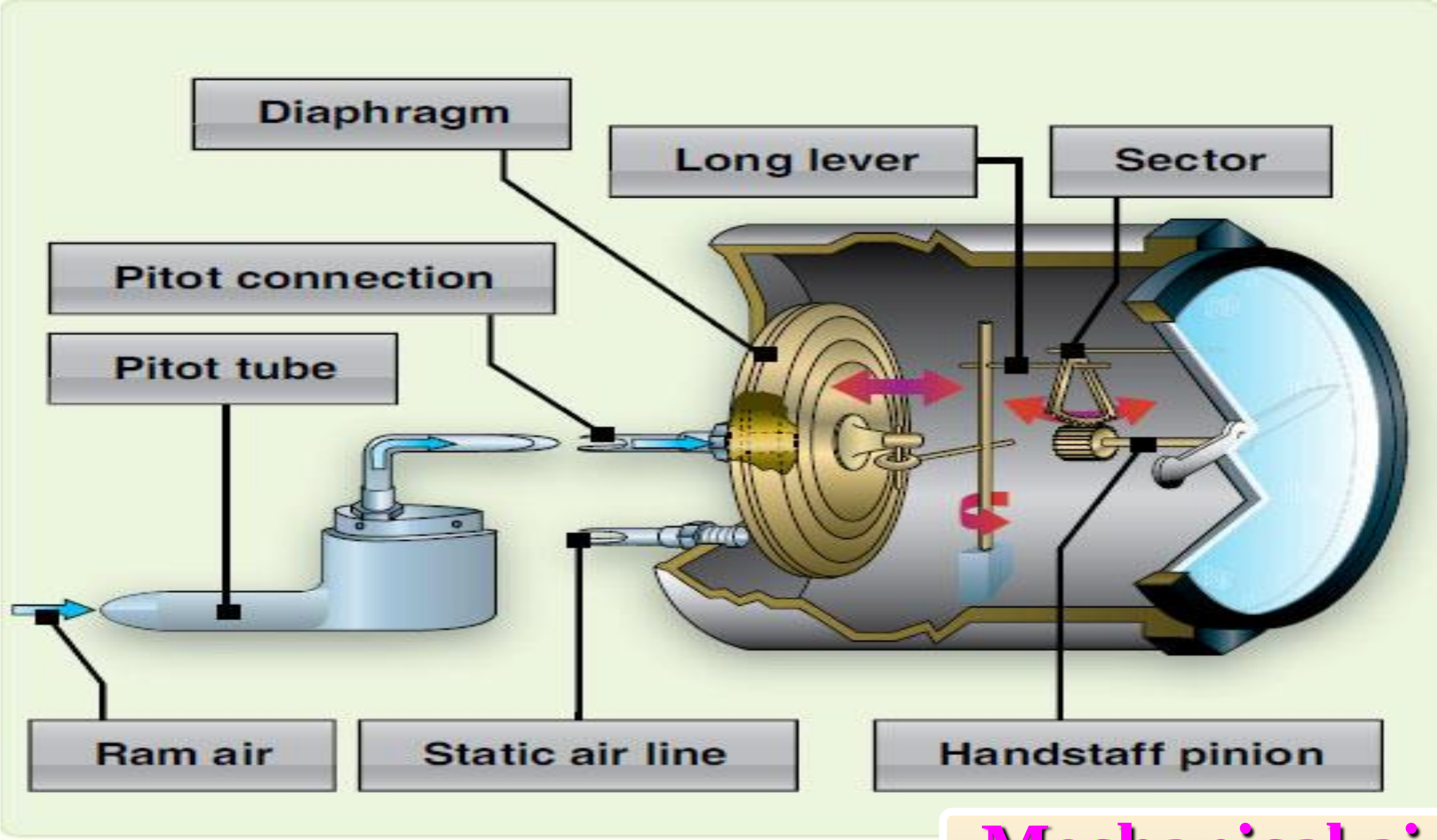
Pressure sensor schematic

Due to changes in differential pressure



Diaphragm expands (contracts) as the airspeed increases (decreases)

