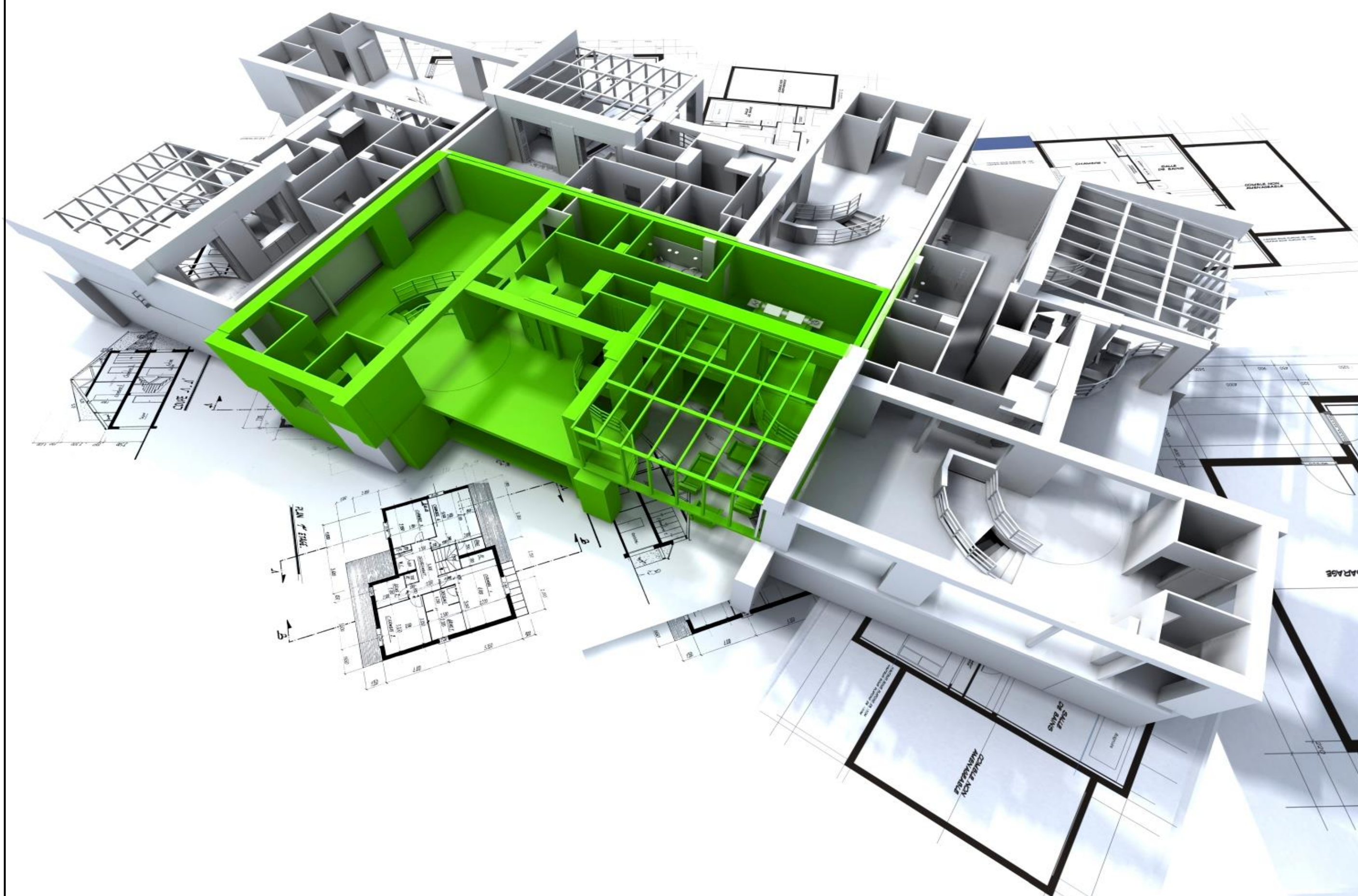


FLUIDS 2

FLUIDS: NON-IDEAL ASPECTS

The simple fluid conservation laws we studied in the last section assume a “perfect” or “ideal” fluid, without any real-world complications (like viscosity). In this section we look at how these issues affect real fluids.

