8.2.3 Air permeability

The air permeability of a fabric is a measure of how well it allows the passage of air through it. The ease or otherwise of passage of air is of importance for a number of fabric end uses such as industrial filters, tents,

Table 8.2 Effect of moisture on insulation values [5]

	Thermal insulation (togs)		
	Staple polyester	Continuous filament polyester	50/50 down/feather
Dry	4.7	6.8	6.6
15% moisture	2.4	3.6	2.8
50% moisture	1.8	2.4	1.5
100% moisture	1.7	2.3	1.3

sailcloths, parachutes, raincoat materials, shirtings, downproof fabrics and airbags.

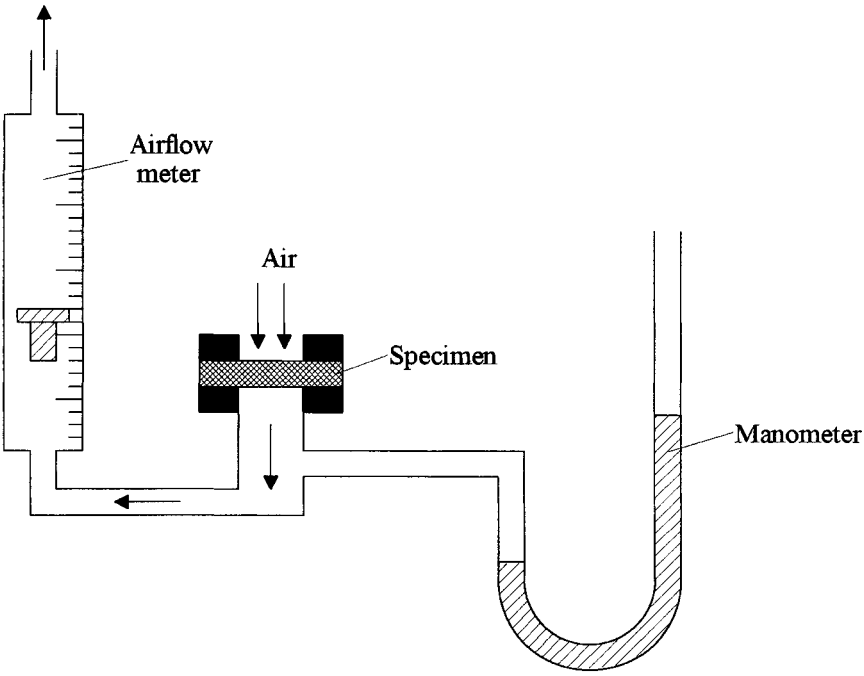
Air permeability is defined as the volume of air in millilitres which is passed in one second through 100 s mm^2 of the fabric at a pressure difference of 10 mm head of water.

In the British Standard test [6] the airflow through a given area of fabric is measured at a constant pressure drop across the fabric of 10 mm head of water. The specimen is clamped over the air inlet of the apparatus with the use of rubber gaskets and air is sucked through it by means of a pump as shown in Fig. 8.2. The air valve is adjusted to give a pressure drop across the fabric of 10 mm head of water and the air flow is then measured using a flowmeter.

Five specimens are used each with a test area of 508 mm^2 (25.4 mm diameter) and the mean air flow in ml per second is calculated from the five results. From this the air permeability can be calculated in ml per 100 mm^2 per second.

The reciprocal of air permeability, air resistance, can be defined as the time in seconds for 1 ml of air to pass through 100 s mm^2 of fabric under a pressure head of 10 mm of water. The advantage of using air resistance instead of air permeability to characterise a fabric is that in an assembly of a number of fabrics, the total air resistance is then the sum of the individual air resistances.

