01 Sep 1975

The Separation Angle for Spheres in a Pipeline

B. Latto

A. Lai

Recommended Citation

Latto, B. and Lai, A., "The Separation Angle for Spheres in a Pipeline" (1975). *Symposia on Turbulence in Liquids*. 32.
https://scholarsmine.mst.edu/sotil/32

THE SEPARATION ANGLE FOR SPHERES IN A PIPELINE

Brian Latto and Alan Lai,
Department of Mechanical Engineering,
McMaster University,
Hamilton, Ontario, Canada.

ABSTRACT

The results of a series of experiments on the measurement of the angle of separation for flow over steel spheres suspended in a vertical 5.18 cm ID pipeline with and without a drag reducing aqueous polymer solution are presented. Data were obtained for sphere-to-pipe diameter ratios of 0.74 and 0.925 with polymer concentrations of 0, 25, 50, and 100 wppm over a Reynolds number range of 1633 to 29400 for single spheres and trains of up to three spheres rigidly connected. It was found that relatively dilute polymer solutions can considerably affect the separation angle. Furthermore, that the angle is dependent on the diameter ratio, number of spheres in a train, the Reynolds number, and the polymer concentration, and at a given diameter ratio and concentration the angle of separation can be correlated as a function of the Reynolds number. The data substantiate a previous hypothesis by Latto, that the observed drag increase of spheres in a pipeline caused by polymer addition, is due to an increase of the separation angle and therefore an increase in the form or pressure drag.

INTRODUCTION

During the last decade considerable interest has been given to efficient transport of materials. With this in mind, research was commenced at McMaster University some 7 years ago on the many aspects of capsule transport in pipelines. The research was initially concerned with the measurement of the pertinent parameters for the operation of vertical and horizontal pipelines with single spheres and cylinders and also trains of spheres. However later research was related to the effects of end caps on cylindrical bodies and was extended to the hydrodynamics of sphere trains in inclined pipelines.

A major portion of the research was on the hydrodynamic suspension of bodies in a vertical 5 cm ID pipeline, which was a convenient arrangement for measuring drag coefficients. Papers have been published on this work by Round, Latto and Anzenavs (1972), and Latto, Round and Anzenavs (1973) which describe the particular system employed. In view of the well known fact that dilute concentrations of certain additives can greatly affect turbulent flow behaviour, it was decided to investigate the effects of polymer additives on the hydrodynamic suspension of spheres in a vertical pipeline. It was observed, as shown in Figure (1), that dilute concentrations of polymer can appreciably increase a capsule's drag coefficient Cd* with a maximum effect when the concentration is 20 wppm. This result was rather surprising and it was hypothesized that the additive delays transition which results in an earlier separation of the flow around a sphere producing an increase in the form drag.

If these observations are correct then there could be a considerable value in the use of drag reducing additives for capsule transport in pipelines. Since the additives increase the capsule's drag coefficient for the more practical d/D ratios, i.e., when d/D approaches unity, whilst considerably reducing the pipeline friction losses. Thus having a pronounced effect on the economics of this type of transportation of materials.

It was for these reasons that the research reported in this paper and a report by Latto and Lau (1975) on a flow visualisation study of the flow phenomena involved when polymer addition is used was initiated.

APPARATUS AND PROCEDURE

A description of the apparatus used for the vertical pipeline research is given by Round, Latto and Anzenavs (1972), Latto, Round and Anzenavs (1973) and Latto and Lau (1975), however, a brief outline is given here of the system used for the flow visualisation research.

Figure (2) shows a diagram of the overall system which was comprised of a 5 cm ID pipeline 24.4 metres in length which could be operated either closed or open loop. The main test section was a vertical 5 cm ID plexiglass tube 3 m long which had a centrally located rectangular hollow 33 cm long plexiglass optical cell, which was filled with an aqueous glycerin solution to avoid optical distortion. The test cell was illuminated from one side through a 1 mm wide vertical slit. An aluminum powder suspension was used as the tracer for the flow visualisation. The pressure and flow rate within the system were controlled by an entrance and an exit valve. Furthermore the spheres were held in a vertical location by means of a flexible sting which permitted horizontal and rotational movement of the spheres as well as velocities that were higher than the normal hydrodynamic suspension values.

Two sphere-to-pipe diameter ratios of 0.74 and 0.925 and polymer solution concentrations of 0.25, 50, and 100 wppm were investigated. The polymer additive used was Reten 423, supplied by Hercules Inc. of New Jersey, (an anionic polyacrylamide having an assessed molecular weight of between 10^7 to 10^8 and a maximum drag reduction effectiveness for turbulent flow in a pipe at a concentration of 10 wppm). Single and trains of up to three spheres rigidly connected were investigated.

The liquid flow rate was varied up to a value for hydrodynamic suspension of the bodies and the resulting Reynolds number range was 1633 to 29,400 based on the water properties at 4°C and the pipe diameter.

The general procedure was to establish a given flow velocity and when hydrodynamic and thermal stability, which was 4°C, were obtained, to take a series of photographs of the flow around the bodies. For water flow without additives the closed loop system was employed. However, when additives were used the system discharged to the drains to avoid polymer additive build up, and consequently aluminum powder had to be continually added to the upstream reservoir. A high concentration of polymer solution was pneumatically injected from a storage tank, at a precalibrated rate, into the pipeline at a location about 15 m upstream of the test section.

Samples were frequently taken from the flow system when using polymers and tested using a capillary tube rheometer which had been previously calibrated with a stock solution. The rheometer is a commonly used instrument for measuring drag reduction effectiveness of a given polymer solution. This procedure ensured that the correct concentration was being used and that no appreciable degradation of the solution had occurred.

