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Experimental studies in magneto-fluid dynamics: flow over a sphere with a cylindrical afterbody

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The measured pressure distributions over the front hemisphere of a hemisphere-cylinder combination placed in an aligned fields magneto-fluid dynamic flow are presented. Integration of the pressure profiles show that the form or pressure drag of the composite body first increases as the magnetic field strength increases, at a fixed flow velocity, but then decreases as the magnetic field becomes still stronger.

1. Introduction

Previous experiments in aligned fields magneto-fluid dynamic flow around a sphere (Maxworthy 1968)† pointed to features which required further investigation. This paper presents the changes which take place in the previously reported surface pressure measurements when a cylindrical afterbody is added to the rear of a sphere.

The justification for such a modification of the sphere geometry is to determine the importance of the character of the rearward flow on the flow over the front half of the sphere. That is, does the existence of a large acceleration of the flow in the neighbourhood of the equator depend critically on whether or not the flow can accelerate beyond the equator and separate there? As a bonus, it is also possible to calculate the form drag of the composite body and compare this to the direct drag measurements of Suzuki (1967) for a similar, but not identical, geometry.

2. Apparatus

The apparatus and techniques are identical to those described in (1) except the sphere geometry is changed to that shown in figure 1. A cylindrical afterbody, four sphere diameters long, is attached with epoxy cement to the rear of the sphere. A small clearance is maintained between the movable portion of the sphere and the afterbody.

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† Hereinafter referred to as (1).

3. Results

As in (1), the details of the resulting pressure distributions (figure 2) are presented in a form (figure 3) to show most readily the dependence on the interaction parameter $N = \sigma B_{\infty}^2 d/\rho U_{\infty}$.† As N increases from a small value C_D‡ increases. This increase is due to two effects which occur simultaneously. The pressure distribution over the nose of the sphere is becoming more uniform at a value of P_{∞}^0† and is spread over a greater area, i.e. θ_S‡ is increasing. The minimum pressure exerted on the nose, i.e. P_θ at $\theta = 90°$,† is increasing from the value found when N is zero. This trend continues until $N \approx 3$, after which the rate of increase begins to fall until C_D, C_P and θ_S all reach extreme values at $N \approx 5$.

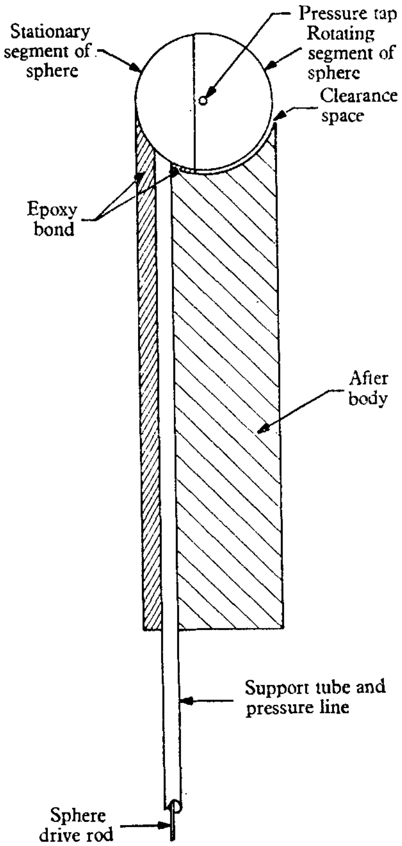

FIGURE 1. Sphere used to measure angular distribution of surface static pressure, modified by cylindrical afterbody (split between sphere and afterbody is exaggerated in this view).

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† Where ρ and σ are the fluid density and electrical conductivity; B_{∞} the applied magnetic field strength; U_{∞} the approach flow velocity and d the body diameter. P_{∞}^0 is the stagnation pressure, P_θ the static pressure at angular position, θ, measured from front stagnation point.

‡ These quantities are defined in the caption to figure 3.

Thereafter C_D begins to decrease, C_P decreases very rapidly and θ_S approaches an asymptotic value of 60°. Thus, the contribution to the drag of the positive pressure between $\theta = 0$ and $\theta = \theta_S$ becomes essentially constant while the negative portion between $\theta = \theta_S$ and $\theta = 90°$ increases in magnitude as N becomes large. From the present results it is not possible to decide on the ultimate value of C_D as N becomes very large. When plotted on rectilinear graph paper (as in figure 3) it seems possible that a small positive asymptotic value is to be reached.

