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MEASURING THE SHEAR STRESS OF FIRE-FIGHTING FOAMS

by

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SUMMARY

Experiments to define the characteristics of torsional vane viscometers when used for measuring the shear stress of foam are described, so that replacement instruments can incorporate improved features. It is shown that shear stress determined by this method is not a fundamental property of the foam but depends upon the instrument dimensions and the method of operation as well as upon the characteristics of the foam. The significant dimensions and operational procedures are identified, and recommendations are made for their adoption.

Note: For the convenience of those who wish to construct and use a foam viscometer a companion Fire Research Note No.1059 provides constructional details and a recommended standard procedure for its use.

KEY WORDS: Foam, viscometer, shear stress

Department of the Environment and Fire Offices' Committee
Joint Fire Research Organization

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INTRODUCTION

Foams made from aqueous solutions of surfactants and air are widely used for the extinction of flammable liquid fires. Foams with an air to liquid ratio between 4 and 14 : 1 are most frequently used. The fluidity of the foam affects the rate at which the foam will spread over the fuel surface and extinguish the fire.

The fluidity is assessed by making a shear stress measurement. In UK a torsional vane viscometer is used. The instrument is described in UK Defence Standard 4 2-3[1] and the Journal of Scientific Instruments[2]. At FRS the shear stress measurement is regularly used to characterise foams used in fire experiments, and thousands of measurements are made in each year. After many years of use, frequently under severe conditions of outdoor fire test sites, the instruments at FRS required rebuilding. This provided an opportunity to consider modifications to their design.

Although the present instruments have given good service, experience has suggested that a number of improvements might be made. These are revealed in the experiments described and the recommended design for the construction of new instruments. They mostly fall into three categories viz:

1) improvements and simplifications to mechanical design and operation

2) accommodation of recently introduced fluorochemical foams with much lower shear stresses than foams hitherto used for fire-fighting

3) providing a more fundamentally correct measurement

The rheology of fire-fighting foams has received little systematic study and to assist in the design improvements of the viscometer many of the experiments were made to discover the behaviour of these foams when subjected to deformation forces.

Figure 1 shows the Defence Standard instrument currently in use.

GENERAL CONSIDERATIONS

The dimensions of shear stress

One of the most important rheological properties of fluids is how their shear stress changes with the rate of shear. The ratio of these two measurements being the viscosity. With many fluids, particularly low molecular weight liquids such as water, their shear stress is directly proportional to the rate of shear and

their viscosity is therefore independent of the rate of shear – these are known as Newtonian fluids.

With many other liquids, particularly solutions of complex molecules and suspensions, their shear stress is not directly proportional to the rate of shear but may be related in a different manner. An appropriate constitutive equation defining the relationship can sometimes be determined. These are known as non-Newtonian fluids and fire fighting foams are of this nature. Constitutive equations defining their behaviour have not been determined,

When making viscosity measurements of fluids in torsional vane (or cylinder) instruments it is assumed that there is a uniform velocity gradient between the moving vane and the wall of the vessel in which the fluid is contained. The rate of shear is stated as velocity difference per unit distance of separation between the moving vane and the stationary vessel. Its dimensions are therefore $L \times T^{-1}/L = T^{-1}$.

In the case of foams a uniform velocity gradient is not established between the moving vane and the vessel wall. The bulk of the foam may remain almost stationary and only a narrow layer of foam close to the prescribed cylinder is in motion; with stiff foams there may even be no significant flow of the foam. To accommodate this it is assumed that all relative motion is at the surface of the prescribed cylinder and the rate of shear is therefore stated as a simple velocity of the prescribed cylinder surface with dimensions LT^{-1}.

Because of this type of behaviour we are restricted to measuring the shear stress of the foam and cannot convert this by its ratio to the rate of shear into a viscosity, as is usual for other fluids. The instrument we are discussing is therefore more correctly described as a shear stress meter rather than a torsional vane viscometer, when it is used for fire foams.

Calculation of shear stress from a torsional vane measurement

In using the shear stress meter the torque developed in the wire is measured and this has then to be related to a surface area to give a shear stress per unit area. This poses a problem because the vertical edges of the vane are moving at one velocity while the ends are moving at a velocity which varies from the edge velocity to zero at the centre. The shear stress across the ends of the prescribed cylinder will vary with the velocity, and the torque attributable to the ends of the prescribed cylinder will depend also upon the varying diameter. The problem would be overcome if we recorded all measurements as torques, and did not relate then to a specific area. This would serve for experiments with a single size of vane, but in the investigations, vanes of different sizes will be used, and the results will be difficult to assess unless they can be related to a surface area. In Defence Standard 42-3 the area of the vertical cylinder prescribed by the rotating vane is used – the area of the cylinder ends being neglected. This procedure has

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been used throughout this report as the most convenient method of comparing results, except in those cases where the torque is purposely related to another area – and in such cases. this is indicated.

Principles of Viscometer Design

Two principles of design used at various times for the measurement of foam shear stress are shown in Fig 2.

In arrangement A a pointer is attached to the vane. The top of the wire is rotated and the scale rotates with the top of the wire. The foam holds the vane until the yield point is reached and this is noted by reading the pointer position against the moving scale. Thereafter the vane rotates,   the pointer, revolving with the scale, indicates the continuous shear stress.

In arrangement B the top of the wire is fixed and the foam sample is rotated by a turn-table and motor. The scale is attached to the vane and its movement is noted against a pointer fixed to the stand. When the turntable is started the vane is carried around by the foam until the yield point is reached, thereafter it remains stationary and the continuous shear is indicated by the sustained deflection.

These two designs appear to be fundamentally identical, but they have some subtle differences which are revealed in the experiments.

Arrangement B is sometimes used in an alternative form in which the pointer is attached to the vane, while the scale is fixed to the stand.

Arrangement C in Fig 2 shows another principle which has not generally been used for foams, but was used in a few experiments for which it was appropriate. This viscometer has no motor drive. The scale is fixed to the vane and can be anchored by means of a locking pin. Torsion can then be applied to the top end of the wire – a friction plate maintaining the torsion. The amount of torsion applied can be noted on the upper scale. When the locking pin is released the vane will rotate to release the torsion and the progress of relaxation can be observed on the lower scale. With Newtonian fluids, if 360° of torsion is applied to the upper end of the wire, the vane when released will rotate 360° and then overswing a considerable amount. The viscosity can be calculated from the amount of overswing: but this does not apply to non-Newtonian fluids with which the vane may come to rest before the applied torsion has been fully released.

Yield stress and continuous shear stress

It is well known that with some non-Newtonian fluids the vane of a viscometer will remain fixed until a considerable torsion is applied, and that thereafter a lower amount of torsion will maintain the vane in motion. We thus obtain two values – the yield stress and the continuous shear stress. It is also well known that some fire-fighting foams, particularly those made from protein, exhibit

considerable differences between the yield value and the continuous shear stress, while other fire foams show only small differences. One object of the experiments was to discover more about these two measurements and whether one is preferable to the other for characterising fire foams.

The progressive change of foam properties

The author has described elsewhere[3] the properties of foam which affect its handling during laboratory investigations. The most relevant are that all foams decay from the moment they are produced by a process of gas transference between 'bubbles'. If the bubble walls are sufficiently thin the liquid liberated from decaying film will be absorbed by the remaining film until a critical bubble wall thickness is reached, after which the liquid liberated by the progressing decay will appear as drainage in the base of the sample. During the decay stage, up to the commencement of drainage, the sample will be changing progressively but will maintain uniformity throughout its depth. When drainage commences the sample will continue to change progressively and will vary in liquid content throughout its depth. Many of the foams used in fire fighting do not commence to drain for several minutes. Experimental methods can therefore be adjusted by selecting a high enough expansion and making the bubbles sufficiently small to ensure that the sample does not begin to lose water by drainage until the experimental measurements have been completed. Measurements must also be made at a standard time from the production of the sample, and at a standard temperature.

EXPERIMENTAL METHODS

To provide information on the behaviour of foams associated with viscometer design, several instruments and types of foam were used in a variety of experiments. The equipment and procedures used are now described.

Production of foam and collection of samples

For a few of the experiments a standard 5 l/min branchpipe was used[4]. Eighteen litres of foaming solution were prepared in a container from which it could be expelled to the branchpipe by applying 690 kPa air pressure. Before collecting a sample the branchpipe was allowed to operate for 15 seconds to ensure uniform operation. Providing the premix was prepared at room temperature the foam temperature would remain within $\pm$ 2°C for several hours.

For the majority of the experiments foam was produced using a laboratory generator[5]. Nine litres of premix were prepared using water from a 600 litre tank which had stood in the laboratory for several days. The container of premix was connected to the foam generator and to the air supply, by flexible tubes, and was immersed in the 600 litre tank. This procedure enabled foam to be produced for several hours with a temperature variation no greater than $\pm$ 1°C.

The premix was metered to the generator at 0.5 l/min and the air rotameter was adjusted to give an expansion close to 10. The air supply was left unaltered while the liquid supply was stopped between successive samples. The gauze packings

in the foam-making tube were selected to give a 'non-draining' foam similar to those used in fire tests. A single container of premix provided approximately 50 samples. It should be noted that duplicate test results will contain an element of variability attributable to slight variation in adjusting the premix rota-meter , as well as differences attributable to the shear stress meter.

Foam concentrates used

Three types of foam concentrate were used in the principal experiments and following the above procedure, using the foam generator, gave foams with the following typical properties.

Protein foam	4 per cent solution
	Expansion 10.3
	Time to commencement of drainage = 3.0 min
	20 cm 25 per cent drainage time = 9.9 min
	Shear stress (Def Standard method) = 30 N/m^2
Synthetic foam	3 per cent solution
	expansion 10.3
	Time to commencement of drainage = 3.7 min
	20 cm 25 per cent drainage time = 13.9 min
	Shear stress (Def Standard method(= 16 N/m^2
Fluorochemical foam	6 per cent solution
	Expansion 10.2
	Time to commencement of drainage = 0.9 min
	20 cm 25 per cent drainage time = 4.2 min
	Shear stress (Def Standard method) 4.4 N/m^2

VISCOMETERS

Gallenkamp Viscometer

A 'Gallenkamp' Universal Torsion Viscometer operating on the principle shown in Arrangement C in Fig 2 was obtained from tne laboratory suppliers[6] This viscometer has no motor and a preselected torsion is applied to the top of the wire while the scale attached to the vane (or cylinder) is anchored). A specific torsion was applied to the top of the wire, and the vane (or cylinder) was then immersed in a foam sample. The vane was released 45s after collecting the sample and the relaxation of the torsion was noted on the scale at intervals

Fig 3 shows the 'Gallenkamp' viscometer ready for use.

Defence Standard Viscometer

A viscometer as described in Defence Standard 42-3 and shown in Fig 1 was used; primarily as a reference instrument.

Experimental Viscometer

A variable speed viscometer was constructed and was used for the majority of the experiments. Fig 4 shows the viscometer being used. The viscometer adopted the

principle, depicted in Arrangement B in Fig.2 The torsion wire being fixed
at the top while the foam sample was rotated on a motor driven turntable.
This design was chosen because extensive practical experience had been obtained
with the Defence Standard viscometer and the experiments would provide practical
experience of this alternative design.

The turn-table was driven by a variable speed 60 watt geared motor[7] which
had a nominal speed range of 2 - 10 rpm; but under the low load conditions of the
viscometer the speed varied from 4 - 12 rpm. At low speeds the power output fell
markedly and the speed was affected by the load. The motor was therefore set to
run at its maximum speed and lower speeds were obtained by using an Adap universal
speed control[8] on the electrical supply which has better power characteristics.
This gave good speed control from 12 to 3 rpm, but at lower speeds the control
was less reliable because of variations depending on the temperature of the
controller, which varied with its running period. By permitting the motor to run
for a period at the start of each session to warm up the controller, and by
checking the speed at intervals an acceptable level of speed control could just
be achieved. If careful experimentation at speeds below 3 rpm was intended,
an alternative control would be desirable.

The viscometer had a brass sample pot - 7.6 cm diam x 7.6 cm high. The sample
pot was filled from the foam generator and placed on the viscometer turn-table ,
and the vane lowered into the foam. The pot was adjusted to ensure that the
pointer was not displaced from the zero position. The viscometer motor was started
30 seconds after commencing to fill the sample pot. In field work with fire foams
a period of 1 minute is usually allowed, because foam samples may have to be carried
some distance, but the 30 seconds period was fully adequate for these laboratory
tests, and resulted in a valuable economy of time many hundreds of measurements being
made. The yield value was noted as the highest deflection reached by the scale,
while the continuous shear stress reading was noted mostly 30 seconds after
starting the motor;this point is discussed later.

The foam temperature was checked several times throughout an experimental
series, and no problems were encountered with significant variations as a result
of the precautions in foam production already described.

In most experiments duplicate samples were taken and their average value used.
If the duplicates did not agree well 3 or 4 samples would be measured. In some tests
5-10 samples were measured where this was an appropriate course.

In most experiments the viscometer was adjusted so that the vane (or cylinder)
was suspended in the centre of the sample pot - ie fully immersed. Only when a
comparison with the Defence Standard viscometer was required, was the viscometer
vane aligned with the surface of the foam sample according to the Defence Standard
operating instructions.

Constructional details of the experimental viscometer are not given because they conformed very closely to the details provided later for a recommended design, except that the speed could be varied.

Important experimental attributes were that the torsion wire could be rapidly changed, as also could the vane (or cylinder).

Vanes, cylinders, and sample pots

A selection of vanes and solid cylinders were constructed of brass. These permitted variations of diameter of 10, 20, 30, 40 and 50 mm, and variations of height of 10, 20, 30, 40, 50 and 60 mm. The vanes were all 2 mm thick and had 3 mm dia. stems. A stainless steel cylinder was used in a few experiments.

For most experiments a brass sample pot 7.6 cm dia. x 7.6 cm ht was used. Sample pots of four different diameters were used to investigate the effect of pot diameter – these ranged from 5 cm to 10 cm diameter.

Figure 5 shows the selection of vanes and cylinders used in the experiments.

Torsion wires and their calibration

Torsion wires of 24, 26, 28 and 32 SWG were used. The wires were 36.5 cm long and were either purchased with end mountings[9], or were prepared from piano wire which was crimped and soldered into end mountings. The viscometer could rapidly be fitted with the wire most appropriate for the shear stress being measured. Deflections could be observed accurately to 1 scale division (3.6 degrees) and wires were generally selected to give deflections of not less than 25 divisions, and not more than 100 divisions. Deflections exceeding 200 divisions were necessary to permanently deform the wire.

Each wire was calibrated by suspending from it a cylindrical weight and timing the period of oscillation. The dimensions and mass of the weight were determined and its moment of inertia calculated.

A constant for each wire could then be calculated as shown by the following example

Dimensions of calibration weight

$$\text{Radius} = 0.05 \text{ m}$$
$$\text{Weight} = 0.402 \text{ kg}$$
$$\text{Moment of inertia} = I = \frac{\text{mass x radius}^2}{2}$$
$$= \frac{0.402 \times 0.05^2}{2}$$
$$I = 0.0005 \text{ kg m}^2$$

$$\text{Period of oscillation} = 4.44.S. = t$$

Torsional Constant for wire $= \dfrac{4\pi^2 I}{t^2 \times 57.3}$ N – m/degree

$$= \dfrac{4\pi^2 \times 0.0005}{4.44^2 \times 57.3}$$

$$= 0.0000175 \quad \text{N – m/degree}$$

$$= 17.5 \ \mu \text{ N – m/degree}$$

Each wire was calibrated in this manner and kept carefully labelled with its torsional constant in μN – m/degree.

When a wire was used in an experiment its torsional constant was used to calculate an instrument constant which depends upon the size of the vane and the number of scale divisions. The following example gives the calculation for a 30 mm wide x 30 mm high vane, used with the wire calibrated in the above example, and the experimental viscometer with the 360 degree scale divided into 100 divisions.

Area of vertical cylinder showed by vane $= \pi$ dh

$$= \pi \times 0.03 \times 0.03$$

$$= 0.00283 \text{ m}^2$$

Instrument constant $= \dfrac{\text{wire constant}}{\text{sheared area x radius}} \times \dfrac{360}{100}$

$$= \dfrac{17.5 \times 10^{-6} \times 360}{.00283 \times .015 \times 100}$$

$$= 1.48 \text{ N/m}^2 \text{ – per division}$$

An alternative procedure which has advantages of convenience can also be used. The scale and vane assembly can be used as the calibration weight.

The moment of inertia of the scale and vane assembly of the experimental viscometer, fitted with a 30 mm x 30 mm vane was determined by timing its oscillation with a wire previously calibrated using the symmetrical weight. It was found to have a moment of inertia of 0.0001090 kg m^2.

Therefore using the scale + vane assembly to calibrate a new wire.

Torsional constant for the wire $= \dfrac{4\pi^2 I}{t^2 \times 57.3}$

$$= \dfrac{0.00075}{t^2} \text{ N – m/degree}$$

And the instrument constant using a 30 mm x 30 mm vane and the scale divided into 100 divisions

$$= \frac{\text{wire constant}}{\text{sheared area} \times \text{radius}} \quad \times \quad \frac{360}{100}$$

$$= \frac{64}{t^2} \quad \text{N/m}^2 \text{ per division}$$

With this factor marked upon the instrument, the instrument constant can be rapidly checked whenever required.

Observing the movement of foam during measurements

By adjusting the viscometer vane, (or cylinder) so that it was partially, or only just, immersed, the movement of the foam around the vane, while the sample pot was rotated, could be observed. By placing a spot or a thin line of dye on the surface of the foam, and a marking arrow on the side of the sample pot, the movements of the foam were more explicitly observed and could be recorded photographically. Slight distortion of the dye pattern was caused in the central zone when the vane was removed before photography, but by careful operation this distortion could be limited so that it did not alter the significance of the photographs.

EXPERIMENTAL RESULTS AND DISCUSSION

The behaviour of a pre-torqued cylinder immersed in foam

Tests were first made with the 'Gallenkamp' viscometer using protein foam and synthetic foam, and a 10 cm dia sample pot. The foams were produced using the 5 1/min branchpipe. The viscometer was fitted with a stainless steel cylinder – 41 mm dia x 25 mm high. The sample pot was filled with foam and the cylinder immersed. The scale (and cylinder) were anchored and a specific torque applied to the top of the wire. The scale was then released and the relaxation of the torque noted at intervals for a period of 4 minutes. The scale was released as soon as the sample could be positioned – which was between 30 and 60 seconds from filling the sample pot.

Fig 6 shows the observation with protein foam and Fig 7 those with synthetic foam. On both figures the degrees of torque equivalent to the shear stress measured in the Defence Standard instrument are indicated.

From Fig 6 we see that with protein foam, when the initial torque exceed 300 degrees, the cylinder revolved over a period of 2 minutes and the torque released to 300 degrees ie the protein foam had a 'hold value', which we can regard also as a yield value, equivalent to 300 degrees of torque. This value is not greatly different from the yield value of 360 degrees measured in the Defence Standard instrument – which is fitted with a vane which may be the reason for the difference.

When the torque applied was less than 300 degrees the cylinder was not held stationary but always rotated to a small extent before being held. From Fig 6 we can note the amount of relaxation which occurs before the cylinder is held, and the values are shown on Fig 8, from which we can see that the amount of slip is proportional to the residual torque. This suggests that the foam cannot hold the cylinder until movement causes deformation of the bubbles setting up stresses.

With synthetic foam, the results in Fig 7 show that it behaves differently from protein foam, and whether the applied torque is above or below the equivalent value to the yield stress measured in the Defence Standard instrument; the cylinder rotates to near complete relaxation of the torque – ie there is no hold value. Note that in these tests a 32 swg wire was used, which has a torsional constant approximately $^1/10$ of the wire frequently used in the Defence Standard instrument; and the variations from return to zero are therefore small.