FLUIDS 2

FLUIDS: NON-IDEAL ASPECTS

OVERVIEW

In this section we will learn about:

- Laminar and turbulent flow
- Reynold's number
- The boundary layer
- Flow development in pipes
- Compressible flow
- Shockwaves and supersonic flow
- Flow regimes

OBJECTIVE

Although simple conservation laws are useful for basic calculations, real fluids are more complex than these equations account for and so they may not produce accurate results. In this section we will learn about these complicating factors.

TOPIC 1 – NON-IDEAL ISSUES

In the previous sections we have covered the three main mathematical principles of general flows (although we applied them specifically to incompressible invisid flow). These were:

1. Conservation of Mass – The Continuity Equation. (relates *Area of flow, Density of fluid and Flow velocity*).
2. Conservation of Energy – Euler's and Bernoulli's Equations. (relates *Fluid pressure, Velocity of flow and Density*).
3. Conservation of Momentum – The Momentum Relationship. (relates *Flow rate to Generated forces*).

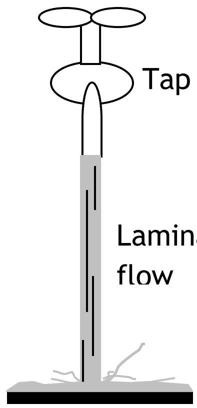
Although these principles are the basis for the whole subject of fluid dynamics, there are many effects in actual fluids which mean that, in real life, flows don't behave like the equations derived from these "perfect" assumptions. In this section we'll look at these important effects which "throw a spanner in the works." The three most important are:

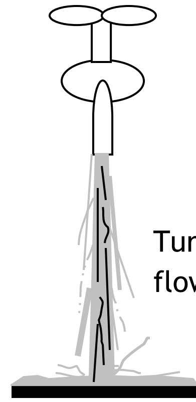
i) Turbulent flow.
ii) Boundary layers.
iii) Compressible flow.

The first two of these are caused by the *viscosity* of the fluid (its internal friction or "gooeyness"), the third one by the heat generated inside fluids as they are compressed. We'll start with i).

TOPIC 2 – LAMINAR AND TURBULANT FLOW

It may not have escaped your attention that two types of flow are commonly seen. Laminar flow is smooth and regular – you often get it by gently turning on a tap so that the flow is clear and with a fairly constant cross-section. Turbulent flow is rough and unpredictable, with much mixing – turn the tap full on and the opaque "sputtering" flow is turbulent. In the examples which we've been dealing with so far, the flow is assumed to be laminar.





Smooth, predictable, quiet, regular, little mixing.

Rough, unpredictable, noisy, mixing between layers.

In some circumstances (but not all the time!) engineers strive to get laminar flow. However, turbulent flow is usually more common in nature.

Osborne Reynolds showed, in 1883, how to predict which type of flow you'd get in a particular situation. He defined the following quantity, called the *Reynold's Number*.

Reynold's number:

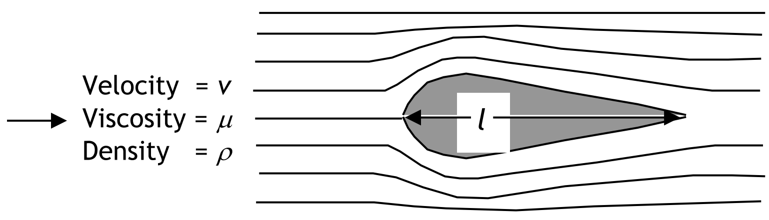
$$\text{Reynold's number} = \frac{\rho v l}{\mu}$$

Where ρ is density, *v* is flow velocity, *l* is the length over which we're considering the flow and μ is the viscosity (more correctly, the coefficient of dynamic viscosity). Typical values of μ are 1.002 x 10^{-3} Pas for water and 1.846 x 10^{-5} Pas for air (both at 20ºC, atmospheric pressure).

