Basic knowledge

Steady flow of compressible fluids

Flow with varying volume

In gases there is a difference between flow at constant volume (incompressible) and flow with varying volume (compressible). In the incompressible flow of gases the flow processes are treated like the flow of a liquid.

For larger changes in the fluid's pressure and temperature the interconnections between pressure, temperature and volume may not be ignored any more. This flow is called compressible. For ideal gases, this relation applies:

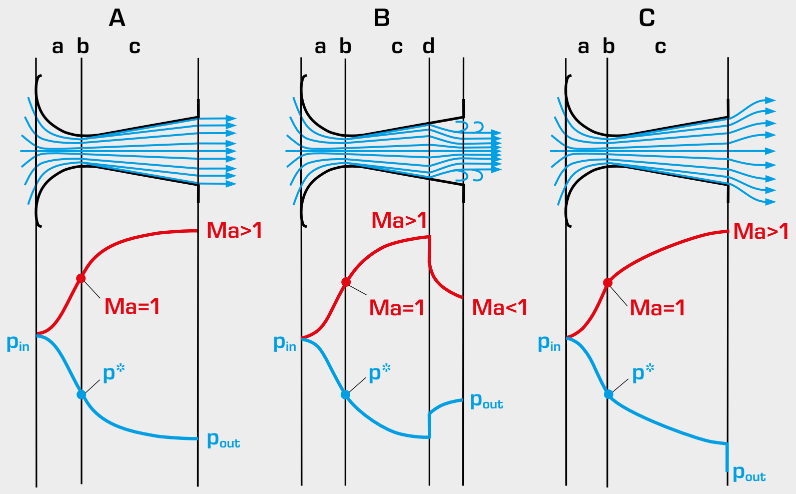
$$p \cdot V = m \cdot R \cdot T$$

Often the term "compressible flow" is used in this context, whereas the fluids are compressible not the flow.

If the velocity of gas flow is larger than Ma 0,3 it must be regarded as compressible. In air, this corresponds to approximately 100 m/s at 1 bar and 0 °C. The dynamic pressures occurring in the flow here are equal to a maximum of 60 mbar.

Below this limit, a gas flow can be considered as incompressible fluid with good approximation. The flow in a fan or the flow around a car for example, can be regarded as incompressible. However, in turbo compressors, gas and steam turbines, jets, fast planes or rockets the flow must be regarded as compressible.

Compressible flow in engineering



Flows through a convergent-divergent nozzle (de Laval nozzle) at different back pressures

A "Adapted" nozzle with ideal pressure ratio. There is supersonic speed at the nozzle outlet.
B Shock wave occurs in the divergent region of the nozzle, after which subsonic speed ensues. There are pressure losses due to stall.
C Underexpansion with jet dispersion behind the nozzle outlet. This results in pressure losses.

a convergent region, **b** narrowest cross-section, **c** divergent region, **d** shock wave, **p*** critical pressure ratio, **Ma** Mach number,
🟥 velocity curve, 🟦 pressure curve

Compressible flows play a key role in the conversion of thermal gradients into kinetic energy in thermal turbomachines. The conversion is caused by the outflow of a gas into guide vane systems or nozzles. At high differential pressures, the flow can reach or even exceed the speed of sound.

So-called de Laval or Laval nozzles are used to generate supersonic speeds. They are distinguished by their convergent-divergent shape.

In the first, convergent part the flow is brought up to the speed of sound. In the second, divergent part the flow is accelerated to supersonic speed by further expansion. During this process the flow rate through the nozzle is determined by the speed of sound in the narrowest cross section. For the convergent part of the nozzle: in the narrowest cross-section of the nozzle the speed of the fluid reaches the speed of sound. The pressure ratio at this point is called critical. The maximum mass flow is achieved at the onset of the critical pressure ratio.

Excessively high back pressures can cause a shock wave to occur in the divergent part of the nozzle, so that the rest of the nozzle operates as a subsonic diffuser and the pressure rises again.