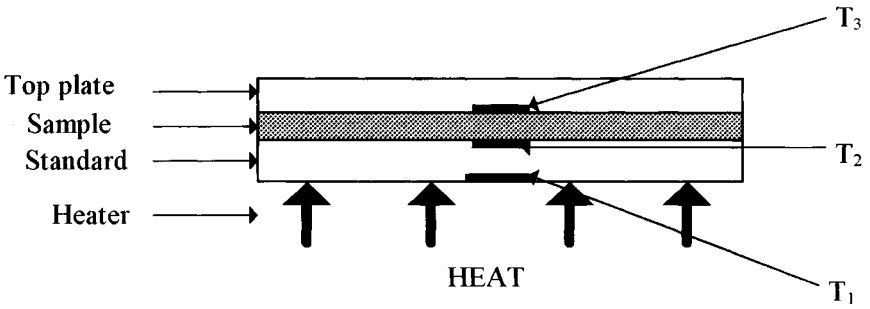
To obtain accurate results in the test, edge leakage around the specimen has to be prevented by using a guard ring or similar device (for example, efficient clamping). The pressure drop across the guard ring is measured by a separate pressure gauge. Air that is drawn through the guard ring does not pass through the flowmeter. The pressure drops across the guard ring and test area are equalised in order that no air can pass either way through the edge of the specimen. A guard ring of three times the size of the test area is considered sufficient.



8.2 The air permeability test.

8.2.4 Measurement of thermal conductivity

The transmission of heat through a fabric occurs both by conduction through the fibre and the entrapped air and by radiation. Practical methods of test for thermal conductivity measure the total heat transmitted by both mechanisms. The insulation value of a fabric is measured by its thermal resistance which is the reciprocal of thermal conductivity (transmittance) and it is defined as the ratio of the temperature difference between the two faces of the fabric to the rate of flow of heat per unit area normal to the faces. As can be seen from this definition it is necessary to know the rate of heat flow through a fabric in order to be able to measure its thermal resistance. In practice the measurement of the rate of heat flow in a particular direction is difficult as a heater, even when supplied with a known amount of power, dissipates its heat in all directions. Two different methods are in use to overcome this problem: one is to compare thermal resistance of the sample with that of a known standard and the other is to eliminate any loss in heat other than that which passes through the fabric being tested. It is important that any measurements of thermal resistance are made at temperatures close to those that are likely to be encountered in use as the thermal conductivity of materials varies with the temperature. This is due



8.3 Togmeter: two plate method.

to the variation in thermal conductivity of the air with temperature and also the dependence of the heat loss through radiation on temperature.

Togmeter

The togmeter [7] avoids the problem of measuring heat flow by placing a material of known thermal resistance in series with the material under test so that the heat flow is the same through both materials. The thermal resistance of the test fabric can then be calculated by comparing the temperature drop across it with the temperature drop across the standard material.

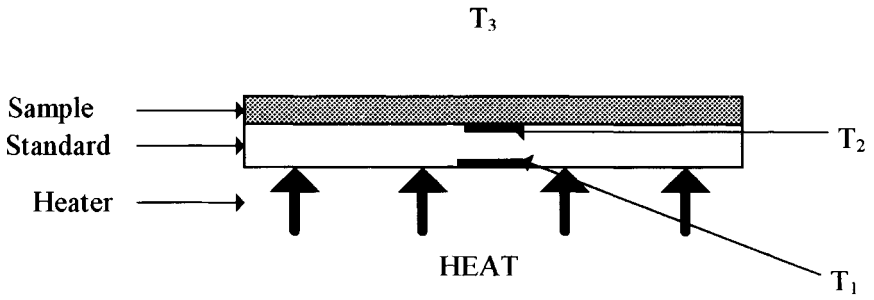
Apparatus

The togmeter consists of a thermostatically controlled heating plate which is covered with a layer of insulating board of known thermal resistance. The temperature is measured at both faces of this standard. The heater is adjusted so that the temperature of the upper face of the standard is at skin temperature (31–35 °C). A small airflow is maintained over the apparatus.

There are two methods of test that can be used with the togmeter:

1 **Two plate method**. In this method the specimen under test is placed between the heated lower plate and an insulated top plate as shown in Fig. 8.3. The top plate has a low mass so that it does not compress the fabric. The temperature is measured at the heater (T_1), between the standard and the test fabric (T_2) and between the fabric and the top plate (T_3).
2 **Single plate method**. In this method the specimen under test is placed on the heated lower plate as above but it is left uncovered as shown in Fig. 8.4, the top plate being used to measure the air temperature (T_3).