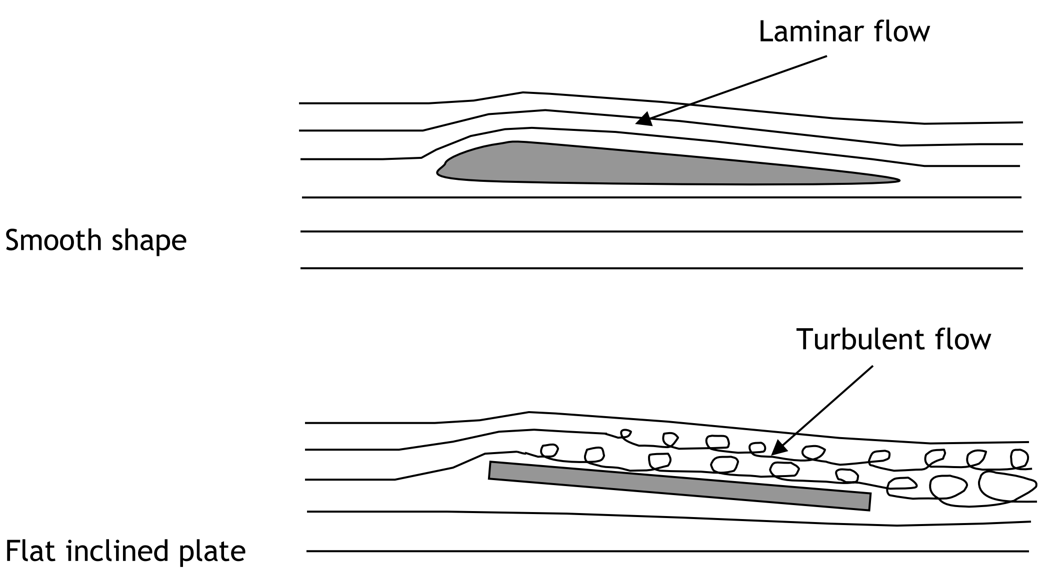
If *R.N* is $\langle$ 2000, then flow is *likely* to be laminar, above 2000, turbulent. Note the use of the word "likely" in the sentence above. Reynold's number is a guide to the type of flow and does not predict it with absolute certainty (the region between approximately 2000 and 4000 is sometimes called the "transition region" where the flow might be either turbulent or laminar). If you think about it, the formula makes sense – fast flow or a liquid which is of high density or flowing over a long distance is likely to be turbulent; whereas viscous fluids (like treacle) aren't! You can probably also see how to generate exceptions to the rule. If fluid is flowing over a very smooth surface, it will stay laminar even when the length l makes the Reynold's number very large. Note, that in the case of pipes, l is the diameter of the pipe.

> *TASK 1*
>
> *Water is passing through a hose of diameter 1cm at 2m/s. What is the Reynold's number – is the flow likely to be laminar or turbulent?*

The diagram below shows a typical application in order for you to see how the parameters are often defined. In this case we want to calculate the Reynold's number of fluid flowing over a smooth airfoil type shape.



Sharp objects or objects which disrupt the flow more are likely to produce turbulent flow. Compare the two shapes below.

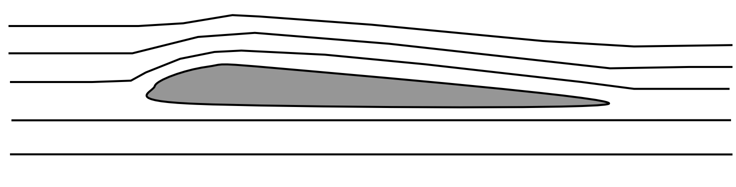


This is one (minor) reason why airfoils have their round shape (the main reason is so that air follows the shape smoothly, due to the Coanda effect). It's not so much that the shape itself generates lift (as you can see, the fluid velocity over the top surface of inclined flat plate is also fast); it's that the smooth shape keeps the flow smooth and predictable and avoids buffeting. It should be noted however that the laminar flow quickly turns turbulent as it travels over the surface of the airfoil.

