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# SOME CAVITATION EXPERIMENTS WITH DILUTE POLYMER SOLUTIONS

by

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A Station of the
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## 1. Introduction

A previous paper (Brennen (1968b)) reported the observation and analysis of wave patterns on the surface of fully developed cavities behind a series of axisymmetric headforms in No.2 water tunnel at Ship Division, NPL. Comparison of theory and experiment appeared to confirm that these waves, which appeared a short distance after separation, grew in amplitude as they were convected downstream and then under certain conditions broke up into turbulence, were the amplified result of a select frequency instability in the separated or cavity surface boundary layer.

The small vertical tunnel (figure 1) was employed to study and extend observation of the same phenomenon to smaller headforms and Reynolds numbers. An additional intention was to investigate the effect of small quantities of polymer additive on the behaviour of this instability. But, a more dramatic phenomenon was manifest with the addition of these drag-reducing chemicals, leaving the original objective unattainable.

## 2. Apparatus

The vertical, gravity-driven tunnel (figure 1) was set in motion by opening the sudden-release flap with the ducting and upper tank filled with liquid. On completion of a run this flap was closed and the system refilled through a small, centrifugal pump. Having been calibrated against a vertical scale, a conventional capacitance wave probe recorded the level of the fluid in the upper tank as a function of time during each run. Study of these records revealed that apart from small intervals at the beginning and end, the level in the upper tank fell at a constant rate and with little surface disturbance during a run. The theoretical, "uniform stream" velocity of the flow in the working section ($U_T$, computed using the ratio of the cross-sectional areas of the upper tank and working section) could be set at any required value in the range 5 to 40 ft/sec by adjusting the variable orifice or iris.

Four different headforms were supported on the 0.15 in. diameter downstream sting; $\frac{1}{2}$ in. and $\frac{1}{4}$ in. diameter spheres (brass ball bearings), a $\frac{1}{4}$ in. diameter cylinder extending across the width of the working section and a 0.3 in. diameter disc, the last two being set normal to the stream. Cavities behind these headforms could be ventilated, the air travelling from the main via a valve and flowmeter, up the hollow sting and emerging through holes 0.1 in. from the back of the sphere or cylinder or 0.16 in. from the face of the disc.

Although fairly large natural cavities resulted from running at the higher speeds (25 → 40 ft/sec) without the introduction of air, ventilation had to be used to produce fully developed cavities at the lower tunnel velocities. Some standardization was achieved by employing, in all of the present experiments, ventilation sufficient to yield choked cavity flow. Thus, for all runs with a particular headform, the cavitation number ($\sigma = (p_u - p_c)/\frac{1}{2}\rho U_T^2$ where $p_u$, $p_c$ are the "uniform stream" and cavity pressures, $\rho$ the density of the liquid) could be assumed to be relatively constant and could be estimated as $\delta^2 - 1$, $\delta$ being the ratio of the cross-sectional area of the working section to that of the flow at the point of maximum width of the cavity (Birkhoff and Zarantonello (1957)). Excessive ventilation for which the jets of air issuing from the holes in the sting appreciably disturbed the cavity surface, had to be avoided.

Equipment giving a flash of about 30 microseconds was employed in taking the still photograph in the middle of each run. Even with this small exposure time the result tended to be somewhat blurred at the highest water speed. The camera shutter operated a pulse on the second channel of the time base recorder thus identifying the precise point in the run at which the photograph had been taken.

## 3. Additives

Solutions of five different substances were employed in the experiments; a surface tension reducing agent (Teepol); three long chain molecule polymers, polyethylene oxide (Union Carbide 'Polyox' WSR 301), polyacrylimide (Dow 'Separan' AP30) and guar gum; and a complex, cationic soap system obtained by correctly mixing an equimolar solution of cetyltrimethylammonium bromide (cetrimide) and $\alpha$-naphthol so as to create a micelle structure in the liquid (Nash (1958)).

Before each run with these solutions a sample was removed from the upper tank and tested for turbulent drag reduction in a rotating wheel rig previously used by Gadd (1965), readings below being given as a percentage of the drag with water. The initial reading before degradation set in was assumed to be the significant value from the point of view of the present experiments.

The fresh solutions of Polyox and Separan, made up in the top tank, were measureably degraded after a single run, due, perhaps, to the fairly violent splashing of the liquid in the receiver tank. Wheel rig tests showed that the degradation incurred by the action of the centrifugal pump when refilling the system was small by comparison. Individual solutions liable to degradation were used for about 5 consecutive runs during which a 50 ppm Polyox solution, for example, would degrade from a value of about 60% to one around 85% when tested in the wheel rig.

## 4. Cavities with Water

The cavities produced in water behind the sphere and cylinder headforms exhibited the same wave formation on the cavity surface investigated and analysed in the earlier paper mentioned above (Brennen (1968)). The waves, whose crests ran normal to the direction of mean fluid flow, appeared some distance after separation. At the higher tunnel velocities they grew in amplitude during convection downstream until they broke up yielding a turbulent surface (plate 3). However below a certain tunnel velocity break up ceased to occur and the waves persisted along the length of the cavity (plate 2). The wave patterns obtained in the present apparatus were somewhat less regular than those obtained in the No.2 Ship Division, NPL water tunnel probably due, in part, to some non-uniformity in the stream flow. Measured wavelengths lay close to an extrapolation to the origin of the mean line through the experimental results of figures 2 and 7 of that previous paper. However the present experiments showed that as the velocity or $R_{\delta_2}$ (Reynolds number based on momentum thickness of the separated boundary layer - see figure 7, Brennen (1968b)) was reduced below a value of about 60 the wave pattern virtually disappeared as in plate 1. Taken in conjunction with the additional effects of surface tension and longitudinal surface curvature, this would be compatible with the absence of any wave patterns on the surface of cavities behind the 3 in. diameter disc of those previous experiments. Predictably then, the 0.3 in. disc of the present experiments produced similarly "clear" cavities.