The air above the test specimen has a considerable thermal resistance itself so that the method is in fact measuring the sum of the specimen



8.4 Togmeter: single plate method.

thermal resistance and the air thermal resistance. A separate experiment is therefore performed without the specimen (i.e. a bare-plate test) to measure the resistance of the air R_{air}.

To determine the air resistance

The heater and the fan are switched on and the apparatus is allowed to reach thermal equilibrium with no specimen present. The top plate is placed underneath the apparatus shielded from radiation by a foil-covered plate, in order to measure the air temperature. The temperature should remain steady at each thermocouple for 30 mins. It may take some time for an equilibrium to be reached. Thermal resistance of air:

$$R_{air} = R_{stand} \times \frac{T_2 - T_3}{T_1 - T_2}$$

where R_{stand} is the thermal resistance of the standard.

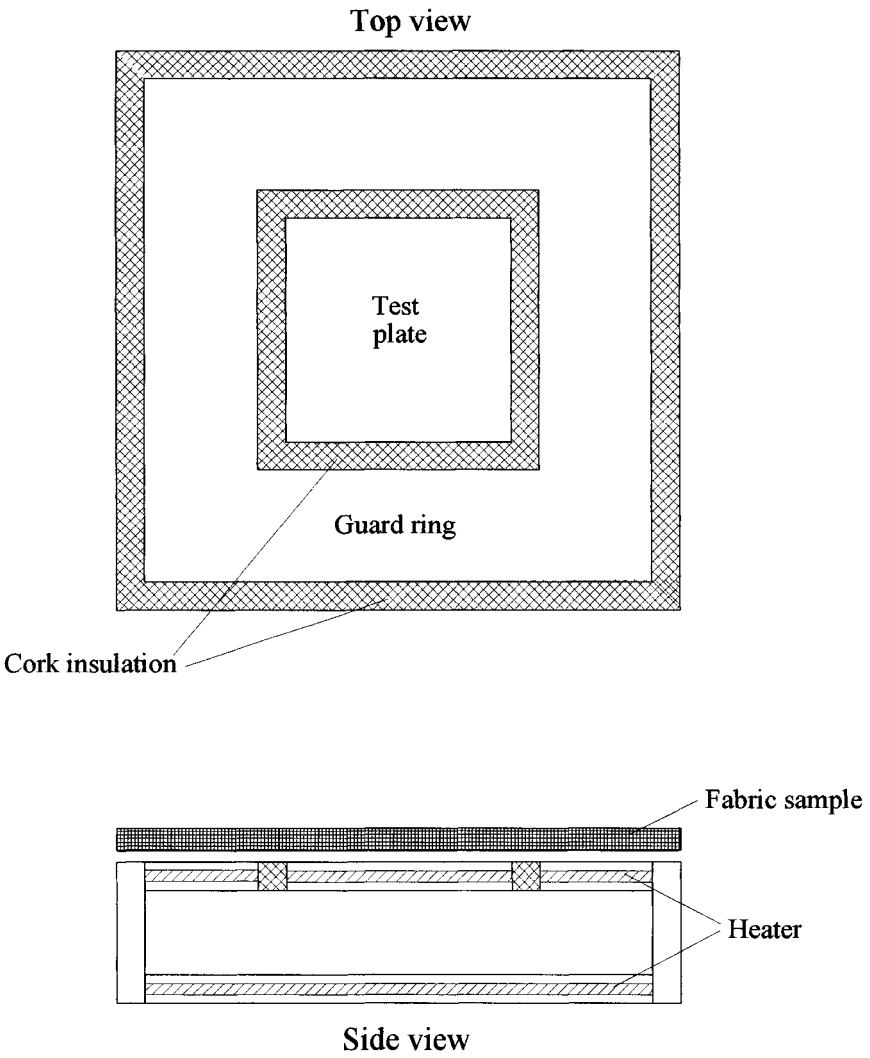
To determine the sample resistance

The above experiment is repeated with the test sample placed on the bottom plate and the apparatus again allowed to reach thermal equilibrium. Thermal resistance of sample:

$$R_{sample} = R_{stand} \times \frac{T_2 - T_3}{T_1 - T_2} - R_{air}$$

Guarded hotplate method

The guarded hotplate [8] is used to measure thermal transmittance which is the reciprocal of the thermal resistance. The apparatus consists of a heated test plate surrounded by a guard ring and with a bottom plate underneath as shown in Fig. 8.5. All three plates consist of heating elements sand-