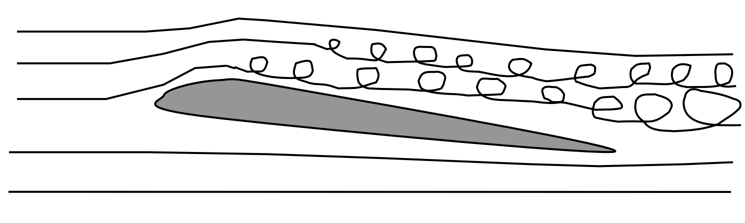
> *TASK 2*
>
> *If air is travelling over a wind-turbine blade at 20kmh. How far will it move before turning turbulent?*

However, even with our smooth airfoils, if we tilt the form back far enough so that it disrupts the stream sufficiently, the flow will detach from the surface and a large area of very turbulent flow will form behind. In aerodynamics this is called a *stall* and causes the wing to lose lift. It can cause the aircraft to crash and happens if it flies too slowly or with too much of a "nose up" attitude. Obviously this is something to be avoided!

Aerofoil in normal operation



Stalled aerofoil – note "nose up" attitude



Now that we know a little more about turbulent flow, let's look at what the Reynold's Number actually is. The Reynold's Number is the ratio between two forces. Firstly, the inertial force (the force due to the fluid's weight and velocity). And secondly, the viscous force (the fluid's internal friction – its viscosity).

Inertial force

$$\frac{\rho v l}{\mu}$$

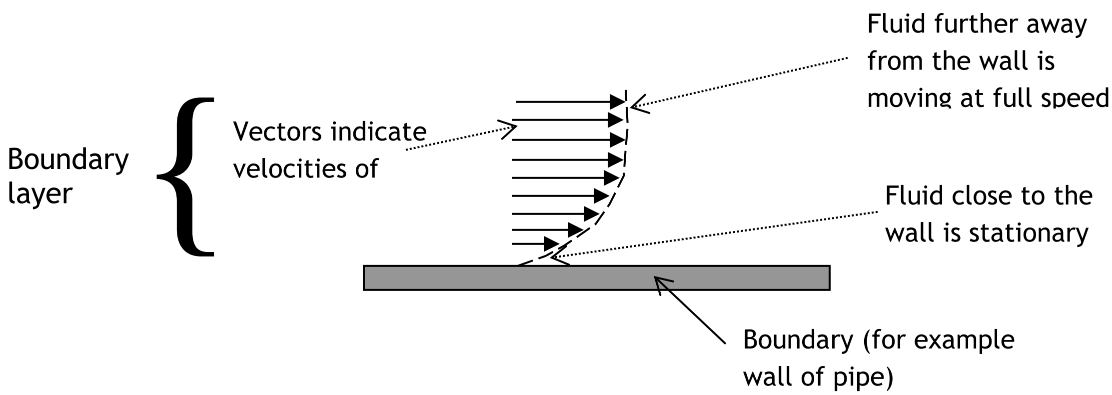
Viscous force

The more viscous force there is, the less likely the flow is to be turbulent – you don't see much turbulence in heavy oil – hence the adage "pouring oil on troubled waters!" This is because the internal friction of the thick fluid – its gooeyness, "damps out" the turbulence. But the faster or denser the liquid (or the longer the surface it's travelling over), the more likely it is to be turbulent.

This is why fluid passing through constrictions in pipes (like we saw in the continuity equation section) won't behave as we expect, because the constriction is likely to cause turbulence in the fluid (another effect, you may get in a similar situation, where liquids flow faster and therefore pressure drops, is that the pressure of the liquid drops to below the vapour point and it "boils" – pockets or bubbles of vapour appear in the fluid. This is called *Cavitation*, and also causes actual flow to diverge from theory).