These results are of considerable significance if we now consider the operation of the experimental viscometer (or the Defence Standard instrument). When the motor is started and a progressively increasing torque is applied to the vane, relaxation will be occurring and will increase until the rate of relaxation equals the rate of application. With synthetic foam, if the viscometer speed is very low, the relaxation rate will equal the application rate at a very low value. With protein foam, if the viscometer speed is very low, the relaxation rate will not equal the application rate until the yield value is exceeded.

Another important deduction is that we cannot measure yield values and consider them to be independent of the rate of shear - on the basis that rate of shear is zero up to the yield point.

A further point of interest is that some relaxation must result from movement of the foam around the sample pot as well as movement around the cylinder.

These experiments were made with a solid cylinder and therefore relate to the resistance of a body of foam moving over a wet brass surface. Different results may occur if a vane is used in place of the cylinder in which case the results may relate to the resistance of one layer of foam moving over another layer: information on this aspect appears later.

VISCOMETER BEARING DESIGN

The first tests with the experimental viscometer revealed erratic operation and this was traced to the design of the bearing at the lower end of the wire. A bearing is necessary to confer stability on the vane, two bearing points a short distance apart appeared to be a suitable design; similar to the Defence Standard instrument. The erratic operation was because the two bearing points had insufficient clearance. Although the vane would rotate freely, and zero accurately, when in the air; when it was immersed in foam a slight lateral displacement could not always be avoided. This caused the vane spindle to hang diagonally between the bearing points and hinder its movement. Careful levelling of the viscometer assists in avoiding this difficulty, as also does maintenance of high weight on the wire, but an adequate clearance at the bearing points was found to be of greatest assistance. Two bearing points 4.25 mm internal diam and 30 mm apart, with a 3.2 mm dia spindle were found to work satisfactorily.

THE DIFFERENT BEHAVIOUR OF WET AND DRY VANES

It was noticed that the first measurement in a series of tests with the experimental viscometer would sometimes be anomalous. This was shown to result from the vane sometimes being dry for the first measurement, while for subsequent test it usually remained wet.

Fig 9 shows series of tests with a cylinder and protein foam. In one case the cylinder was wet from the previous measurement. In the other case the cylinder was carefully dried. The dry cylinder gave a shear stress reading 30 per cent lower than the wet cylinder. Similar differences were observed with a vane, and with other foams.

All readings were therefore made with cylinder or vane, wetted by the foam liquid, by conducting a preliminary test.

THE BEHAVIOUR OF A CONTINUOUSLY TORQUED VANE IMMERSED IN FOAM

Fig 10 shows the scale deflections during the first 3 minutes of rotation of the experimental viscometer using synthetic foam. A 30 mm x 30 mm vane was used and three speeds. A 28 SWG wire was used with a constant of 2.96 $\mu N - m/degree$.

At the highest speed the shear showed an initial peak from which it immediately fell back and then steadied at a near constant value – the foam therefore apparently had a yield value higher than the continuous shear. At the lowest speed the shear rose smoothly to a steady value, exhibiting no yield stress in excess of the continuous stress.

Fig 11 shows similar observations for protein foam. In this case, even at the lowest speed a yield value in excess of the continuous shear was obtained.

Fig 12 shows measurements of the yield stress and the continuous stress for protein foam at various speeds. From this figure we can infer that at zero speed protein foam has a yield stress markedly in excess of the continuous stress.

Fig 13 compares the behaviour of the vane in 3 types of foam. The protein foam shows a yield stress markedly above the continuous stress as in the previous tests. The synthetic foam shows no yield value in excess of the continuous stress. The fluorochemical foam shows an initial yield value in excess of the continuous stress, but this is for a different reason than is the case with the protein foam. In this very fluid foam there is a substantial overswing of the vane due to its inertia, and not because the foam has a yield stress in excess of the continuous stress.

From the many subsequent tests made it was readily apparent that the registering of a yield value higher than the continuous stress was attributable partially in the case of protein, and substantially with synthetic and fluorochemical foams, to the characteristics of the instrument and not to the properties of the foam. With fluid, low shear stress foam, a stiff wire, and a high speed, a large overswing occurs and the vane oscillates about the continuous stress value at which it finally settles. At the other extreme, with a stiff foam, a soft wire, and a low speed, the vane will rise to the continuous shear value with no overswing, except in the case of protein foam.

In view of these observations it was decided to adopt the continuous shear stress reading as the best basis of comparison. In most cases the continuous shear reading settles to a steady value by 30 seconds after reaching the yield point and there is no difficulty in recognising when this has occurred and in obtaining reproducible results. In some cases, particularly with the stiffer protein foams, the continuous reading will show a slight continuous change, which may be upwards or downwards, and reproducibility will be improved by reading the continuous shear stress at a standard interval after starting the motor − say 30 seconds. In the experiments however this time was varied between 30 and 90 seconds because of the wide range of vane speeds used. With a high shear stress foam, and a low speed, the 30 second interval is insufficient to permit equilibrium to be reached.

Another phenomenon of interest is that the scale does not rotate smoothly past the fixed pointer but progresses in a series of smoothed−out jerks. The probable explanation of this is the inertia of the vane assembly. When the vane begins to move, as the motor is started, it will lag behind the foam endeavouring to turn it, while it accelerates to the same speed of rotation. On catching−up the vane will overshoot the speed of rotation of the foam, and consequently slow down, and a fresh oscillation will ensue. It is the same effect as that which provides an instrument contribution to the difference between yield and continuous shear stress. Its magnitude can be estimated from the moment of inertia of the vane assembly and the wire constant. The moment of inertia of the vane and scale were determined by measuring the period of oscillation with a wire previously calibrated with the cylindrical weight. A 30 mm x 30 mm vane was used. The moment of inertia was 0.000081 kg m^2 = I. At a rotational speed of 8.5 rpm (0.892 radians/s) = W.

Kinetic energy of vane assembly $= \frac{1}{2} I W^2$

$= 0.0000322$ N - m

Using a 28 SWG wire with a constant of 3.01 μN - m/degree

Kinetic energy of vane assembly $= \dfrac{0.0000322}{0.00000301} = 10.7$ degrees of twist

$= 3.0$ scale divisions

Using a 30 mm x 30 mm vane $= 0.765$ N/m^2 shear stress

Typical shear stress values are

Protein foam	=	30 N/m^2
Synthetic foam	=	15 N/m^2
Fluorochemical foam	=	5 N/m^2

The 0.765 N/m^2 representing the degrees of twist required to provide the kinetic energy of the vane assembly are equivalent to increases in the observed yield values as follows

Protein foam	=	$2\frac{1}{2}$ per cent
Synthetic foam	=	5 per cent
Fluorochemical foam	=	15 per cent

With the experimental viscometer the vane is accelerated immediately the motor starts and the kinetic energy lag appears as jerks in the movement of the vane and scale. The yield point is reached when the vane, turning with the foam and sample pot, accumulates sufficient torsion in the wire to cause the vane to shear the foam, instead of continuing to turn with the foam. Since at this point the vane is revolving, at a speed close to that of the sample pot, an additional quota of torsion must be created in the wire to counteract the kinetic energy of the vane and decelerate it to rest.

If the experimental viscometer is designed with minimum moment of inertia it will reduce this kinetic energy effect. Therefore the scale should be light-weight and the weight required to keep the wire taut should be of narrow diameter.

THE BEHAVIOUR OF FOAM AROUND ROTATING VANES AND CYLINDERS

The movement of foam around a rotating vane was observed using 30 mm x 30 mm, and 50 mm x 50 mm vanes and various foams. With the vane just immersed, as is required in the Defence Standard test, the foam piles up on the leading edge of the vane and a cavity forms on the trailing edge. Foam can be seen flowing around the vertical edge of the vane and over the top edge. There is considerable motion of the foam in the vertical plane. Movement is primarily within the prescribed cylinder. The foam appears to be moving in what might be described as a figure of 8 pattern. It would seem to be a very approximate, or even an erroneous concept, to equate the area sheared by the vane to the prescribed cylinder.

Experiments with the 30 mm x 30 mm vane, just immersed, and a radial line of dye, showed that the dye was distributed throughout the circle of the vane and very slightly beyond. At larger diameters up to the sample pot wall the dye line remained undisturbed showing that there was no velocity gradient in a considerable portion of the foam. The locating arrow on the sample pot, with which the dye line was initially aligned, permitted it to be seen that the undisturbed outer sections of the foam sample moved as a block relative to the pot. This was barely noticeable with stiffer foams and 30 s operation and increased to almost 360 degrees for the more fluid fluorochemical foam and 5 min operation.

Figs 14-19 are photographs of the foam surface after a selection of tests with a dye line on the surface and illustrate the above observations.

With a solid cylinder 40 mm dia, partially immersed; in fluorochemical foam, when operated at 4 rpm or less, the foam slipped on the surface of the cylinder, and a spot of dye close to the cylinder remained essentially undisturbed. At higher rotational speeds, eg 12 rpm, a rotational flow of foam, close to the cylinder, approximately 5 mm thick, occurred. A spot of dye placed close to the cylinder was rapidly dispersed around this 5 mm thick annulus of foam. Substantial slip of the foam on the cylinder surface also persisted. The dye indicated elongation of some of the bubbles. However in the many experiments in which cylinders and vanes were used over the complete range of speeds no discontinuties were observed to suggest a transition from surface slip to foam slip (eg Figs 32, 33, 34). An exception to this might be the variation with speed of the shear stress attributable to the ends of the cylinder prescribed by a vane which is shown in Fig 25.

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THE VARIATION OF SHEAR STRESS WITH SPEED OF ROTATION OF VANES

Tests were conducted with three types of foam at varying speeds of rotation. At each speed a measurement was made with two vanes 20 mm and 50 mm high – both being 30 mm wide. By taking the differences between the measurements with the two vanes the contribution of the ends of the vane were eliminated and a torque obtained attributable to a vertical prescribed cylinder 30 mm high and 30 mm diameter; for which the precise velocity is known.

Figs 20, 21 and 22 show the yield values and continuous shear stresses for the three types of foam, while Fig 23 shows the three curves for continuous shear on one figure.

It is interesting to note that the relationship between the yield value and the continuous shear is significantly different for the different types of foam; and that contrary to the indications obtained with the cylinder experiments shown in Fig 7 the synthetic foam has a significant shear stress at zero rate of shear. This latter point is examined in more detail later.

From Fig 23 it can be seen that a rotational speed of 8.5 rpm with the 30 mm wide vane is probably as good a choice of speed as any other. If a change is made from this speed which is used in the Defence Standard instrument, a different value will be obtained. However a change of $\pm$ 1 rpm would not result in a significant difference with protein or fluorochemical foam and would be only $\pm$ $2\frac{1}{2}$ per cent with synthetic foam.

It was at first thought that these curves relating shear stress to the rate of shear represented the data required to define constitutive equations for these foams but the experiments with vanes of various diameters which follow later indicate that further complexities exist.

THE EFFECT OF VANE HEIGHT ON THE CONTRIBUTION
OF THE VANE ENDS TO THE SHEAR STRESS

Tests were first made with vanes 30 mm wide.   By using vanes of different heights
the contribution of the ends can be calculated by difference.   Fig 24 shows
the results obtained.   While the contribution of the ends to the total area
sheared continues to fall as the vane height is increased, their contribution
to the shear stress falls to approx 10 per cent of the total shear at 30 mm
height and remains at this percentage for higher vane heights.   With the
Defence Standard instrument which uses a vane 30 mm x 30 mm, and relates the
torque to the area of the vertical prescribed cylinder, the value obtained will
be 5 per cent high - (only one end being immersed) and increasing the vane
height will not reduce this error with a 30 mm wide vane.

THE EFFECT OF SPEED ON THE CONTRIBUTION OF THE VANE ENDS
TO THE SHEAR STRESS

Fig 24 is based upon the averages for measurements at six speeds.   Fig 25 shows
the effect of vane speed on the contribution of the ends by a 30 mm wide vane -
comparing the ends and vertical cylinder on a basis of their contribution per
unit area.   The ends contribute between 40 and 60 per cent per unit area of
the vertical contribution, with a peak value at 6 rpm.

THE EFFECT OF VANE WIDTH ON THE CONTRIBUTION OF THE VANE ENDS
TO THE SHEAR STRESS

Fig 26 shows the effect of vane width on the contribution of the ends.   Above
30 mm width the contribution of the ends to the area sheared continues to increase
while their contribution to the shear stress becomes close to constant at
35 per cent of the total shear for a 20 mm high vane, and 18 per cent for a
50 mm high vane.

All these measurements were made with synthetic foam and may not be applicable
to other foams, or to markedly stiffer or more fluid foams.   We can however
reasonably conclude that the contribution of the vane ends to the total shear
is a complex relationship.   By using a vane with a small width, a large height,
and a selected speed, the error from neglecting the ends in the calculation
can probably be reduced to less than 5 per cent.

An alternative, or complementary procedure, would be to include the ends in the
calculation, assuming that they contribute the same shear stress per unit area
as the vertical area - ie that the shear is independant of speed.   We can
however allow for the effect of the varying diameter across the ends on the torque.

Consider a vane of width 2γ

If the area sheared by the ends is regarded as making the same contribution per unit area to the torque as the vertical area

End torque $=$ end area x radius

$$= \pi\gamma^3$$

If the end contribution to the torque is regarded as being dependent upon the radius

End torque $\infty \int_0^\gamma 2\pi\gamma^2\, d\gamma$

$\infty \; {}^2/_3 \; \pi \; \gamma^3$

${}^2/_3 \pi\gamma^3 = 67$ per cent of $\pi\gamma^3$

From Fig 25 we note that at 8.5 rpm – the Defence Standard speed – the end contribution per unit area was 42 per cent of the vertical contribution.

A more correct result will be obtained if 67 per cent of the end area is added to the vertical area in the calculation than if it is included at full value or neglected altogether, as is Defence Standard procedure.

THE EFFECT OF WIRE GAUGE ON THE SHEAR STRESS READING

Measurements were made on synthetic foam with a 30 mm x 30 mm vane at six speeds using 24, 28 and 32 SWG torsion wires. The results in Fig 27 show that in spite of a sixteen fold variation in the wire constants good agreement was obtained with all three wires. We can therefore select a wire appropriate for the type of foam being examined without introducing a displacement in values. A wire to give a deflection of not less than 25 divisions and not more than 100 divisions is a satisfactory choice.

Note that this will only be true if the continuous shear is measured. If the yield value is measured the change in wire gauge changes the rate of application of torque and will have an equivalent effect to changing the speed.

THE EFFECT OF SAMPLE POT DIAMETER ON THE SHEAR STRESS READING

Sample pots of 5 different diameters were used to measure the shear stress of
the three types of foam.   A 30 mm x 30 mm vane and a speed of 8.5 rpm were used.
Fig 28 shows the results obtained.   With the fluid fluorochemical foam the
sample pot diameter did not affect the shear stress reading but with synthetic
and protein foams there was a significant difference of the order of 10-15
per cent between the largest and smallest pots used - the largest diameter pot
giving the highest result.   The curves in Fig 28 indicate that at large pot
diameters the dependence of the shear stress reading on pot diameter diminishes.
The largest pot diameter used was 10 cm - giving 35 mm clearance between the
vane and the pot side.   This diameter pot is slightly too large to hold
securely, with wet hands, when gripped around the side, and it has to be
handled holding the fingers on the bottom of the pot and the thumb on the top
edge - an inconvenient method of handling.   A sample pot $7\frac{1}{2}$ - $8\frac{1}{2}$ cm diameter
would be a good compromise between ease of handling and affecting the reading.

The cause of this pot diameter effect is not simply explained.   It is probably
largely influenced by the amount of slip which occurs at the pot wall which
varies with the pot diameter (Fig 16), but the elastic properties of the foam
illustrated in Fig 8 may also be involved.

THE EFFECT OF VANE WIDTH ON THE SHEAR STRESS READING

Tests were made using vanes 10, 20, 30, 40 and 50 mm width.   At each width
vanes 50 mm and 20 mm high were used;   the difference between the two readings
eliminated the end effect, and gave the torque attributable to a 30 mm vertical
cylinder – whose speed was known.   Each vane width was tested at six speeds.
The differences were determined by graphing the observed results as in Fig 29
and measuring the intercepts between the 20 mm and 50 mm curves.   In spite
of the observed results all giving good curves as in Fig 29;   when the intercepts
were measured and converted to N/m^2 by dividing by the vertical sheared area
the results were less uniform.   They are shown in Fig 30 in which the shear
stress is plotted against the rate of shear in mm/s.

It was expected that all the observations would fall on a single curve identical
to that in Fig 21 which shows the shear stress rising in almost direct proportion
to the rate of shear.   Fig 21 was obtained by varying the rate of shear by
varying the speed of rotation, Fig 30 by varying the width as well as the speed
of rotation.   The data in Fig 30 can be smoothed-out and curves for each vane
width as well as each speed can be drawn.   This has been done in Fig 31.

It can be seen that the rate of shear is not the sole primary factor affecting
the shear stress but the vane width also has a major effect.   These tests alone
make it evident that the shear stress as measured by this instrument is dependent
on the instrument design and is not solely a property of the foam.

The cause might be attributed to the pattern of foam movement around the moving
vane which has been described earlier.   As the vane width is increased and
the speed reduced we move further away from the concept of shearing a vertical
cylinder – the foam shears over a shorter path and a lower shear stress
indication results.

COMPARISONS BETWEEN A VANE AND A SOLID CYLINDER

It had now become apparent that the measurements with vanes depend to a large
extent on the dimensions of the vane, irrespective of the rate of shear;   and
to a lesser extent on other instrument details such as sample pot diameter,
inertia of the vane assembly, rate of application of shear, time of observation
and method of calculation.   It might be possible to overcome some of these
difficulties by using a solid cylinder instead of a vane.   This change however
introduces some important fundamental differences.   For the vane to turn it has
to displace a cylinder of foam;   in the ideal situation a cylinder of foam will

be sliding inside another cylinder of foam. With a solid cylinder no displacement of foam is necessary and we measure the resistance of foam sliding around the surface of the brass cylinder. We do not know whether the thickness of the liquid film on the surface of the cylinder will be the same as the thickness of the film between 'layers of bubbles' in the foam, and the measurement with the cylinder might depend more upon the viscosity of the liquid than does the measurement with the vane. On the other hand the resistance of the cylinder may depend to a large extent on the bubble size, which will affect the extent of contact between bubble walls and the cylinder. In this case the measurement with the cylinder will reflect the physical state of the foam rather than the liquid from which it is made.

A 30 mm x 30 mm vane was compared with a 30 mm x 30 mm solid cylinder using the three types of foam. Figs 32, 33 and 34 give the comparisons obtained.

With synthetic and fluorochemical foam the curves for the cylinder apparently pass through the origin; these foams having zero shear stress at zero rate of shear when a solid cylinder is used. With a vane these two foams have a substantial shear stress at zero rate of shear. This is consistent with the concept of the difference between foam sliding over the smooth wet surface of the cylinder and layers of interlocking from bubbles sliding over one another when being displaced by the vane.

With the protein foam the cylinder showed a definite yield value at zero rate of shear. It is difficult to formulate a simple picture of the mechanism by which the protein foam bubbles exhibit a yield value at zero rate of shear with the smooth cylinder.

At rates of shear which are used in the Defence Standard test – ie 8.5 rpm, the measurements with the cylinder reveal the major differences between the different types of foam in a similar manner to those made with the vane.

<div align="center">

Shear Stress at 8.5 rpm – N/m^2

	With cylinder	With vane
Protein	61	50
Synthetic	24	21.5
Fluorochemical	3.8	4.4

</div>

It appears therefore that, providing an appropriate speed is selected, a solid cylinder will serve to characterize a foam equally as well as a vane, although the characterization may be on a slightly different basis.