(1) Some concepts



Mechanical airspeed meter

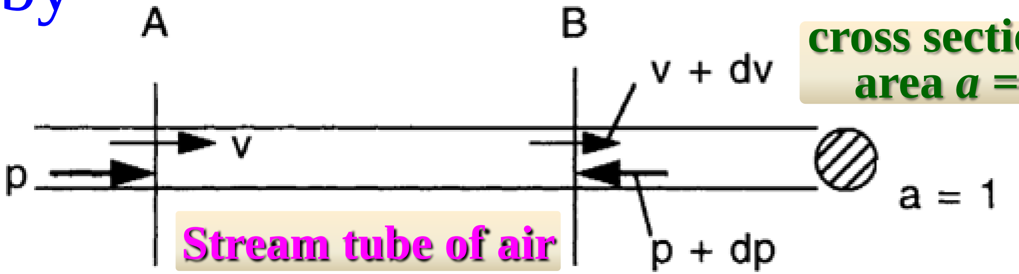
(2) Types of airspeed

- According to hydrodynamics, the airspeed can be derived from the measurement of dynamic pressure.
- For incompressible flow (the density is considered to be constant), dynamic pressure q_c is defined by

$$q_c = p_t - p_s = \frac{1}{2}\rho v^2$$

ρ : air density; v : air speed

The airstream is moving with velocity v and travelling from Section A to Section B



cross sectional area a = 1

Stream tube of air

- From the *fluid continuity equation*, we have:

Mass flow at A equals to that at B

$$\rho a v = (\rho + d\rho) a (v + dv)$$

(2) Types of airspeed

Neglecting second order terms

$$\rho dv + v d\rho = 0$$

- Force acting on air stream tube between sections A and B equals to mass per second multiplying change in velocity: $pa - (p + dp)a = \rho a v dv$ $\quad \rho dv + v d\rho = 0$

Fluid differential momentum equation: $dp + \rho v dv = 0 \rightarrow \dfrac{dp}{d\rho} = v^2$

$$\int_{p_s}^{p_t} dp = -\rho \int_{v}^{0} v dv \rightarrow \boxed{p_t - p_s = \frac{1}{2}\rho v^2}$$

(2) Types of airspeed

- From the dynamic pressure q_c, we can directly derive a quantity regarding airspeed:

$$v = \sqrt{\frac{2(p_t - p_s)}{\rho}} = \sqrt{\frac{2q_c}{\rho}}$$

Function of q_c and air density

- Substituting ρ_0 for ρ (a constant, i.e. air density at sea level), we have:

For airspeeds below 350km/h

$$v_c = \sqrt{\frac{2q_c}{\rho_0}}$$

$\rho_0 = 1.225$ kg/m^3, determined in the standard atmospheric conditions

- v_c is known as the *calibrated airspeed*.

(2) Types of airspeed

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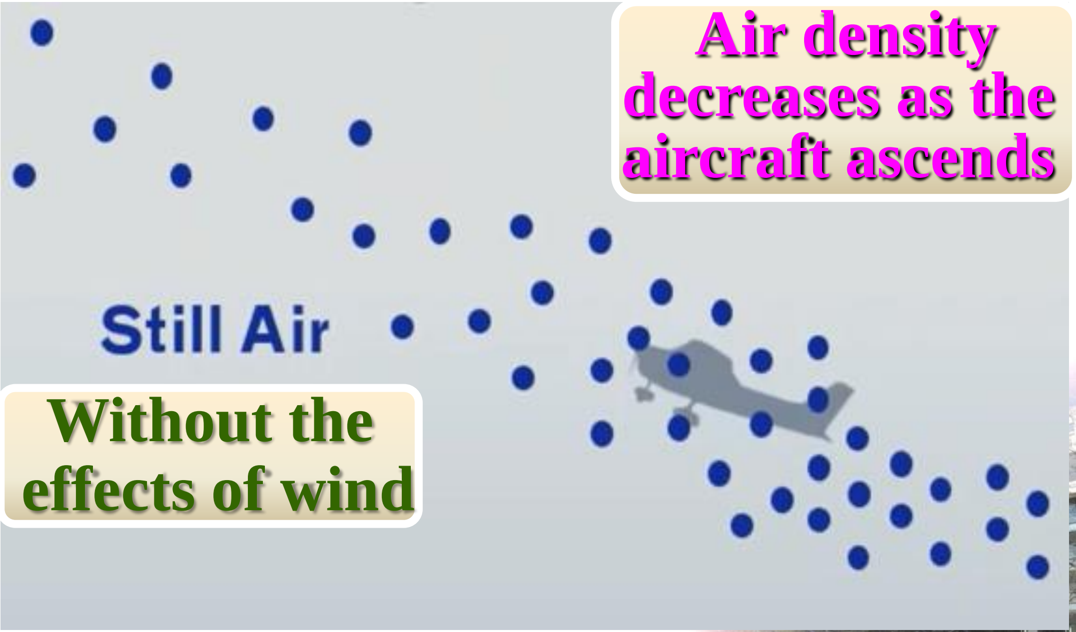
- *Calibrated airspeed* v_c is derived directly from the dynamic pressure and calibrated to reflect standard atmosphere *adiabatic* air flow at sea level. It also can be considered as the dynamic pressure expressed in units of speed, rather than pressure.
- *Indicated airspeed* is basically the same quantity as calibrated airspeed but includes the airspeed system errors. Calibrated airspeed is usually derived by the air data computer and the inherent errors can be compensated by the computer.

