2-8 ANGLE OF CONTACT

The **angle of contact** is defined to be the angle between the surface of the liquid and the solid surface at the point of contact.

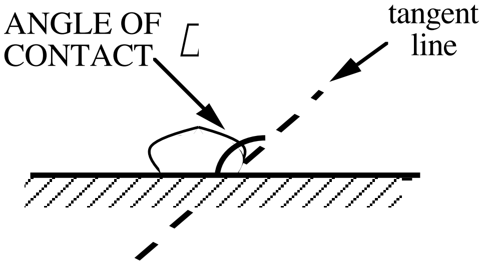

Fig 2.17 Angle of contact for a liquid that does not "wet" the solid surface

You will observe that for a water-glass contact, as in the next diagram, the angle of contact is much smaller;

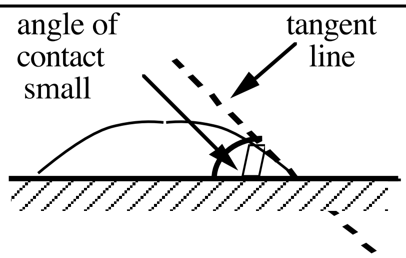

Fig 2.18 Angle of contact for water-glass contact

for mercury-glass, as in the next diagram, it is almost 180°.

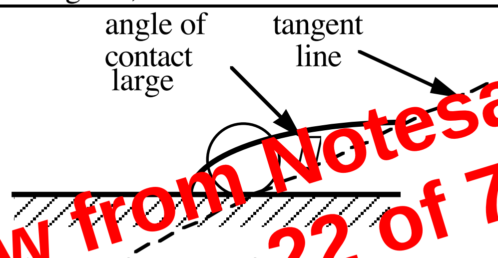

Fig 2.19 Angle of contact for mercury-glass contact

When the angle of contact is less than 90°, the liquid is said to **wet** the solid surface, while it is said **not to wet** the surface if the angle of contact is greater than 90°.

When the angle of contact is not 0° or 180°, the angle explicitly enters those equations which directly or indirectly involve the force exerted by a solid on a liquid due to surface tension.

3-3 REYNOLDS NUMBER

What factors determine whether a fluid will flow in streamlined or in turbulent motion? You could guess some of these more or less easily.

(i) Speed of flow - faster flow gets turbulent more easily.

(ii) Stickiness of fluid - thick, sticky liquids like glycerine become turbulent less easily than thin liquids like water. [Just what physical quantity is involved here is not obvious. It is called the **kinematic viscosity** and we cannot say anything about it till next lecture. The symbol for it is η/ρ (see post lecture).]

(iii) A more unexpected result which turns up is that the size of the system is important.

For water flowing at the same speed through narrow pipes, the flow becomes turbulent more easily in the tube of larger radius.

More thorough experimental investigation will collect all these results thus. We define for any system a number R, called the **Reynolds number**

$$R \equiv \frac{vL\rho}{\eta}$$

where v is a typical flow speed of the fluid, L is a typical length scale and η/ρ the kinematic viscosity of the fluid.

Then it is found experimentally that if this number is not too large (smaller than about 2000) the motion will be streamline; whereas if $R \geq 2000$ then turbulence can set in.

There is no theoretical explanation of this value of 2000, it is just found to be the case.

3-4 THE EQUATION OF CONTINUITY

For fluids which are flowing in streamlined motion, what laws do they obey? Firstly there is the so called equation of continuity:

for an incompressible fluid moving in streamline motion in a tube of variable cross-section, the flow speed at any point is inversely proportional to the cross sectional area

$$\text{Speed} \propto \frac{1}{\text{area}}.$$

The reason behind this is very easy to grasp. If you want a more rigorous statement, see the post-lecture material.

One sees many applications of this. Four examples follow.

Demonstrations

(i) In flowing rivers, when going from deep to shallow, the flow speed increases (often becoming turbulent).

(ii) In the circulatory system of the blood there is a **branching effect**.

When a fluid flows past a Y-junction made up of pipes of the same diameter, the total cross-sectional area after the branch is twice that before the branch, so the flow speed must fall to half.