TESTS WITH CYLINDERS OF DIFFERENT DIAMETERS

Further experiments were therefore made using cylinders of various diameters
to discover if measurements with cylinders are independent of the cylinder diameter
and depend only upon the rate of shear: in which case they will provide a more
fundamental measurement of the shear characteristics of the foam than do
measurements with a vane.

Fig 35 shows the results of tests with synthetic foam using cylinders 20, 30,
40 and 50 mm diameter, and speeds from 1.5 to 12.3 rpm. With each diameter
tests were made with 20 and 50 mm high cylinders and the difference between the
two measurements was related to a 3 cm high vertical cylinder – ie eliminating
the ends effect. A rather fluid foam was used to permit all the measurements
to be made with a single 28 SWG wire – the observed deflections varying from
7 to 183 scale divisions.

Referring to Fig 35 we see that the results with the different diameter cylinders
do not fall on a single curve and that some other factor than rate of shear
affects the shear stress. There is no consistent change with diameter, and the
curves are much closer together than those in Fig 31 for similar tests with vanes,
which showed a consistent change with increasing diameter.

A further test was made using a stiffer foam, which necessitated using wires of
four gauges. 20 mm and 40 mm diameter cylinders were used. The results in
Fig 36 confirm that the measurement with a cylinder is highly dependent upon
the cylinder diameter. Further with the 20 mm diameter cylinder the results
fall on a straight line passing through the origin, while with the 40 mm diameter
cylinder a curve, which does not pass through the origin, was obtained. This
suggests that there is some fundamental difference between the measurements with
the two cylinders.

The explanation of this was observed by operating the cylinders partially
immersed with a radial dye line on the surface of the foam. The 20 mm dia
cylinder was tested at 8 rpm and the 40 mm dia cylinder at 4 rpm, so that the
rate of shear was the same with the two cylinders, ie 8.4 mm/s. With the
40 mm dia cylinder the dye rapidly distributed in an annular ring about 5 mm
wide around the cylinder and the flow of the foam in this annular ring could
be readily observed. With the 20 mm diamcylinder the dye line was not
disturbed and the foam slipped around the surface of the cylinder without any
flow occurring in the foam. This shows that the adherence of the foam to the
cylinder is affected by the curvature of the cylinder.

It was therefore concluded that the use of a cylinder in place of a vane would not result in a fundamental measurement of the deformation properties of the foam when subjected to strain, and the measurement would depend upon the instrument's characteristics as well as those of the foam.

These experiments also revealed important practical disadvantages of cylinders as compared with vanes. Foam clings to the cylinder when it is withdrawn and it is troublesome to remove. This was done by blowing, and foam was spread around. Also when the cylinder is inserted into a full sample pot the foam overflows creating a troublesome mess. With a vane there is no overflow problem and the foam may slip cleanly off the vane or is easily removed using the finger and thumb.

CONCLUSIONS AND RECOMMENDATIONS

1. The experiments have shown that the measurement made with this type of viscometer is an equilibrium value; when the rate of relaxation equals the rate of application of torque. Relaxation occurs at the surface of the vane edge, in an annulus of foam around the rotating vane, and at the surface of the pot holding the foam. The rate of relaxation depends upon the width of the vane or cylinder as well as upon the linear velocity of the cylinder surface and also upon the diameter of the sample pot. The viscometer does not therefore provide a measure of a fundamental property of the foam, but a value which depends upon the instrument dimensions as well as upon the foam characteristics.

2. A similar statement applies when a solid cylinder is used in place of the vane, although there are some differences in the relationships. Solid cylinders also have practical disadvantages as compared with vanes. (Cleaning between tests).

3. Because of the above findings the shear stress measurements must be regarded as arbitrary assessments of foam quality which are only comparable when made with instruments having the same significant dimensions. Such measurements should not be used as fundamental foam properties in calculations — as for instance in predicting the thickness to which a foam layer will spread under its own weight, or the pressure drop when foam is pumped through pipes.

4. The contribution of the ends of the prescribed cylinder to the shear
    measurement could be reduced by changing the dimensions of the vane, and
    selecting the most favourable speed; and an allowance for the ends could
    be introduced into the calculation. Since however we would still have an
    arbitrary measurement any such changes have little merit. Vane dimensions,
    speed and method of calculation should therefore be maintained close to
    those used in the Defence Standard instrument so that future measurements
    will be reasonably comparable with past measurements. The vane dimensions
    should be changed to the round metric units of 30 mm x 30 mm x 2 mm and
    the speed increased to 8.75 rpm which is more readily obtained with a
    synchronous motor.

5. The vane should be fully immersed in the foam as this will tend to reduce
    errors due to variations in flow of foam over the vane, partial filling
    of the sample pot, and adjustment of the vane height.

6. A wire of a gauge suitable to the foam being examined should be selected:
    a wire to give a deflection between 25 and 100 divisions is a satisfactory
    choice. The gauge of wire used does not affect the result obtained.

7. The vane must be clean and free from grease and must be wetted with the
    foam solution before a measurement is made. A dry vane will give a
    significantly lower result.

8. The continuous shear stress should be measured rather than the yield
    value which is influenced by the inertia of the vane assembly. The
    continuous shear is read when the reading falls back from the yield value
    and assumes a near constant value, normally between 30 and 60 seconds
    from starting the motor.

9. The bearing at the lower end of the wire should be designed as described
    with two bearing parts 30 mm apart and 4.25 mm dia with a 3.2 mm dia vane
    spindle.

10. A sample pot $7\frac{1}{2}$ cm diameter x $7\frac{1}{2}$ cm ht should be used. This permits ease
    of handling, provides a satisfactory margin for adjustment of vane height
    and maintains the effect of pot diameter at an acceptably low value.

11. The design principle used for the experimental viscometer, in which the
    sample pot is rotated and the continuous shear can be read on the
    stationary pointer and scale at the front of the instrument, is preferred
    to the alternative design in which the wire is rotated – as in the Defence
    Standard design.

Other design points of value are simplicity in changing the torsion wire, simple adjustment of the vane height, a clamp to hold the wire when transporting the instrument, provision of a plumb-bob for levelling, and simple adjustment to zero reading.

12.   For the convenience of users a separate Fire Research Note No 1059 provides details of the construction of a viscometer to the preferred design and instructions for its use.   Viscometers to this design can be referred to as 'Fire Research Station Foam Viscometer' to distinguish them from other instruments.

13.   A problem still remains, to design a foam viscometer which will measure only the deformation characteristics of the foam and not be dependent upon the instrument dimensions.   Considerable thought has been given to this and there is no simple, obvious solution.   A possible method may be to use a rotor with around 8 crossed vanes which eliminate flow of foam around the vane and shear a cylinder of foam without introducing the slip which occurs on the surface of a solid cylinder.   This approach was not pursued because such a complex vane would have practical disadvantages of difficulty in washing between consecutive tests – perhaps acceptable for laboratory investigations, but not for use on the fire test ground.

A completely different approach than the vane and torsion wire may be required.