The resulting series of photographs for each flow velocity were greatly enlarged and the separation angle for each case established. Data for which the bodies were obviously rotating, eccentric or gyrating, were rejected. However, the results for a particular condition did not vary more than about 5% in most cases.

RESULTS AND DISCUSSION

In order to determine theoretically the location of the point of separation on a body it is necessary to have a knowledge of the pressure field over the body. For small pressure gradients such as would be found with low velocities in bounded media, this is difficult to predict or empirically measure due to the rather complex flow patterns encountered. This situation becomes even more complex for trains of bodies.

No data are available in the open literature on the effects of polymer additives on the separation angle for spheres or other bodies in a pipeline. However, a few papers have been published on the effects of additives on capsules in pipelines, e.g., Latto, Round and Anzenavs (1973), Anzenavs (1972), Aly (1974), Lee (1974), Stow and Elliot (1970), and Chenard (1967), but these were primarily concerned with operating parameters and are not pertinent to the present research. However, Sarpkaya, Rainey and Kell (1973) did publish the results of their work on the flow of dilute polymer solutions about circular cylinders, which unfortunately cannot be used for spheres in bounded media.

The results for separation angle are discussed under the following headings:

(i) Relationship to bulk velocity for pure water flow
(ii) Effect of polymer for single steel spheres
(iii) Effect of polymer on steel sphere trains of steel spheres, and
(iv) Effect of sphere to pipe diameter ratio.

(i) Results for Water

The data obtained were for pipe Reynolds numbers in the range 1600 to 29,400. Figure (3) shows the percentage change in the separation angle versus flow velocity U. It is apparent that the separation angle increases with Re but does not exceed the equatorial region. The maximum ϕ being about 80° for a Re of 29,399. The general trend is certainly in agreement with that expected for external flow in non-bounded media. As the Re is increased there is a wall jet effect which creates an earlier separation point or a larger ϕ. This is apparent from Figure (4) which shows two typical photographs for water. Large scale vortices exist for the low (laminar) pipe flow as shown in Figure (4a), in contrast to the high frequency turbulence at the high Re numbers, Figure (4b).

Figure (5) shows two typical photographs for a two sphere train. The flow patterns for these and also for three spheres (not shown) are somewhat similar to that obtained for single spheres but are altered by a pronounced wall jetting effect. The actual values for ϕ, obtained from the photographs, for sphere trains are presented in Figures (6) to (10). At the lower Re numbers, two spheres have a larger ϕ than three spheres, but approach the same value at the maximum Re used of 29,400.

The trends are generally the same for all the systems used but are mainly presented as a basis for the polymer data.

(ii) Effect of Polymers on Single Spheres

Polymer concentrations of 20, 50, and 100 wppm were investigated. The resulting data for ϕ are presented in Figures (3) and (6) and show that polymer can increase the separation angle. An interesting observation is that the maximum effect occurs at about 20 wppm which is close to the value for maximum drag reduction of 10 wppm for Reten 423. This general observation confirms the hypothesis that ϕ is increased with polymer addition which consequently increases Cd*. As the concentration is increased above 20 wppm, the viscosity and viscoelasticity have an effect on ϕ and actually Re should be based on the solution and not the solvent properties.

(iii) Effect of Polymers on Sphere Trains

Figures (7) to (10) show that polymer additive does have a pronounced effect on ϕ for the last sphere in a train, however the results cannot really be correlated with the data for single spheres. In fact, for two spheres the maximum change in ϕ is 8% when the concentration is 50 wppm in contrast to the concentration of 20 wppm required for the maximum change in ϕ for single spheres. Furthermore, the shape of the curves for three spheres is not similar to those for two spheres, such that for two spheres, polymer always increases ϕ for all values of Re. Whereas, for three spheres, the effect on ϕ is very much a function of Re.

At this stage in the research few rigorous explanations of the phenomena involved can be given. Examination of the photographs for polymer addition, see Figure (11), do not reveal any obvious explanation for the trends. However, it was observed that the wall jetting was more stabilized as the number of spheres was increased. It is quite conceivable that the high frequency turbulence is being suppressed.

It is interesting to note that the data for the separation angle for the d/D ratio of 0.74 may be correlated using the following simple empirical equation

$$\phi/Re^{k} = f(C) \qquad (1)$$

where $k = 0.14$ for $n = 1$
$k = 0.13$ for $n = 2$
$k = 0.085$ for $n = 3$

In fact, the data have been correlated with the following empirical equations.

$$\frac{\phi}{Re_D^{0.14}} = 8.2 + 2.305\, C^{.18} + 11\, e^{-C/110} \qquad (2)$$

$$\frac{\phi}{Re_D^{0.13}} = 24.11 + 0.2\, C^{.10} + 2\, e^{-C/100} \qquad (3)$$

$$\frac{\phi}{Re_D^{0.085}} = 28.8 + 2.0\, C^{.2} + 4\, e^{-C/150} \qquad (4)$$

for $0 < C < 100$ (wppm)
and where ϕ is in degrees.

(iv) Effect of Diameter Ratio

Unfortunately, due to some difficulties with the system only a few experiments were performed with one other diameter ratio of 0.925. However, the data obtained were sufficient to indicate trends that may be expected. Figures (12) and (13) show that the effect of polymer on ϕ is certainly dependent on the d/D ratio. It may be expected that as d/D approaches zero, the data should be that for a sphere in a semi-infinite media. Therefore, as d/D approaches unity the divergence from external non-bounded flows will be maximised which is substantiated by the present work. As in the case of two spheres, the maximum effect is when the concentration is about 50 wppm. It could well be that the reason for the concentration being higher for the maximum effect for sphere trains compared to that for single spheres is that appreciable mechanical degradation of the polymer is taking place.