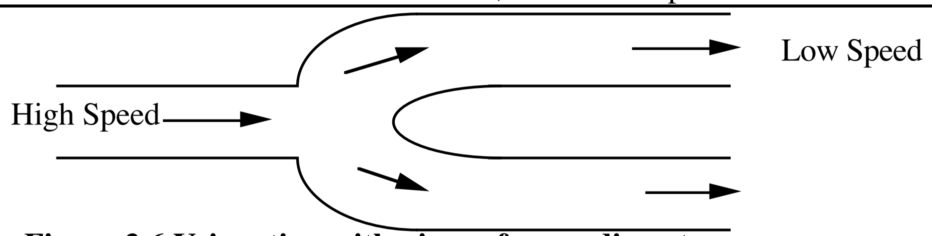

Figure 3.6 Y-junction with pipes of same diameter

Conversely, if it is important to keep the flow speed up, the pipes after the branch must have half the cross-sectional area of those before.

Atomiser: This same effect makes atomisers and spray guns work.

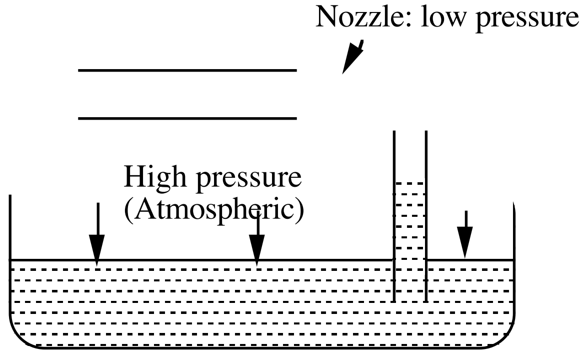

Figure 3.11 An "Atomiser"

It is most important that the free surface of the liquid should be open to the atmosphere, else the high pressure outside the container and the low pressure inside will result in the container being crushed. {Fly sprays always have a small air hole.]

A spinning ball or cylinder moving through a fluid experiences a sideways force.

There is a high pressure on one side (so a big force) and low pressure (small force) on the other. The ball experiences a net sideways thrust. This is one of the ways players can get cricket or ping pong balls to swerve.

Demonstration

Spinning cylinder.

POST-LECTURE

3-6 MORE ON REYNOLDS NUMBER

There are several points to note about the definition of the Reynolds Number.

(a) It is not a precise physical quantity. The quantities *L* and *v* are only typical values of size and speed. It is often not possible even to say *which* length you are talking about. For a body moving through a fluid it might be either length or breadth or thickness - or any other dimension you might think of. For a fluid flowing through a channel or a tube, it turns out that it is the diameter of the tube which enters. It is not until you learn more about the Reynolds Number that you can really hazard an intelligent guess at which one you should use.

This imprecision in its definition reflects the fact that the basic physical law is itself rather vague - indeed it can often only be stated as we did: "The flow of fluid in a system is more likely to be turbulent if the system is large, than if it is small". It is not surprising then that the magic number of 2000 is also only rough.

b) The "stickiness" index, the kinematic viscosity, is given the strange symbol η/ρ for the following reason. There are many ways in which this "stickiness" or **viscosity** manifests itself. Basically, how fast the fluid flows determines one measure of stickiness known as the coefficient of viscosity (η) - see next lecture. How easily the fluid becomes turbulent is related to this but to the density (ρ) as well - or if you like, it defines a different measure of stickiness. It is pointless to say any more at this stage, except to give units.

η is measured in units of Pa.s; to give you a feeling for what numbers occur, for water $\eta \sim 10^{-3}$ Pa.s.

(c) The Reynolds number is a dimensionless number as you can see from its definition:

$$[R] = \frac{[m.s^{-1}][m][kg.m^{-3}]}{[Pa.s]}$$

This will be understood when you come to see where the Reynolds Number comes from. It is a **ratio** of two quantities - essentially a scaling number.

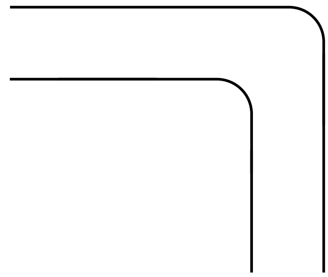

Figure 3.13 A drain with a corner in it!

Use continuity to decide where the flow speeds up, and when it slows down.

You cannot apply this to water flowing around a bend in the river. A Reynolds number calculation shows that the situation is quite different.

3-8 BERNOULLI'S EQUATION

If you really want a more careful derivation of Bernoulli's equation, you can look it up in another book. It goes along the same lines as the proof of the equation of continuity. Just remember that, because you are using the equation of conservation of energy, it is important that there should be no energy dissipation through turbulence. Bernoulli's equation only really applies when the motion is strictly streamline.