The positions of separation, $\theta$, for both spheres and the cylinder have been plotted against a Reynolds number, $U_T D/\nu$, based on tunnel velocity and headform diameter in figure 3. Estimated cavitation numbers for the $\frac{1}{4}$ in. sphere, $\frac{1}{2}$ in. sphere and cylinder experiments (see section 2) were 0.1, 0.25 and 0.5 respectively. Thus the relatively small difference between the $\theta$ curves for the two spheres is probably due to the difference in cavitation number. The dependence of $\theta$ on Re, much greater than its dependence on $\sigma$ at the low Re of the present experiments, provides a sensible extension to results reported previously for a higher range of Reynolds number (Brennen (1968a)).

In the light of the "meniscus" appearance of the cavity surface profile at separation, especially pronounced at the lower speeds (e.g. plate 1), it seemed likely that variation in surface tension would influence the observed position of separation. Surprisingly, then, the addition of sufficient Teepol to the water to reduce the surface tension from 0.146 lbs/ft$^2$ to 0.063 lbs/ft$^2$ had no measurable effect either on $\theta$ (see figure 3; first graph) or on any other aspect of the cavity appearance in the photographs. This suggests that the fact that the cavity surface is far from being tangential to the sphere at separation results almost entirely from the presence of the boundary layer, rather than from any surface tension effects.

## 5. Cavities with dilute solutions of Polymer

As is immediately apparent from the photographs the effect of the additive was much more dramatic in the majority of cases than the originally envisaged modification of the wave patterns observed on the surface of cavities in water. It appeared that it could cause marked instabilities in the attached flow around the sphere and cylinder headforms which were then reflected in the irregularities of the separation line and cavity surface as the disturbances were convected downstream.

All four headforms were first run with standard solutions of 50 ppm Polyox. In marked contrast to the other headforms the cavities behind the disc were clear and showed little difference from those with water. Since the two spheres and the cylinder revealed similar phenomena, the behaviour with the $\frac{1}{2}$ in. sphere is first described in some detail and used as a base for the other observations. When running at the lowest operational speed ($\sim 4$ ft/sec) with the $\frac{1}{2}$ in. sphere, the additive had little visible effect on the cavity. However, with slight increase in speed three-dimensional (as opposed to planar or axisymmetric) irregularities appeared on the cavity surface (plate 4). Then above about 7 ft/sec the separation line became gradually distorted into a wavy pattern like that of plate 8 or type II, figure 2 and the most upstream points of separation (referred to as peaks) began to show a downstream shift from the separation location for water under the same conditions (figure 3). Further increase in speed caused the troughs in the separation line to become sharper (type III), resulting in the separation appearance of type IV, figure 2 or like that of plate 5. The pronounced irregularities in the cavity surface appeared to contain a typical longitudinal wavelength, observable in the cavity profile, and a typical spanwise or lateral wavelength of the same order of magnitude reflected in the separation line ($\varepsilon$) , both of which sharply decreased with increasing speed. The shift in separation compared with that for water, with which is associated a narrowing of the cavities, tended to die away at the highest speeds. Also at this end of the speed range fairly intense spots or trails of turbulence could be detected in the cavity surface "wake" of each of the separation line troughs (e.g. plate 9).

In the case of the $\frac{1}{4}$ in. sphere, both surface and separation irregularities were observed at the lowest speed with fresh polyox. An additional difference was manifest at intermediate speeds, the separation pattern of type IV appearing in the modified type IVa form like that of plate 6. The centre of the upturned U is seemingly hollowed out to produce a "pincer" pattern. Since this reverted to the basic type IV when the spanwise wavelength decreased sufficiently (as in plate 9) it seems likely that the "pincer" pattern is an effect of the large ratio of spanwise wavelength to axisymmetric curvature of the separation region in this case.

The major difference between the behaviour with the $\frac{1}{2}$ in. sphere and the cylinder was the absence in the latter case of any significant shift of the upstream limits of separation from the position of separation with water (figure 3). Surface irregularities were observed at all speeds and separation line distortion above about 8 ft/sec (plate 5).

A number of high speed cine films (Fastax camera, 6000 frames/sec) were made of the cavities behind the $\frac{1}{4}$ in. sphere in 50 ppm Polyox solution. Even at this high frame speed, the fluid motions could only be satisfactorily discerned for the lower tunnel velocities. However it was clear that the peaks and troughs in the separation line did move about in a lateral direction, in what appeared to be a fairly random manner and with a speed much smaller than the longitudinal fluid velocity. This, at least, excluded any connection with surface roughnesses.

It is worth stressing that the water cavities remained virtually clear (i.e. as plate 1) up to roughly 8, 16 and 11 ft/sec for the $\frac{1}{2}$ in. $\frac{1}{4}$ in. and cylinder respectively.

Neither aging (plates 7, 8 and 9 were taken when running with a 50 ppm Polyox solution which had been aged for 8 days (Brennen and Gadd (1967))) nor degradation had any measurable effect on the magnitude of the spanwise wavelength exhibited at a particular speed. Both, however, yielded more even patterns of disturbance, presumably due to the increased homogeneity of the solution and both slightly raised the critical speeds at which the various types of irregularity and distortion occurred. Compared with plates 7 and 8 fresh Polyox produced separation line distortion of types II and IVa respectively. However, even in the most degraded fluid (yielding a turbulent drag of some 92% of that of water in the rotating wheel rig) the threshold speeds were not raised by more than about 3 ft/sec.