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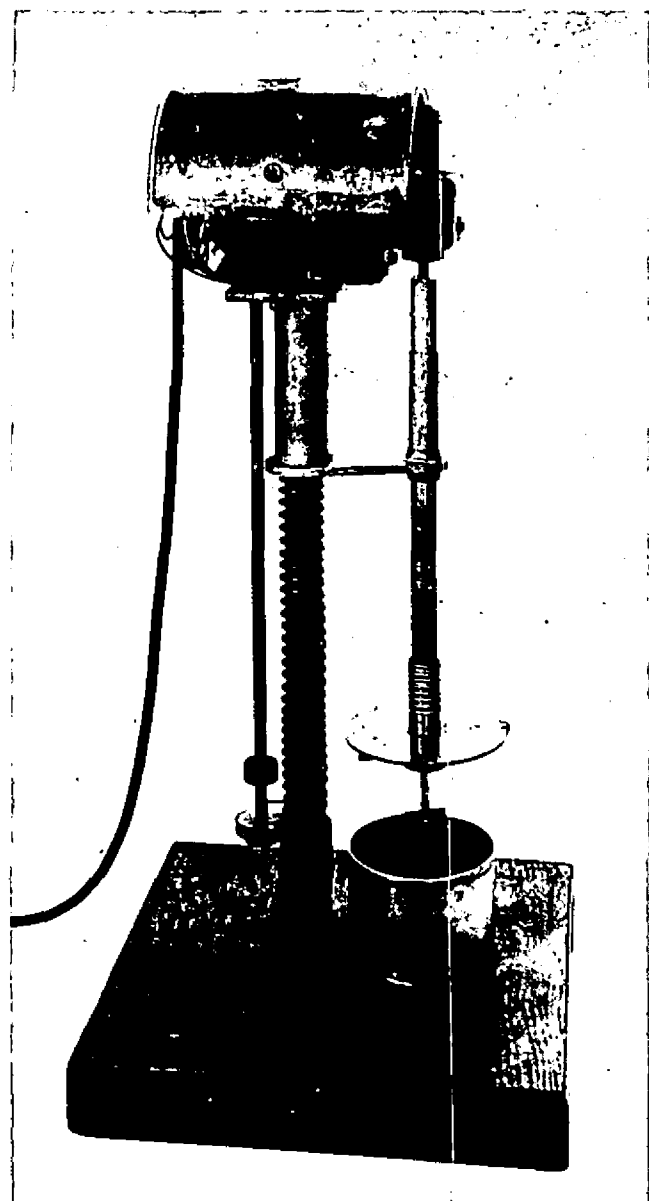
FIG 1.   'DEFENCE STANDARD' FOAM VISCOMETER
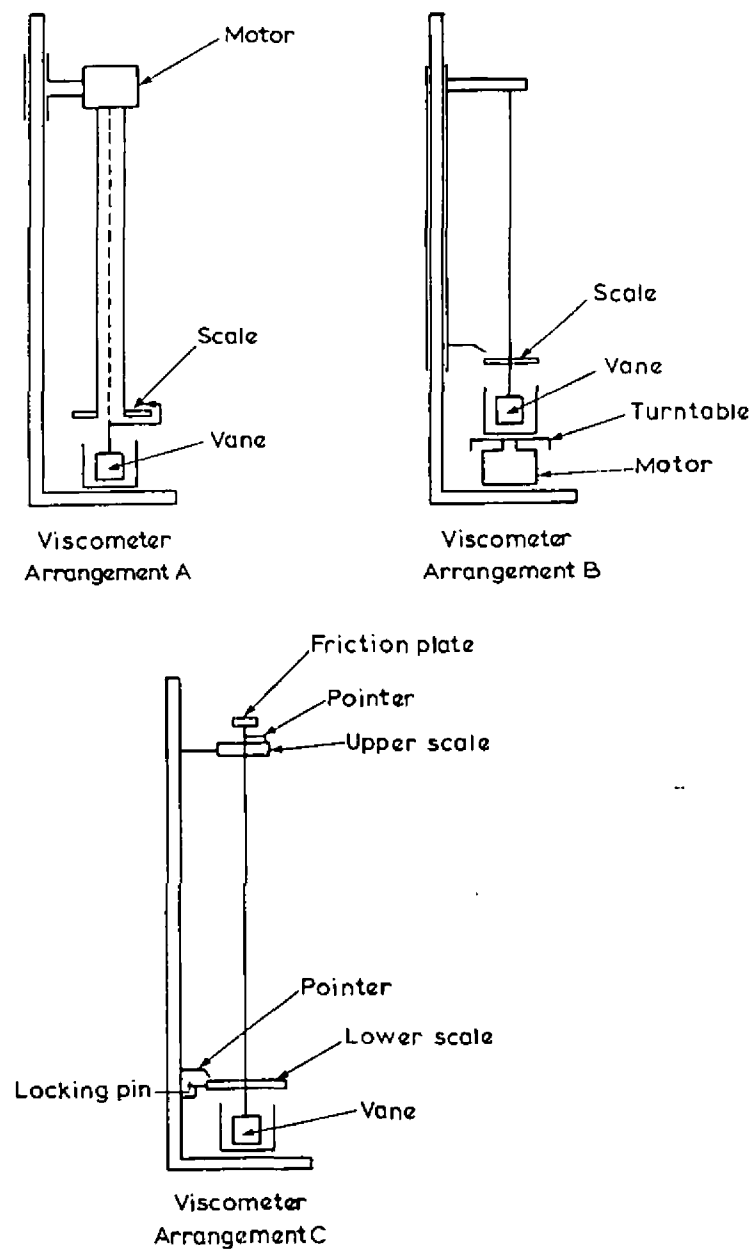
Figure 2 Various viscometer arrangements
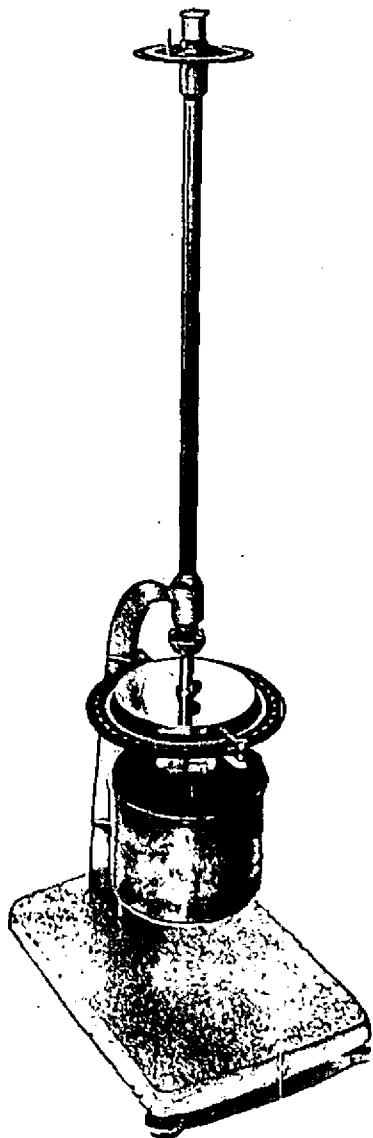
FIG 3.   'GALLENKAMP' UNIVERSAL TORSION VISCOMETER
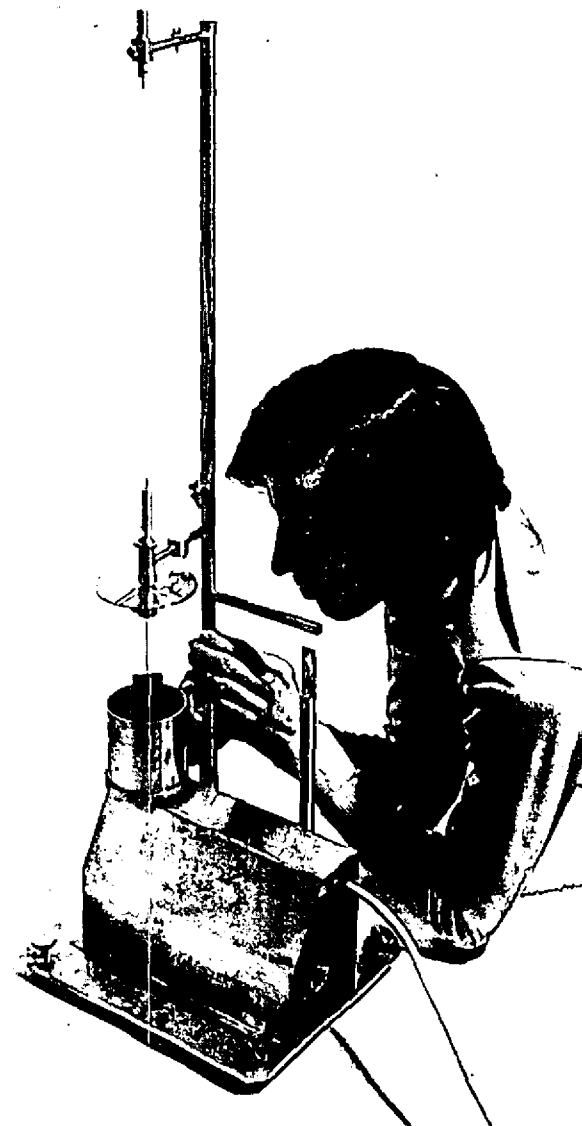
FIG 4.   EXPERIMENTAL VARIABLE SPEED VISCOMETER
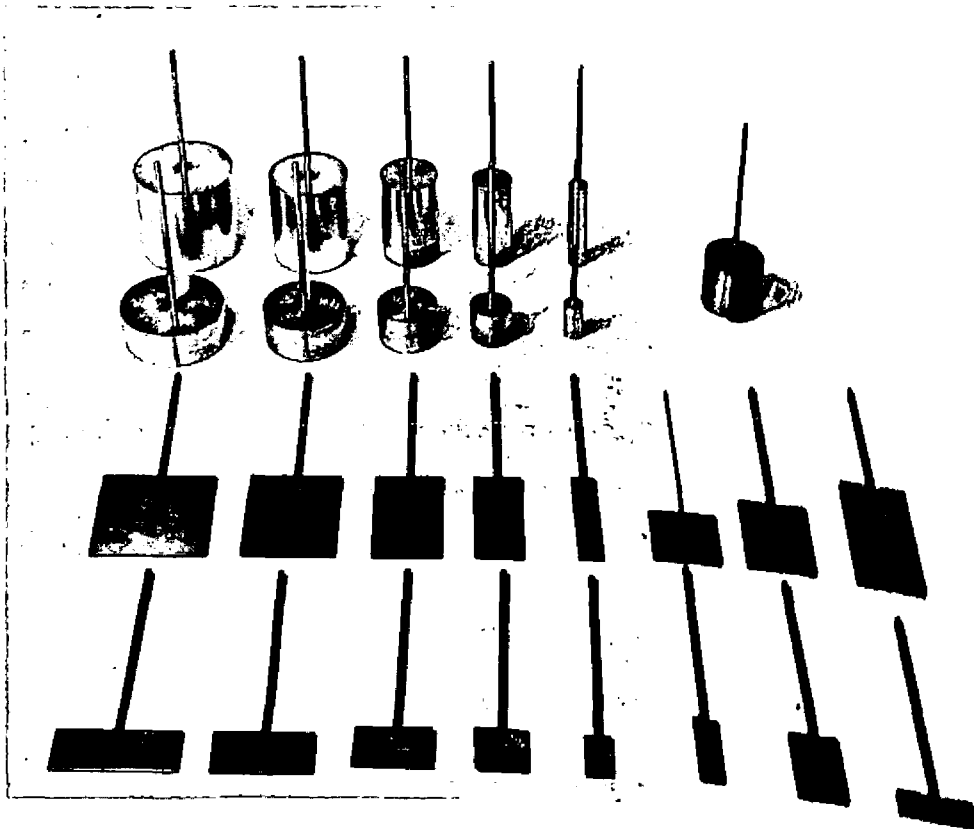
FIG 5.   SELECTION OF BRASS VANES AND CYLINDERS
                USED IN THE TESTS
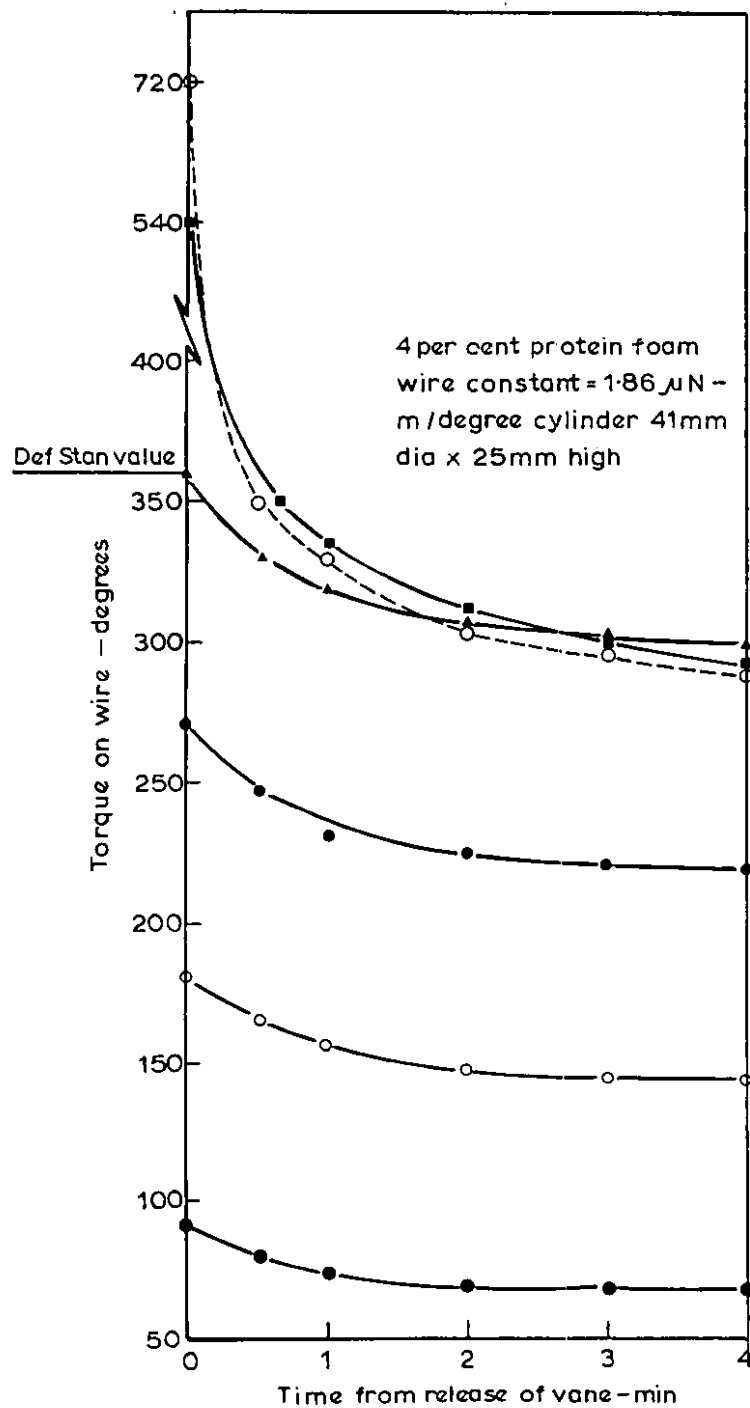
Figure 6 Behaviour of a torqued cylinder in protein foam
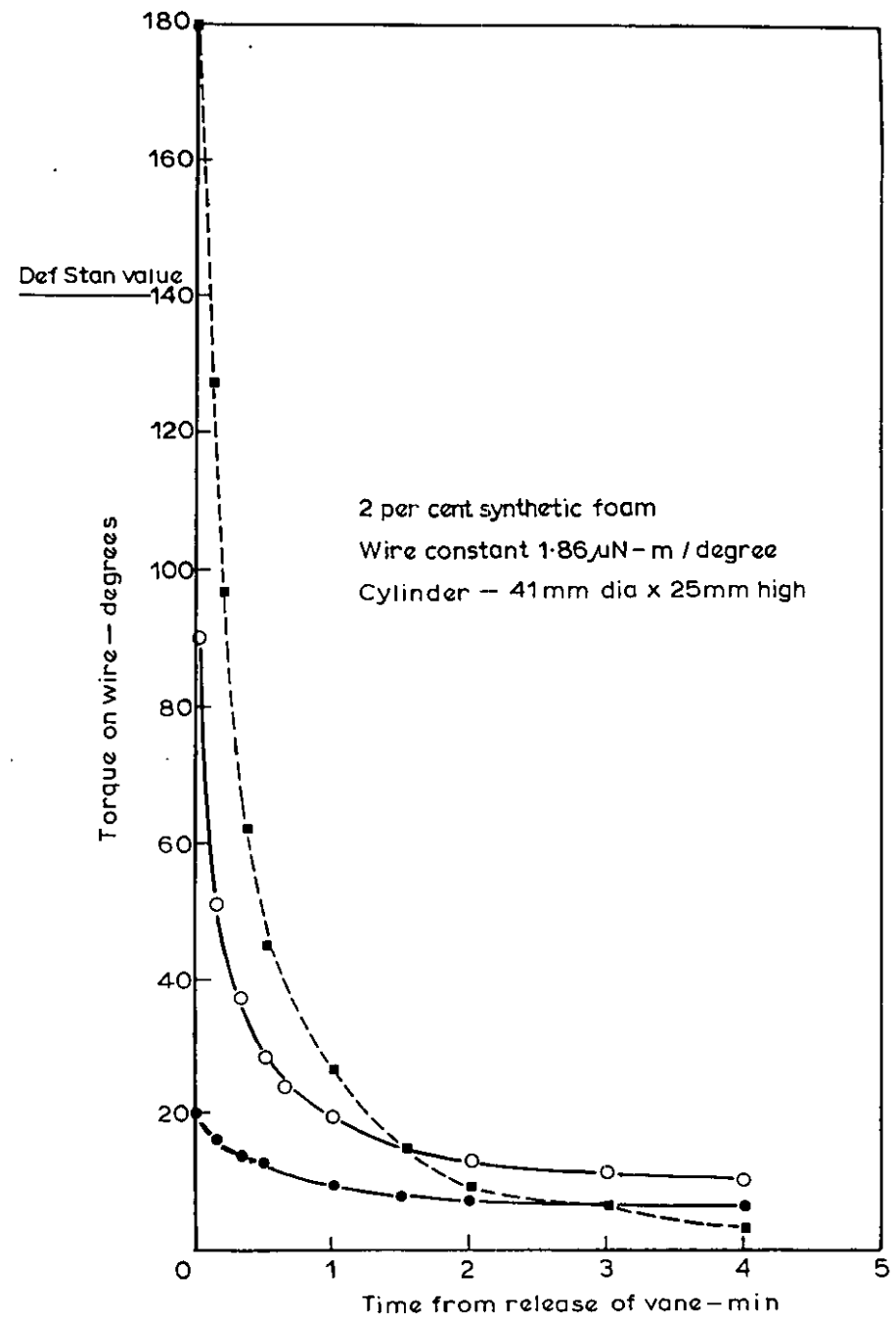
Figure 7 Behaviour of a torqued cylinder in synthetic foam
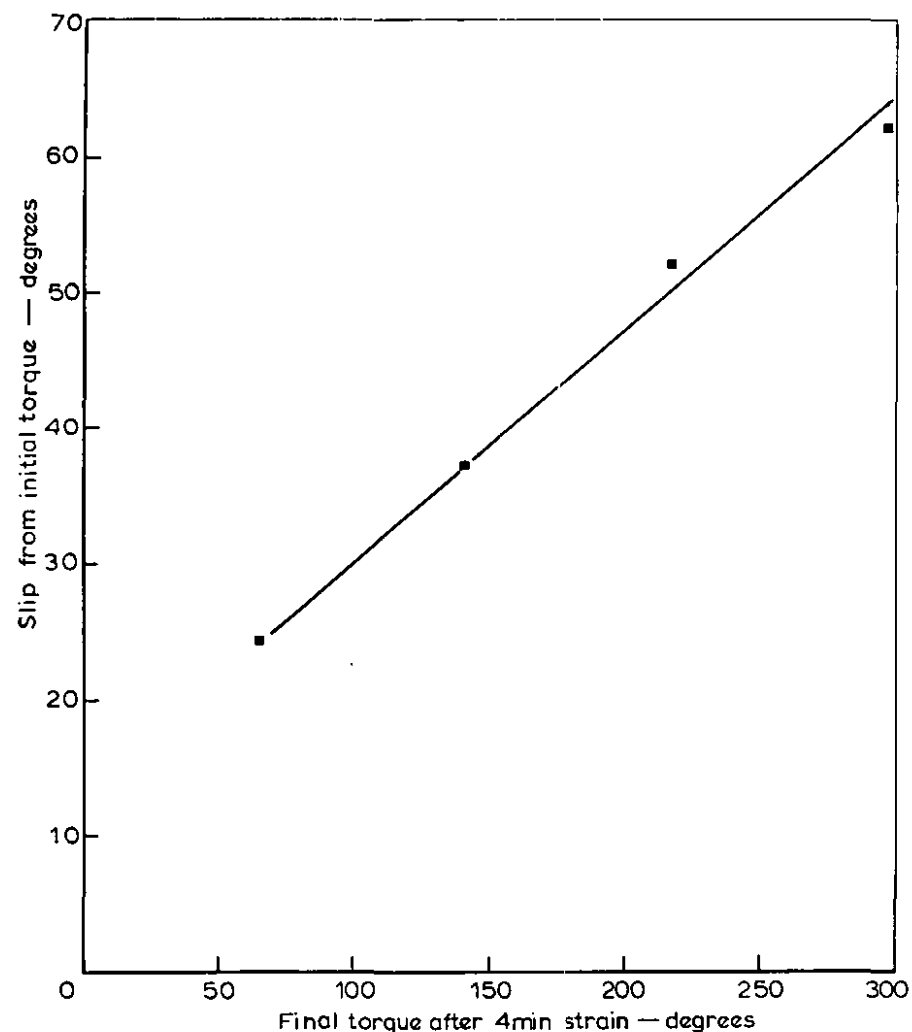
Figure 8 Behaviour of a torqued cylinder in protein foam
Relationship between residual torque after 4min
and the torque dissipated in slip
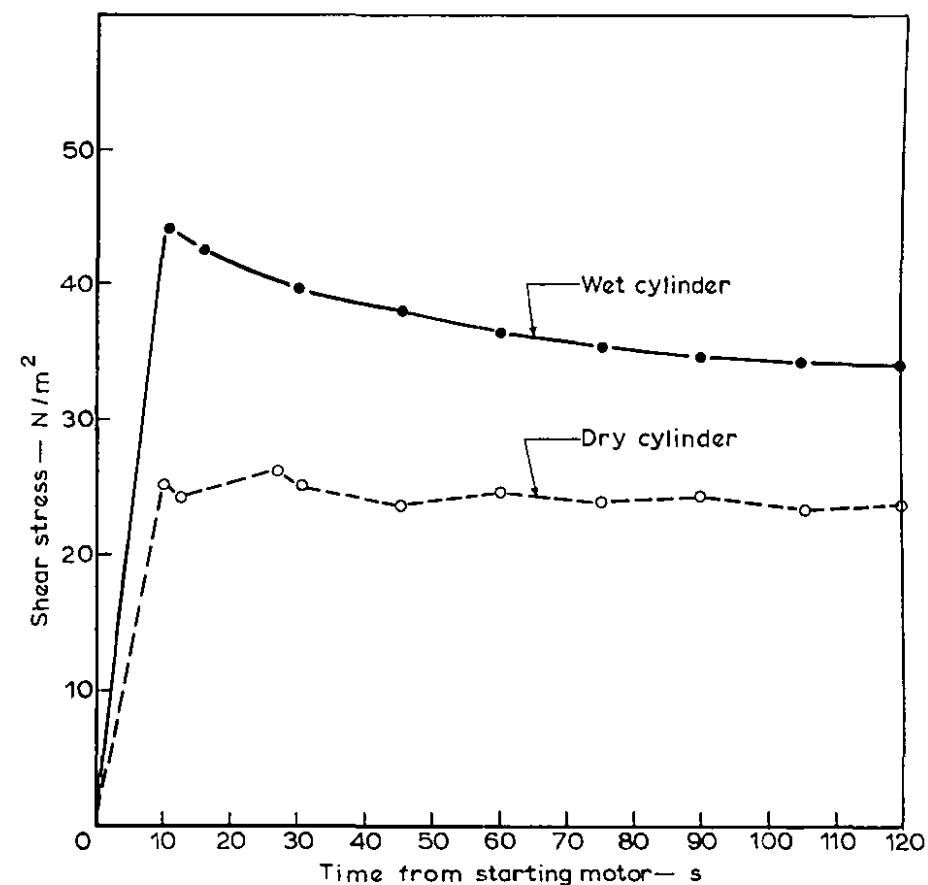
Figure 9 Comparison of shear stress measurements with
wet and dry cylinders -30mm dia x 30mm high
protein foam 12·3rpm - instrument constant 0·255
N/m^2 - per division
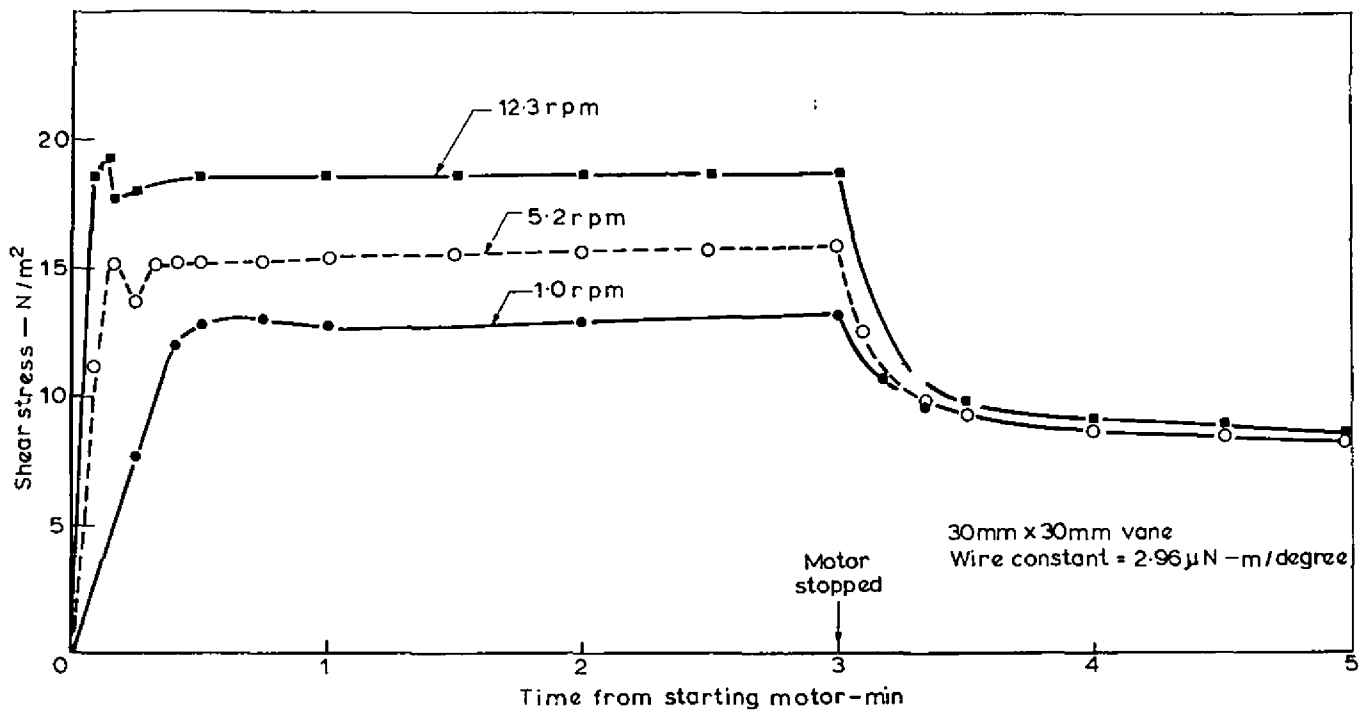
Figure 10 The behaviour of a torqued vane in synthetic foam at three speeds
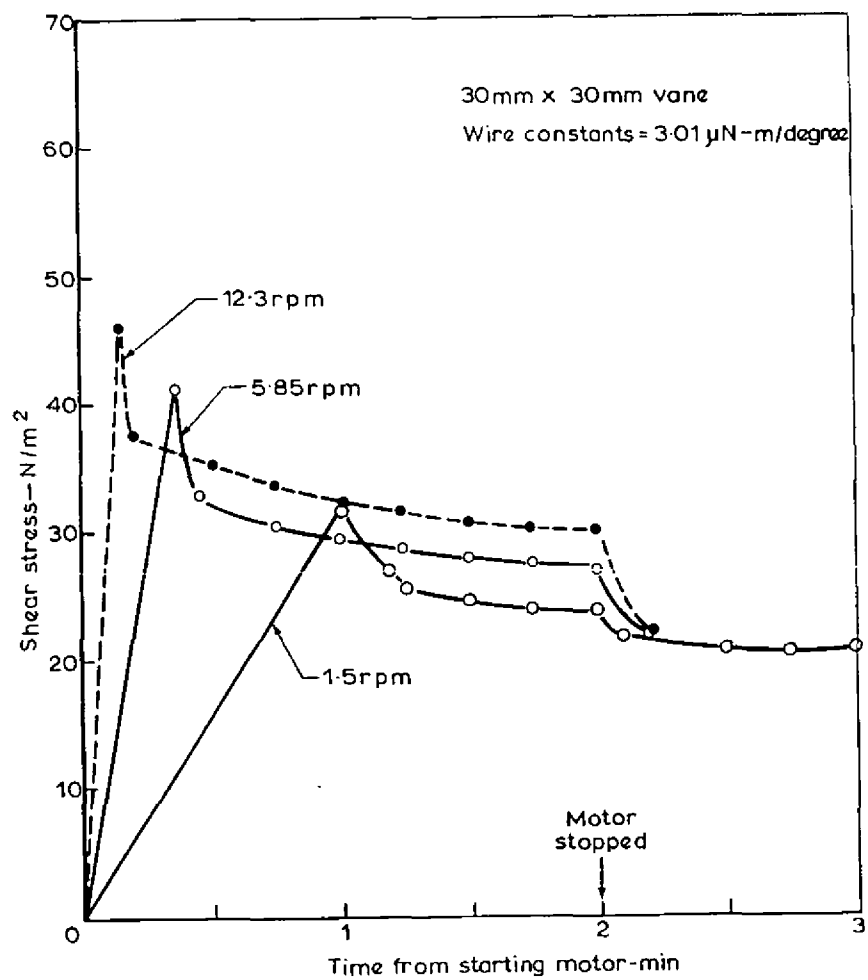
Figure11 The behaviour of a torqued vane in protein foam
at three speeds
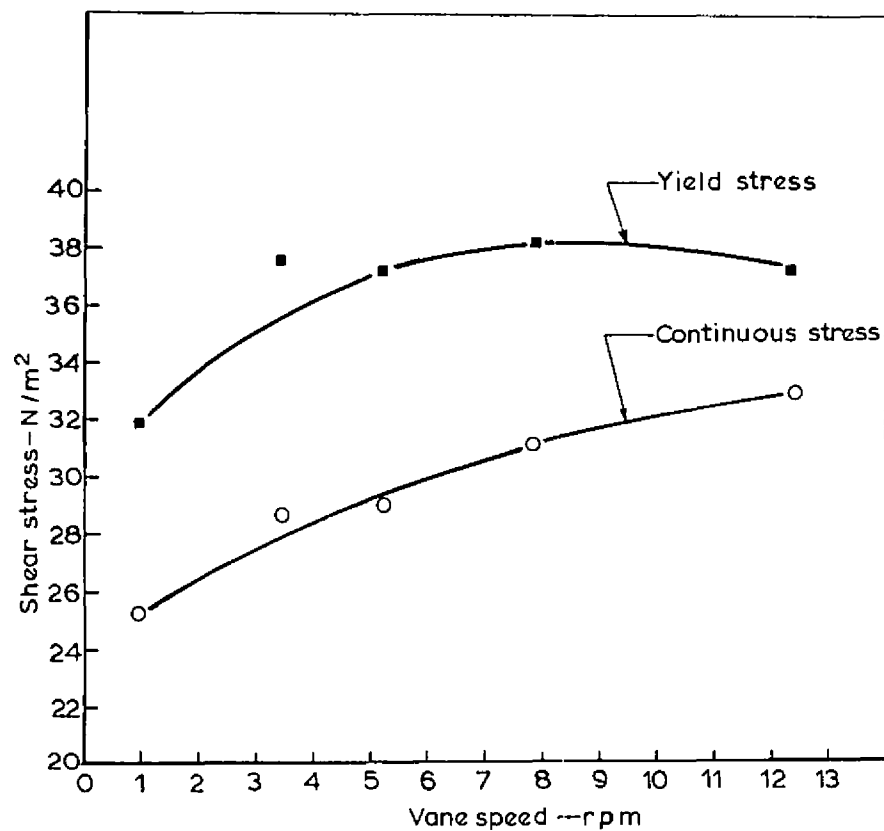
Figure 12 Comparison of yield and continuous shear stress
protein foam—30mm × 30mm vane, 26 swg
wire = 7·9μN —m/degree
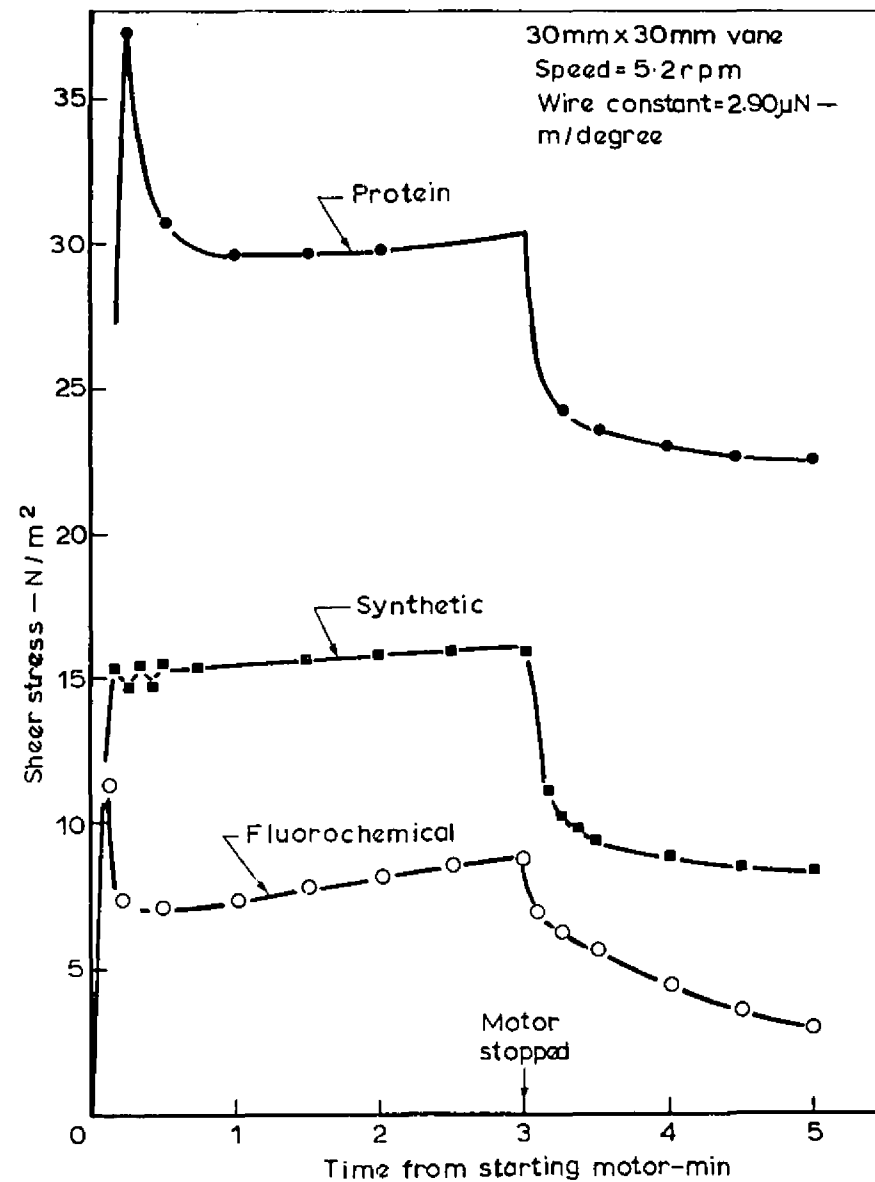
Figure 13 The behaviour of a torqued vane in three
types of foam
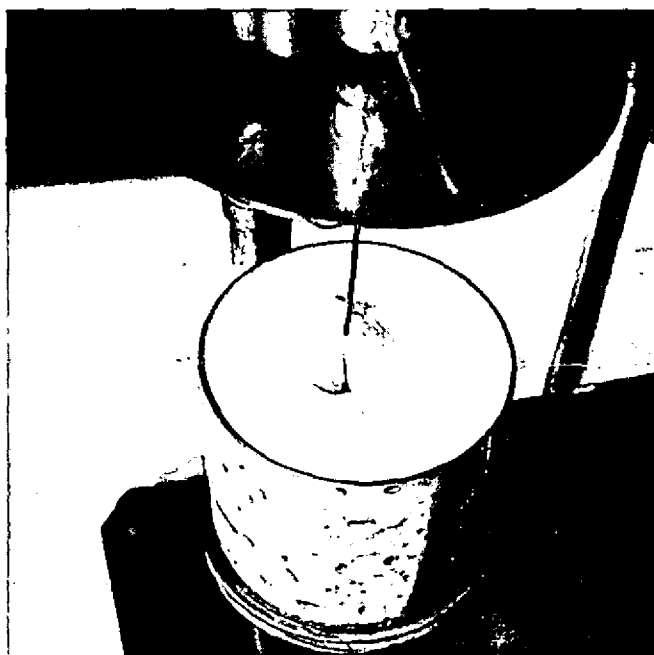
FIG 14.   THE FLOW OF FOAM OVER AND AROUND
           A 30 MM X 30 MM VANE – ALIGNED WITH THE FOAM
           SURFACE – AND POT ROTATED AT 8.5 RPM
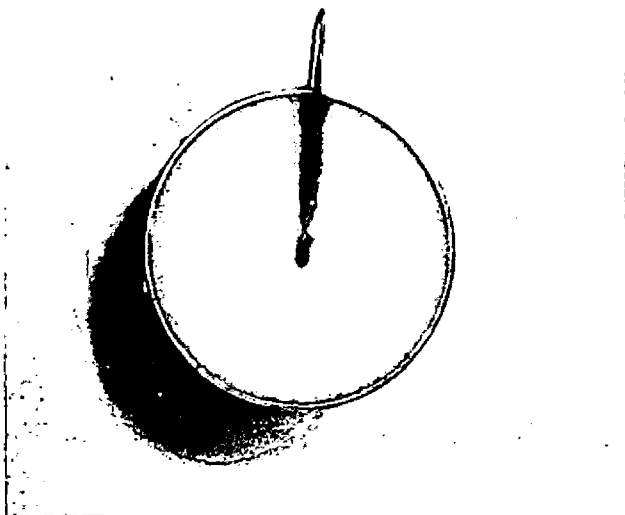
Before rotation
Dye line aligned with
fixed pointer
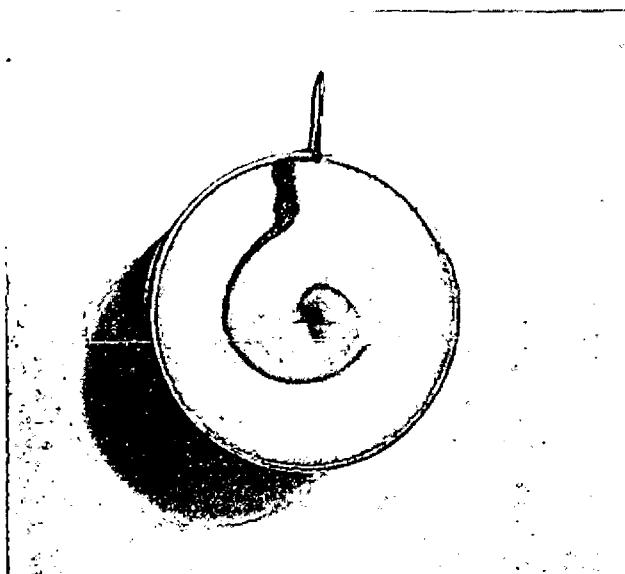
After 1 minute rotation
Dye line is distributed only
close to vane and foam
slips around in the pot 10°
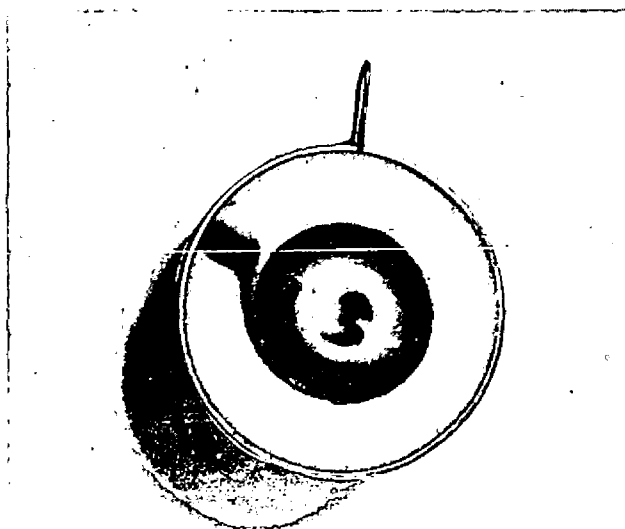
After 5 minutes rotation
Outer portion of foam still
undisturbed but has
slipped around in the pot 60°