8.5 The guarded hotplate.

wiched between aluminium sheets. All the plates are maintained at the same constant temperature in the range of human skin temperature (33–36 °C). The guard ring and bottom plate, which are maintained at the same temperature as the test plate, ensure that no heat is lost apart from that which passes upwards through the fabric under test. The whole apparatus is covered by a hood to give still air conditions around the specimen. The whole of the surroundings of the apparatus is maintained at fixed conditions between 4.5 and 21.1 °C and 20 and 80% RH, the exact conditions being specified as part of the test.

With the test fabric in place the apparatus is allowed to reach equilibrium before any readings are taken. This may take some time with thick specimens. The amount of heat passing through the sample in watts per square metre is measured from the power consumption of the test plate heater. The temperature of the test plate and the air 500 mm above the test plate are measured.

The measured thermal transmittance consists of the thermal transmittance of the fabric plus the thermal transmittance of the air layer above the fabric which is not negligible. Therefore the test is repeated without any fabric sample present to give the bare plate transmittance. The transmittance of the air layer above the plate is assumed to be the same as that of the air layer above the sample.

Combined transmittance of specimen and air U_1:

$$U_1 = \frac{P}{A \times (T_p - T_a)} \text{ W/m}^2\text{ K}$$

where: P = power loss from test plate (W),
A = area of test plate (m^2),
T_p = test plate temperature (°C),
T_a = air temperature (°C).

The bare plate transmittance U_{bp} is similarly calculated and then the intrinsic transmittance of the fabric alone, U_2, is calculated from the following equation:

$$\frac{1}{U_2} = \frac{1}{U_1} - \frac{1}{U_{bp}}$$

8.2.5 Measurement of water vapour permeability

The water vapour permeability of fabrics is an important property for those used in clothing systems intended to be worn during vigorous activity. The human body cools itself by sweat production and evaporation during periods of high activity. The clothing must be able to remove this moisture in order to maintain comfort and reduce the degradation of thermal insulation caused by moisture build-up. This is an important factor in cold environments.

The main materials of interest are those fabrics that incorporate a polymer layer that makes the fabric waterproof but which still allows some water vapour to pass through. There are two main types of these materials: those that contain pores through which the moisture vapour can pass and those containing a continuous layer of hydrophilic polymer. The mechanism of water vapour transmission through the second type is quite different from that of the first type. In particular the rate of diffusion through the

hydrophilic polymer layer is dependent on the concentration of water vapour in the layer. The higher the concentration, the higher the rate of transfer. In the materials where transmission is via pores the rate is independent of water vapour concentration. This has a bearing on the results obtained from the different methods of testing water vapour permeability from the two types of material which can rank them differently depending on the test method used.

Cup method

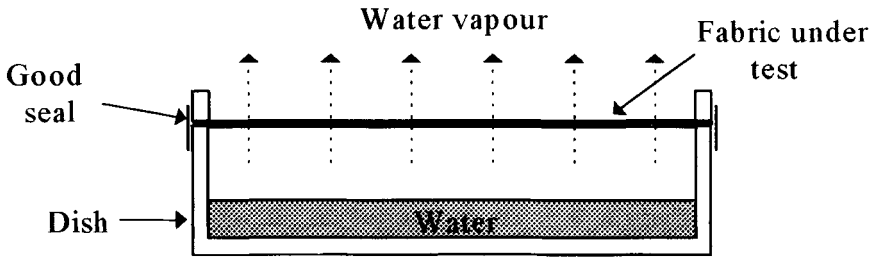
In the British Standard version of this method [9] the specimen under test is sealed over the open mouth of a dish containing water and placed in the standard testing atmosphere. After a period of time to establish equilibrium, successive weighings of the dish are made and the rate of water vapour transfer through the specimen is calculated.

