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discussion

Frictional Moment of Flow Between Two Concentric Spheres, One of Which Rotates[1]

C. RANDALL TRUMAN.[2] The author's extensive experimental results for the flow in the narrow space between two concentric rotating spheres are an interesting contribution to the literature. Munson and Menguturk [4] determined (for the case of the inner sphere rotating) that the nature of flows in narrow-gap geometries ($\beta \approx 0$) and wide-gap geometries ($\beta >> 0$) are substantially different. While the author has shown the existence of basic differences in flows in gaps that are extremely small ($\beta \leq 0.011$) and gaps that are not so small ($0.024 \leq \beta \leq 0.206$), it should be noted that only narrow-gap geometries were considered in detail. Would the author comment on whether the narrow spacings for which data are given would be of practical interest in turbomachinery and/or geophysical flows?

Useful empirical relations between torque and spacing and Reynolds number are the result of the author's experiments. However, the empirical relations from other sources require further discussion, especially since reference [6] is in Russian and reference [7] in Japanese. To obtain better agreement with experimental results in the upper range of Re for Regime I, equation (A1) [7] (outer sphere rotating) and equations (A2) [6] and (A3) [7] (inner sphere rotating) were introduced. A discussion of the derivation and significance of these relations would be enlightening.

As was done for the enclosed rotating disk [8], the author defined four flow regimes which depend on the clearance ratio and Reynolds number. Daily and Nece [8] made the following observations for the enclosed disk:

1 Regime I exists for all clearance ratios, if Re is sufficiently small.
2 For small clearance ratios, Regime II may never exist.
3 For large clearance ratios, Regime III may never exist.
4 Regime IV exists for all clearance ratios if Re is sufficiently large.

From Figs. 3 and 5, it is clear that the first three observations also hold for concentric rotating spheres with narrow spacing. However, for very small β (Fig. 3), there is no region corresponding to Regime IV. For larger Re, would the author expect to find $C_M \propto \mathrm{Re}^{-1/5}$? Considering the above similarities, are the four flow regimes defined by the author directly analogous to those for the enclosed rotating disk? The author presents a comparison of torque coefficients for the rotating sphere and the rotating disk in Fig. 10. Further discussion of the Reynolds number dependence of C_M/C_{MD} would be helpful. Would the author explain how C_M/C_{MD} can depend on Re for Regimes III and IV when the empirical relations for the sphere and the disk [8] have the same Reynolds number dependence?

The only major shortcoming of this work is that no comparison is made with previous experimental results [1, 2, 10][3] for the narrow-gap geometry; agreement with other experiments would be reassuring. Even though the author's primary concern is torque data, a comparison of present results with energy [11] and linear [4, 12] stability predictions would be useful.

Interested readers are referred to a recent comprehensive review of the flow between concentric rotating spheres by Joseph [13].

Additional References

10 Zierep, J., and Sawatzki, O., "Three Dimensional Instabilities and Vortices Between Two Rotating Spheres," 8th Symposium on Naval Hydrodynamics, 1970.

11 Munson, B. R., and Joseph, D. D., "Viscous Incompressible Flow Between Concentric Rotating Spheres. Part 2. Hydrodynamic Stability," *J. Fluid Mech.*, Vol. 49, Part 2, 1971, pp. 305–318.

12 Yakushin, V. I., "Instability of Fluid Motion in a Thin Spherical Layer," *Izv. Akad. Nauk SSSR, Mekh. Zh. i Gaza*, Vol. 4, No. 1, 1969, pp. 119–123, (*Fluid Dyn.*, Vol. 4, No. 1, 1969, pp. 83–85).

13 Joseph, D. D., "Global Stability of the Flow Between Concentric Rotating Spheres," Chapter VII, *Stability of Fluid Motions I*, ed. B. D. Coleman, *Springer Tracts in Natural Philosophy*, Vol. 27, Springer-Verlag, New York, 1976, pp. 202–217.

R. E. NECE.[4] Perhaps the primary significance of the comprehensive experiments reported in this interesting paper is that the author, through direct flow visualization techniques and conclusions based upon variations of frictional moment over a wide range of Reynolds number—clearance ratio combinations, has indeed verified and delineated the existence of the four flow regimes for this rotating flow problem. It is interesting to note that the transition from one regime to another, as indicated by variations of C_M with R_e for discrete respective β values, is about as smooth for the rotating inner sphere as for the case of a smooth disk rotating in a housing [8]. There appears to be a sudden onset of turbulence providing an abrupt rise in C_M at a transition from regime II to regime IV for the rotating outer sphere case for intermediate clearance ratios.

For all β values and for all flow regimes other than regime I the values of C_M are considerably higher when the inner sphere rotates than when the outer sphere rotates. It is not clear how much of this difference can be attributed to the physical differences in the flow fields (especially the influence of the Taylor vortices in regime II for the rotating inner sphere) and how much is due simply to the definition of C_M. Both C_M and the sphere Reynolds number have been defined in terms of R_1 regardless of whether the inner or outer sphere rotates. If R_2 had

[1]By K. Nakabayashi, published in the March, 1978, issue of the JOURNAL OF FLUIDS ENGINEERING, Vol. 100, No. 1, p. 97.

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[3]Numbers 10–13 in brackets designate Additional References at end of discussion.