FIG 15.   THE MOTION OF SYNTHETIC FOAM AROUND A
           30 MM X 30 MM VANE IN 7.5 CM DIAM POT
           ROTATED AT 8.5 RPM
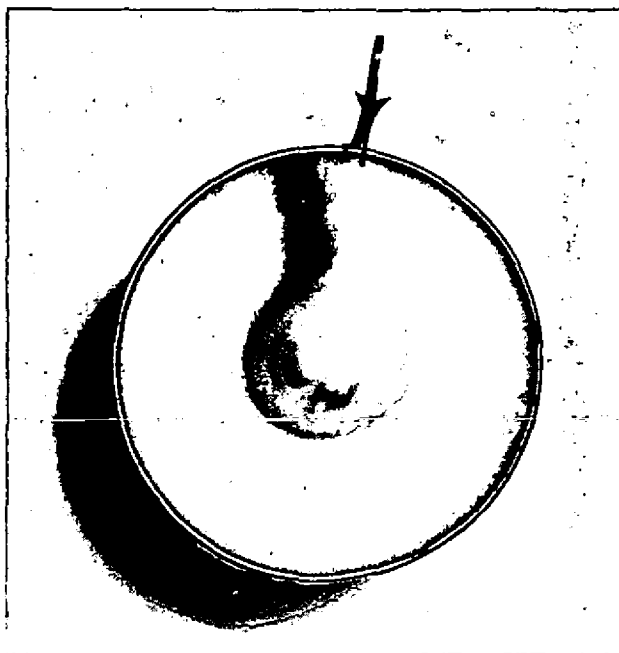
After 5 minute stirring
in 10 cm diam pot
Foam has slipped around
in the pot 10°
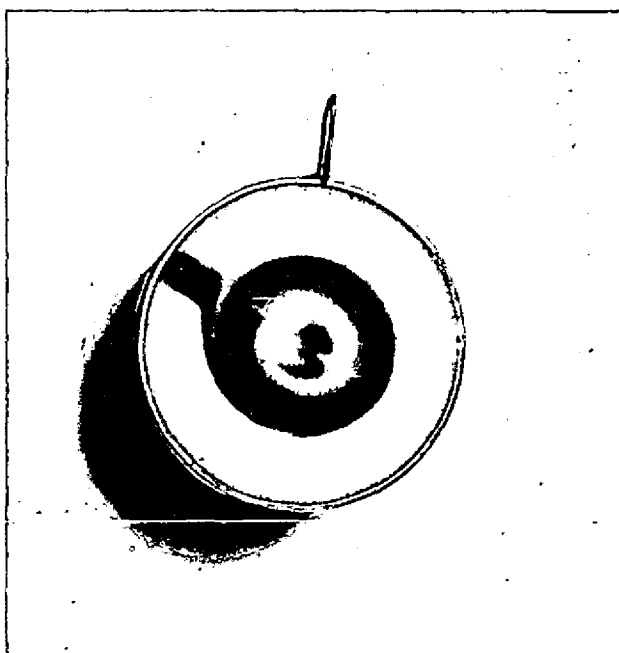
After 5 minutes stirring
in 7.5 cm diam pot
Foam has slipped around
in the pot 6C°

FIG 16.   THE EFFECT OF POT DIAMETER ON THE SLIPPING RATE
OF SYNTHETIC FOAM IN A POT
ROTATED AT 8.5 RPM WITH A 30 MM X 30 MM VANE
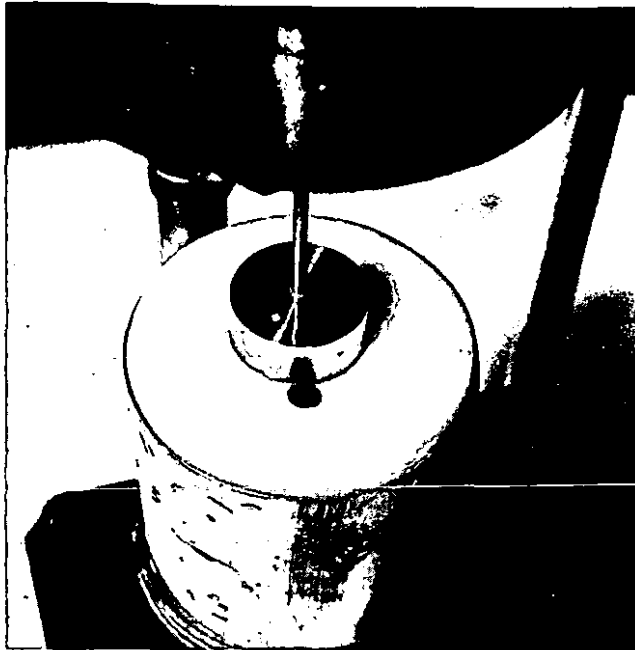
Rotated at 1.5 rpm
for 8 mins (= 12 revolutions)
Dye spot close to cylinder
remains undisturbed
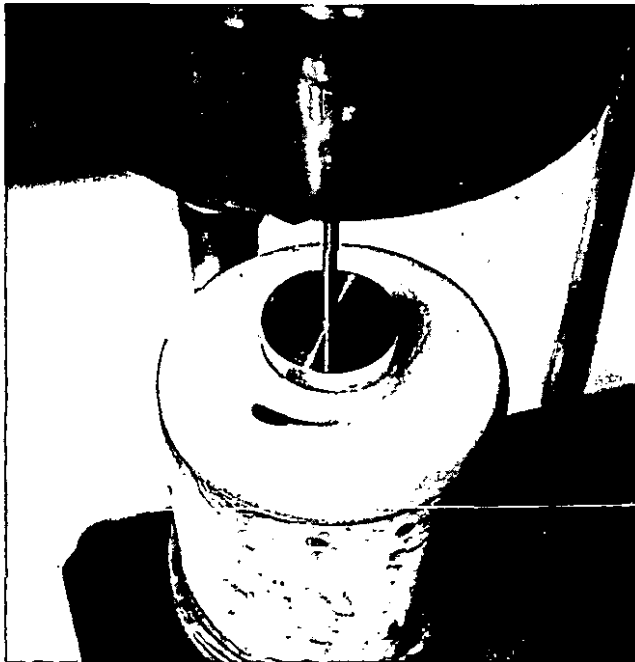
Rotated at 12 rpm
for 1 min
Dye spot is distributed

FIG 17.   THE EFFECT OF THE SPEED OF ROTATION
OF A 7.5 CM DIAM POT ON
THE MOVEMENT OF SYNTHETIC FOAM
AROUND A 30 MM DIAM CYLINDER
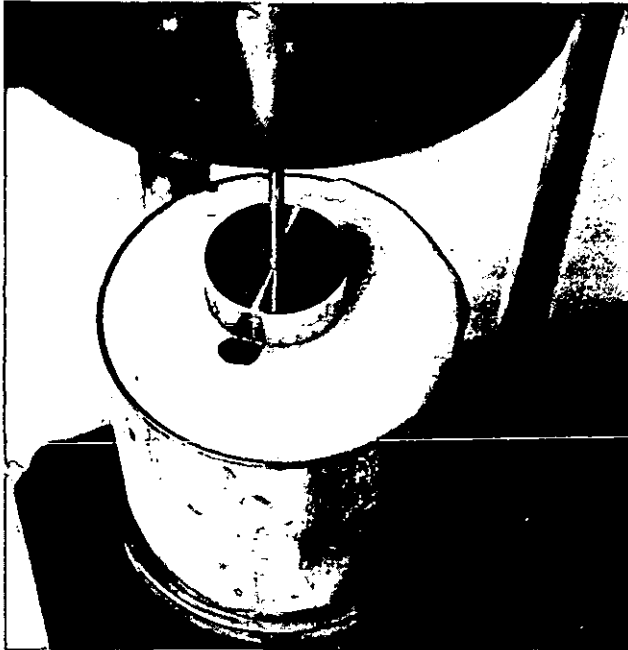
Shear stress = 23 N/m^2
Dye spot close to cylinder
remains undisturbed
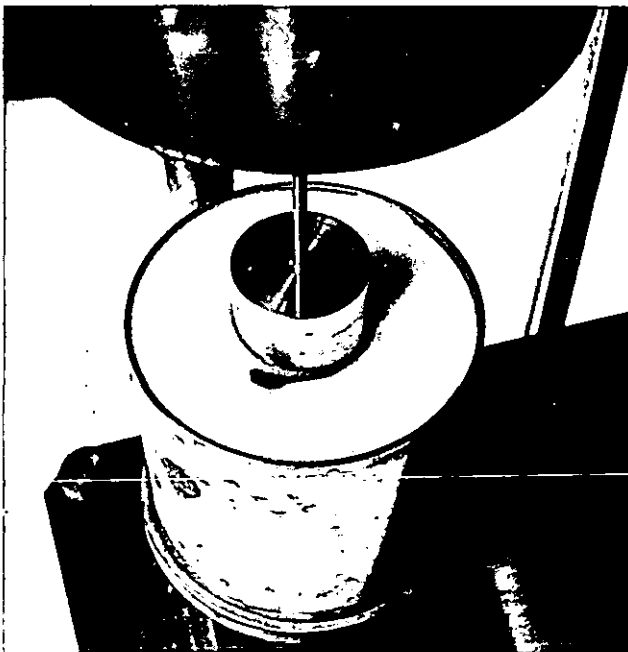
Shear stress = 8.5 N/m^2
Dye spot close to cylinder
is distributed showing
flow of foam close to cylinder

FIG 18.   THE EFFECT OF SHEAR STRESS ON THE MOVEMENT OF
SYNTHETIC FOAM AROUND A 30 MM DIAM CYLINDER IN A POT
ROTATED AT 4 RPM FOR 3 MIN
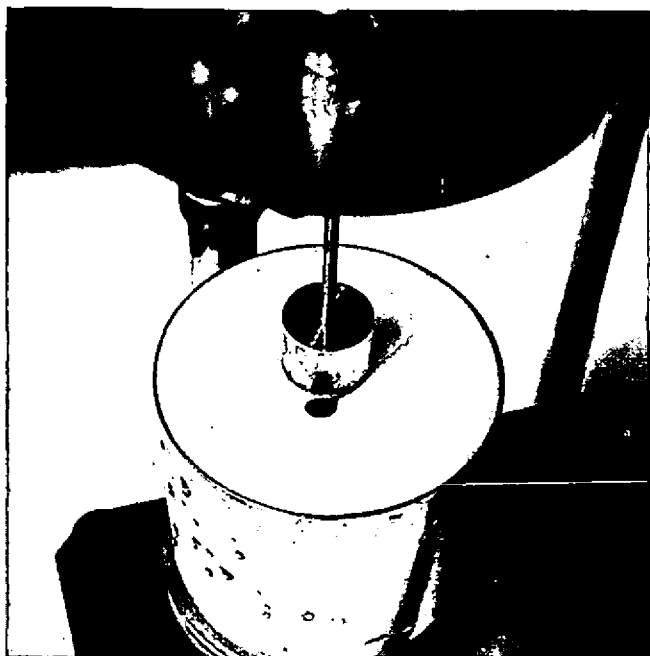
20 mm dia cylinder
After rotation at 8 rpm
for 3 mins
(160   mm/min peripheral velocity)
Dye spot remains undisturbed