Nonetheless, provided there is not too much turbulence, the law will approximately apply. Certainly, in all of the experiments we did on screen the flow must have been pretty turbulent, yet they all showed the characteristic effect of pressure drop.

Q 3.3 Medical textbooks often quote Bernoulli's equation simply as

$$p + \rho g h = \text{constant}$$

implying that the kinetic energy term ($\frac{1}{2}\rho v^2$) is not important but the gravitational potential energy term is.

Use the average speed for blood flow quoted above and a typical human blood pressure of 10^4Pa to explain why this is so.

Q 3.4 In section 2 above, you analysed streamlined flow round a corner. Using the result of that analysis show how the **pressure** changes as the liquid goes round the corner. Can you reconcile this with the kind of simple minded diagrams drawn for the lift force on wings drawn in figure 3.3 above?

Q 3.5 When you are in the dentist's chair, the dentist uses a device based on the venturi effect to suck saliva out of your mouth. Discuss.

Demonstration

(i) The rate at which solids fall through liquids (this has already been discussed in chapter FE4).

(ii) The spin-down effect, tea leaves in the bottom of a stirred cup migrate to the centre (not the outside as you might expect).

(iii) Smoke rings.

(iv) Vortex rings in liquids.

These are all traceable (in the end) to molecular adhesion, but their explanation and connection with one another is very complicated. However, we have to start somewhere. We must select **one** physical effect to measure, and try to understand the others in terms of it. We choose to concentrate on the existence of a **velocity gradient**.

When a fluid (e.g. air) flows past a stationary wall (e.g. table top), the fluid right close to the wall does not move. However, away from the wall the flow speed is not zero. So a velocity gradient exists.

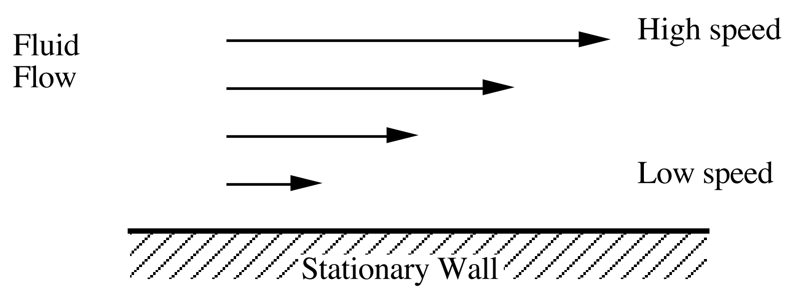

Fig 4.1 Velocity gradient in a stream of fluid moving past a stationary wall

We will find that the magnitude of this gradient (how fast the speed changes with distance) is characteristic of the fluid. We will use this fact to define viscosity.

Demonstration

Observe the velocity gradient in a tank of treacle.

4-2 THE COEFFICIENT OF VISCOSITY

A simple experiment set-up capable of demonstrating the law of viscosity involves a small metal plate suspended in a tank of liquid. Before the experiment starts the weight of an attached pan is adjusted so that the plate is neutrally buoyant - i.e. it does not tend to sink in the liquid or to rise.

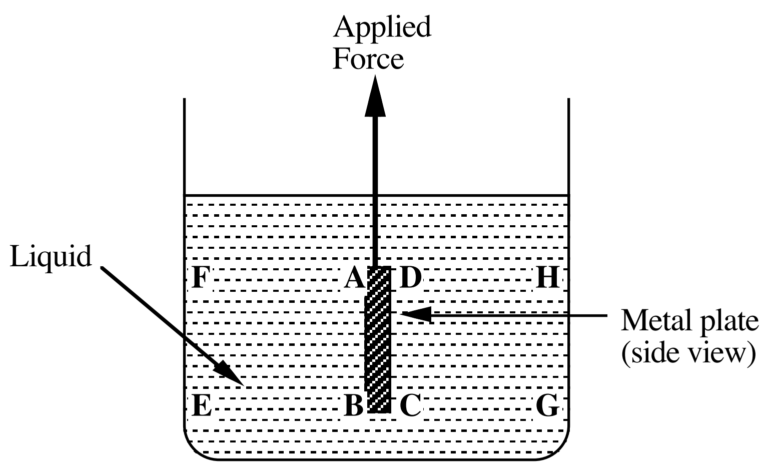

Fig 4.2 Experiment to measure coefficient of viscosity: static situation

4-3 ALTERNATIVE STATEMENT OF NEWTON'S LAW

Since there are many manifestations of viscosity, there are many different statements of the basic law. We have given Newton's statement, relating velocity gradient to shear stress (pressure).