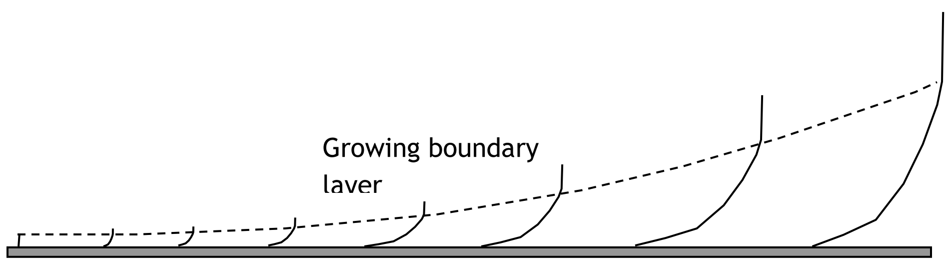
TOPIC 3 – BOUNDARY LAYERS

Like Laminar and Turbulent flow, *Boundary Layers* are also caused by viscosity - a frictionless fluid wouldn't have a boundary layer. You may remember from your first year that a boundary layer causes the fluid to stick to the surface against which it is flowing – like the surface of a pipe, edge of a river channel or surface of an airfoil. This means that the fluid at the very edge of the boundary is stationary.

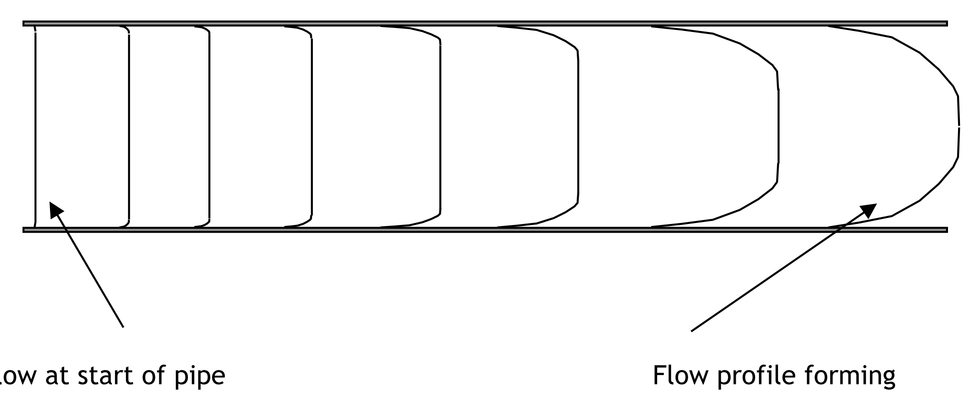


This is the reason why you can't wash dust of a car bonnet with a hose!

As the fluid moves along the surface of the wall, the boundary layer grows (this is closely related to the onset of turbulence, if the layer grows enough it will become *detached* from the wall and result in more turbulence – remember the stall in airfoils).

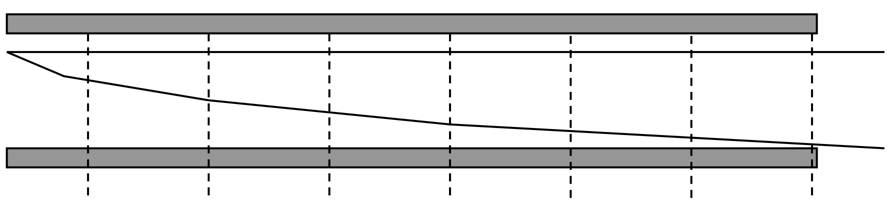


As you can imagine, such behavior profoundly affects the flow in pipes and further removes them from the ideal situations expressed in our simple fluid equations.



This means, of course, that all our formulae only apply to average (or peak) velocities because the real fluid is moving at different speeds over the width of the pipe. Just what this profile is depends on the pipe parameters and also the fluid's initial conditions. In smooth circular pipes, for example, the speed across the width of the pipe varies as the fourth power of the radius.

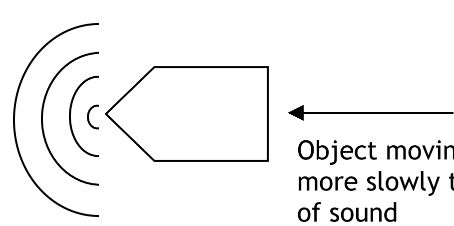
Friction in fluids also produces another effect. Suppose that we measure the pressure at different places in a pipe of uniformly flowing fluid. We'd expect the pressure in the pipe to be the same all the way through providing that the pipe width was constant ($p = const + \frac{\rho v^2}{2}$). But in reality we'd find that the pressure falls.