CONCLUSIONS

The position of the point of separation for single and trains of spheres in a pipeline cannot be expected to go beyond the equatorial region of the final body for realistic transportation velocities and geometries. The trend of the separation angle variation with flow rate is somewhat different to that which may be expected for non-bounded external flows. This is mainly due to the wall jetting effect which is more pronounced as the d/D ratio approaches unity. However, the dynamic effects of untethered capsules cannot be excluded especially when comparing single and trains of bodies.

It is quite evident that polymer addition to the flow media affects the location of the point of separation of the flow around a sphere or the last sphere in a train of spheres in a pipeline. In actual fact, the separation angle can be changed by as much as 10% by concentrations of between 20 and 50 wppm. In the majority of cases it was observed that polymer causes an earlier separation of the flow. This certainly substantiates previous observations that polymer addition increases the drag of bodies in a pipeline. It is still uncertain as to the mechanism involved but it could be hypothesized that the polymer supresses the high frequency turbulence and therefore the stability of the flow. This was to some extent confirmed by a lengthening of the vortices in the wake of the spheres.

The research confirms previous observations that concentrations of between 20 to 50 wppm have the most pronounced effect on the separation angle and would be the best range to use for transportation of capsules in pipelines.

It is apparent that more research is needed on the effects of diameter ratio, geometry, pipeline size and polymer concentration on the separation angle and transportation efficiency for moving capsules in inclined and horizontal pipelines for which the flow patterns are more complex than those investigated in this research.

NOMENCLATURE

Cd*	sphere drag coefficient = $2\Delta P/\rho U^2$
U	mean velocity of fluid in the pipeline
ρ	density of liquid
n	number of bodies in series
ϕ	half angle of separation point from the rear of the body
C	polymer concentration, wppm
wppm	weight parts per million
Re	Reynolds number = $U\,D/\nu$
ν	kinematic viscosity of the solvent
D	diameter of the pipeline
d	diameter of the body
k	power to which Re is raised for the correlations.

REFERENCES

1. Round, G. F., Latto, B., and Anzenavs, R. A., 1972, "Drag Coefficients of Freely-Suspended Spheres and Sphere Trains in a Vertical Tube, Proc. Hydrotransport II, Coventry, F1.1-F1.12.
2. Latto, B., Round, G. F., and Anzenavs, R. A., 1973, "Drag Coefficients and Pressure Drops for Hydrodynamically Suspended Spheres in a Vertical Tube With and Without Polymer Addition", Can. J. Chem. Eng., 51, 536.
3. Aly, S. L., 1974, "The Hydrodynamic Suspension of Sphere and Cylinder Trains in a Vertical Tube Using Water and Polymer Solutions, M.Eng Thesis, McMaster University.
4. Lee, S. W., 1974, "An Experimental Study of the Hydrodynamic Suspension of Cylinders in a Vertical Pipeline", M.Eng Thesis, McMaster University.
5. Anzenavs, R. A., 1972, "An Experimental Study of the Hydrodynamic Suspension of Spheres and Sphere Trains in a Vertical Pipe Using Water and Polymer Solution", M.Eng Thesis, McMaster University.
6. Stow, F. S., and Elliott, J. H., 1970, "Drag of a Tethered Ball in Solutions of Drag Reducing Polymers", Polymer Letters, 8, 611.
7. Latto, B., and Lai, A., 1975, "Flow Separation on Spherical Capsules in a Vertical Pipeline With Polymer Addition", Report No. ME/75/FM/R12, McMaster University.
8. McNown, J. S., and Newlin, J., 1951, "Drag of Spheres Within Cylindrical Boundaries", Proc. 1st U.S. National Congress of Applied Mechanics, Chicago, 6, 801.
9. Chenard, J. H., 1967, "Drag of Spheres in Dilute Aqueous Solutions of Poly (Ethylene Oxides) Within the Region of the Critical Reynolds Number", M.Sc. Thesis, Naval Postgraduate School.
10. Sarpkaya, T., Rainey, R. G., and Kell, R. E., 1973, "Flow of Dilute Polymer Solutions About Circular Cylinders", J. Fluid Mech., 57, 1, 177.