Another statement, which research workers use, specifically points up the difference between solids and liquids.

Solids

When a shearing stress is applied to a solid it suffers a shear (i.e. a shear deformation)

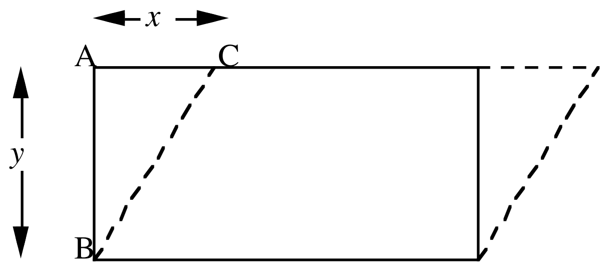

Fig 4.6 Shearing of a solid (side view)

A solid deforms instantaneously and then stops deforming. When the shearing stress is removed, if the solid is elastic the deformation recovers.

Liquids

When a shearing stress is applied to a liquid it suffers a shear deformation also, sometimes slowly sometimes fast. However, so long as the shear is applied it continues to shear. When the stress is removed, the shearing stops, but does not recover.

The basic law of behaviour of elastic solids and viscous liquids are:

Elastic solids obey Hooke's law which says

shear stress   shear deformation

{Remember: shear $= \frac{\text{length AC}}{\text{length AB}}$ }

Viscous liquids obey Newton's law which says

shear stress   velocity gradient.

However the velocity gradient is the same thing as time rate of change of shear deformation..

This can be seen as follows, with reference to figure 4.6:

$$\text{velocity gradient} = \frac{\text{speed}}{\text{transverse length}} = \frac{\frac{dx}{dt}}{y}$$

$$\text{rate of shear} = d/dt\,(x/y) = 1/y\,(dx/dt)$$

provided y is constant, as it is.

So, Newton's law can be restated

shear stress   rate of shear deformation.

The flow characteristics of the different non-newtonian fluids may be summarised thus:

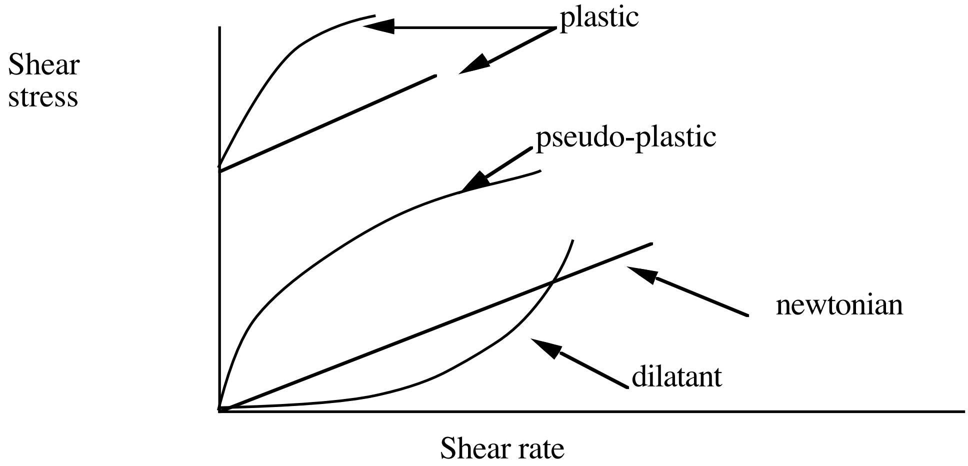

Fig 5.2 Variation of shear rate with shear stress for newtonian and non-newtonian fluids

Another way in which the non-newtonian nature of a fluid can show itself is in its radial velocity profile as it flows through a narrow tube.

For newtonian fluids this radial velocity profile is parabolic.

For non-newtonian fluids the radial velocity profile is not parabolic. It is somewhat sharper for dilatant fluids and for pseudoplastics it is blunter. For plastic materials there is a completely flat region in the centre where the shearing stress is less than the yield value.

Demonstration

The protoplasmic flow in the plant known as "slime mould" has a distinctly non-parabolic radial velocity profile.