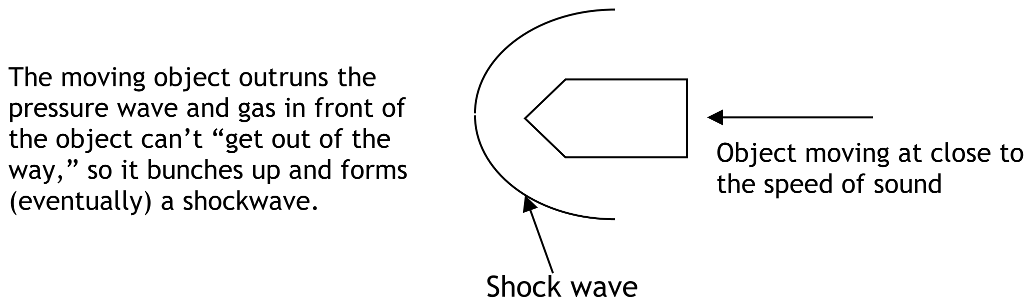
This, again, is due to the fluid's viscosity – energy is being lost in the internal friction of the fluid (flow in pipes in analogous to electricity in wires: pressure is voltage, mass flow $\dot{m}$ is current and our loss of pressure is due to "resistance" in the pipe).

TOPIC 4 – COMPRESSIBLE FLOW

Liquids are not compressible. Gases are also not, providing that they are travelling (or an object is travelling through them) at less than 0.3 the speed of sound (known as Mach 0.3). Slow gases like these are incompressible because, when something moves through them, a pressure wave (a sound wave, if you like) travels ahead and "tells" the molecules to "get out of the way" – to rearrange themselves (molecules have repulsive forces between them and don't "like" being too close together).



If, however, the object gets faster (above Mach 0.3), eventually the molecules in front can't get out of the way (because the object is travelling as fast as the pressure wave telling them to move) and they "bunch up" or compress - this is the region of "compressible flow." At even faster speeds they bunch even further, eventually (above the speed of sound, Mach 1) forming a barrier known as a shockwave.



The shockwave is a major disturbance to the gas (when the shockwave from the front of a supersonic aircraft meets the ground, it's known as a "Sonic Boom"). Unfortunately compressible flow also means that the equations we've looked at carefully up until now breakdown gradually above about Mach 0.3 and we need a new set.

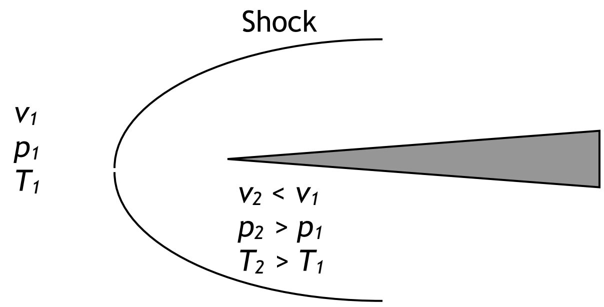
> *TASK 3*
>
> *Look up some videos on "supersonic shockwaves" on youtube.*

The main reason why our previous equations don't work, is that the energy in the system becomes so great that the gas itself heats up. So a new set of equations have to be developed which are based, not only on flow relationships, but also on the thermodynamic equations that you are studying in the other half of the module. For example, the equation analogous to Bernoulli's equation must now also incorporate heat energy.