Some experiments with different concentrations also supported the conclusion that the drag-reducing effectiveness of the Polyox solution influenced the critical speeds to a limited extent but had no apparent effect on the spanwise spacing of the disturbances occurring. An increase to 100 ppm (fresh solution) had virtually no effect on the cavities behind the $\frac{1}{4}$ in. sphere. Running with the cylinder at 15 ft/sec, solutions of 10, 20 and 50 ppm all produced separation distortion of type IV. Only with the 5 ppm solution, which incidentally degraded more rapidly than the higher concentrates, did there appear to be any weakening towards types III or II.

Solutions of 50 ppm of Separan exhibited the same phenomena except that in fresh condition the critical speeds were slightly above those of fresh Polyox. Since Separan yields slightly less turbulent drag reduction this finding was in line with the previous observations.

On the other hand, 50 ppm of guar gum had a much reduced effect. At all speeds the separation position was very close to that for water (figure 3) with only the odd irregularity in the separation line (plates 10, 11). However the cavity surface irregularities were considerably greater than with water and at the lower speeds appeared to contain a predominance of longitudinal disturbance (plate 10) which may account for the lack of separation line distortion. At the higher speeds this gave way to the kind of "streaky" surface of plate 11.

The positions of the upstream limits of the separation lines have been plotted against $U_T D/\nu$ in figure 3, the value used for $\nu$ being that for water in all cases since the maximum expected change (4 or 5%) in viscosity due to the polymer additive (Brennen and Gadd (1967)) would have little effect on the resulting graphs. The spanwise wavelengths, $\varepsilon$ , are presented in figure 4 and appear to be relatively independent of anything but fluid velocity.

Hoyt (1966) photographed natural cavities in water and in 50 ppm Polyox behind an axisymmetric headform (3 in. diameter at separation) at a tunnel speed of 25 ft/sec and observed that the Polyox cavity was much more striated. The average distance between each striation (~ 0.04 in.) is plotted in figure 4. Hoyt (1967) also reproduced photographs taken by Ellis of a natural cavity on a hemispherical headform ($\frac{1}{4}$ in. diameter) at a speed of about 45 fps. Although the cavity is very thin, resulting in interference from the cylindrical surface, the characteristic type IV separation can be detected and the value of $\varepsilon$ (figure 4) agrees with the present experiments.

## 6. Cavities with solutions of Cetrimide/α-Naphthol

Experiments were performed using the $\frac{1}{4}$ in. and $\frac{1}{2}$ in. spheres and solutions of 508 and 1524 total p.p.m. of the cetrimide/α-naphthol soap system, both of which yielded turbulent drag reduction of the same order as fresh 50 ppm Polyox in the rotating wheel rig. In addition, both solutions exhibited strong viscoelasticity when swirled in a beaker, that is at very small shear rates. The swirl decayed much more rapidly than with water and there was a visible recoil (Nash (1958)).

In both solutions the $\frac{1}{2}$ in. sphere produced cavities with similar three-dimensional surface irregularity patterns at all speeds, the typical wavelengths clearly decreasing with increasing $U_T$. The disturbance "amplitude" appeared less with the lower concentration especially at the higher speeds. Typically the irregularities seemed more violent immediately after separation than further downstream, suggesting a viscoelastic damping effect during convection of the disturbance along the cavity (plate 12). Only slight irregularities occurred in the separation line at any speed (e.g. plate 12).

A similar, but more subdued effect occurred with the smaller sphere at the lower speeds (plate 13). In this case, however, the effect died away with increasing $U_T$ resulting in cavities indistinguishable from those with water.

With the polymer solutions the shift in the positions of separation from those for water with the two spheres seemed roughly related to the degree of distortion in the separation line. But although there is virtually no distortion with the cetrimide solutions, the 1524 ppm concentrate exhibited an appreciable and fairly constant separation shift (figure 3). This may be due to slight pseudoplasticity in the more concentrated solution. Bizzell and Slattery (1962) calculated that a reduction in the non-Newtonian flow index, n, from 1.0 to 0.9 or 0.8 caused a downstream shift of 4.6° or 8.6° in the separation position for non-cavitating flow around a sphere. White (1967) found that although 508 ppm cetrimide solution was Newtonian, 1000 ppm exhibited a reduction to around n = 0.9 at least at low shear rates.

## 7. Discussion

In his resistance measurements of pipe flows, White (1968) found that whereas a certain critical wall shear stress, $\tau_w$ , had to be exceeded before polymer solutions exhibited drag reduction, the cetrimide/α-naphthol solutions were only effective up to a critical $\tau_w$ above which, he suggests, the micelle structure may become disrupted. In the present experiments $\tau_w$ will presumably increase from zero at stagnation to a maximum value and then fall away again to zero at separation. In the case of a sphere, very rough calculations suggest that the peak occurs around $\theta = 60°$ and takes a value of the order of magnitude, $\rho U_T^2 / \sqrt{\frac{U_T D}{\nu}}$ . Thus for the two spheres the peak values, $(\tau_w)_{max.}$ (in lbs/ft$^2$), will be very roughly given by the following table:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $U_T$ | | 5 | 10 | 15 | 20 | 30 | ft/sec |
| $(\tau_w)_{max}$ | $\frac{1}{4}$ in. sphere | 0.5 | 1.5 | 2.7 | 4.2 | 7.7 | $lbs/ft^2$ |
| | $\frac{1}{2}$ in. sphere | 0.4 | 1.0 | 1.9 | 2.9 | 5.4 | $lbs/ft^2$ |