The water vapour permeability index is calculated by expressing the water vapour permeability (WVP) of the fabric as a percentage of the WVP of a reference fabric which is tested alongside the test specimen.

Each dish is filled with sufficient distilled water to give a 10 mm air gap between the water surface and the fabric. A wire sample support is placed on each dish to keep the fabric level. Contact adhesive is applied to the rim of the dish and the specimen, which is 96 mm in diameter, is carefully placed on top with its outside surface uppermost. The cover ring is then placed over the dish and the gap between cover ring and dish sealed with PVC tape as shown in Fig. 8.6.

A dish which is covered with the reference fabric is also set up in the same way. All the dishes are then placed in the standard atmosphere and allowed to stand for at least 1 h to establish equilibrium.

Each dish is then weighed to the nearest 0.001 g and the time noted. After a suitable time for example overnight the dishes are reweighed and the time noted again.



8.6 The water vapour permeability test.

Calculate:

$$\text{WVP} = \frac{24M}{At} \text{g/m}^2\text{/day}$$

where: M = loss in mass (g),
t = time between weighings (h),
A = internal area of dish (m^2).

$$A = \frac{\pi d^2 \times 10^{-6}}{4}$$

where d = internal diameter of dish (mm).

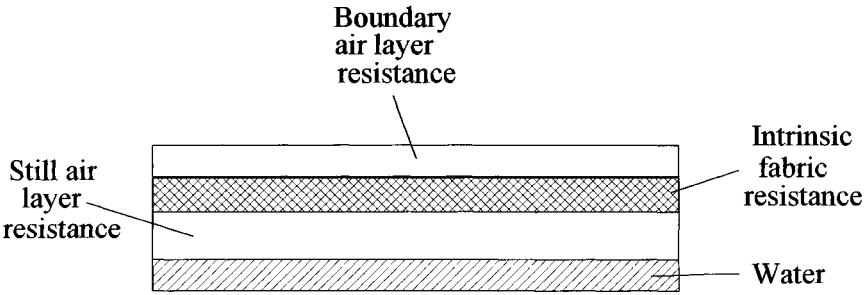
$$\text{Water vapour permeability index} = \frac{(\text{WVP})_f \times 100}{(\text{WVP})_r}$$

where WVP_f is the water vapour permeability of the test fabric and WVP_r is the water vapour permeability of the reference fabric.

The ASTM method E 96–80 [10] procedure B is similar to the above method although the air gap above the water surface is 19 mm (0.75 in) and an air velocity of 2.8 m/s (550 ft/min) is used over the surface of the fabric.

The airgaps above the specimen are important with these tests as the air itself has a high resistance to water vapour permeability [11]. Figure 8.7 shows that the total resistance to water vapour permeability of the experimental set-up depends on three factors.

The experiment is sometimes carried out with the cup inverted so that the water is in contact with the inner surface of the fabric [11]. This form of the test tends to give more favourable results for hydrophilic films.



8.7 The various resistances to water vapour permeability.

Sweating guarded hotplate method

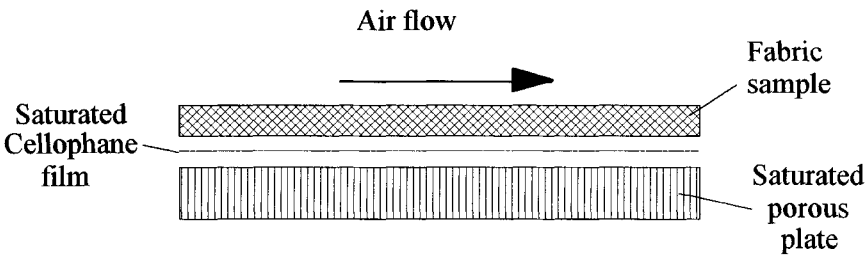
An alternative method to the cup method is to use a plate that is heated to skin temperature and supplied with water in order to simulate sweating. This is much closer to actual conditions of use than the cup method but it requires a more sophisticated experimental procedure. A number of methods have been described that differ in the way of supplying the water to the fabric and in the way of measuring the water vapour passing through it.