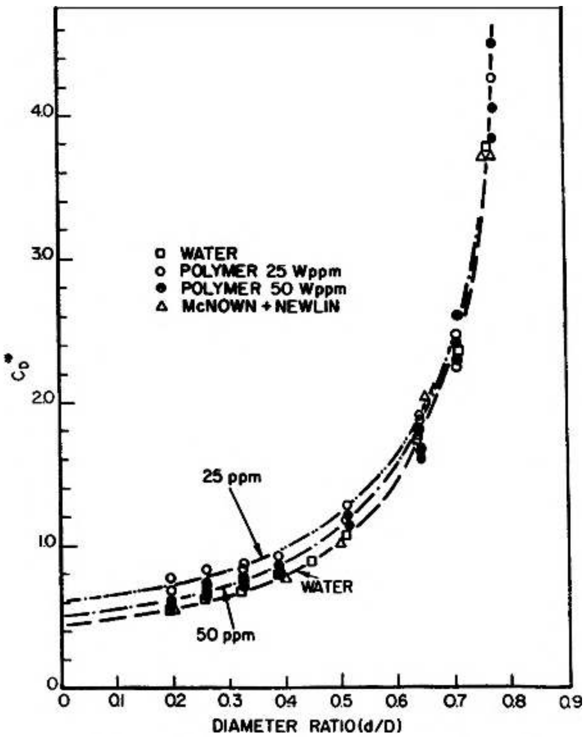


Figure (1) Data for spheres in a 5 cm ID pipeline when using Reten 423

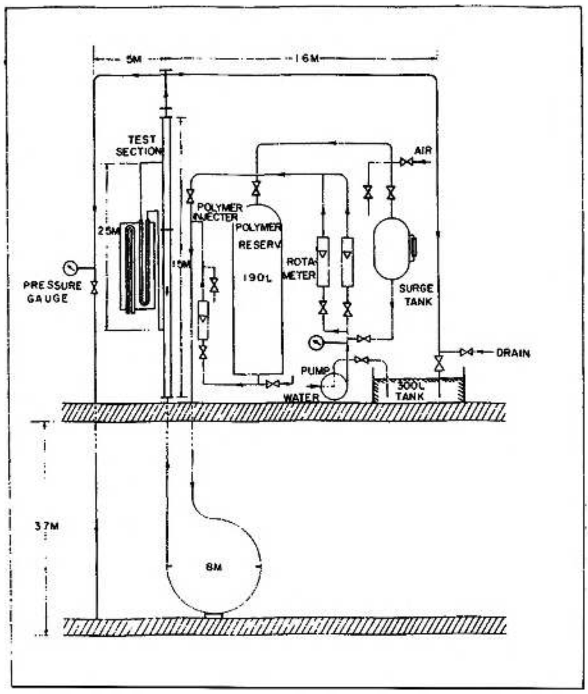


Figure (2) System for capsule research

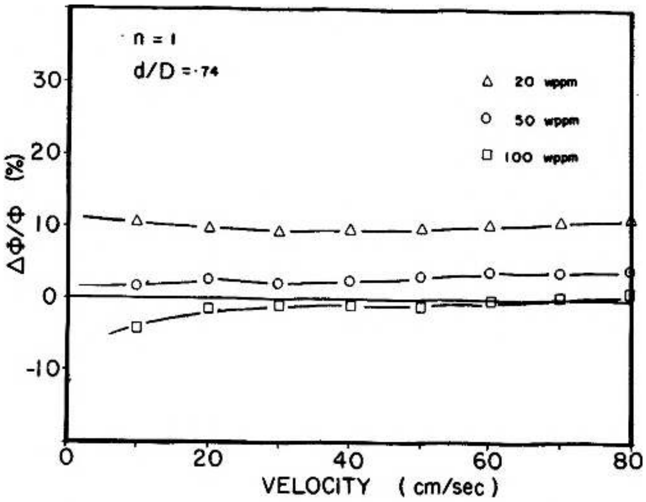


Figure (3) Single sphere with d/D = 0.74

Figure (4a) U = 4.85 cm/s, C = 0 wppm and d/D = 0.74

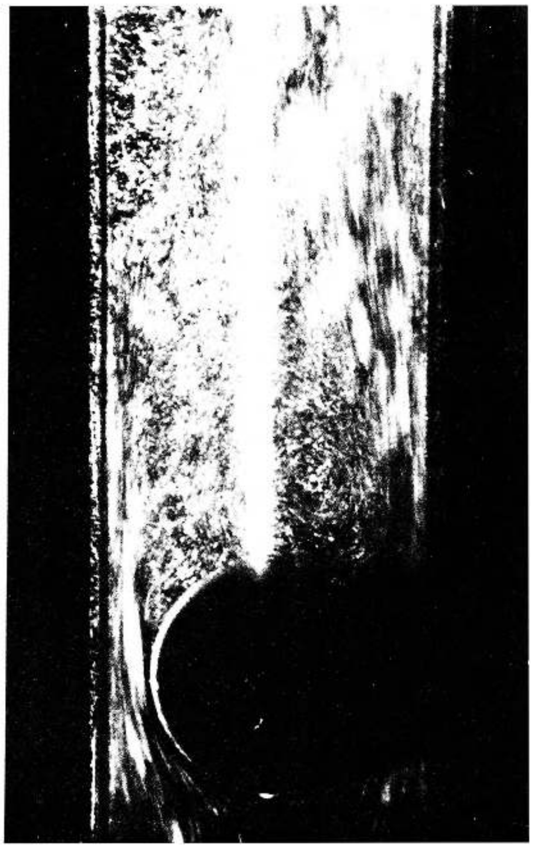
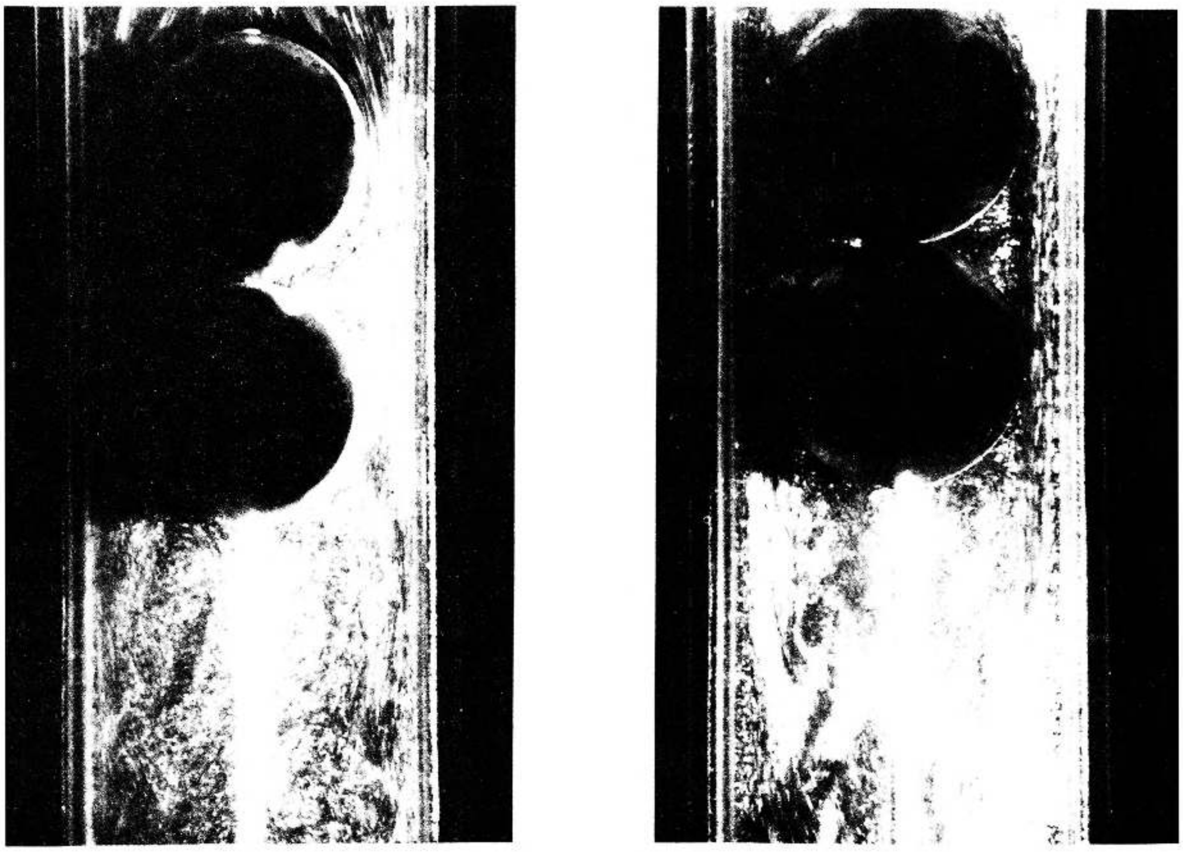