Supersonic flow

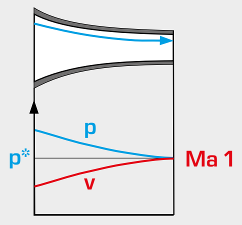
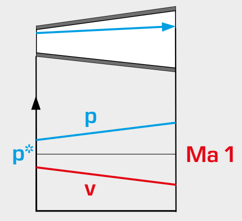
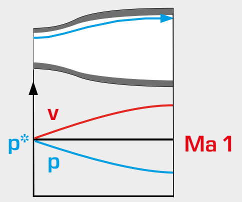
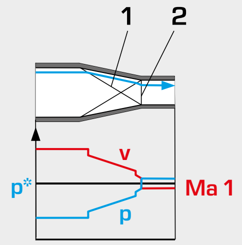
Supersonic flows behave differently from flows with subsonic speed in many ways, and therefore display very interesting phenomena.

Whereas subsonic flows are accelerated by reducing the cross-section and decelerated by enlarging the cross-section, in supersonic flows it is exactly the opposite.

In supersonic flows, changes in the cross-section may easily result in shock waves, whereas in subsonic flows stalling is a risk.

Basically, deceleration of supersonic velocity is caused by shock waves. In a shock wave the velocity is reduced suddenly, thereby causing a sudden increase in pressure and temperature. When talking about shock waves we distinguish between oblique shocks and normal shocks. An oblique shock abruptly reduces the velocity but does not result in subsonic velocity. On the other hand, a normal shock wave always leads to subsonic speed.

To keep the losses in supersonic diffusers small, a combination of several oblique shocks and one final normal shock is used.

	Nozzle Flow is accelerated, pressure drops	**Diffuser** Flow is decelerated, pressure rises
Sub-sonic Ma < 1		
Super-sonic Ma > 1		

Pressure and velocity curve

v velocity, **p** pressure, **p*** critical pressure ratio,
1 oblique shock wave, **2** normal shock wave