The sweating guarded hotplate [11] is similar to the guarded hotplate which is used to measure thermal resistance. In the normal test the power required to maintain the plate at a given temperature is related to the dry thermal resistance of the material. If the plate is saturated with water the power required is then related to the rate at which water evaporates from the surface of the plate and diffuses through the material in addition to the dry thermal resistance.

In order to measure the water vapour permeability of a material, therefore, it is first necessary to measure the dry thermal transmittance U_1 as described in section 8.2.2 on measuring thermal conductivity. The measurement is then repeated with the plate supplied with moisture. This is achieved by using a saturated porous plate covered with a Cellophane film, as shown in Fig. 8.8, which allows moisture to pass through but not in sufficient quantity to wick into the fabric. A moisture vapour permeability index i_m is calculated from the following formula:

$$i_m = \frac{\left[\frac{PR_{tot}}{A}\right] - (T_p - T_a)}{S(p_s - \phi p_a)}$$

where: $R_{tot} = 1/U_1$ = resistance of the fabric plus boundary air layer (m^2K/W),
A = surface area (m^2),
T_p = temperature of the saturated plate surface,



8.8 The sweating hotplate.

T_a = temperature of the ambient air,
P = power required to maintain a constant saturated plate surface temperature (W),
S = Lewis relation between evaporative mass transfer coefficient and convective heat transfer coefficient (1.65×10^{-2} K/Pa),
p_s = saturated water vapour pressure at the plate surface (Pa),
p_a = saturated water vapour pressure of the ambient air (Pa),
ϕ = relative humidity of the ambient air.

The i_m value is a relative measure which should vary between 0 for completely impermeable materials and 1 for completely permeable materials.

The moisture permeability index i_m can be combined with the dry thermal resistance R_{tot} to give i_m/R_{tot} which is a measure of both evaporative heat flow and other forms of heat flow. The higher the value for i_m/R_{tot}, the better the material is at dissipating heat by all mechanisms.

The moisture vapour transmission rate (MVTR) for the sweating guarded hotplate is:

$$\text{MVTR}_{\text{plate}} = 1.04 \times 10^3 \left(\frac{i_m}{R_{tot}} \right) \text{g/m}^2/24\,\text{h}$$

8.3 Moisture transport

In order to keep the wearer dry and hence comfortable, clothing that is worn during vigorous activity, such as sports clothing, has to be able to deal with the perspiration produced by such activity. There are two main properties of clothing, that affect the handling of moisture. Firstly there is the ease with which clothing allows the perspiration to be evaporated from the skin surface during the activity. Secondly after the activity has ceased, there is a need for the moisture that is contained in the clothing layer next to the skin to dry out quickly. This ensures that the wearer does not lose heat unnecessarily through having a wet skin. Some workers [12] also consider that the extent to which the wet fabric clings to the skin is also important to the comfort of a garment.

Moisture is transmitted through fabrics in two ways:

1 By diffusion of water vapour through the fabric. This appears to be independent of fibre type but is governed by the fabric structure. The measurement of air flow through the fabric provides a good guide to its ability to pass water vapour in large quantities.
2 By the wicking of liquid water away from the skin using the mechanism of capillary transport. The ability of a fabric to do this is dependent on the surface properties of the constituent fibres and their total surface

area. The size and number of the capillary paths through the fabric are also very important but these are governed by factors such as the fibre size, the yarn structure and the fabric structure. The capillary network of the fabric is dependent on the direction under consideration so that the wicking properties through the thickness of the fabric may be different from those in the plane of the fabric. Also the rate of wicking may be different along the warp (wale) direction than along the weft (course) direction.