Before leaving non-newtonian fluids, one further complication needs to be mentioned viz. that there are some fluids whose viscous behaviour depends very much on the time they have been sheared and the time they have been at rest. There are two types of these. The **thixotropic** fluids are like the pseudo-plastics in that the viscosity decreases with increasing shear rate but as well show the property that at constant shear rate the viscosity decreases with time. Further, after being sheared at high rates and left at rest, the fluid does not recover its higher viscosity behaviour until after a certain characteristic time has elapsed which may be as long as several hours.

The other type is the **rheopectic** fluid which is akin to the dilatant fluid in the same way that the thixotropic fluid is akin to the pseudo-plastic fluid.

It is important to realise that there is basically no difference between a thixotropic and a pseudo-plastic material. It is just that for a pseudo-plastic material the characteristic time is so small as to be not observed in normal circumstances.

Demonstration

Thus it is that if a thixotropic varnish which is like jelly after being left at rest for a long time is mixed up, it becomes quite liquid and stays like that for many minutes after the mixing has ceased.

For a pseudo-plastic material, the return to its original state would be instantaneous.

Demonstration

This was shown by placing a paste of plaster of Paris on an inclined plane. It did not flow appreciably under these circumstances but when the table was vibrated it flowed freely. On stopping the vibration, however, the flow ceased instantaneously. If the material on the vibrating table has been "quick-clay", which is thixotropic, the flow would have continued when the vibration ceased. This would then have been a demonstration of what happens in certain earthquakes where buildings are destroyed because they were built on "quick-clay".

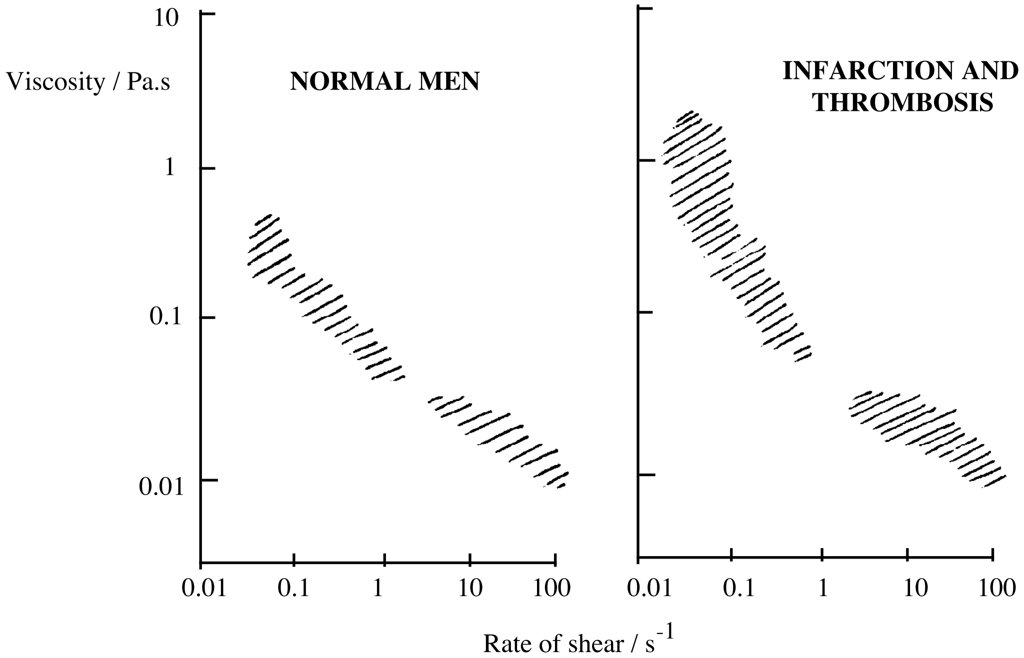

Fig 5.6 Blood flow data

Notice the similarity between these figures, and figure 5.1.

Blood's viscous behaviour is partly due to aggregation of the red cells. These aggregates can, and do, form when the shear rate is low, but at higher shear rates they break up, giving a lower viscosity.

This however is not the whole story - the viscosity of the interior of the red cells plays a major part. If the red cells were rigid particles, when their concentration reached 65%, blood would have the consistency of concrete. This however does not happen.

Blood is still very fluid even at 99% red cell concentration. The reason for this is that the red cells are not rigid but in fact fluid. Thus it is that blood can flow in the small capillaries - the cells deform as they flow. Any condition which leads to more rigid red cells leads to a much greater blood viscosity.