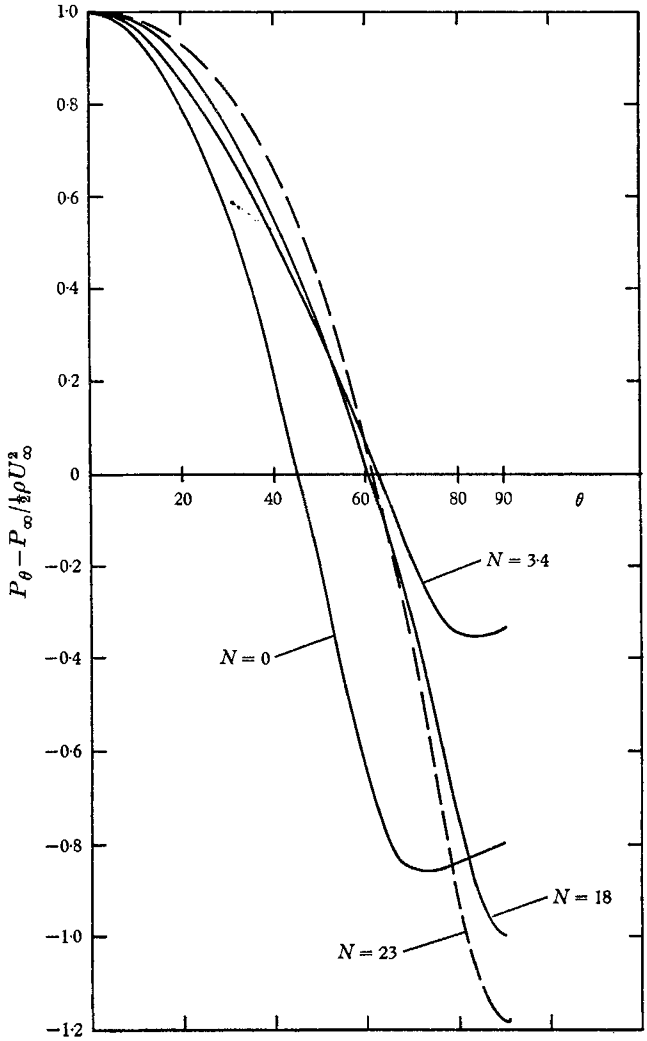

FIGURE 2. Distribution of static pressure with angular position around the sphere, for various values of the interaction parameter.

The similarity to results found in (1) is immediately evident. Only quantitative differences are noted. In this case maximum C_D occurs for N equals 5 while in the former case the value was 10. Similarly, the maximum value of C_D is 0·51;

0·46 previously. θ_S asymptotes 60° for large N; a value of 63° was found previously. In detail, the two cases do not quite correspond, but the qualitative behaviour is unmistakably the same. Any significance these subtle differences might have is discussed in that which follows.

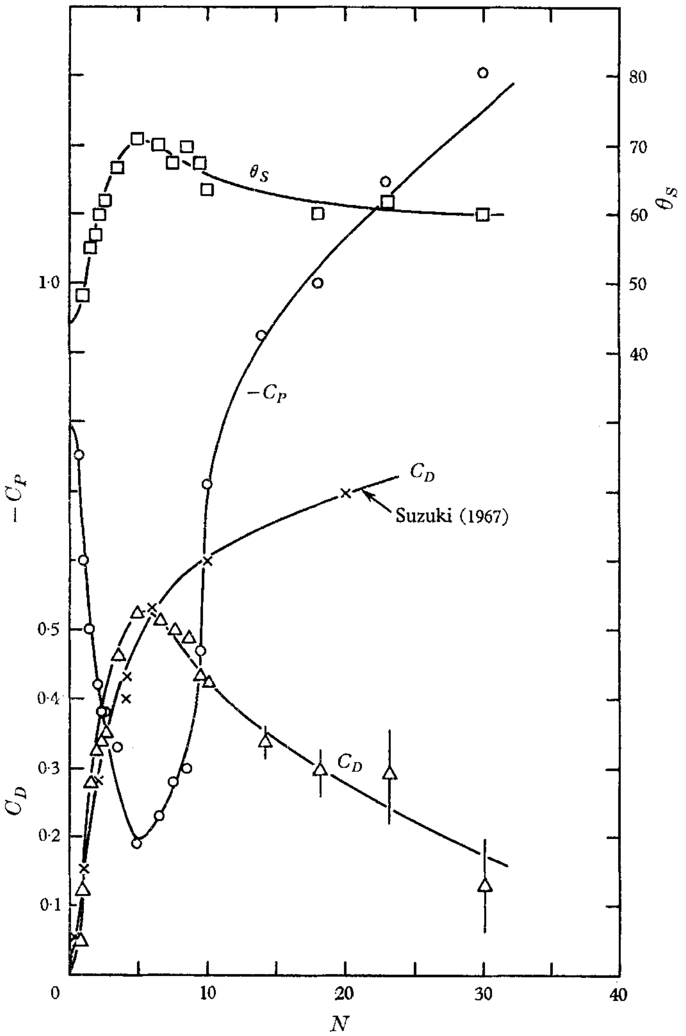

FIGURE 3. Variation of drag coefficient (C_D), angle (θ_S) at which $P_\theta = P_\infty$, and the pressure coefficient C_P at $\theta = 90°$,