40 mm dia cylinder
After rotation at 4 rpm
for 3 mins
(160   mm/min peripheral velocity)
Dye spot distributes around cylinder

FIG 19.   THE EFFECT OF DIAMETER ON THE MOVEMENT OF
SYNTHETIC FOAM AROUND A CYLINDER
IN A ROTATED POT
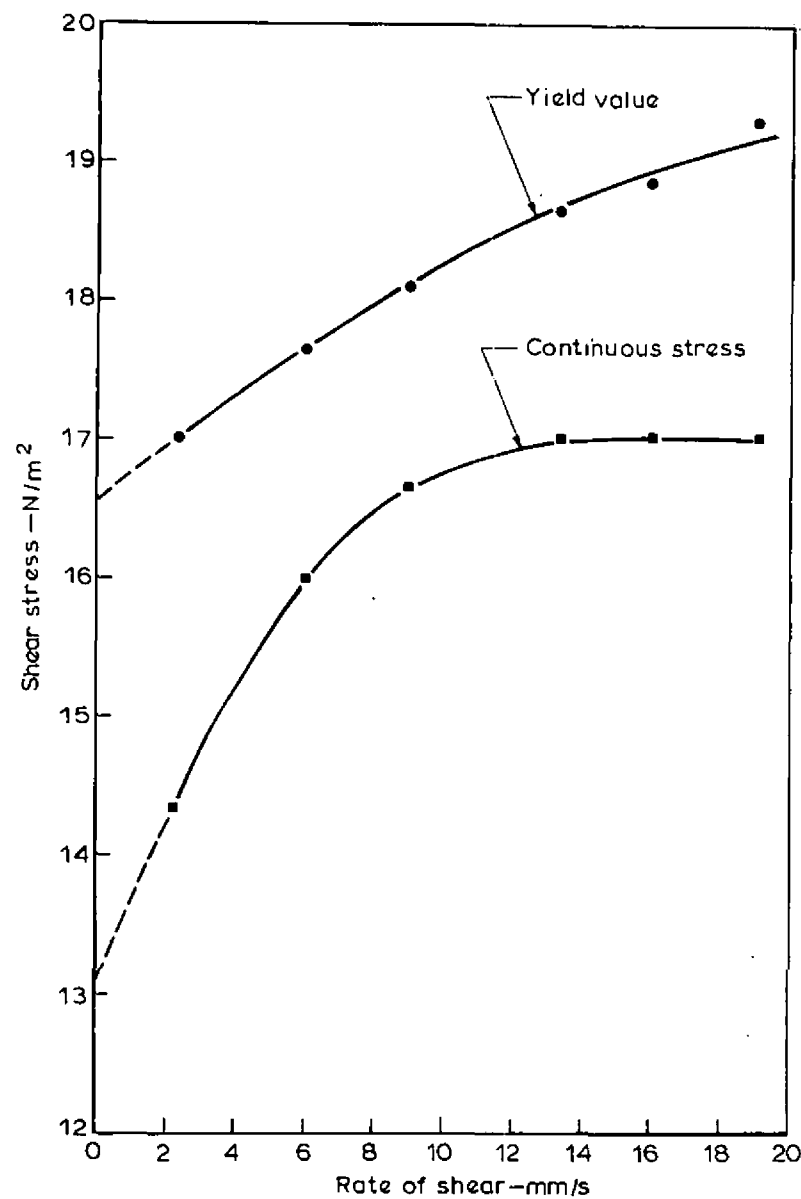
Figure 20 The shear stress of protein foam at various rates
of shear – from the differences between measure
-ments with 50mm and 20mm high vanes -30mm
wide operated at six speeds
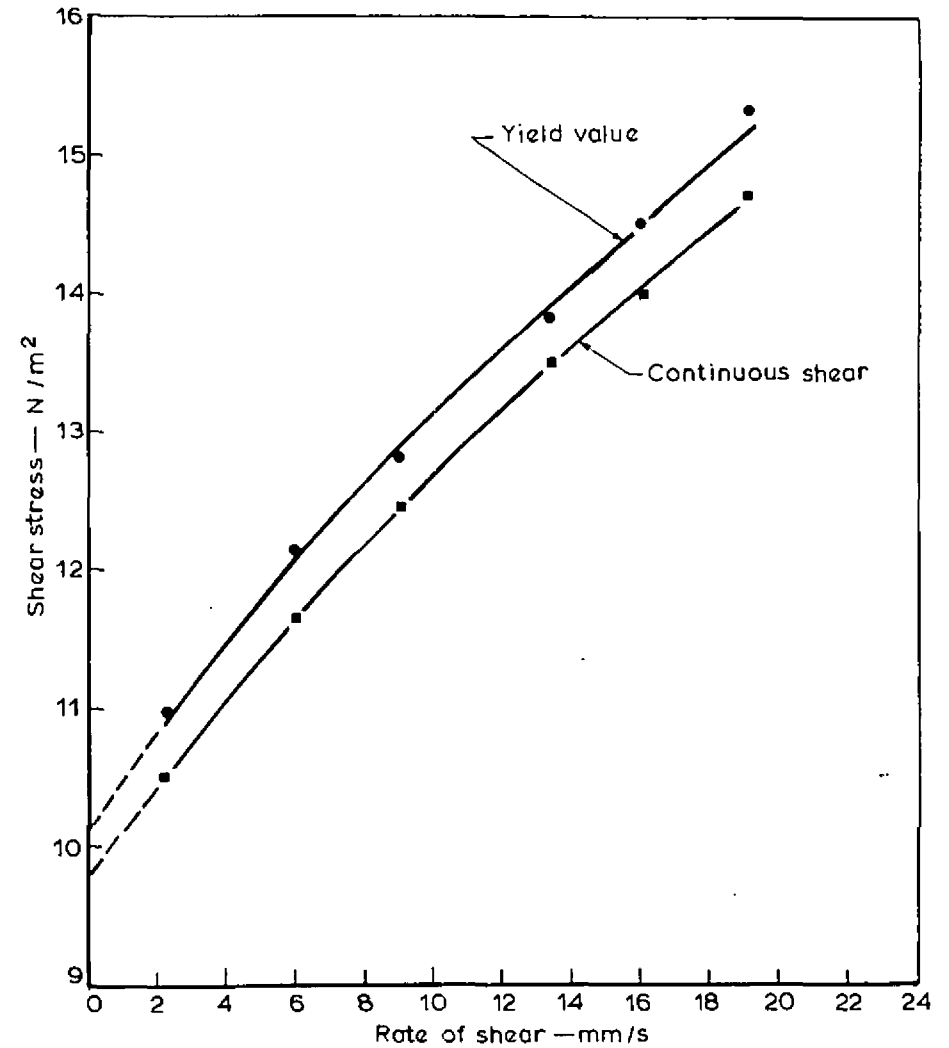
Figure 21 The shear stress of synthetic foam at various
rates of shear–from the differences between
measurements with 50mm and 20mm high vanes
30mm wide operated at six speeds
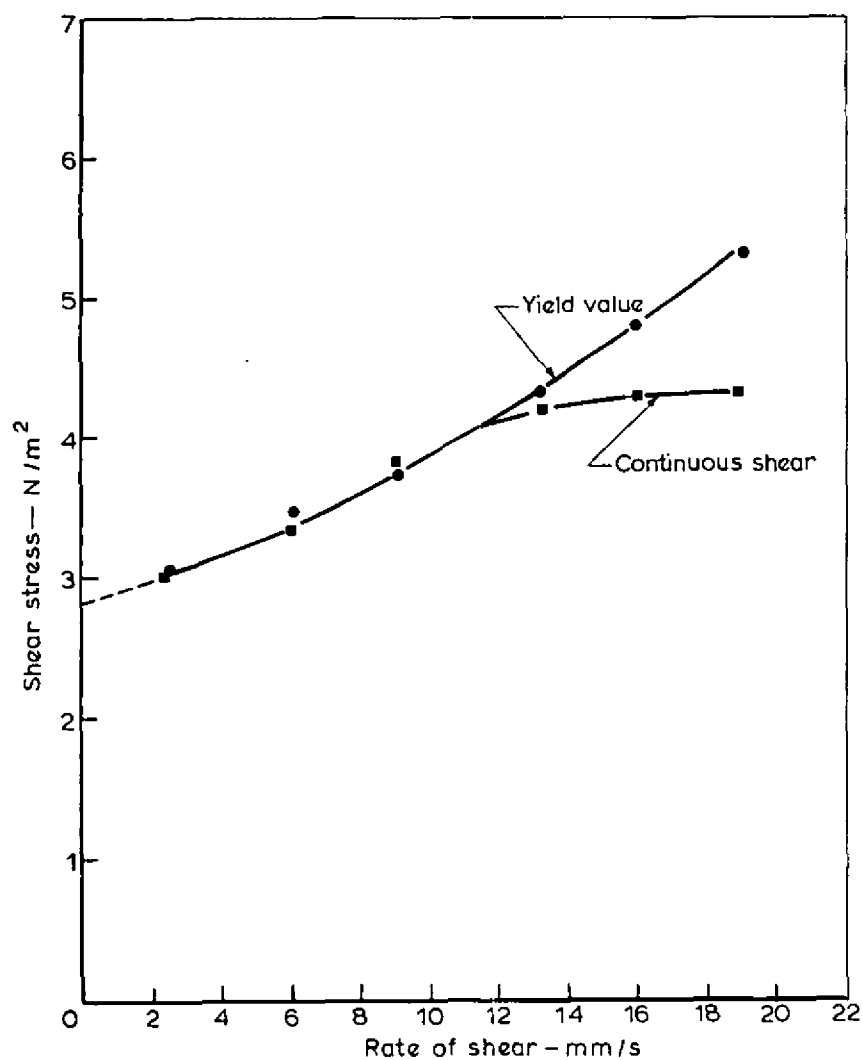
Figure 22 The shear stress of fluorochemical foam at various rates of shear from the differences between measurements with 50mm and 20mm high vanes 30mm wide operated at six speeds
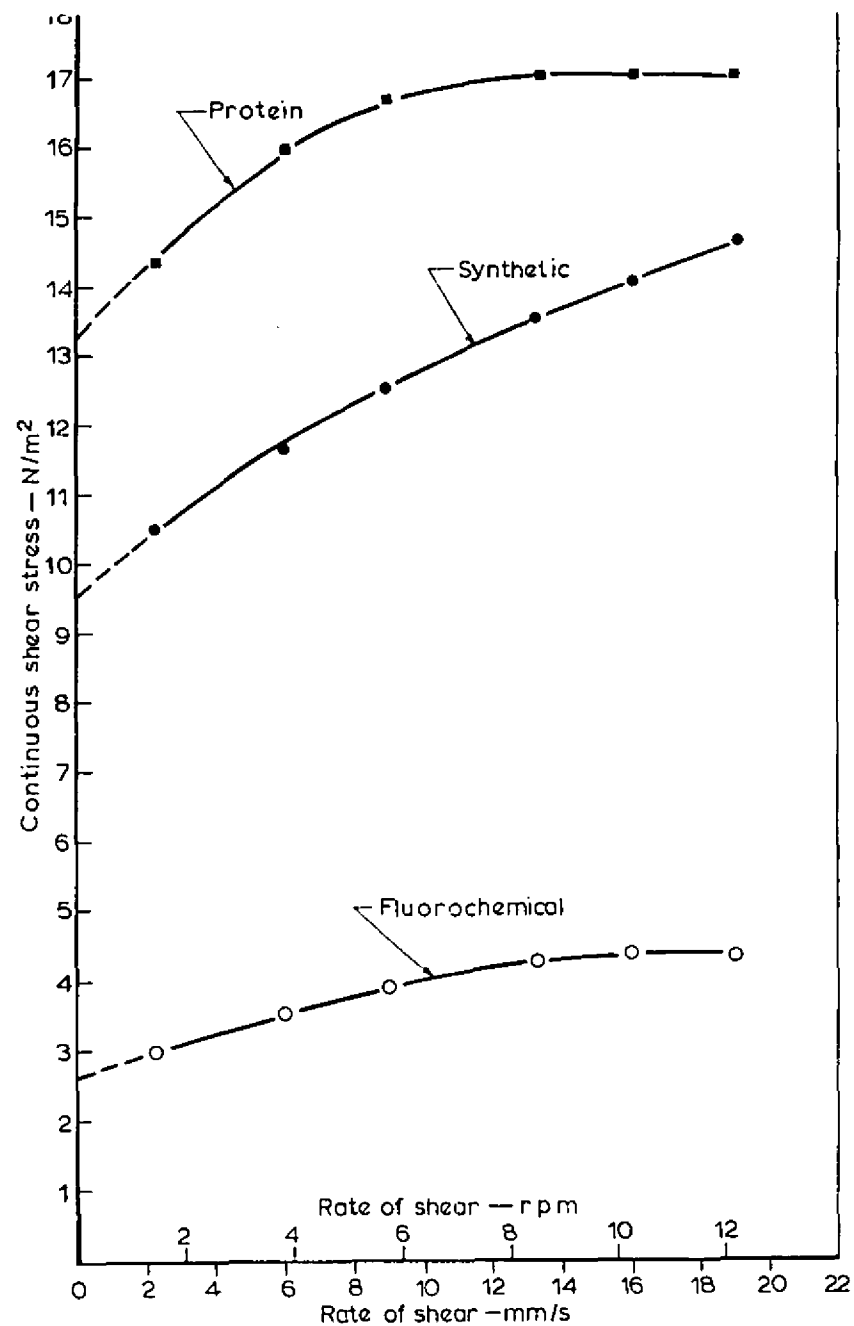
Figure 23 The relationship between the continuous shear stress and the rate of shear for three types of fire foam - from the differences between measurements with 50mm and 20mm high vanes -30mm wide operated at six speeds
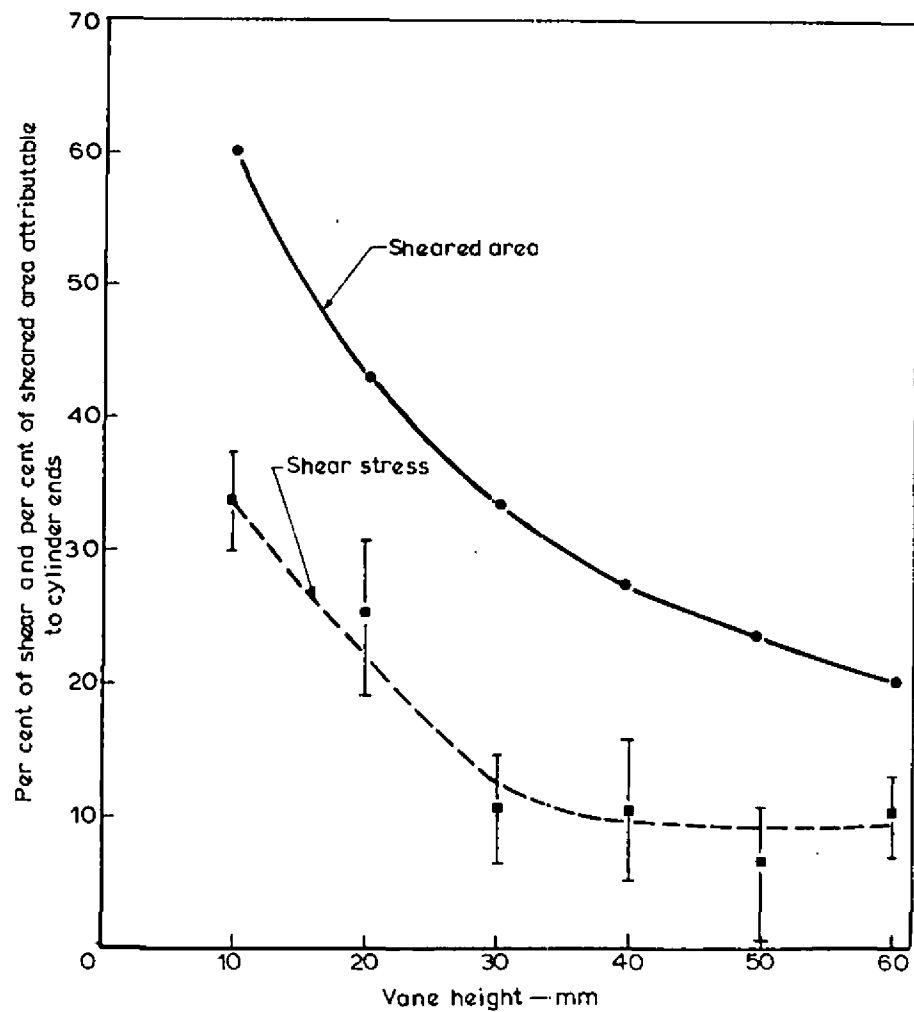
Figure 24 The effect of varying the vane height on the per-
centage contribution of the cylinder ends to the
shear stress and the sheared area, synthetic foam
: 30mm wide vanes: average of six speeds
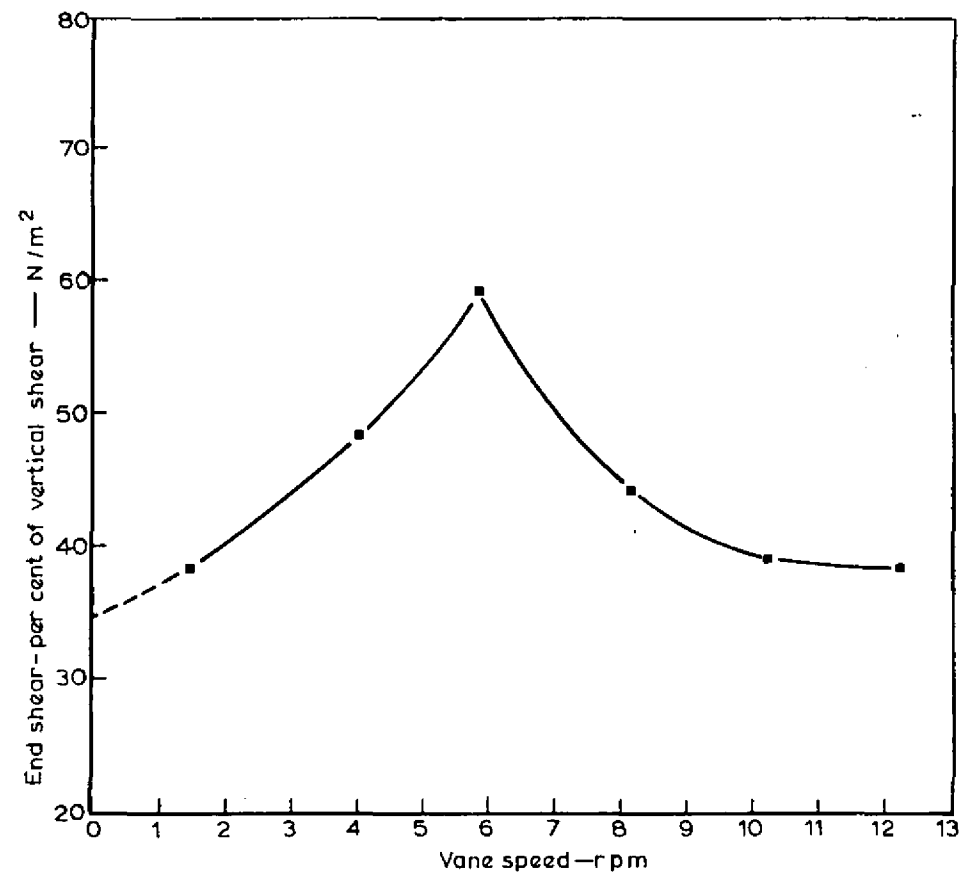
Figure 25 The average shear stress per m² on the ends as