Figure (4b) U = 104.34 cm/s, C = 0 wppm and d/D = 0.74



(a)

(b)

Figure (5) Two spheres rigidly connected with d/D = 0.74 and C = 0 wppm.
(a) U = 4.9 cm/s and (b) U = 65.5 cm/s.

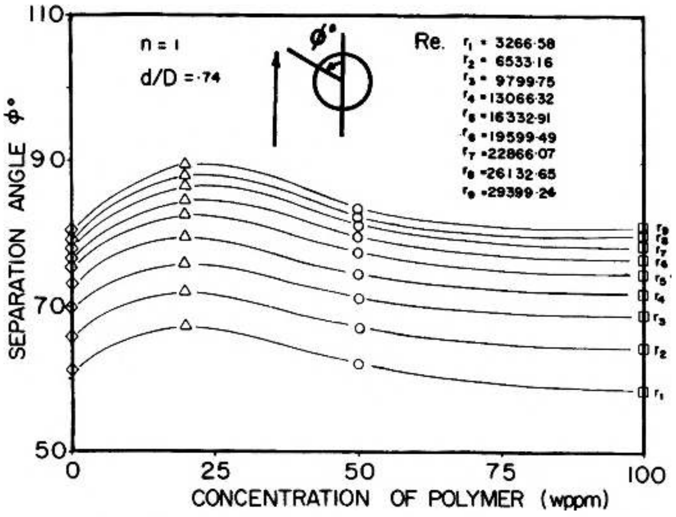


Figure (6) Single sphere with d/D = 0.74

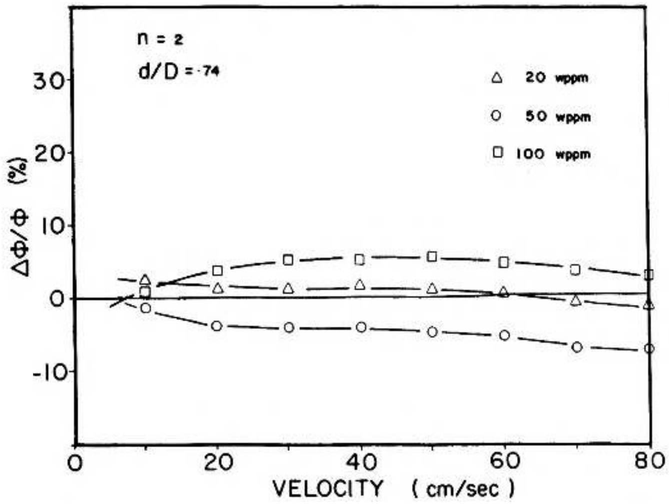


Figure (7) Train of two spheres with d/D d/D = 0.74