Demonstration

An important consequence of the rheological nature of blood is that when it is artificially pumped, as it is in certain types of heart surgery where the heart is by-passed, special pumps have to be used. These are of a roller type. They pump the blood so that the red cells are not damaged by too high shear rates but yet at a rate sufficiently great so that aggregation does not occur.

One final aspect to mention is the effect of drugs on the blood flow. These in general affect the flow just by dilating or contracting the blood vessels.

Demonstrations

Thus it is that when a cigarette is smoked, there is a short term reduction in blood flow due to the nicotine constricting the blood vessels. This can be seen by measuring the blood flow in the vessels of the ear lobe by passing a light beam through it.

It is thought, however, that as well, prolonged ingestion of nicotine has a long term effect leading to an increase in aggregation of cells and hence a higher viscosity and reduced blood flow.

Friction force with 3 blocks = 20 N (steel on aluminium)

The laws stated are crude laws, the sort obtained with crude apparatus. Even with this apparatus, complications are evident - the tendency of the object to stick again after it has started to slide. With more refined apparatus, these complications can be examined. As well, the dependence of friction on velocity can be investigated.

Demonstration

In a simple apparatus of this type, an object connected to a horizontal spring balance rests on a table which can be rotated underneath it. The spring balance measures the friction force.

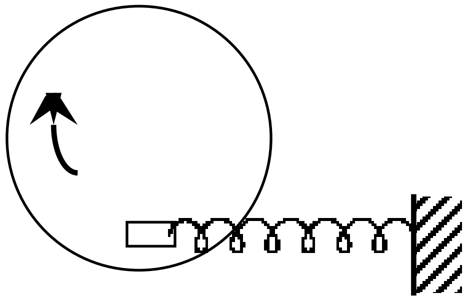

Fig 6.5 Using a spring balance to measure the frictional force

This apparatus made evident the fluctuations which occur in the friction force and showed that whereas at low velocities the friction force was essentially independent of the velocity, it did decrease when the velocity became high.

6-3 EXPLANATION OF THE LAWS OF SLIDING FRICTION FOR METALS

To explain the laws of friction, it is necessary to introduce additional experimental information.

Firstly, a variety of techniques show that even when the surfaces look smooth, they are **microscopically rough**. This is shown by:

Demonstrations

Photographs taken with electron microscopes.

The oblique sectional technique. If cuts at small angles to a surface are made, surface irregularities are magnified.

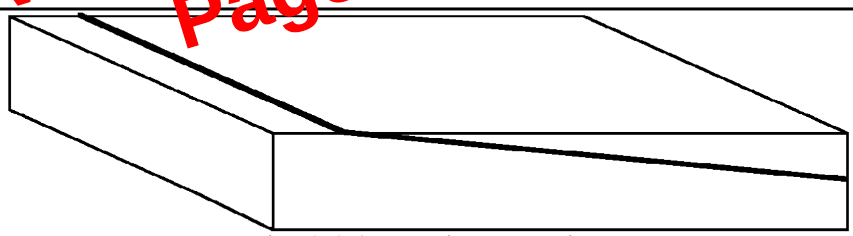

Fig 6.6 An oblique section

Since the surfaces are rough, it is tempting to think that the friction must be due to the intermeshing of the surfaces. But the sliding of such surfaces over each other is non-dissipative. That this cannot be the explanation is also shown by the fact that after a certain degree of polishing, further polishing results in an increase of the friction.

Once it is realised the surfaces are rough, it is apparent however that the real area of contact must be small - the surfaces must only touch at a few points.

Demonstration

This was shown by placing two irregular lead plates in contact with each other. It was further shown that the real area of contact increased as the load increased.

6-5 HEATING EFFECTS

Friction is a non-conservative force. When objects slide on each other, kinetic energy is converted to heat resulting in increase in the temperature of the surfaces.

Demonstrations

An abrasive saw cutting a pipe produces sparks.

Fire can be produced by the high speed rubbing of one piece of wood on another.

Refined experiments show that very localised temperature increases of up to 2000 K for 10^{-4} seconds or less are produced.

Demonstration

These local hot spots are basic to the polishing process. When a metal such as a denture casting is polished, local thermal softening of the metal leads to flow and filling up of gaps. Obviously, a high melting point polishing agent is necessary for efficient polishing.