（2）Types of airspeed

- The calibrated airspeed is the same as the *true airspeed* (v_t) at sea level. At the altitude which the aircraft is flying, calibrated airspeed differs from true airspeed.
- As altitude increases (the air density decrease), indicated airspeed is less than true airspeed.



(2) Types of airspeed

- The calibrated airspeed is a basic quantity essential for the pilot to fly the aircraft safely, which determines the aerodynamically generated lift and drag forces and moments acting on the aircraft.
- *Mach number* is the ratio of the true airspeed to the local (at the altitude which the aircraft is flying) speed of sound.
- *Vertical speed* is the rate of climb or descent, which can be derived by differentiating pressure altitude.

(3) Airspeed from air measurement

- For incompressible flow (the density is considered to be constant), dynamic pressure q_c is

$$q_c = p_t - p_s = \frac{1}{2}\rho v_t^{\ 2}$$

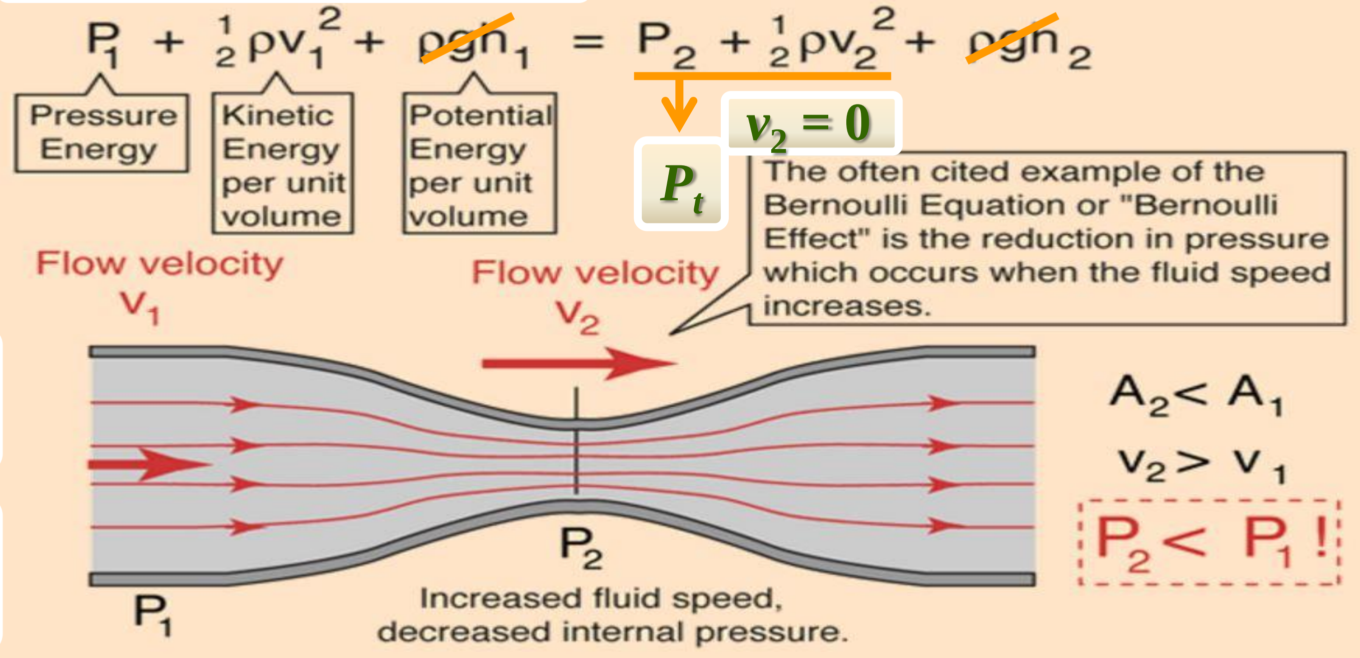
Bernoulli's equation:

ρ : air density;
v_T : true airspeed

$$v_t = \sqrt{\frac{2q_c}{\rho}}$$

For airspeeds below 350km/h

Speed-pressure relationship



(3) Airspeed from air measurement

- However, air is a compressible fluid. The change in density due to the high dynamic pressures resulting from high airspeeds must therefore be taken into account.
- At airspeeds above 350km/h but less than the speed of sound, we have the *modified Bernoulli's equation*:

$$\frac{\gamma}{\gamma-1}\frac{p_t}{\rho_t}=\frac{\gamma}{\gamma-1}\frac{p_s}{\rho_s}+\frac{1}{2}{v_t}^2$$