These values are to be compared with threshold shear stresses for onset of drag reduction with fresh Polyox, 6-day old Polyox, Separan and guar gum of order 0.02, 0.09, 0.04 and 0.25 $lbs/ft^2$ respectively and for the upper critical shear stress for 508 and 1524 ppm cetrimide solutions of order 0.15 and 0.3 $lbs/ft^2$. Although these rough figures taken from White (1968) and others are only intended to demonstrate orders of magnitude the present observations for the various headforms and additives correlate at least qualitatively when considered on a basis which assumes that the instabilities arise from regions of the attached flow for which $\tau_w$ is in the "effective" regime for the particular additive. For the Polyox and Separan solutions the region for which $\tau_w$ is supercritical will increase in extent as the speed, $U_T$, is raised and thus the disturbances may be progressively more developed by the time separation is reached. Guar gum has a much higher threshold $\tau_w$ and the instability is less pronounced than with Polyox at the same speed. On the other hand the effect of increasing speed with the cetrimide solutions is to reduce the extent of the effective $\tau_w$ region and thus inhibit the instability. In the case of the $\frac{1}{4}$ in. sphere the disturbances disappeared above a certain speed. The influences of aging, degradation and concentration also fit into this picture satisfactorily.

Two additional and related factors which are probably important are

(i) the residence time of the fluid particles within the boundary layer on the headform, or, more accurately, the ratio of this time to the relaxation time of the additive molecule - and

(ii) the magnitude of the accelerations which the particles undergo during this residence.

If the residence time were decreased by reducing the size of the headform and increasing the flow velocity in such a way that the Reynolds number and therefore purely viscous effects remained unchanged then it is to be expected that non-Newtonian, viscoelastic effects would become more marked. This correlates with the observations on the different sizes of sphere. The apparent absence of instabilities in the case of the disc may be due to the relatively much smaller thickness of and different acceleration pattern within that wetted surface boundary layer.

In their more developed state, the irregularities in the separation line are suggestive of a spanwise distribution of hairpin vortices in the attached flow. Adhering longer to the wetted surface than the intervening gaps of less disturbed flow, these peaks of disturbance cause the troughs in the separation line. Thus the cavity surface appears most disturbed in the wake of each trough. Such vortices can develop during transition as described by Stuart (1965) but would not normally be expected to occur in the presence of a strong streamwise acceleration, as in the present experiments. Pfenniger (1967) hypothesised that the effect of the addition of polymer molecules to a fairly steady flow was to absorb kinetic energy from these hairpin vortices, allowing them to penetrate further away from the surface before breaking up. The result would be an increase in the laminar sublayer thickness and a reduction in the skin friction. If the present interpretation of the observed phenomena is correct, it suggests that in the presence of strong flow acceleration the polymer molecules encourage the formation and growth of hairpin notices. This however is speculative and a complete explanation must probably await a more detailed exploration of the exact nature of the disturbances, their formation and growth.

8. Acknowledgements

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13th November 1968
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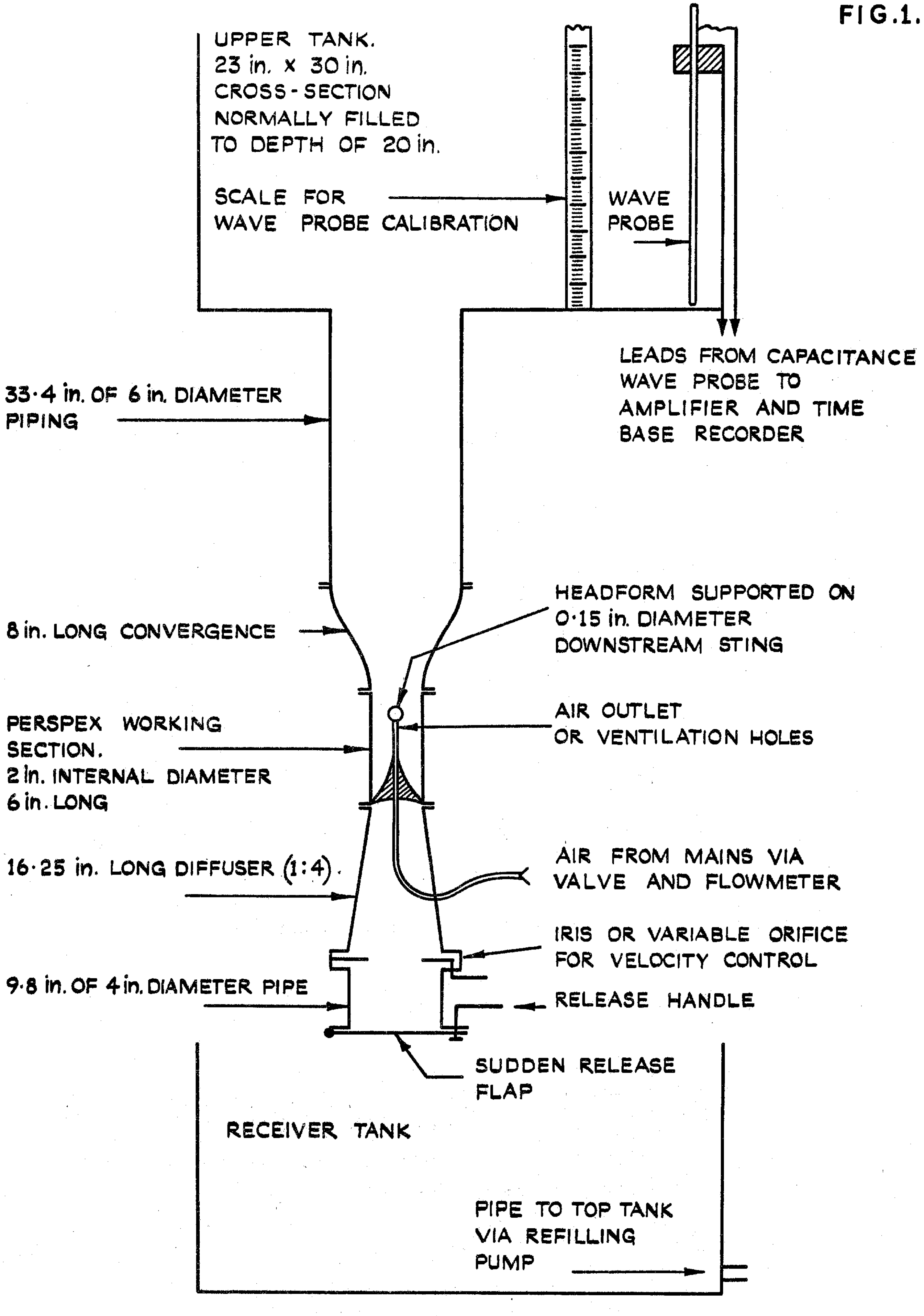