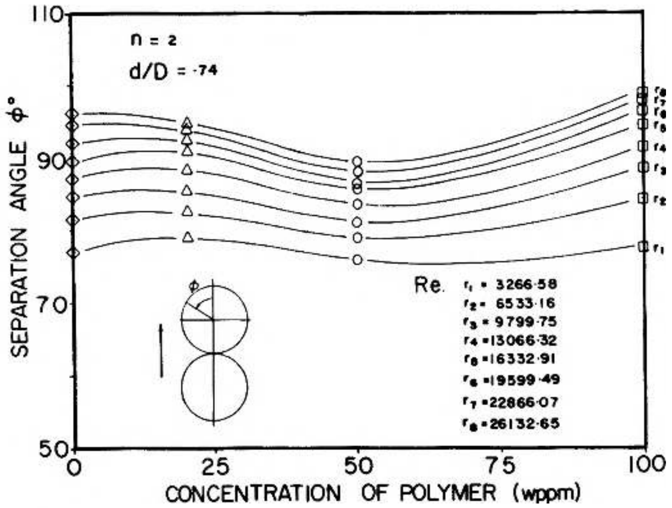


Figure (8) Train of two spheres with d/D = 0.74

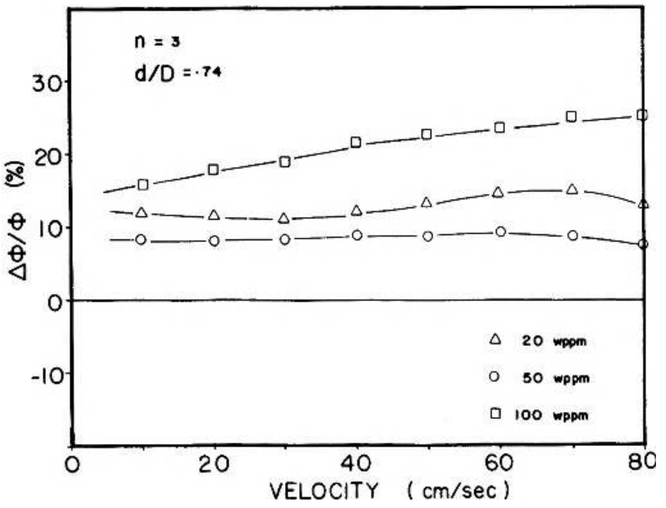


Figure (9) Train of three spheres with d/D = 0.74

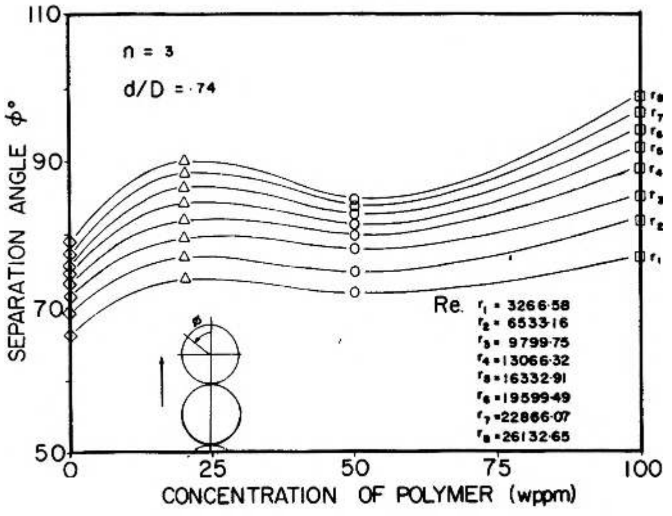
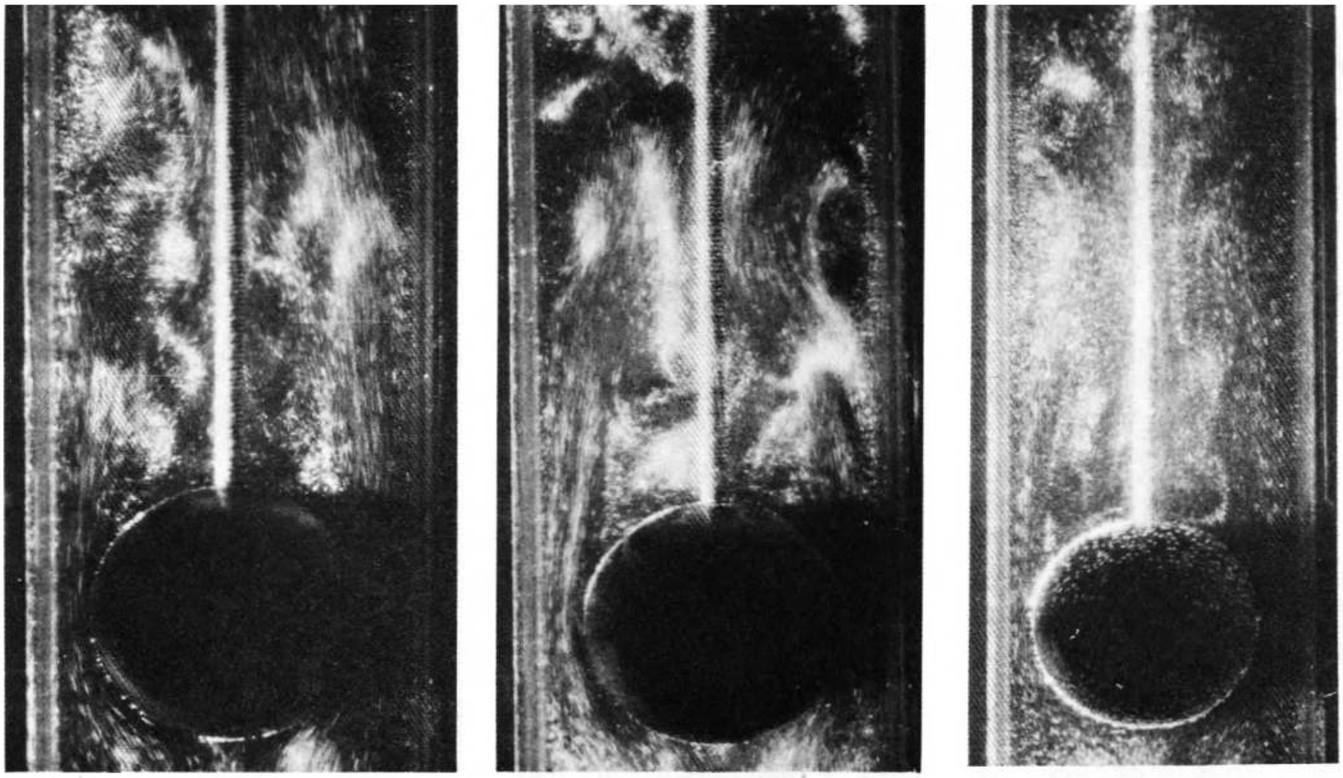
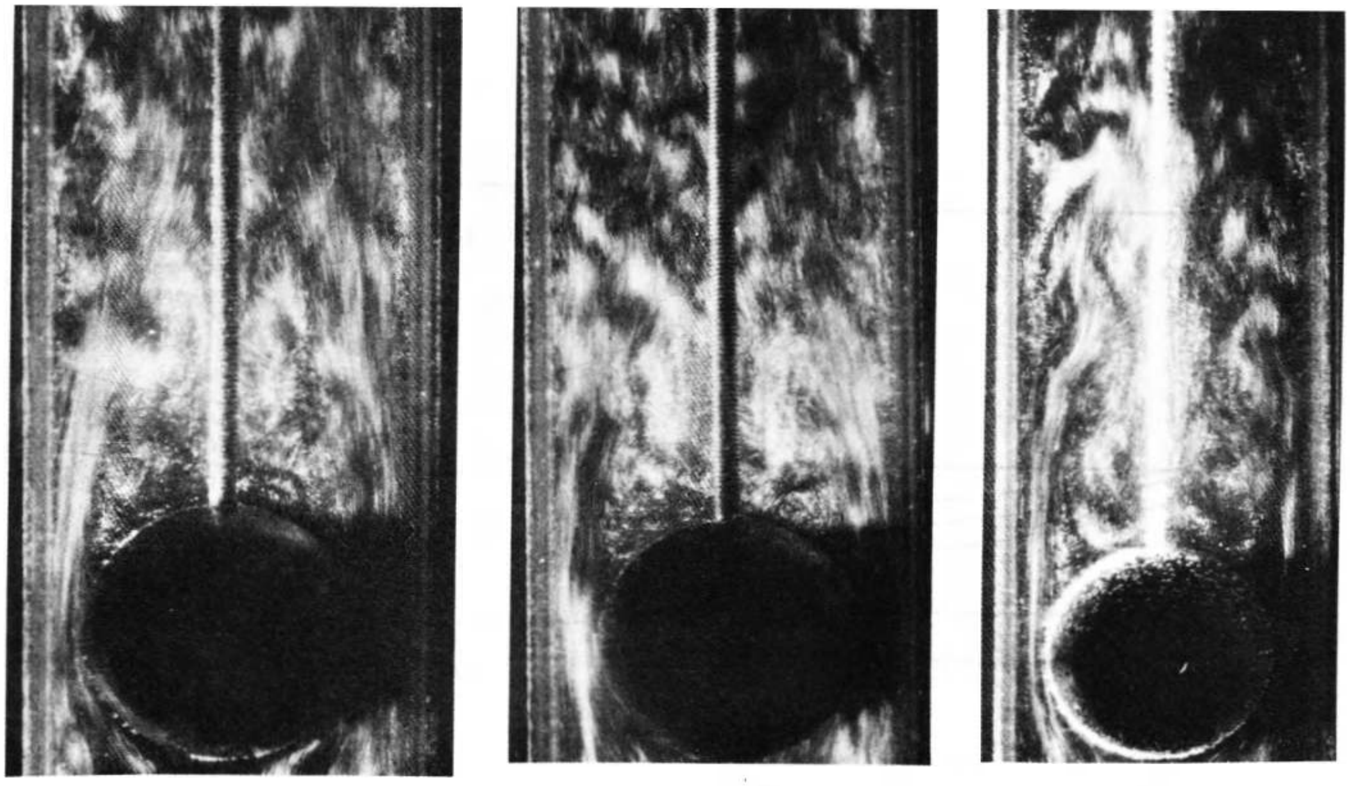