γ = 1.4 for air, adiabatic index

Air density change takes place due to high airspeeds

(3) Airspeed from air measurement

Fluid differential momentum equation:

$$dp + \rho v_t dv_t = 0$$

$$dp + \frac{1}{K^{1/\gamma}} p^{1/\gamma} v_t dv = 0$$

$$\int_{p_s}^{p_t} \frac{1}{p^{1/\gamma}} dp = -\frac{1}{K^{1/\gamma}} \int_{v_t}^{0} v_t dv$$

$$\frac{\gamma}{\gamma-1}\left[p_t^{(\gamma-1)/\gamma} - p_s^{(\gamma-1)/\gamma}\right] = \frac{1}{K^{1/\gamma}} \cdot \frac{v_t^{\,2}}{2}$$

For adiabatic flow, we have:

$$\frac{p_t}{\rho_t^{\,\gamma}} = \frac{p_s}{\rho_s^{\,\gamma}} = K$$

***K* is constant**

$$\frac{p_t^{1/\gamma}}{\rho_t} = \frac{p_s^{1/\gamma}}{\rho_s} = K^{1/\gamma}$$

$$\frac{\gamma}{\gamma-1}\left(\frac{p_t}{\rho_t} - \frac{p_s}{\rho_s}\right) = \frac{v_t^{\,2}}{2}$$

Modified Bernoulli's equation

(3) Airspeed from air measurement

$$\frac{\gamma}{\gamma-1}\left[\left(\frac{p_t}{p_s}\right)^{(\gamma-1)/\gamma}-1\right]=\frac{1}{K^{1/\gamma}p_s^{(\gamma-1)/\gamma}}\cdot\frac{v_t^2}{2}$$

$$\frac{\gamma}{\gamma-1}\left[\left(\frac{p_t}{p_s}\right)^{(\gamma-1)/\gamma}-1\right]=\frac{\rho_s}{p_s}\cdot\frac{v_t^2}{2}$$

Speed of sound A **is defined by** $A^2=\gamma\, p_s/\rho_s=\gamma\, R_a T_s$

$$\frac{p_t}{p_s}=\left[1+\frac{(\gamma-1)}{2}\cdot\frac{v_t^2}{A^2}\right]^{\gamma/(\gamma-1)}$$

$\gamma = 1.4$

$$\frac{q_c}{p_s}=\frac{p_t}{p_s}-1=\left[1+0.2\cdot\frac{v_t^2}{A^2}\right]^{3.5}-1$$

(3) Airspeed from air measurement

$$v_t = A \cdot \sqrt{5 \cdot \left[\left(\frac{q_c}{p_s} + 1 \right)^{\frac{2}{7}} - 1 \right]}$$

- Substituting p_0 (atmospheric pressure at sea level) for p_s and A_0 (speed of sound at sea level) for A, the calibrated airspeed v_c is derived by

$$v_c = A_0 \cdot \sqrt{5 \cdot \left[\left(\frac{q_c}{p_0} + 1 \right)^{\frac{2}{7}} - 1 \right]}$$

Function of q_c only

(3) Airspeed from air measurement

- Mach number M can be derived directly:

$$M = \frac{v_t}{A} = \sqrt{5 \cdot \left[\left(\frac{q_c}{p_s} + 1 \right)^{\frac{2}{7}} - 1 \right]}$$

- True airspeed v_t is related to the Mach number and local speed of sound:

$$v_t = MA = M\sqrt{\gamma \cdot R_a T_s}$$

$R_a = 287.05287 \mathrm{m}^2/\mathrm{K} \cdot \mathrm{s}^2$

T_s: local atmospheric temperature

(3) Airspeed from air measurement

- The actually measured (indicated) air temperature made by means of a temperature sensor on an aircraft is the *total temperature* T_t, and T_s therefore is derived from T_t :

$$\frac{\gamma}{\gamma-1}\left(\frac{p_t}{\rho_t}-\frac{p_s}{\rho_s}\right)=\frac{v_t^{\,2}}{2} \rightarrow \frac{1}{\gamma-1}(T_t-T_s)=\frac{1}{\gamma\cdot R_a}\frac{v_t^{\,2}}{2}$$

$p=\rho R_a T$

$A^2 = \gamma R_a T_s$

$$\frac{T_t-T_s}{T_s}=\frac{\gamma-1}{2}M^2$$

$$T_s=\frac{T_t}{(1+0.2M^2)} \leftarrow$$

(3) Airspeed from air measurement

- The quantity true airspeed v_t in practice is derived from the Mach number and the measured air temperature T_t at the position as close as possible to a stagnation point:

$$v_t = MA = M\sqrt{\gamma \cdot R_a T_s}$$

$$\downarrow$$

$$v_t = \sqrt{\gamma \cdot R_a} M \sqrt{\frac{T_t}{(1+0.2M^2)}}$$

The end of *Airspeed*