[4]Professor, Department of Civil Engineering, University of Washington, Seattle, Wash. Mem. ASME.

been used in the definition for the case of a rotating outer sphere the values of C_M would be significantly smaller for the larger clearance ratios β. Correlation based upon the use of the rotating body radius as the characteristic length in the definitions of both C_M and R_e would make the differences in C_M for the two rotation cases even more apparent. Some measurements of boundary layer thicknesses and/or tangential velocities in the quasi-"core" region which presumably exists between the separated boundary layers on the two spherical surfaces in regimes II and IV could be informative: flow visualization tests at large β in regime IV were apparently quite limited. Does the author have any additional data which might describe in some more quantitative fashion any details of the flows adjacent to the rotating spherical surfaces?

Author's Closure

The author is grateful to Professor Nece as well as to Mr. Truman for their comments.

In regard to Mr. Truman's first comment, various kinds of narrow curvilinear spaces can be found in some fluid machines. My interest came from a study of bearings which have curved, concave, and convex surfaces about an axis of rotation. The spherical annulus is the simplest geometric shape of this class. I am not aware of any direct application of this work to geophysical flows.

Clearly, the quantitative size of the difference between C_M values for the cases of inner sphere rotation or outer sphere rotation, at a given R_e, may depend upon the definition of C_M, as pointed out by Professor Nece. I choose to define the C_M's so that the difference is zero in regime I to emphasize that the viscous force is the only force which determines the values of C_M in regime I, independent of which sphere rotates. In the three other flow regimes, the differences in C_M values, at given R_e, are attributed to the effects of centrifugal forces, which cause the onset of different flow regimes, depending on which sphere rotates.

Both discussers ask about the relationship of the current research to that of other investigators. In particular, the question of flow regime transitions is raised. There may be two reasons for the rapid increase in C_M at a change of flow regime. The onset of turbulence, as pointed out by Professor Nece, is one reason. This effect is seen in the case of the outer sphere rotation when one changes from regime I to III or from regime II to IV.

A second effect is responsible for the rapid increase in C_M at transition from regime I to II when the inner sphere rotates. Here, I found that various modes of Taylor-Görtler instability occurred. I arranged all my data to be of the type illustrated in Fig. 2(*b*) by careful and gradual acceleration of the inner sphere's rate of rotation. Other modes, which gave slightly lower C_M values for regime II, were obtained when the inner sphere was accelerated rapidly to its steady state value, as seen in some of the data from [1], [10] and [14].[5] I also observed the lower values of C_M, for relatively large β, when the sphere was accelerated quickly. It is concluded that no unique flow configuration is obtainable in regime II for condition of arbitrary acceleration to steady state.

In regard to Mr. Truman's request for enlightenment about the basis for equations (A1), (A2), and (A3) from references [6 and 7], these are not empirical results, but are theoretical results obtained by solution of the Navier-Stokes equations for the case of small but nonzero value of β in [7] and for arbitrary values of the ratio $a = R_2/R_1$ in [6].

In answer to Mr. Truman's question, the expression $C_M \infty R_e^{-1/5}$ is expected as $R_e \rightarrow \infty$ even for very small β, but I could not find such a relationship, because I could not operate at a sufficiently high R_e. I believe that the Reynolds number dependence of C_M/C_{MD} can be obtained simply by comparing empirical formula with each other for both the rotating sphere and rotating disk.

The author does not have any additional data of the type requested by Professor Nece.

[5]Number 14 in brackets designates an Additional Reference at end of closure.

Additional Reference

14 Wimmer, M., "Experiments on a Viscous Fluid Flow Between Concentric Rotating Spheres," *J. Fluid Mech.*, Vol. 78, Part 2, 1976, pp. 317–339.

Periodic Discontinuities in the Acceleration of Spheres in Free Flight[1]

C. T. CROWE.[2] This paper represents a very careful experimental study of the acceleration of spheres in a gas stream. The observed periodic nature of the drag force is worthy of continued study.

The authors propose that the periodicity is the result of periodic detachment of vortices behind the sphere. However, if the vortices were shed as a corkscrew (as implied by Torobin and Gauvin, reference [14]),[3] a lateral force more than a force in the direction of the sphere's motion might be expected. Still, the true nature of the mechanism of vortex shedding remains unknown.

The authors are not the only researchers to find an augmented drag coefficient of a spherical particle. Rudinger [1], conducting an experiment very similar to that described in this paper, measured drag coefficients considerably larger than those reported for a sphere in steady flow. He attributed the discrepancy to turbulence causing a zig-zagging motion of the particles. The authors might consider his findings in regard to their experimental results.

Crowe [2] also measured particle drag coefficients in a shock tube and reported values only slightly larger than the standard values for a sphere. In Rudinger's as well as Crowe's work, the nature of the data acquisition did not permit detection of periodicity.

Although unlikely, the presence of the particle in the convected flow behind the shock wave may attenuate the speed of the contact surface. The authors should establish that this momentum coupling is unimportant.

The authors also make no reference to the Basset force which may also augment the drag coefficient.

In summary, this paper represents an important contribution to the study of gas-particle flow. The care with which this experimental study was executed is noteworthy.

[1]By A. L. Tyler and D. L. Salt, published in the March, 1978, issue of the ASME Journal of Fluids Engineering, Vol. 100, No. 1, pp. 17–21.

[2]Professor of Mechanical Engineering, Washington State University, Pullman, Wash.

[3]Numbers in brackets designate Additional References at end of discussion.