8.3.1 Wetting

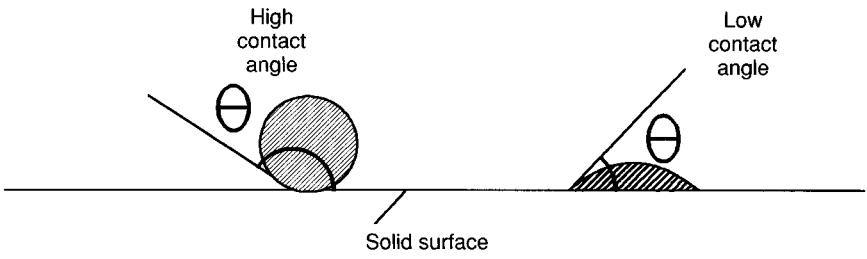
For wicking to take place the fibre has first to be wet by the liquid. In fact it is the balance of forces involved in wetting the fibre surface that drives the wicking process. When a fibre is wetted by a liquid the existing fibre–air interface is displaced by a new fibre–liquid interface. The forces involved in the equilibrium that exists when a liquid is in contact with a solid and a vapour at the same time are given by the following equation:

$$\gamma_{SV} - \gamma_{SL} = \gamma_{LV} \cos\theta$$

where γ represents the interfacial tensions that exist between the various combinations of solid; liquid and vapour; the subscripts S, L and V standing for solid, liquid and vapour,

θ = equilibrium contact angle,
γ_{LV} = the surface tension of the liquid.

The contact angle is defined as the angle between the solid surface and the tangent to the water surface as it approaches the solid; the angle is shown as θ in Fig. 8.9. The angle is determined by the three interfacial tensions: if γ_{SV} is larger than γ_{SL} then $\cos\theta$ is positive and the contact angle must be between 0° and 90°. If γ_{SV} is smaller than γ_{SL} then the contact angle must be between 90° and 180°. A high contact angle for water with the surface means that water will run off it, a low contact angle means that



8.9 Contact angle.

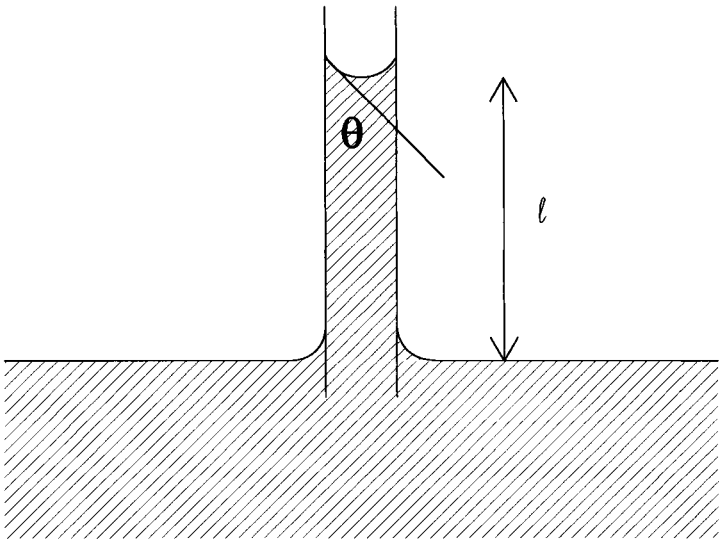
water will wet the material. Water repellent materials exhibit a high contact angle. A contact angle of less than 90° also means that water will wick into the material by capillary action. A contact angle of 90° or more means that water will not rise by capillary action. The measured (apparent) contact angle shows hysteresis in that the contact angle for a liquid that is advancing is usually higher than that for a liquid that is receding. The advancing contact angle is usually used in wicking calculations.

8.3.2 Wicking

In the absence of external forces the transport of liquids into fibrous assemblies is driven by capillary forces that arise from the wetting of the fibre surfaces described above. If the liquid does not wet the fibres it will not wick into the fibrous assembly. In the case of contact angles above 90°, liquid in a capillary is depressed below the surface instead of rising above it. In order for the wicking process to take place spontaneously, the balance of energy has to be such that energy is gained as the liquid advances into the material, therefore γ_{SV} must be greater than γ_{SL}:

$$\text{Work of penetration, } W_p = \gamma_{SV} - \gamma_{SL} = \gamma_{LV}\cos\theta$$

The wicking rate is dependent on the capillary dimensions of the fibrous assembly and the viscosity of the liquid. For a simple capillary of radius r the rate of progress of the liquid front shown diagrammatically in Fig. 8.10 is given by:



8.10 Capillary rise.

$$\frac{dl}{dt} = \frac{r\gamma_{LV}\cos\theta_A}{4\eta l}$$

where θ_A = advancing contact angle,
η = viscosity of liquid,
l = length of liquid front.

