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Rotating Cylinder Apparatus for Rarefied Gas Flow Studies

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A rotating cylinder type apparatus is described, suitable for determining drag in cylindrical Couette flow of rarefied gases, and for evaluating tangential momentum accommodation coefficients at gas–solid boundaries. The apparatus is equipped with a damping device using diffusion pump oil for eliminating undesirable oscillations in the system. Tangential momentum accommodation coefficients of argon on aluminum were determined with an accuracy of ±2.5%. The results obtained indicate that the apparatus may be used over a wide pressure range, corresponding to free molecule and continuum flow conditions.

INTRODUCTION

SINCE the early work of Millikan[1] the rotating cylinder type apparatus has been often employed to study transport processes in rarefied gases and to evaluate momentum accommodation coefficients at gas–solid boundaries.[2–8] In these apparatus the gas is generally contained between two concentric cylinders, the inner one rotating, the outer one suspended on a torsion balance. The drag exerted on the outer cylinder is determined from the measured angle of rotation of the outer (drag) cylinder. One of the major difficulties encountered in such experiments is the undesirable oscillations of the drag cylinder. In order to minimize the level of the oscillations most of the recent investigations[4–7] utilized electromagnetic damping devices of varying design. In this paper an apparatus is described that does not require such electromagnetic damping devices, and is thus simpler both in design and in use. The apparatus here presented can be used to measure the drag within ±2.5% over a wide pressure range, and is suitable for determining momentum accommodation coefficients of gases at the surface.

EXPERIMENTAL APPARATUS

The rotating concentric cylinder apparatus is shown schematically in Fig. 1. The inner and outer cylinders are made of 7075-T6 aluminum. The 6.350 cm diam and 6.350 cm long inner cylinder is rotated at 3600 rpm by a synchronous electric motor. The rotor is totally enclosed by plates placed on both ends of the outer cylinder and is supported by precision ball bearings mounted in these plates.

The outer cylinder (total length 6.350 cm) is constructed in three sections. The drag on only the center section is measured, thereby minimizing end effects.[7] The center section of the outer cylinder (drag cylinder, 3.775 cm long, 7.112 cm i.d.) is suspended on a 12.7 cm long and 0.0127 cm diam tungsten wire. The two rigidly mounted end sections (7.112 cm i.d.) are separated from the drag cylinder by a narrow (0.10 cm) gap.

The novel feature of the apparatus is the vibration damper shown in Fig. 1. This damper consists of two thin walled (wall thickness 0.10 cm) concentric tubes filled with DC-703 diffusion pump oil. The 11.4 cm long and 1.90 cm diam outer tube is attached to the drag cylinder while the 19.5 cm long and 1.50 cm diam inside tube is attached to the stationary frame. There is a baffle plate mounted at the top of the outer tube (Fig. 1) to prevent oil from escaping during the outgassing period. A mirror is attached to the side of the outer tube to monitor the rotation of the drag cylinder. The entire system is mounted inside a 39 cm long and 11.4 cm supporting tube.

The drag measuring apparatus is placed inside a 45 cm diam bell jar vacuum system. The lowest pressure attainable in the system is 1×10^{-6} Torr. The test gas (commer-

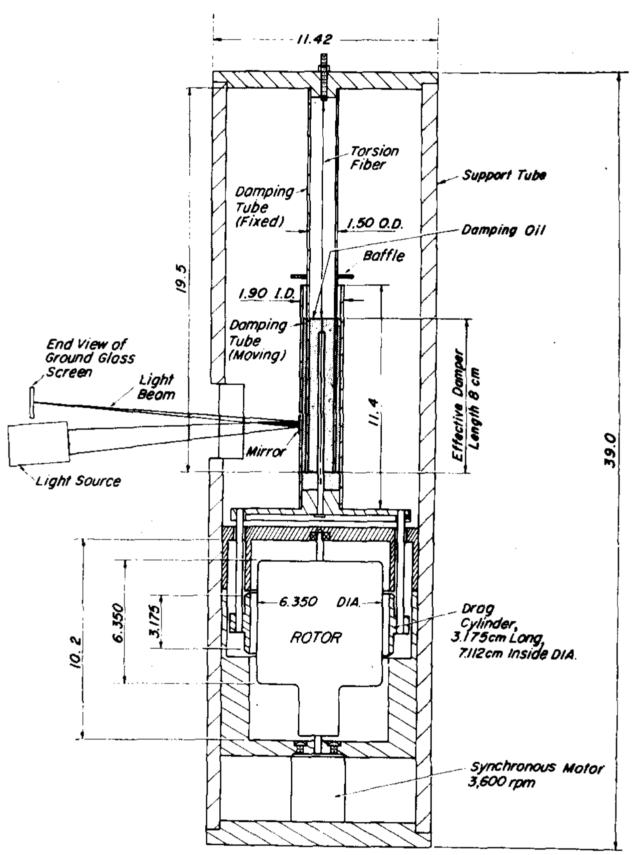

FIG. 1. Schematic of experimental apparatus. All units in centimeters.

cially pure argon) is admitted into the chamber through an adjustable leak. The pressure measurements are made with two precision McLeod gauges. Neither the vacuum system nor the concentric cylinder apparatus is baked out during the experiments.