Figure (10) Train of three spheres with d/D = 0.74



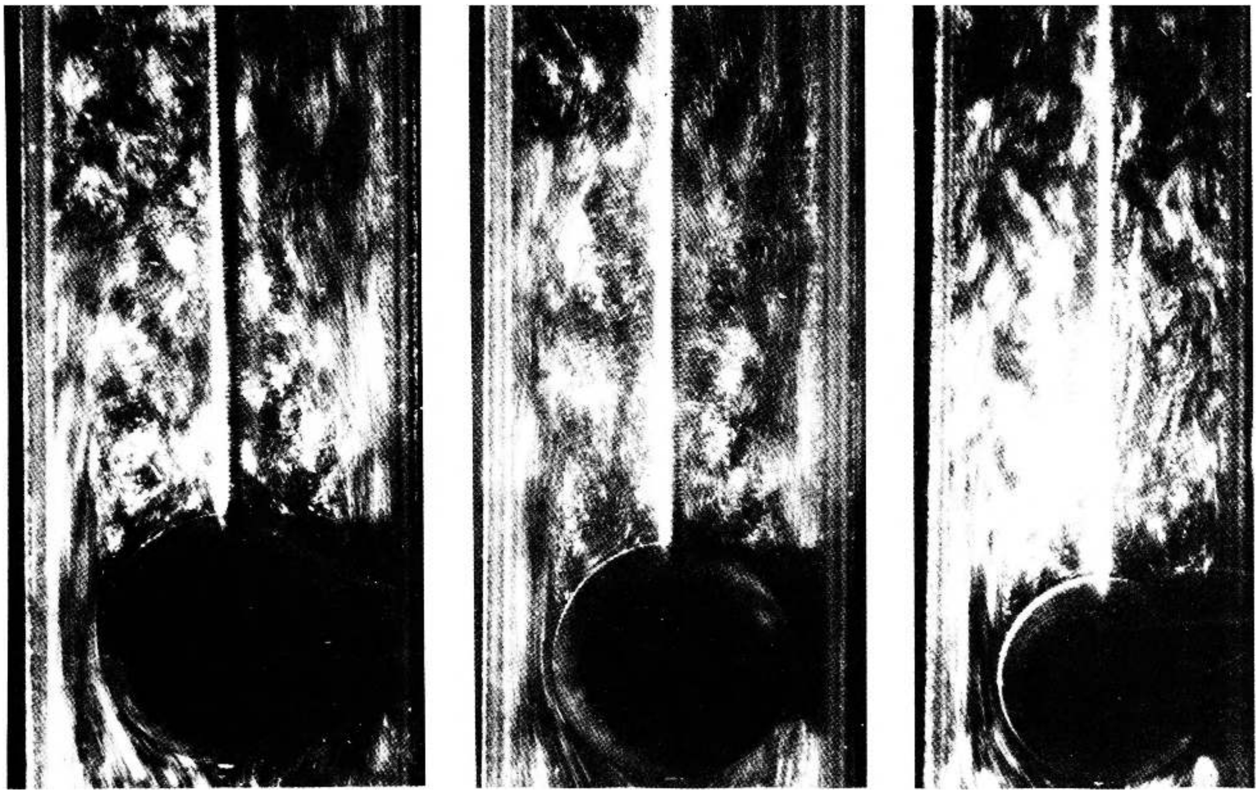
(a) (b) (c)