The wetting of fibres is purely dependent on their surface properties, in particular in the case of wetting with water, whether the surface is hydrophobic or hydrophilic. Therefore the wetting and wicking properties of fibres can be modified by surface finishes and experimental studies can also be affected by the remains of processing oils and finishes. Wetting is also affected by the presence of surfactants in the liquid which alter its interfacial tensions.

When wicking takes place in a material whose fibres can absorb liquid the fibres may swell as the liquid is taken up, so reducing the capillary spaces between fibres, potentially altering the rate of wicking.

8.3.3 Longitudinal wicking

The distance l travelled along a capillary by a liquid in time t is given by:

$$l = \left(\frac{rt\gamma_{LV}\cos\theta_A}{2\eta}\right)^{0.5}$$

If the material is vertical the height to which the liquid wicks is limited by gravitational forces and ceases when the capillary forces are balanced by the weight of liquid:

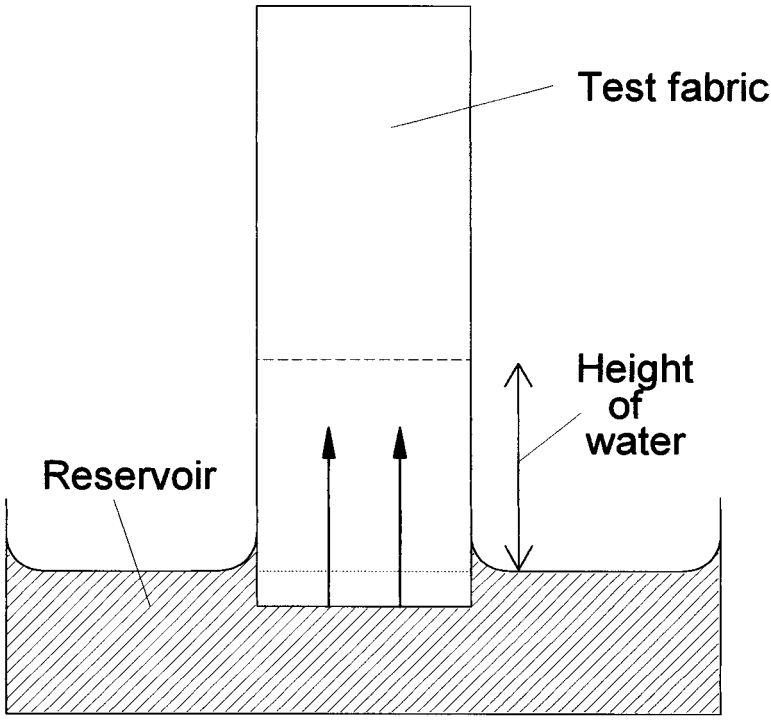
$$\text{Equilibrium height } l = \frac{2\gamma_{LV}\cos\theta_A}{rg\rho}$$

where ρ = liquid density,
g = gravitational acceleration.

8.3.4 Wicking test

In this test [13] a strip of fabric is suspended vertically with its lower edge in a reservoir of distilled water as shown in Fig. 8.11. The rate of rise of the leading edge of the water is then monitored. To detect the position of the water line a dye can be added to the water or, in the case of dark coloured fabrics, the conductivity of the water may be used to complete an electrical circuit. The measured height of rise in a given time is taken as a direct indication of the wickability of the test fabric.

The simple form of the test does not take into account the mass of the water that is taken up. This will depend on the height the water has risen



8.11 Wicking test.

to, the thickness of the fabric and the water-holding power of the fabric structure. One way of allowing for this is to weigh the fabric at the end of the test and hence obtain the mass of the water taken up by the fabric. The mass can then be expressed as a percentage of the mass of the length of dry fabric which is equivalent to the measured height of water rise.