It is the heating of the surfaces which causes the coefficient of friction to decrease at high velocities. The high temperature enhances the plastic flow, and if it is high enough a layer of essentially liquid metal is produced which acts as a lubricant.

Demonstration

The heating of the surfaces is basic to skiing. A lubricating layer of water is produced. As the ambient temperature decreases, it is harder to produce and maintain this layer and the skis stick.

6-6 LUBRICATION

The reduction of friction between two surfaces by placing another material between them is known as **lubrication**.

Demonstration

A block will slide much easier on a table if a layer of oil is spread on it.

Hydrodynamic lubrication

The type of lubrication in which the surfaces are completely separated by a thin film of fluid is known as **hydrodynamic lubrication.** It results in very low coefficients of friction, of the order of 0.001 and completely eliminates wear.

Demonstration

This type of lubrication is used in journal bearings. A complete film is formed if the load is not too high and the speed of the rotating shaft is great enough.

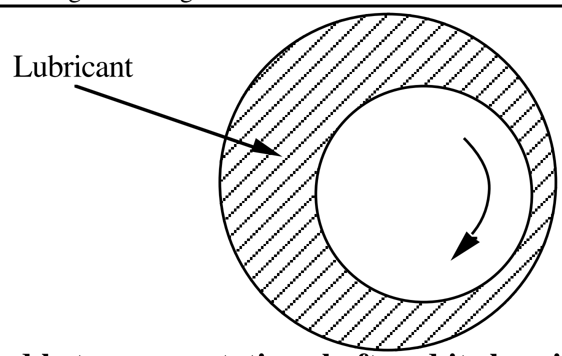

Fig 6.9 Lubricant squeezed between a rotating shaft and its bearing (hydrodynamic lubrication)

In this type of lubrication, the frictional energy loss is due only to the viscous forces in the lubricant (see post-lecture material). The viscosity cannot be reduced indefinitely, however, since the separation between the surfaces decreases as the viscosity decreases and eventually the surfaces come into contact.

7-4 IMPEDANCE MATCHING

When there is an impedance mismatch between two media, it is possible to take steps to increase the transfer of energy between the two. One method, for specific devices, was mentioned in the lecture. For large quantities of the media, this can be done by intervening a third medium between the two. Then so long as the specific impedance of this third medium is intermediate between that of the first two, it is found that the transmission of energy is greatly increased.

Perfect transmission of energy occurs, in theory, when

$$z_3 = \sqrt{z_1 z_2}$$

(where z3 is the specific impedance of the intervening medium) and where the thickness of the medium is a quarter wavelength.

You may recall from your optics lecture (L4) that a very similar condition - with refractive index rather than specific acoustic impedance - describes the ideal way to reduce reflections at air to glass boundaries in optical systems.

7-5 FREQUENCY RESPONSE OF THE EAR

Because of physical limitations, the ear will not respond to all frequencies. The main limitation comes from the geometry of the cochlea. If you remember what you have learnt about resonance, then a solid body can resonate with a sound wave if its size is roughly similar to the wavelength of the sound (in that material). Hence if you consider the basilar membrane to look schematically like this

Fig 7.10 A very schematic representation of the basilar membrane

The lowest frequency it can pick up well will correspond to the width of the big end, and the highest frequency will correspond to the width of where exactly the last nerve cell is located at the small end.

However, there are other factors which limit the frequency range, especially at the high frequency and the most important is the elasticity of the eardrum. This determines its ability to follow a very high frequency vibration. It is found, and you would expect it to be so, that as people age, the elasticity of their skin decreases and so therefore does the highest frequency they can hear. For young people, the upper range is about 20 - 30 kHz, but in middle age, it is found that the upper limit of hearing can drop by 80 Hz every six moths.

Also the state of the joints in the ossicular chain clearly influence frequency response, since these too must vibrate at the same frequency as the drum.

Also the state of the joints in the ossicular chain clearly influence frequency response, since these too must vibrate at the same frequency as the drum.

Q7.2: In general how would you expect that the frequency range of the ear would vary with the **size** of the animals? [Ans 25]

7-6 REFERENCES

Bekesy "The Ear" *Scientific American*, August 1957, p 66.

van Begerjk et al "Waves and the Ear", *Heinemann Science Study Series*.

LECTURE

8-1 INTRODUCTION

Sound experienced by human falls in the frequency range 0 - 20 kHz. Sound above this frequency is known as **ultrasound**. It can be detected by some animals.