Velocity of sound in gases

$$c = \sqrt{\kappa R T}$$

c speed of sound, **κ** adiabatic exponent, **R** gas constant,
T temperature

Mach number as a measure of the velocity

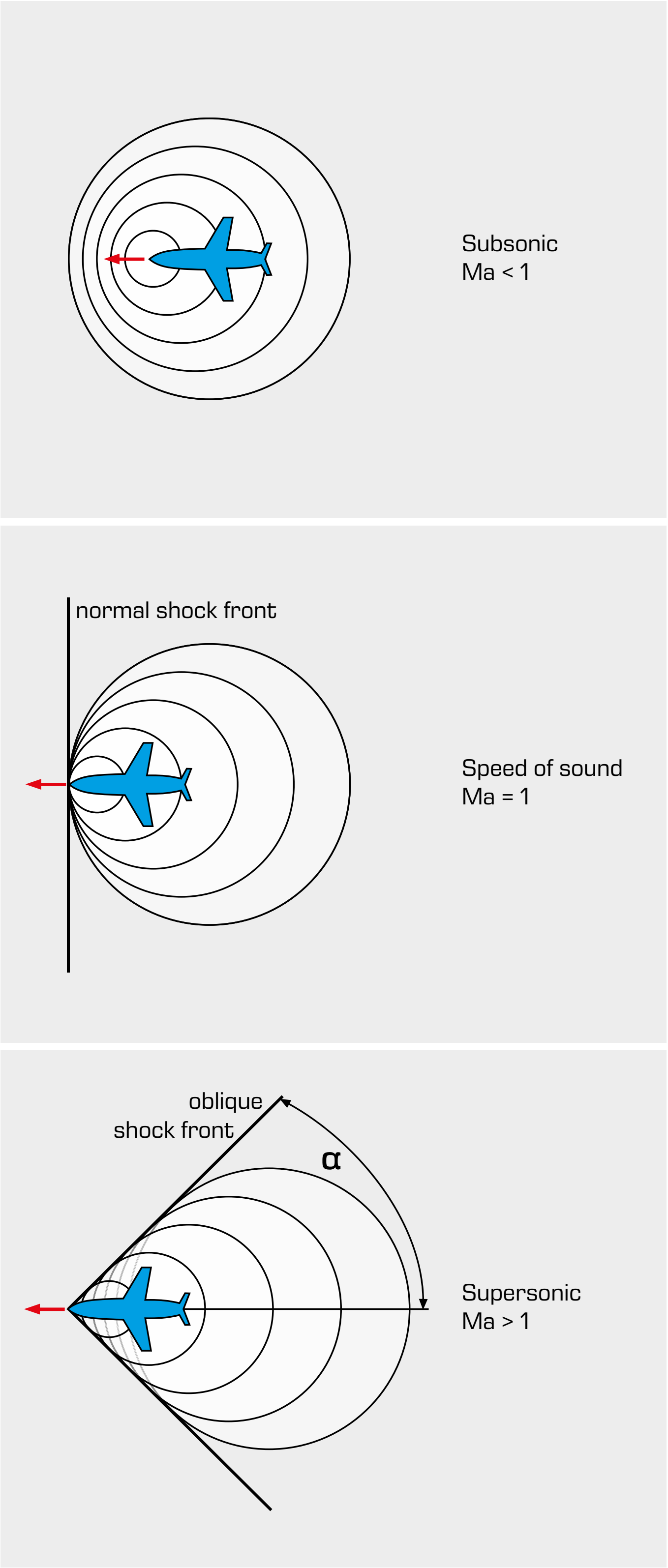
$$Ma = \frac{v}{c}$$

Ma Mach number, **v** velocity of the fluid,
c speed of sound

Basic knowledge

Steady flow of compressible fluids

Flow around and movement at supersonic speed



Diffusion of sound waves at different velocities of the sound source in the medium

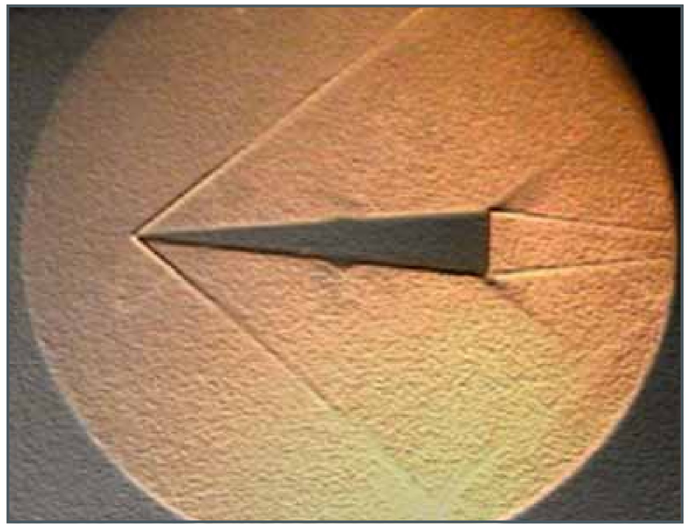
Whereas at subsonic speeds the sound emitted by the body also diffuses to the front, this is not so in the case of supersonic speed. Here all sound waves form a common front in the shape of a cone, the so-called Mach cone. The Mach angle of the cone is a measure of the Mach number.

Angle of the Mach cone

$$\sin \alpha = \frac{1}{\text{Ma}}$$

Ma Mach number, **α** Mach angle

A typical example of a shock front is the “sonic boom” of an aircraft flying at supersonic speed. Here, the shock front meets the observer with its abrupt change in pressure and is perceived as a bang.



Oblique shock fronts (Mach cone) on a wedge-shaped drag body at Ma = 1,59

The table shows an abstract from a common university curriculum. GUNT devices cover this content to the greatest extent.

Learning objectives for the field of steady flow of compressible fluids	GUNT products
Pressure and velocity curves in pipe flow	**HM 230**
Energy equation of gaseous fluids	**HM 230**
Outflows from orifices Critical pressure ratio Critical velocity	**HM 260, HM 261**
Speed of sound	**HM 261, HM 230, HM 172**
Maximum outflowing mass	**HM 261, HM 230, HM 260**
Outflow from extended nozzles Behaviour of de Laval nozzle with variable back pressure	**HM 260, HM 261**
Movement with speed of sound	**HM 172**
Flow through column and mazes	

Using GUNT equipment you can address the main topics of the steady flow of compressible fluids in your fluid mechanics laboratory in detail.

The compact HM 172 Supersonic wind tunnel offers outstanding possibilities in the visualisation of supersonic flows.