a percentage of the shear stress per m² on the
vertical side of the cylinder prescribed by a 30mm
wide vane rotating at various speeds in synthetic
foam - average values for measurements with vanes
of five different heights
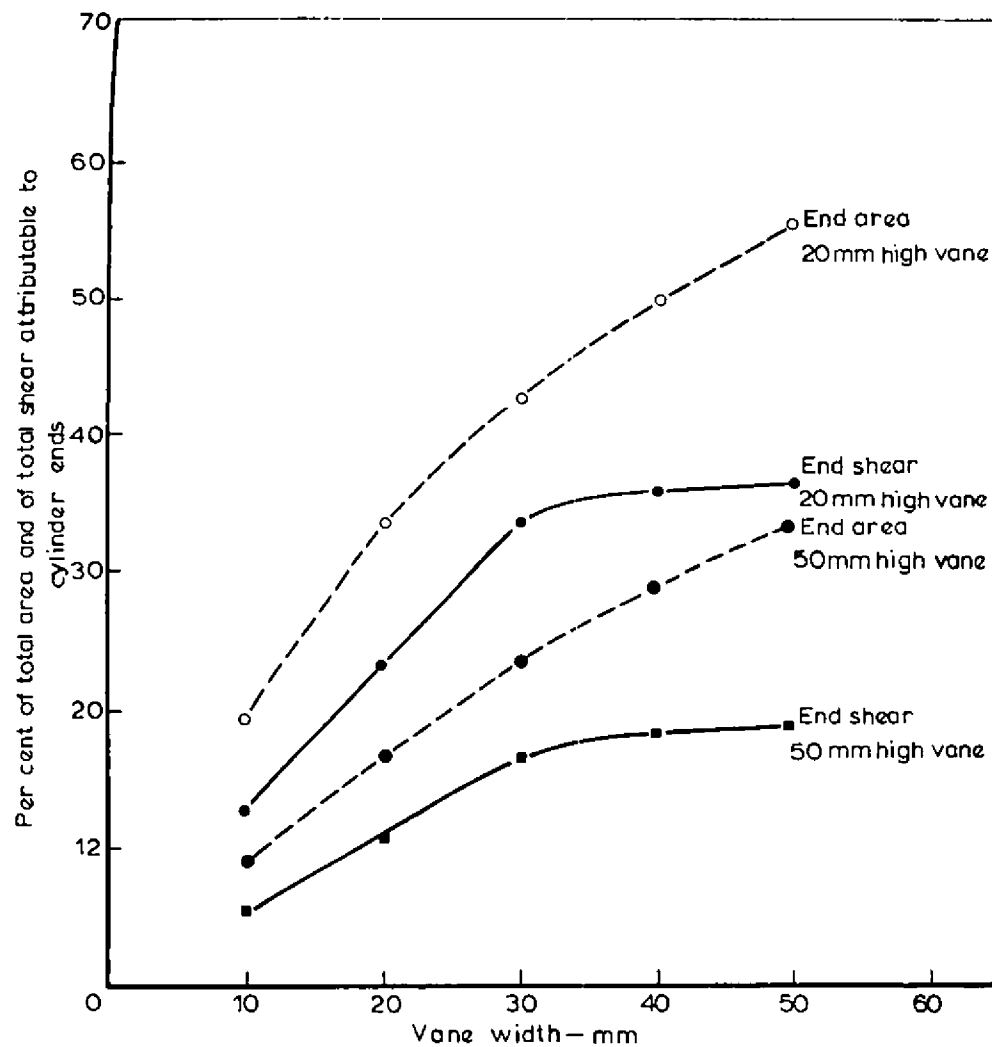
Figure 26 The contribution of the ends of the cylinders pre-
scribed by vanes 30mm and 50mm high, and of
varying widths to the total prescribed area and
the total shear, average values
1·5 —12·3 r p m
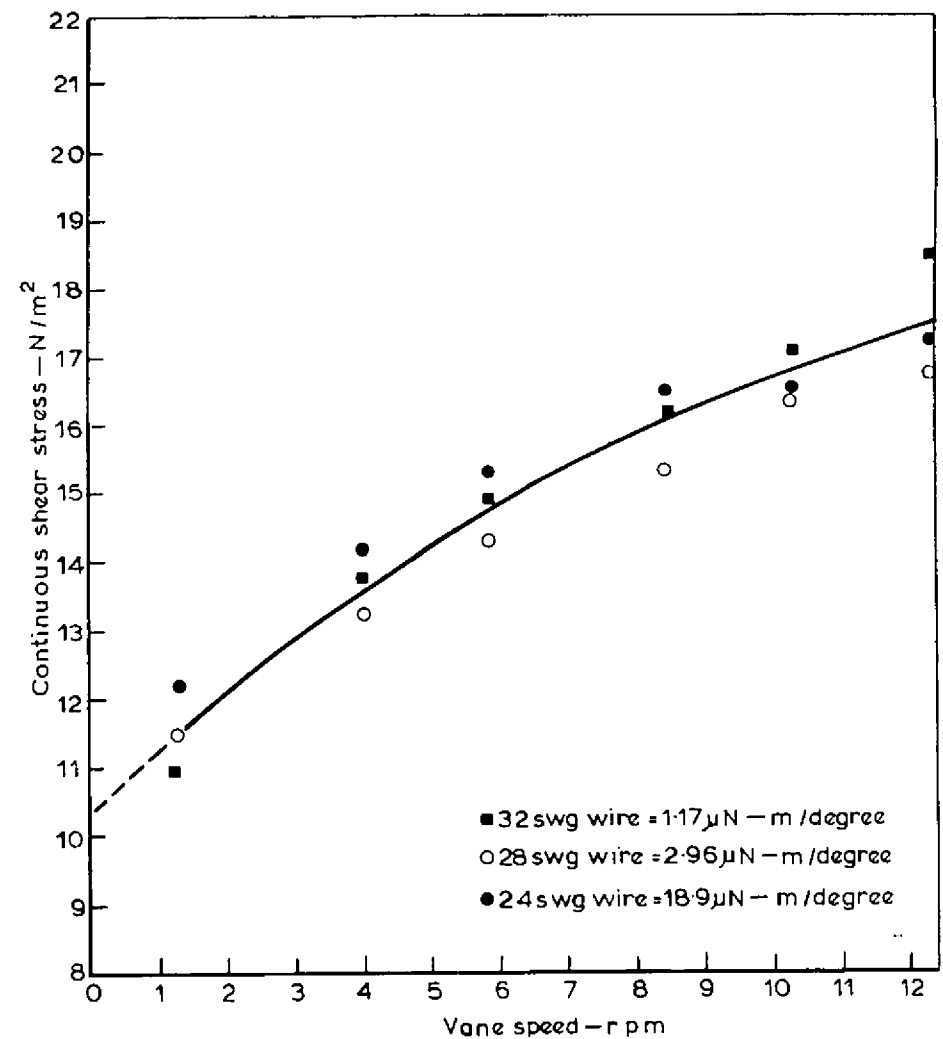
Figure 27 The continuous shear stress of synthetic foam
measured with wires of three different gauges —
30mm x 30mm vane at various speeds
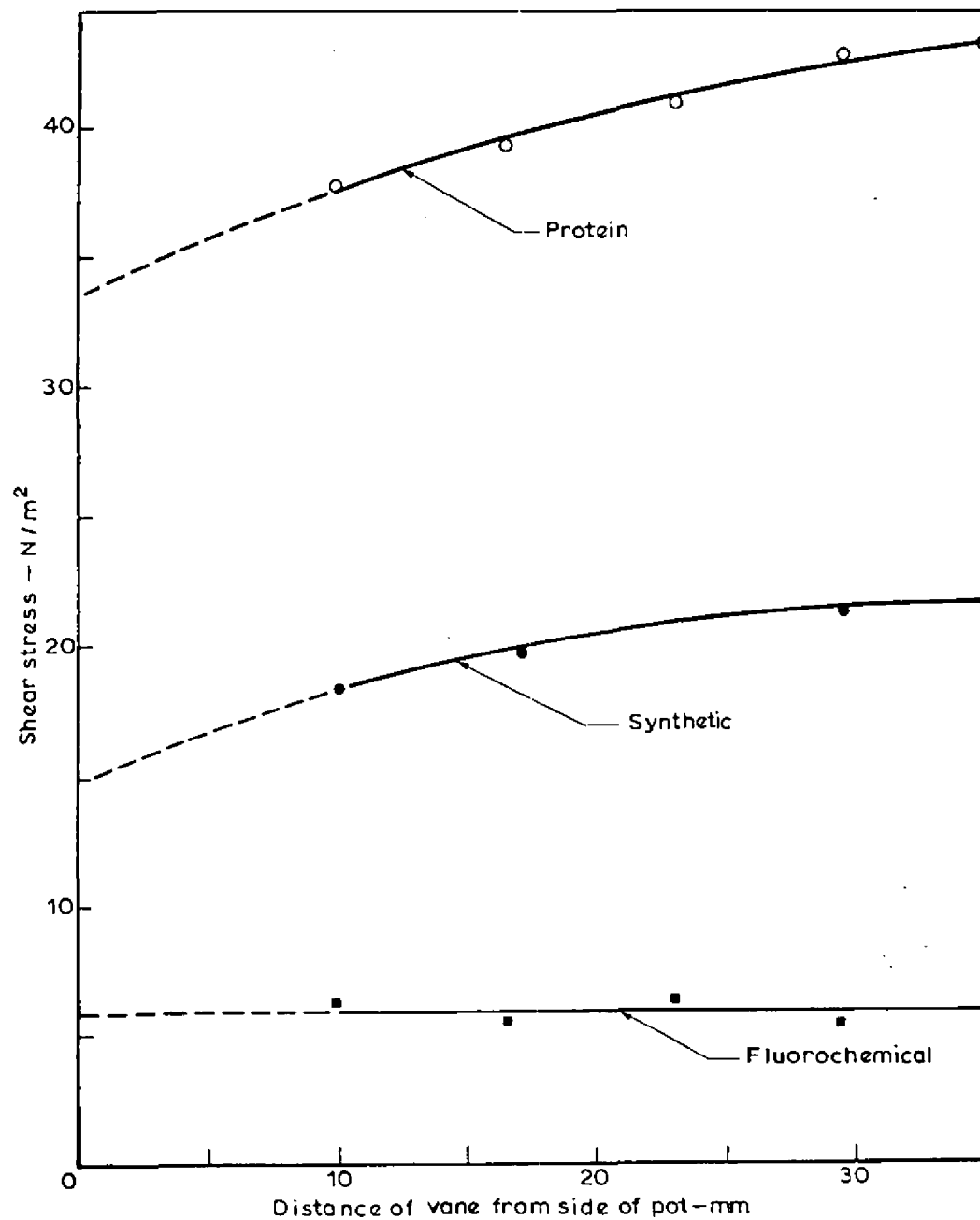
Figure 28 The effect of sample pot diameter on the shear stress 30mm × 30mm vane – 8·5 r p m
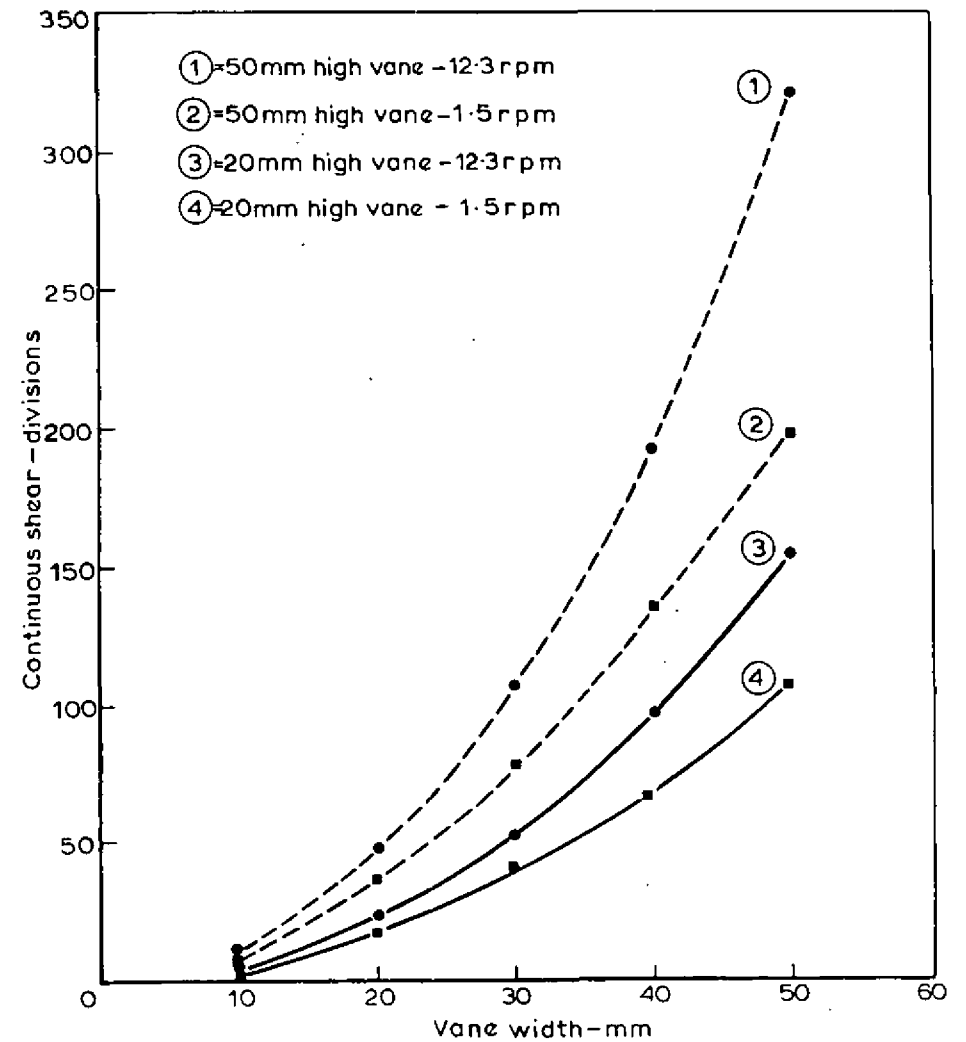
Figure 29 The variation of the continuous shear of synthetic foam with vane width – two vane heights each at two speeds
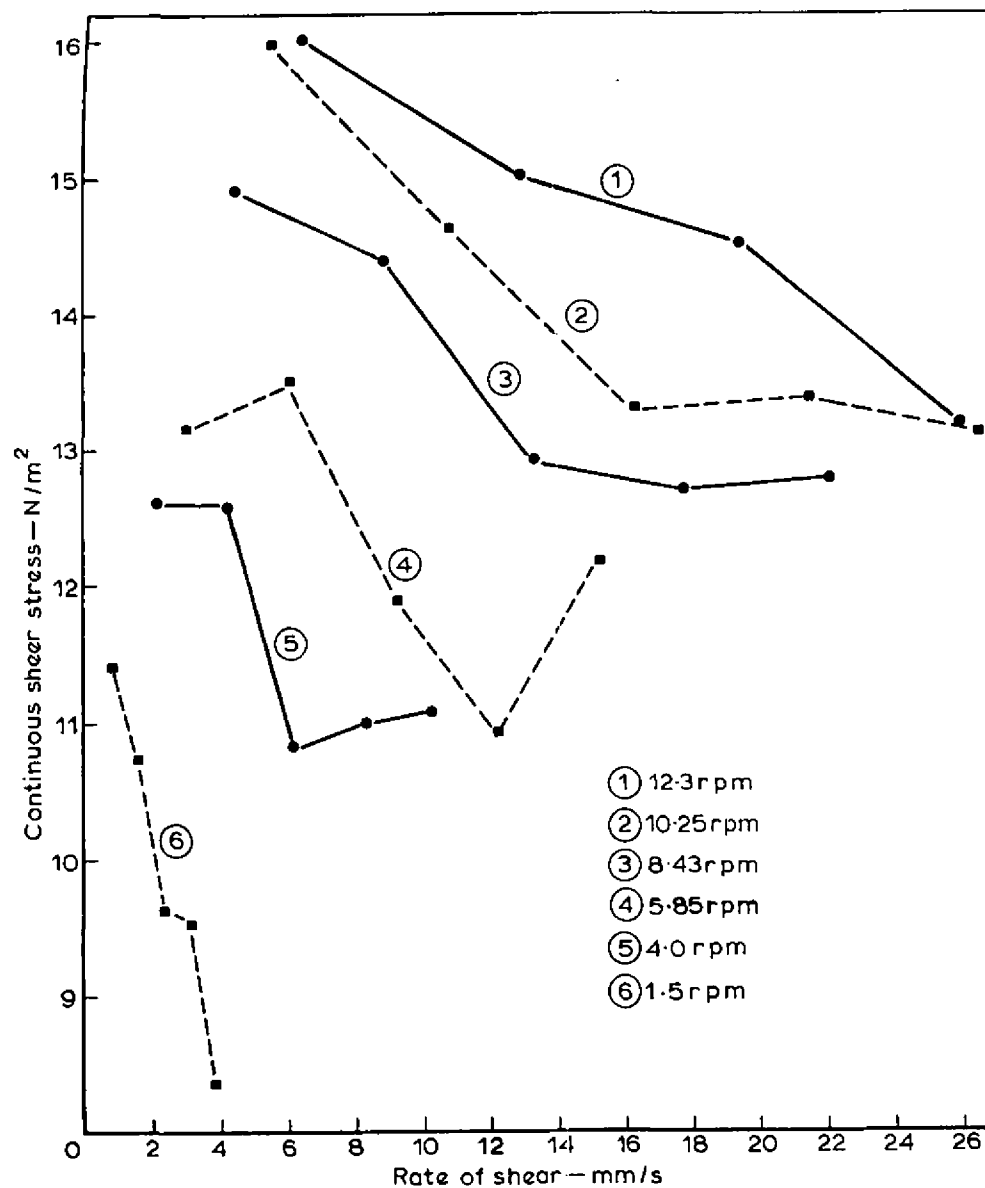
Figure 30 The shear stress of synthetic foam at various rates
of shear from the differences between measure—
ments with 50mm and 20mm high vanes of various
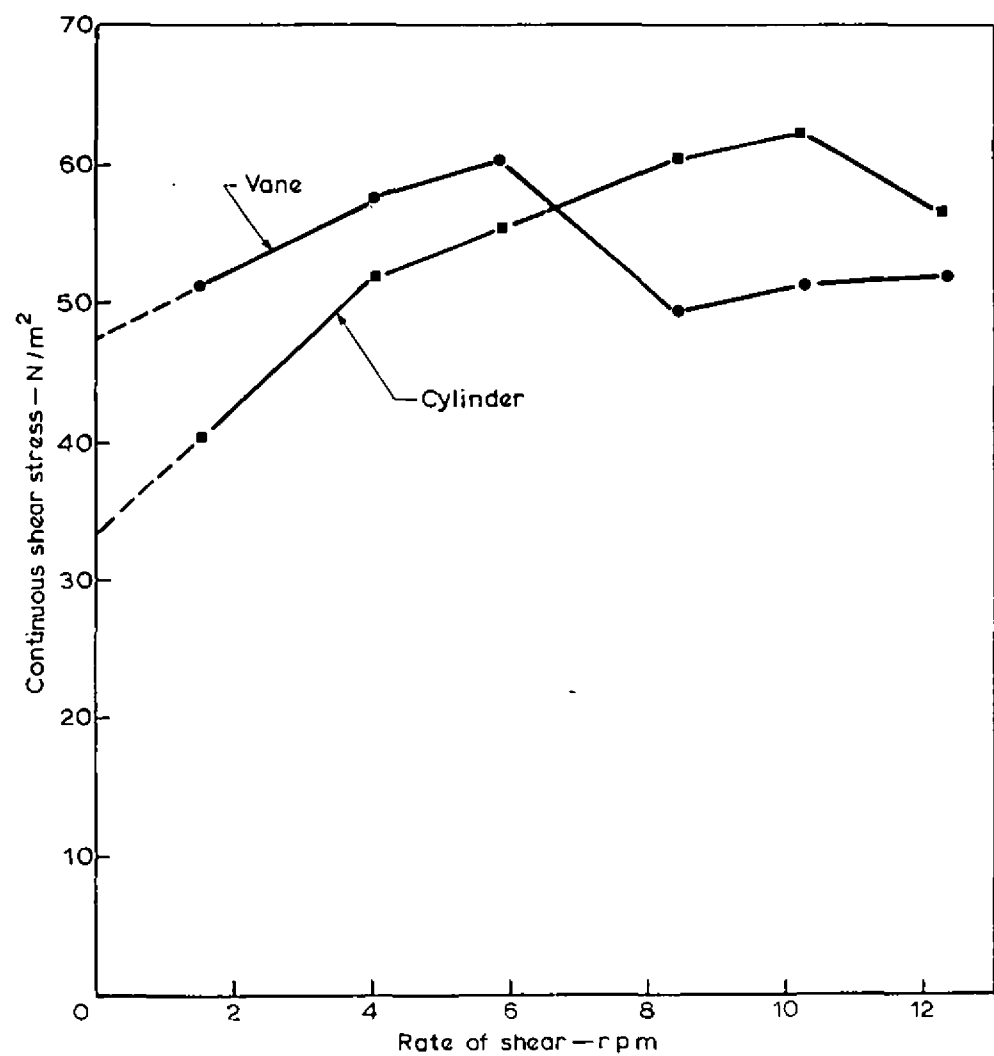widths at six different speeds
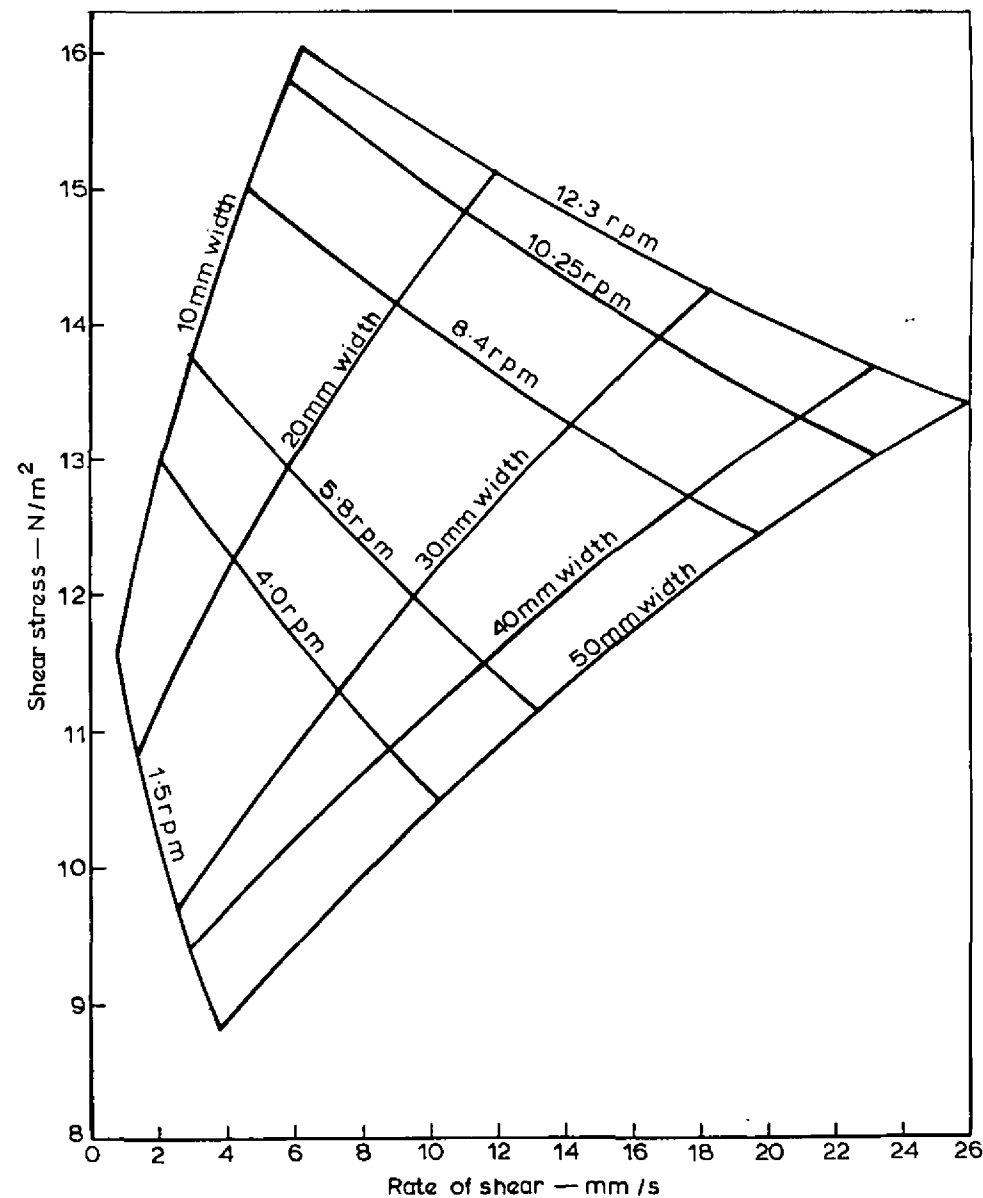
Figure 31 The shear stress of synthetic foam at various
rates of shear from the differences between
measurements with 50mm and 20mm high vanes
of various widths at six different speeds