where $C_D = \text{drag}/\tfrac{1}{2}\rho U_\infty^2 \tfrac{1}{4}\pi d^2$

and $C_P = (P_{90°} - P_\infty)/\tfrac{1}{2}\rho U_\infty^2.$

4. Discussion

The results presented in the previous section need to be discussed not only in an absolute sense, but also in their relevance to the previously mentioned sphere measurements (1). The latter comparison is the easiest to make and suggests that the model adopted in (1), with a stagnant slug of fluid downstream of the sphere, is correct. However, the slight change in the position of formation of the slug apparently has fairly serious consequences. In the present case the fluid is forced to leave the sphere surface at $\theta = 90^\circ$ and then flows over the simulated rearward slug. In the previous case the flow separated naturally at $\theta = 115^\circ$ and the stagnant fluid region which was formed was smaller in diameter than the sphere and presented a different boundary condition to the outer flow. These two differences must be the cause of the quantitative disagreement between the two cases, since this information, when transmitted upstream by an 'Alfven-wave' mechanism, can cause a change in the upstream flow approaching the body. The detailed changes depend on many interacting features, and it is even difficult to decide, *a priori*, which geometry will have the largest drag at a given value of N. Nevertheless, the slight changes which have taken place in the rearward slug-like flow are enough to alter the flow upstream and point to the importance of knowing the location of the separation point, not only because it sets the value of the base pressure, but also because it changes the upstream inviscid flow far more dramatically than in the corresponding non-magnetic case.

Using knowledge gained in (1),† it is possible to attribute the decrease in pressure at the joint between sphere and cylinder to a loss in total pressure suffered along streamlines which form the inviscid outer flow and to a concomitant acceleration of this outer flow to a large velocity. This accelerated flow then flows along the solid afterbody. Since immediately after the equator the pressure is lower than the static pressure far from the body, there must be an increase in the local magnetic field strength. Far downstream there is no radial inward flow to maintain this field concentration and the magnetic and pressure fields will eventually become uniform far enough from the nose. However, streamlines which have passed close to the body have suffered a total pressure loss and this results in a final inviscid velocity profile with a defect in momentum, the 'vortical wake' of Tamada (1962).‡ It is important to know the axial location of this uniform condition and its variation with N because of the difficulties it must create for any direct measurements of the drag, e.g. Suzuki (1967). In that experiment the direct force on a frontal section of a 'semi-infinite' body was measured. It was essential that the pressure, at the split between this front section and its support, be equal to the undisturbed, freestream, static pressure. If, in fact, the flow along the afterbody still has a large velocity at the location of the split, then the static

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† The reader is referred to (1) for all of the detailed discussion concerned with total pressure loss due to Joule heating and the use of the radial balance of Lorentz force and radial pressure gradient in the almost parallel outer flow.

‡ Right against the surface there is, of course, a viscous layer which the arguments presented to date have ignored. Viscous effects must be included to give the complete picture.

pressure would be low and the measured force too large. It is believed that this partially explains the difference (shown in figure 3) between the present results and those of Suzuki (1967) at large N for a similar geometry.

The value of the ultimate drag at large N is of some interest. From the experiment it is not possible to even determine the sign of this drag, so that simple physical arguments must be forwarded to show that it is in fact, positive.† These are based on the observation that the flow over the front half of the sphere is essentially inviscid so that its drag, measured from the pressure distribution, is mainly due to Joule losses. Since the latter can only be positive, C_D must also be positive. The only way viscosity can enter this argument is due to the small displacement effects of the boundary layer on the sphere surface and to the formation of intense free shear layers in the outer flow when N becomes very large. Since these contributions must also be positive the total drag will be positive.

5. Conclusions

Pressure distribution measurements over the nose of a sphere-cylinder combination have shown that the drag coefficient at first increases from zero, and then decreases as the interaction parameter N increases. At large N a low velocity region exists over the nose of the combination and high velocity flow is created in the neighbourhood of the joint between hemisphere and cylinder.

Duncan E. Griffith maintained the liquid sodium tunnel and was instrumental in designing and building a pressure measuring system that worked so well under very adverse circumstances. Edward Coury helped with the final experiments. Their contributions are gratefully acknowledged.

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REFERENCES

Maxworthy, T. 1968 Experimental studies in magneto-fluid dynamics: pressure distribution measurements around a sphere. *J. Fluid Mech.* **31**, 4.

Suzuki, B. H. 1967 Magneto-fluid dynamics drag measurements on semi-infinite bodies in aligned fields. Ph.D. thesis, California Institute of Technology, Pasadena.

Tamada, K. 1962 Flow of a slightly conducting fluid past a circular cylinder with strong, aligned magnetic fields. *Phys. Fluids*, **5**, 7.

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† An identical argument holds for the results of (1) where it was erroneously stated that the drag of the front half of the sphere becomes negative for large N.