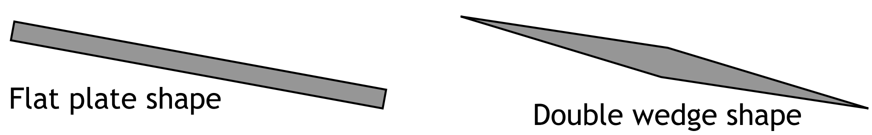
$$\underbrace{C_pT\rho}_{\text{Heat Energy}} + \underbrace{p}_{\text{Energy due to pressure}} + \underbrace{\frac{\rho v^2}{2}}_{\text{Kinetic Energy}} + \underbrace{\rho g h}_{\text{Potential Energy}} = \underbrace{\text{Constant}}_{\text{Total Energy}}$$

There are two particular cases: The region between Mach 0.3 and Mach 1, where the flow is compressible but there are no shockwaves present, and the region above Mach 1 where shockwaves are present. Different equations are used in these two regions.

In the case of shockwaves, the flow doesn't change gently as it did in previous cases, but very rapidly across the shock boundary. As you might imagine, velocity decreases across the shock but pressure and temperature increase.

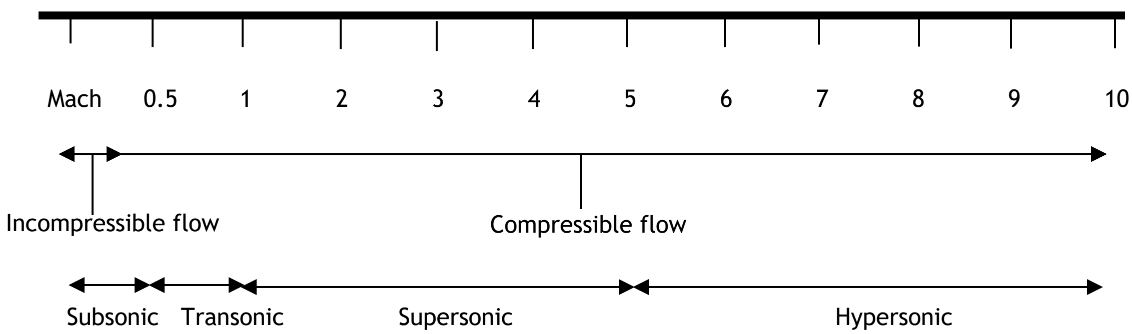


The complexity of working out such relationships (due to experimental problems) is why it took so long for humans to design supersonic aircraft (over 40 years). Incidentally, the best shape for a supersonic wing is a flat plate or a double wedge. Both of these are hopeless at low speeds – so designing planes which have to fly at both fast and slow speeds is a very difficult task.



Despite the difficulties in working out the formulae, the equations for supersonic flow turn out to be fairly simple in the end. The really complex problems are in the so called *Transonic Region* which is where subsonic flow becomes supersonic. For example on an aircraft wing where the main flow is subsonic but turns supersonic as it moves over the wing (you might remember that the air speeds up as it moves over the top of a wing). This is difficult because the flow is neither "one thing nor the other" – it displays traits of both subsonic and supersonic flow and neither set of equations gives very accurate results (much of the data comes from experiment). Unfortunately, a lot of flow situations (such as modern passenger aircraft design) are in this region.

The diagram below summarizes the main flow regions based on speed.



At the beginning of any fluid dynamics analysis problem the first task is to identify the flow region so that the correct equations and assumptions can be used.

SUMMARY

- There are many effects which cause fluids to behave differently in reality from the perfect assumptions made in simply derived equations.
- These effects include those caused by:
    - Turbulence
    - Boundary layers
    - Fluid compressibility
- The first two of these effects are a result of viscosity.
- Reynold's number is an important predictor of turbulence in flows (and other things in fluids too).
- A Reynold's number >2000 means that flow is likely to be turbulent.
- The shape of an object is important in maintaining smooth flow over a surface.
- Airflow can become detached from an airfoil causing a stall.
- Cavitation is caused by vapor bubbles appearing in liquids and can also cause theory and practice to diverge.
- Boundary layers form where fluids met boundary walls and have a major effect on fluid behavior.
- Developed flow in pipes have a parabolic flow profile.
- Pressure falls along the length of a pipe due to losses.
- Slow gasses and liquids can usually be regarded as incompressible.
- Compression grows as speed in gasses increases, but is often negligible below Mach 0.3
- Above the speed of sound shockwaves form.
- Identifying the correct flow type is an essential first step to solving fluid problems.