FIG. 1. THE VERTICAL, GRAVITY - DRIVEN WATER TUNNEL

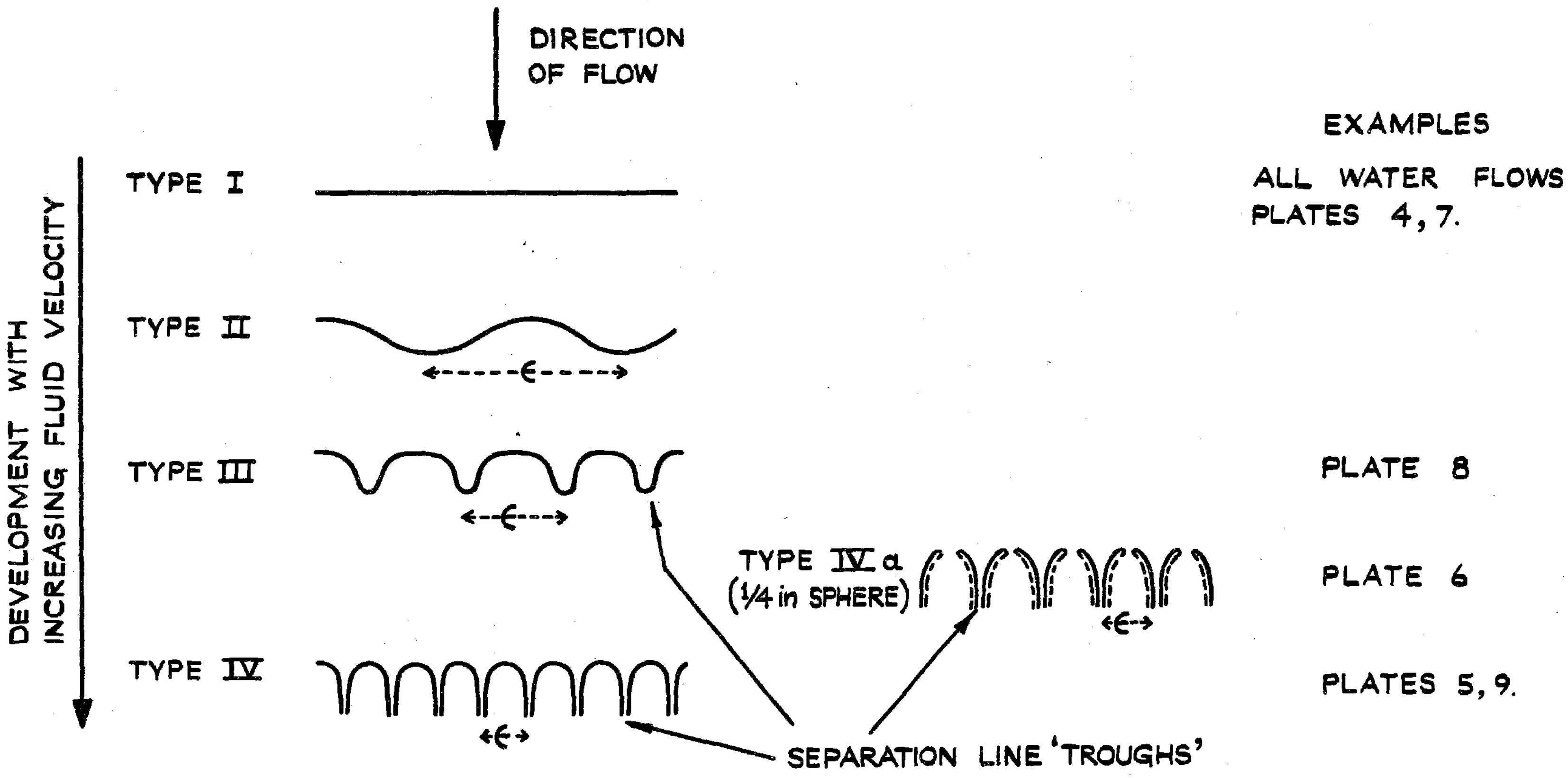



FIG. 2. TYPES OF SEPARATION LINE DISTORTION OCCURING WITH THE DILUTE POLYMER SOLUTIONS, INDICATING THE PROGRESSIVE DEVELOPMENT OF THAT DISTORTION. WETTED SURFACE ABOVE THE LINES, CAVITY BELOW

THE LATERAL WAVELENGTH OF THE IRREGULARITIES IS $\epsilon$

FIG. 2.