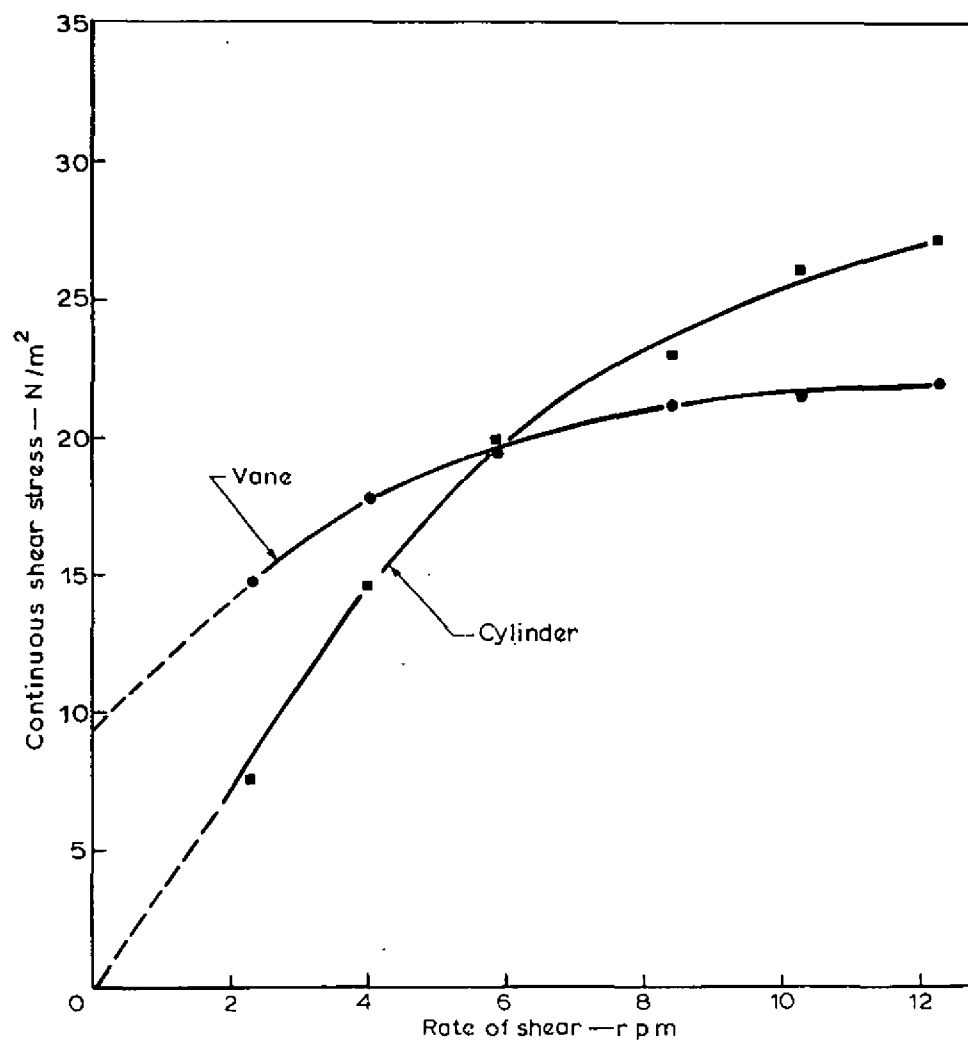Figure 32 The continuous shear stress of protein foam measured with 30mm x 30mm vane and solid cylinder

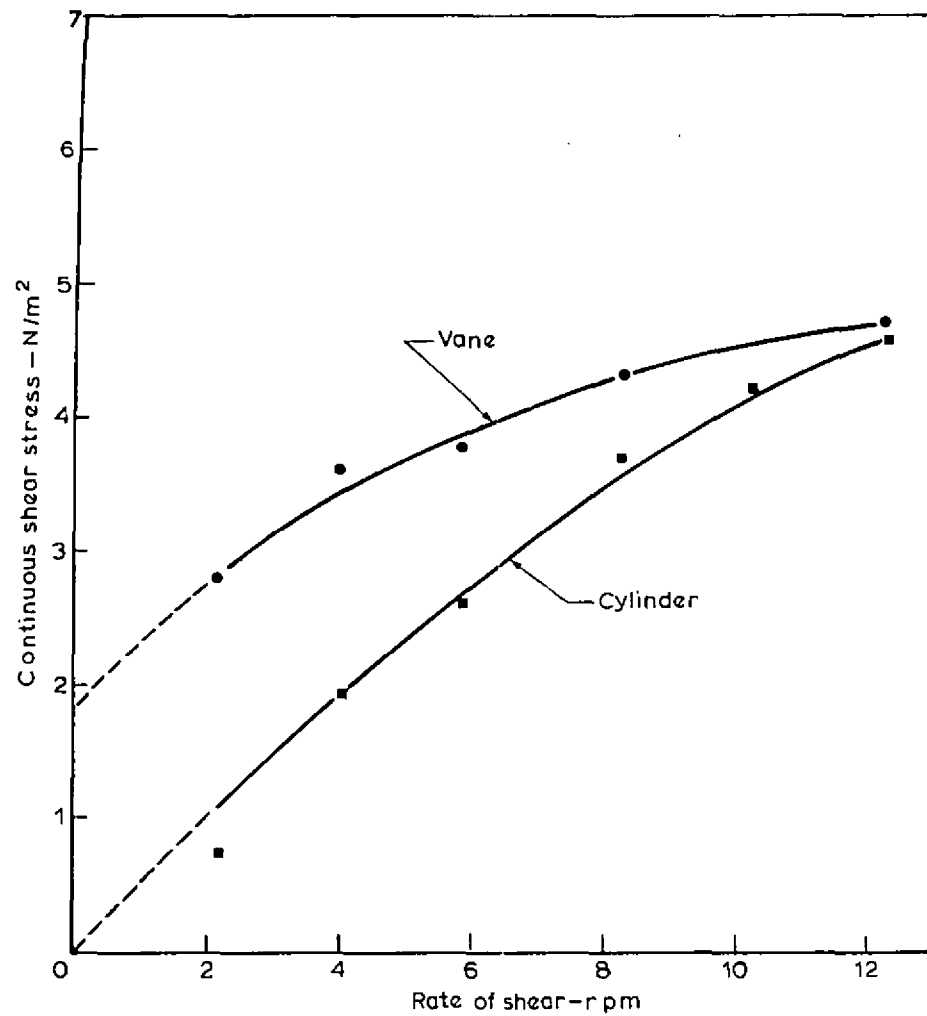Figure 33 The continuous shear stress of synthetic foam measured with 30mm x 30mm vane and solid cylinder

Figure 34 The continuous shear stress of fluorochemical
foam measured with 30mm x 30mm vane and
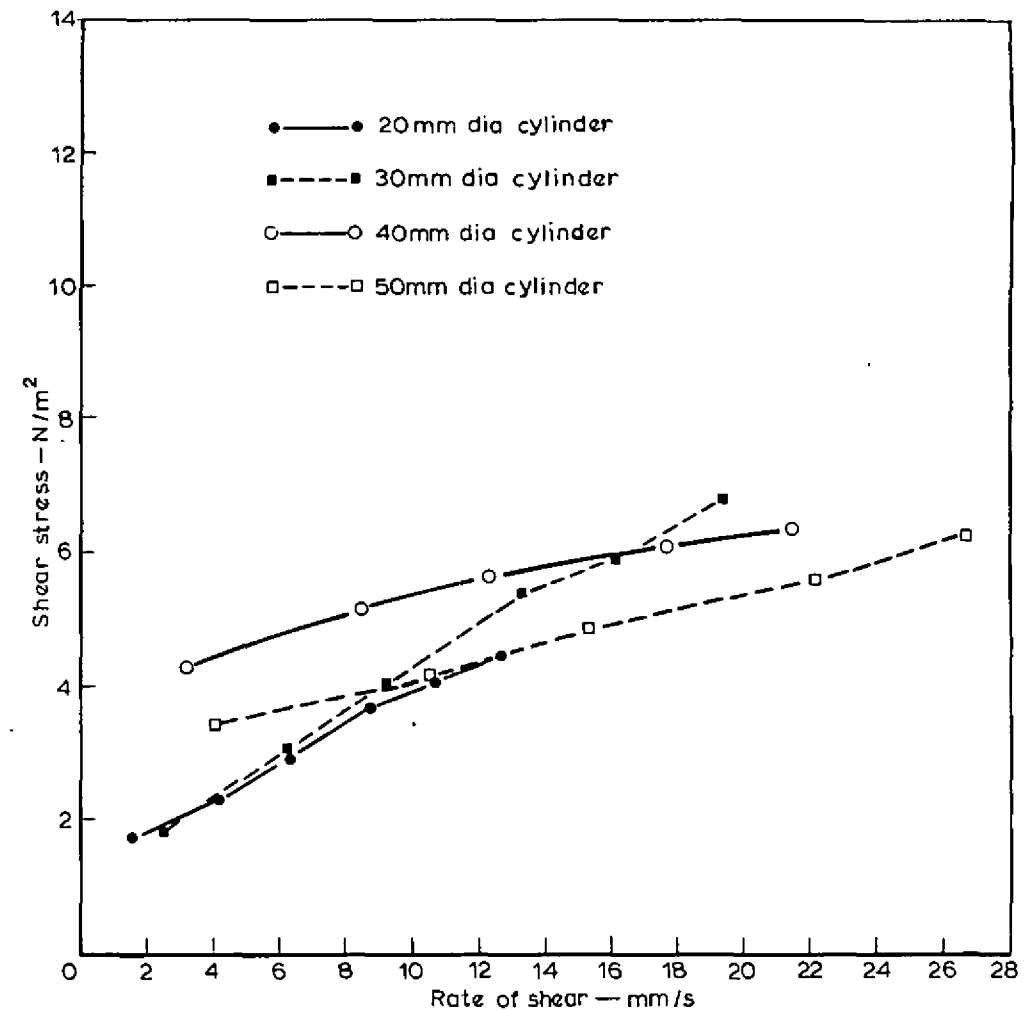solid cylinder

Figure 35 The shear stress of synthetic foam at various
rates of shear from the differences between
measurements with 50mm and 20mm high
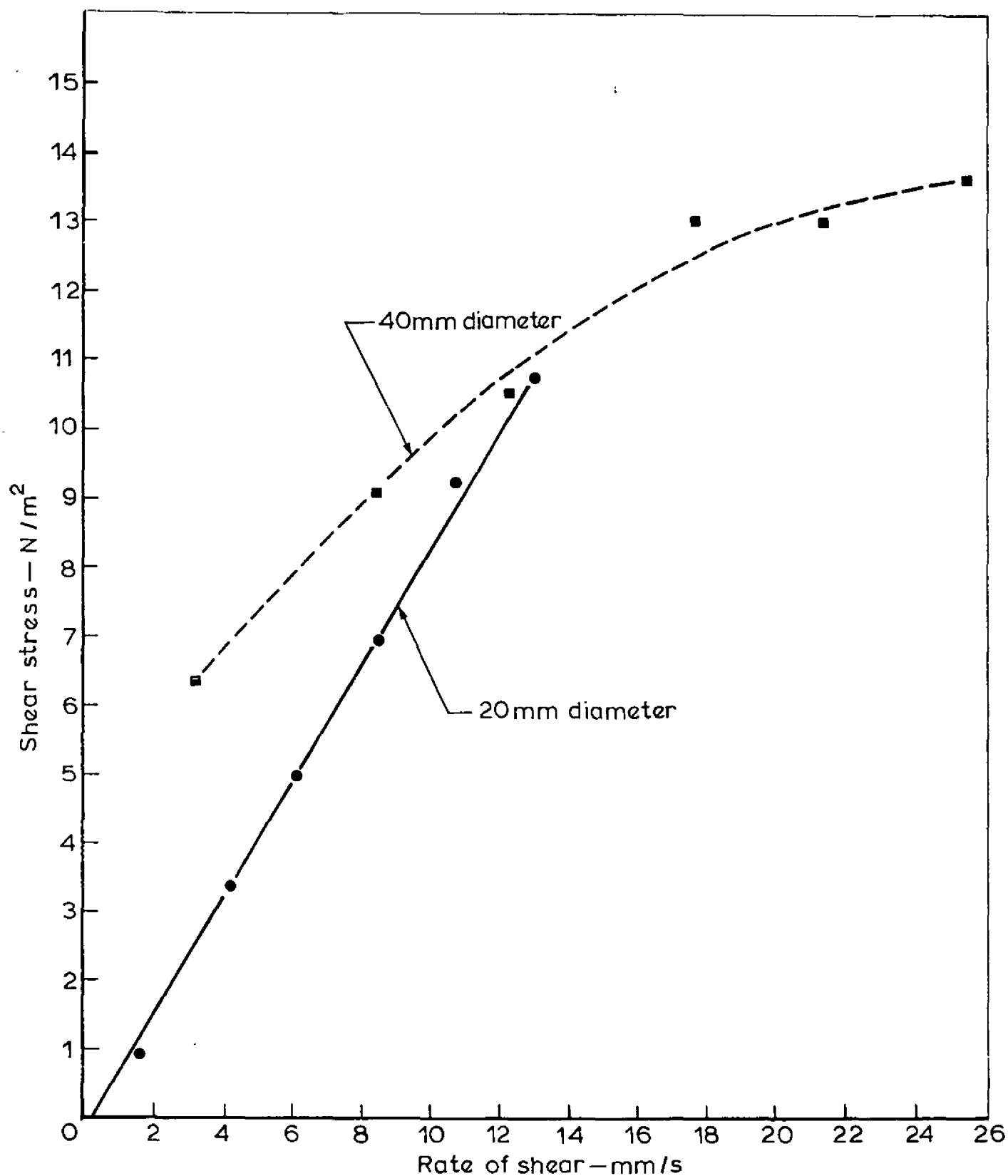cylinders of various diameters at six different
speeds

Figure 36 The shear stress of synthetic foam at various rates of shear from the differences between measurements with 50mm and 20mm high cylinders 20mm and 40mm diameter at six different speeds