Demonstration

A dog can hear low frequency ultrasound such as that produced by a Galton whistle (the principle of this whistle is discussed in the T.V. lecture).

Ultrasound has many important applications some of which will be discussed in this lecture. These arise partly because sound at these high frequencies has short wavelengths and partly, just because it is sound, it is a pressure wave and hence will travel in materials.

Though the use of ultrasound by man is of relatively recent origin, BATS have always used it. For a long time it was thought bats made no noise but by recording them on magnetic tape and playing the tapes back at a slower speed (this reduces the frequency of the recorded sound) it was found that they make sounds in the 40 - 55 kHz regime. They use this ultrasound for navigational purposes and also for locating their prey. The ultrasound is produced in short duration screeches of about 10 - 15 milliseconds and that part of it which has bounced off something back into the direction of the bat is heard by it. The elapsed time gives the bat information on how far the object reflecting the pulse of ultrasound is from it.

8-2 GENERATION AND DETECTION OF ULTRASOUND

Demonstration

Sound is produced when an object vibrates

Fig 8.1 Production of sound using a tuning fork

Ultrasound is produced in the same way but to get ultrasound we have to make a vibration at ultrasound frequencies. One device for doing this is the Galton whistle but ultrasond can be produced much more conveniently and efficiently by making use of piezo-electric materials such as barium titanate.

These have the property that when a voltage is applied in a certain direction, the dimension of the material in that direction increases, and if the sense of the voltage is revesed then the dimension decreases. By applying a high frequency alternating voltage, the material is caused to vibrate at a high frequency and so ultrasound is produced.

Demonstration

The effect can be demonstrated by having an ultrasound generator mounted on a car which can run on rails either towards or away from a stationary ultrasonic detector. The frequency of the detected sound can be measured with a digital frequency meter..

Detailed measurements with such apparatus show that the change in frequency is proportional to the velocity of the source. Since the change in frequencyu is proportional to the velocity, a measurement of this change can be used to determine the velocity of the source. Or, alternatively, if the wave is reflected from a moving surface the change in frequency of the reflected wave relative to the incident one gives the velocity of the moving surface. In this latter form there are many uses of Doppler techniques with ultrasound in medicine. For example it is possible to detect the foetal heartbeat as early as the l0th week, and by measuring the motion of blood vessel walls it is possible to learn about their elasticity.

Demonstration

In clinical medicine, the technique is used to detect blood flow in arteries and veins by means of an external probe. This is placed against the skin and more or less angled along the blood vessel. A paste is applied between the skin and probe to improve impedance matching and so lessen power loss by reflection. The ultrasound produced by the probe is reflected from the flowing blood and then detected by the probe. A probe such as this shows quite different sounds for arteries and veins. For arteries, the sound is characteristic of the pulsatile blood flow in arteries. In veins, it is more like a wind-storm which cycles with the respiration. The probe can detect blockages in arteries and veins. (N.B. The medical term "patent" which is used in describing this technique means "unblocked".)

Doppler techniques have been used in a different way to measure the blood flow in research projects on animals.

Demonstration

Small probes are placed around arteries during an operation. They heal in place with the leads coming out of the skin. In an experiment, the leads are connected to a telemetering device carried in a package on the animal. In this way it is possible to look at patho-physiological conditions in conscious animals in realistic situations. This technique has been used for example on dogs which have been made hypertensive. It has also been used on small monkeys to study the effect of severe oxygen lack on the circulation. In a proposed experiment it is to be used on baboons to study the effect of diet on coronary disease.

8-4 ECHOSCOPY

If a pulse of waves of known velocity is setn out from a transmitter and the time taken for the puse to return after being reflected from a distant object is measured then this time is a measure of the distance of the object. This technique is called the "pulse-echo" technique and with electro- ,magnetic waves is of course **radar**. This technique can also be used with ultrasound. It is of course the technique used by bats for navigation. It is used it as **sonar** for depth sounding, detection of submarines and shoals of fish.

In medicine, the technique is used and is then known as **echoscopy**. If ultrasound travelling in one medium encounters another, in general some will be transmitted into the other medium as well as being reflected.

How much energy is reflected depends on the sound power reflection coefficient, which in turn depends on the specific acoustic impedances of the two media If these are almost the same, little energy is reflected; if they are widely different, much energy is reflected.