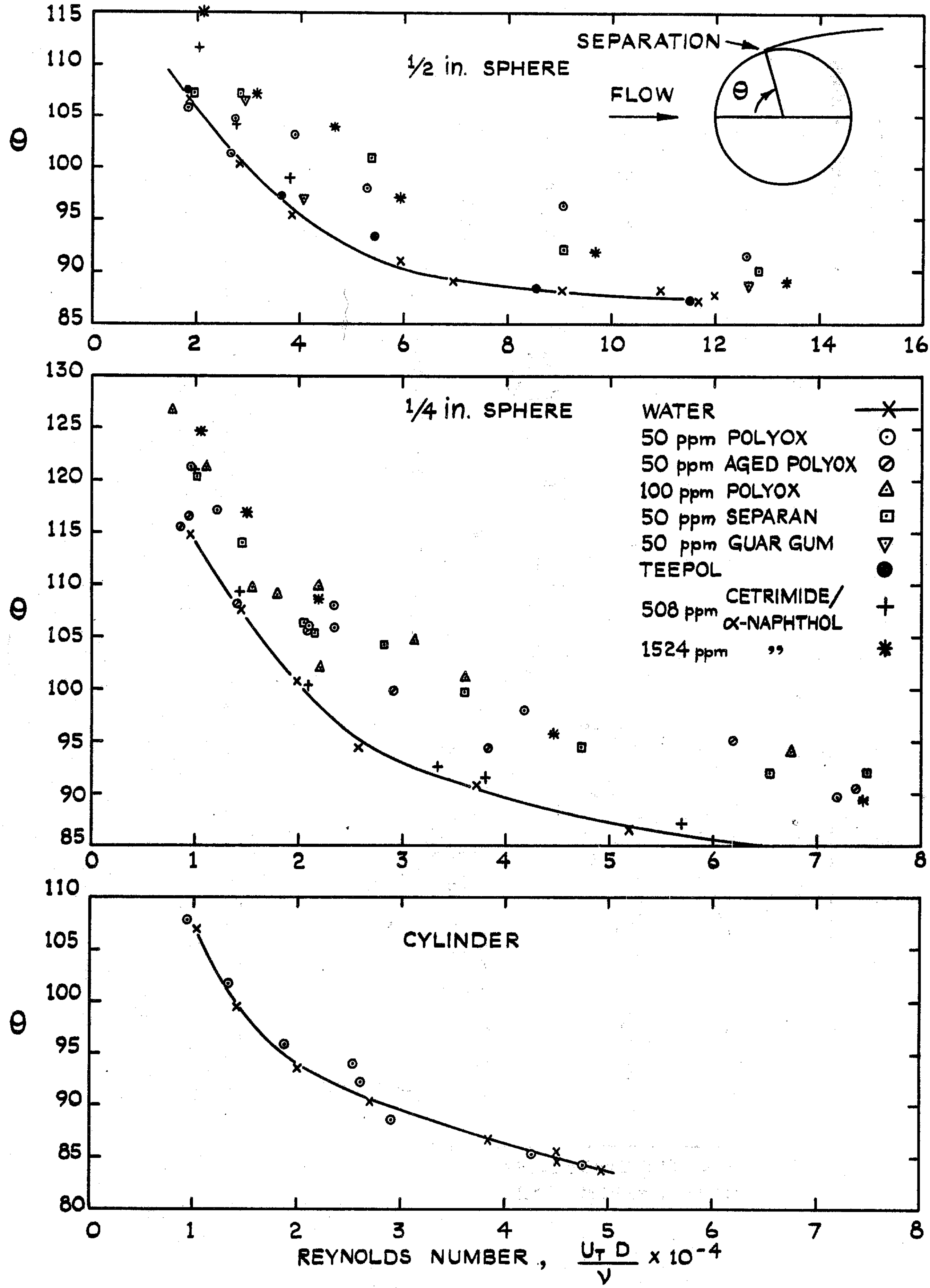



FIG. 3. ANGLE OF SEPARATION, θ, AGAINST REYNOLDS NUMBER

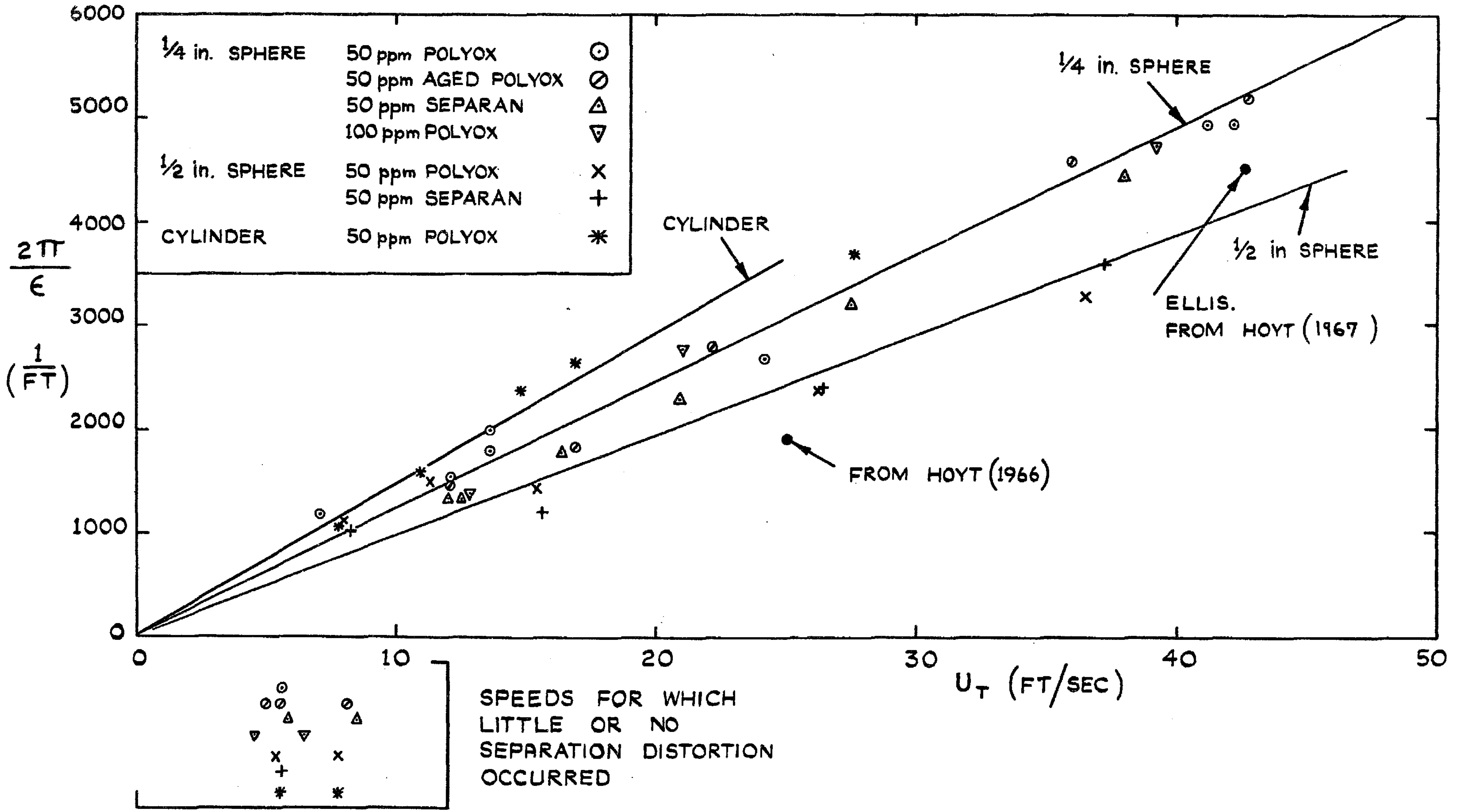
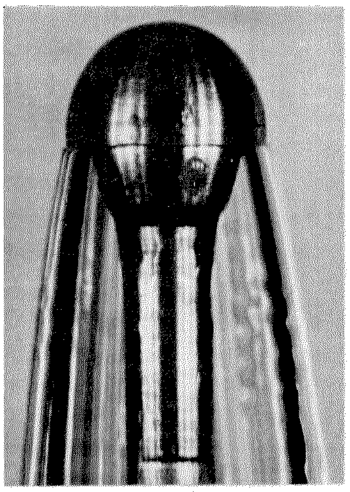



FIG.4. VARIATION OF SEPARATION DISTORTION WAVELENGTH, $\epsilon$, WITH TUNNEL VELOCITY, $U_T$.

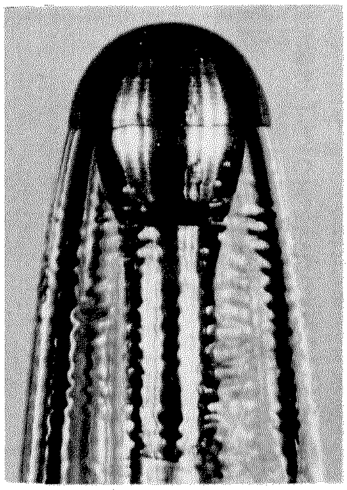
FIG.4.

