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1. Introduction

The title of this project is "Lift and Drag Forces on Droplets and Particles in Wall-Bounded Shear Flows." The project is in the first year of a year continuation of DOE contract DE-FG02-88ER13919. The purpose of this renewal proposal is to request, and provide justification for, the second year of support.

This project has two goals. One goal is to calculate the lift force on a spherical droplet or particle that translates through a shear flow. The other goal is to measure the inertial migration velocity that is caused by the lift force.

In the previous three years of DOE support, certain ranges of the relevant Reynolds numbers were identified as being of importance in the inertial deposition of aerosols from turbulent shear flows. The present study will focus on these ranges of Reynolds numbers. There are two Reynolds numbers that must be considered. The Reynolds number, Re_G, based on the local shear rate is typically between 10^{-2} and 10^{-1} for aerosols as they pass through the viscous sublayer. The Reynolds number, Re_G, based on the relative ("slip") velocity between the aerosol and the surrounding fluid is typically of order unity for the aerosols that deposit as they pass through the viscous sublayer.

Many workers in the field have argued that shear-induced lift may be important in the deposition process. In some analyses, the Saffman lift force is used to estimate the importance of shear-induced lift in the viscous sublayer. The P.I. discussed some of this work in a paper published during the previous funding period (Physics of Fluids A 1, 1211-1224 (1991)).

There are two possible problems with using Saffman's lift force to compute the shear-induced lift force. First, Saffman's theory is

an asymptotic theory based on the assumption that both Re_G and Re_s are small compared to unity. Second, and possibly more important, Saffman assumes that $Re_G^{1/2} >> Re_s$. The P.I. has generalized Saffman's analysis (J. Fluid Mech. 224, 261-274 (1991)) to arbitrary shear rates. His results show that the Saffman lift force seriously overestimates the magnitude of the lift force for $Re_G^{1/2} << Re_s$. Since the theory is asymptotic, it is not clear whether it can be used when Re_s is order unity. That is the motivation for the current study.

Section 2 contains a technical progress report for the current funding period. Section 3 describes the work that remains to be done on the project. Section 4 contains a summary of the status of the project; a summary of papers that have been published, accepted for publication, or submitted for publication during the current funding period; and a list of talks presented during the current funding period.

2. Technical Progress Report for the Current Funding Period

A. Development of spectral-finite volume computer code

During the current funding period, Mr. Pradeep Cherukat has been supported as a research assistant under the subject contract. Mr. Cherukat is a PhD student in Clarkson University's chemical engineering department. Mr. Cherukat has developed a numerical algorithm and a computer program that solves the Navier-Stokes equation for the three-dimensional flow around a rigid sphere in a shear flow. A novel feature of his algorithm is the use of a Fourier expansion of the velocity and pressure fields in the azimuthal angle, ϕ. Derivatives or integrals with respect to ϕ may be expressed in terms of the Fourier coefficients. This approach has the advantage that the code can be used to simulate axisymmetric or weakly three-dimensional flows with a relatively small number of grid points in the ϕ direction. Conventional finite volume techniques require a large number of grid points in ϕ - even for axisymmetric flows. The program computes the velocity and pressure fields as a function of time starting from some initial values. The time-stepping procedure treats the nonlinear terms explicitly or semi-implicitly. On each time step, the program solves simultaneously the continuity and linearized momentum equations for the velocity and pressure fields. The generalized minimum residual method (GMRES) is used for that purpose.

Mr. Cherukat has tested the program for several cases. First, the case of axisymmetric Stokes flow was studied. It was found that the code could reproduce the Stokes drag coefficient to within a fraction of a percent. Next, finite (but small) Reynolds number axisymmetric flows were studied. The code reproduces not only the drag coefficient, but the flow field as given by the Oseen solution.

The first three-dimensional case that was examined was a Stokes flow in which a non-rotating sphere translates through a linear shear flow. An analytical solution is available for this case. Mr. Cherukat was able to reproduce the flow field and to obtain a value of the torque that was accurate within a few percent for a modest amount of spatial resolution. As final test, the sphere was allowed to rotate for the same Stokes flow, and the angular velocity of rotation was shown to agree well with theory.

Now, Mr. Cherukat is using the code to study the flow field around a sphere in a shear flow at finite Reynolds numbers. The main results of interest are the lift and drag forces acting on the sphere. A continuation method will be used in which low Reynolds numbers are studied first and the converged steady-state result from each run is used as an initial value for the next run at a slightly higher Reynolds number. Most of the runs to date have been made on a SUN SPARC workstation in the P.I.'s laboratory. Mr.

Cherukat recently gained access to an IBM RISC workstation with 128 Megabytes of main memory. The machine is in Clarkson's new computer simulation laboratory. The P.I. has applied for time on the Cray-2 computer at NCSA and the connection machine at NPAC.

B. Construction of homogeneous flow apparatus

In collaboration with Dr. Alan Graham's group at Los Alamos National Laboratory, the P.I. developed a homogeneous flow apparatus that can be used to carry out measurements of the inertial migration velocity induced by the lift force on a small particle. The apparatus consists of a vertical chamber containing two identical timing belts that can be driven by shafts connected to an electric motor. The hfa will contain a moderately viscous liquid - either mineral oil or an aqueous solution of polyalkylene glycol. Since the belts rotate in the same sense, a shear flow is created in the center of the apparatus between the upward moving belt and the downward moving belt.

The apparatus was constructed at Los Alamos over the last year. During the summer, Mr. Nick Tetlow, an undergraduate student at University of Northern Arizona, assembled the hfa, eliminated leaks, and was able to make some initial runs with it. The P.I. visited Los Alamos during the period 8/17/91-8/21/91. During that period, the P.I. and Mr. Tetlow performed some preliminary test runs with the apparatus. At moderate speeds, the belts turn smoothly and the flow field appears to be laminar. However, the aluminum arches will require a sharper flow splitter. Dr. Graham's experience with previous hfa's indicates that it should be possible to solve this problem by gluing a piece of metal foil to the flow splitters at the top and bottom of the hfa.

The hfa was shipped to Clarkson and arrived during the fourth week of September. Mr. Cherukat is working on a modification to the chain drive that should make the apparatus more stable and safer.

C. Asymptotic analysis

During the current funding period, the P.I. has performed an asymptotic analysis of the disturbance flow created by a sphere translating through an unbounded linear shear flow. The approach is based on the results presented by the P.I. in a paper published during the previous funding period (J. Fluid Mech. 224, 261-274 (1991)). In that paper, results were presented for the Fourier transform of the leading order approximation to the disturbance flow created by a particle translating parallel to a linear shear flow, $\mathbf{v} = Gx\hat{\mathbf{z}}$, where $\mathbf{v}$ is the velocity field and $\hat{\mathbf{z}}$ is a unit vector in the z direction. The P.I. has used numerical integration to determine the x-component of velocity as a function of x for y=z=0. The results will be useful in checking the results obtained with Mr. Cherukat's computer program. The P.I. also derived an analytical expression for the x-component of velocity at large values of x. This result may be used to determine the leading order effect of a distant wall. A manuscript reporting the results will be submitted for publication before the end of the current funding period.

3. Future Work

A. Numerical evaluation of shear-induced lift

Mr. Cherukat is testing the influence of the size of the computational region and the grid spacings on the lift force predicted by his computer program. Before the end of the current funding period, it should be possible to obtain values of the lift force over the ranges of particle Reynolds numbers that are

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