Figure (11(i)) Single sphere in a polymer solution with d/D = 0.74 : (a) U = 5.0 cm/s, and C = 20wppm; (b) U = 5.1 cm/s, and C = 50 wppm; (c) U = 5.2 cm/s and C = 100 wppm.



(a) (b) (c)

Figure (11(ii)) Single sphere in a polymer solution with d/D = 0.74 : (a) U = 14.8 cm/s and C = 20 wppm ; (b) U = 15.0 cm/s and C = 50 wppm ; (c) U = 15.2 cm/s and C = 100 wppm .



(a) (b) (c)

Figure (11(iii)) Single sphere in a polymer solution with d/D = 0.74: (a) U =51.5 cm/s and C = 20 wppm; (b) U = 67.1 cm/s and C = 50 wppm; (c) U = 97.2 cm/s and C = 100 wppm.

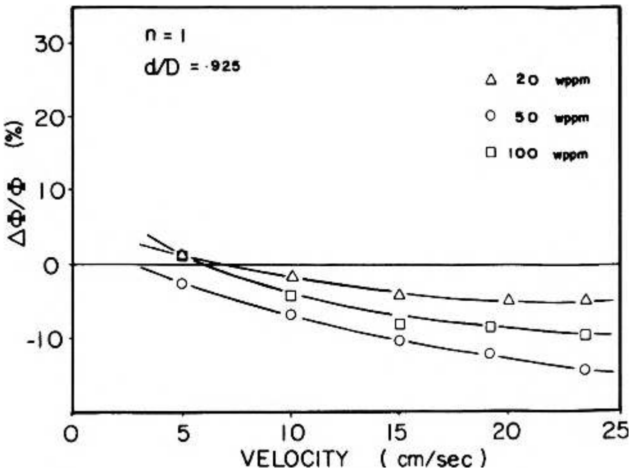


Figure (12) Single sphere with d/D = 0.925

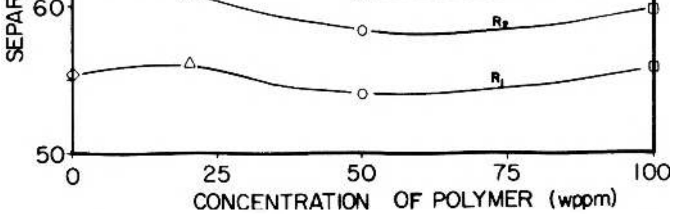


Figure (13) Single sphere with d/D = 0.925

DISCUSSION

Larry Chorn, Univ. of Ill.: Do you think the present work has any application to the anomalous results you see when you put a pitot tube or a hot wire into a polymer solution to look at velocity profiles:

Latto: I personally wouldn't think so. I tend to agree with most researchers, that with small pitot tubes or hot-film anemometers there is entanglement of the polymer around the tube or film with possibly an actual physical build up of agglomerates at the entrance of the pitot tube or on the surface. I don't think that the present work is applicable in that there is bounded flow, which for d/D approaching unity causes wall jetting which affects the separation conditions. Furthermore instruments usually suffer from microscopic phenomena due to individual particle action, whereas this research is more macroscopic in nature.

M. Poreh, Technion, Haifa: The results are indeed very interesting. I want to point out that theoretically when you consider the drag of bodies like a sphere or cylinder, you should be very careful whether you work at high Reynolds number, above the critical Reynolds number, or at a low Reynolds number. If you have initially a laminar boundary layer and there is hardly a turbulent boundary layer in the front part, then the polymers tend to decrease the separation angle and increase the drag. But if you have a very high Reynolds number and the drag coefficient has already gone down, then the effect of long boundary layer thicknesses being reduced by the polymers is to increase the separation angle and decrease the drag. This was the reason why, when you were at this large confinement which is equivalent to a higher velocity, the polymers tend to delay separation. We have published theoretical work in the 1974 BHRA Drag Reduction Conference in Cambridge which explains this phenomenon.

Latto: I agree, and we are continuing the research to obtain more extensive data for wide d/D ratios and higher bulk fluid velocities using instrumented tethered bodies. This will enable us to approach semi-infinite boundary conditions as well as very constrained conditions. Furthermore, with tethered bodies with wide velocity ranges both laminar and turbulent flow conditions can be investigated. However, tethered bodies do introduce other factors and the research tends to diverge from the original practical concept.