# PLATES 1 TO 9

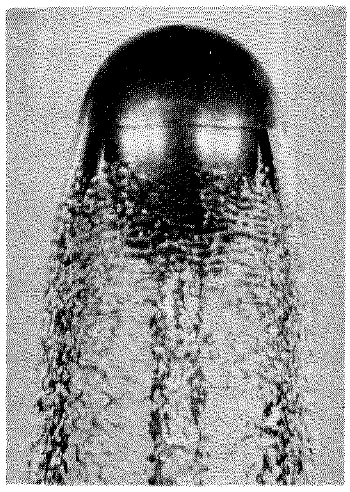
**WATER**



**1.** $\frac{1}{4}$ in. Sphere. 11·5 fps.

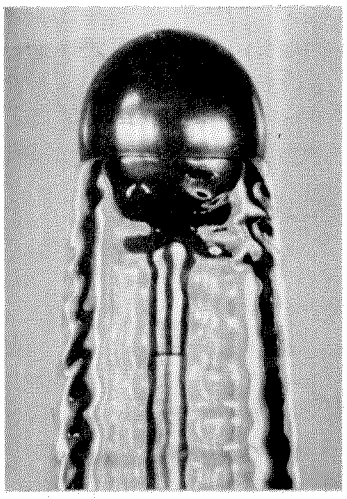


**2.** $\frac{1}{4}$ in. Sphere. 21·6 fps.

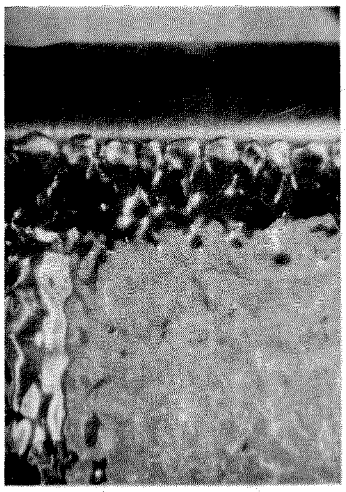


**3.** $\frac{1}{2}$ in. Sphere. 26·3 fps.

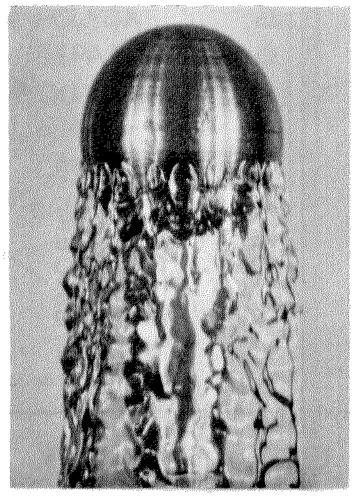
**FRESH 50 ppm POLYOX**



**4.** $\frac{1}{2}$ in. Sphere. 5·4 fps.

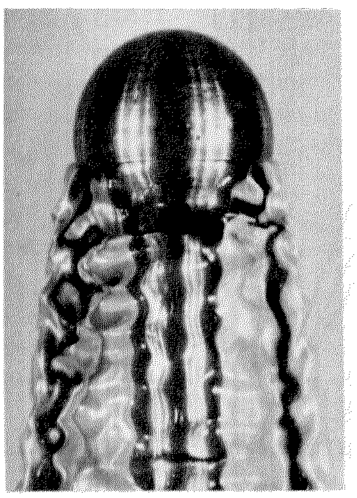


**5.** Cylinder. 10·9 fps.

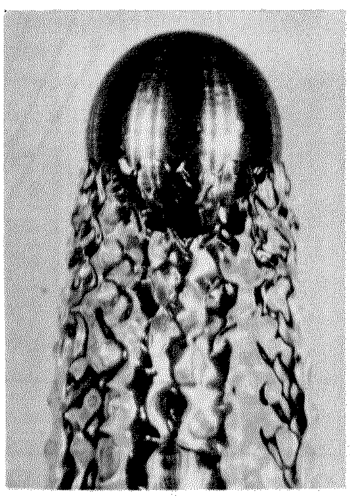


**6.** $\frac{1}{4}$ in. Sphere. 13·6 fps.

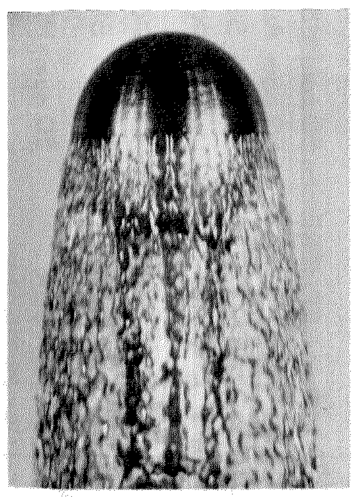
**AGED 50 ppm POLYOX**



**7.** $\frac{1}{4}$ in. Sphere. 8·2 fps.

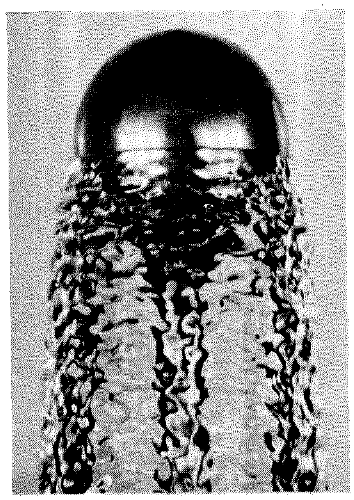


**8.** $\frac{1}{4}$ in. Sphere. 12·1 fps.

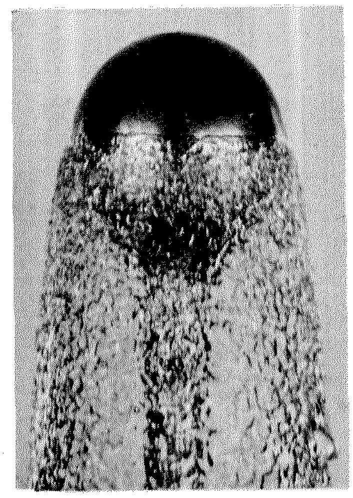


**9.** $\frac{1}{4}$ in. Sphere. 36·0 fps.

**50 ppm GUAR GUM**

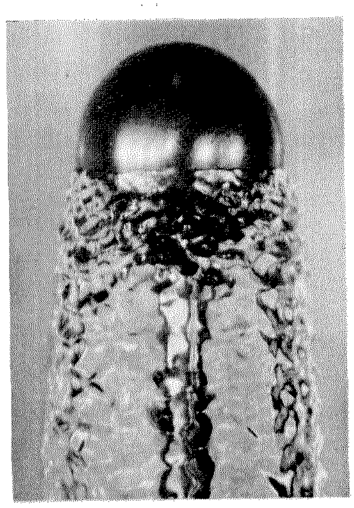


**10.** $\frac{1}{2}$ in. Sphere. 11·8 fps.

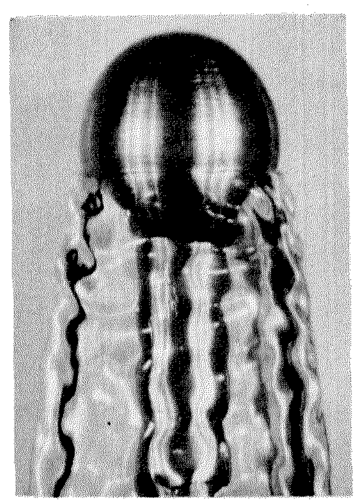


**11.** $\frac{1}{2}$ in. Sphere. 36·7 fps.

**CETRIMIDE/ α-NAPHTHOL**



**12.** 1524 ppm
$\frac{1}{2}$ in. Sphere. 13·5 fps.



**13.** 508 ppm
$\frac{1}{4}$ in. Sphere. 8·3 fps.

## Distribution

| | |
|---|---|
| Froude Committee | (20) |
| Ship Model Laboratories | (30) |
| Shipbuilders and Shipowners | (35) |
| Universities | (25) |
| NPL Staff | (30) |
| Ship Office | (60) |