Since there is a gas between the inner and outer cylinders the rotation of the inner cylinder produces a torque on the drag cylinder, moving it through an angle until this torque and the retarding torque due to the tungsten wire balance each other. Thus, the drag can be determined from the angle of rotation once the spring constant of the torsion fiber is known. The spring constant is determined by attaching the fiber to a cylinder of known polar moment of inertia and measuring this system's period of torsional vibration. The calibration cylinder has the same weight as the drag cylinder, ensuring that the extension of the fiber was the same during the experiments and the calibration. The rotation of the drag cylinder was measured by directing a beam of light onto a mirror mounted on the drag cylinder and by observing the position of the reflected light beam on a ground glass scale.

RESULTS

Using commercially available argon as the test gas, experiments were performed to evaluate the usefulness of the apparatus and the magnitude of experimental errors. From the experimentally observed quantities the tangential momentum accommodation coefficient σ was determined.

In any given experiment the pressure was held constant for a period of 10–30 min and during this time the position of the drag cylinder was recorded every 15 sec. Since the chamber pressure tended to drift slowly, McLeod gauge readings were taken every 2 min. Figure 2 shows the results of two consecutive typical data runs. From these data it can be observed that the deflection of the light beam (and consequently the drag) becomes constant about 10 min after the pressure is adjusted to a new constant value. Also, within the time periods of the experiments (1–2 h) the coefficient does not change noticeably, indicating that the soaking effect reported by Kuhlthau[6] does not influence the data (see Table I). This soaking effect would result in an increase in the value of the coefficient σ, when the system is allowed to stand for several hours at a pressure below ~0.1 Torr.

The above procedure was repeated both with the gas in the chamber (measured drag) and with the lowest pressure attainable in the system (residual drag).[5,7] The true drag was computed by subtracting the residual drag from the measured drag. All these measurements were made at sufficiently low gas densities, where the Knudsen numbers (Kn, defined as the ratio of mean free path to the gap size) were greater than 7, and where the expression for drag derived from free molecule considerations is expected to be valid.

In order to estimate the tangential momentum accommodation coefficient the following expression developed by Bowyer and Talbot[7] for free molecule drag in cylindrical Couette flow was used: $\tau=0.5\ \rho V(2RT/\pi)^{\frac{1}{2}}(a/b)^2$. Here τ is the shear stress on the outer drag cylinder (radius b), ρ and T are the gas density and temperature, respectively, and V is the surface speed on the rotor (radius a). The foregoing expression is valid only for the case of complete accommodation ($\sigma=1$). In order to include σ in the results the formula presented by Kennard[9] for free molecule plane Couette flow was employed, $\tau=0.5\rho V(2RT/\pi)^{\frac{1}{2}}[\sigma/(2-\sigma)]$. Combining these two equations results in

$$\tau=0.5\rho V(2RT/\pi)^{\frac{1}{2}}(a/b)^2[\sigma/(2-\sigma)]. \quad (1)$$

Values of σ are calculated from Eq. (1) using the data of 16 different measurements. The results are shown in

TABLE I. Results of drag measurements.

Run	Elapsed time[a] (min)	Chamber pressure (mTorr)	Kn	Net torque (dynes×cm)	σ
1	10–15	1.3	10.94	6.450	0.984
	15–20	1.5	9.47	7.584	0.993
	130–140	1.3	10.94	6.250	0.968
	140–150	1.2	11.85	6.189	1.003
2	10–20	1.4	10.16	6.782	0.971
	20–30	1.32	10.77	6.712	0.996
	30–40	1.4	10.16	6.799	0.973
	40–50	1.43	9.94	6.886	0.969
	50–60	1.45	9.81	6.921	0.964
	60–70	1.45	9.81	6.973	0.968
	70–80	2.0	7.11	9.283	0.950
	80–90	1.95	7.29	9.152	0.956
	90–100	2.0	7.11	9.117	0.941
3	20–30	1.95	7.29	9.222	0.960
	30–40	1.85	7.69	9.284	0.989
	40–50	1.95	7.29	9.352	0.967
				Average	$\sigma=0.972$

[a] Before each run the chamber was at its lowest pressure (1×10^{-6} mm Hg) for several hours. Elapsed time is measured from the time when the test gas is admitted into the vacuum chamber.

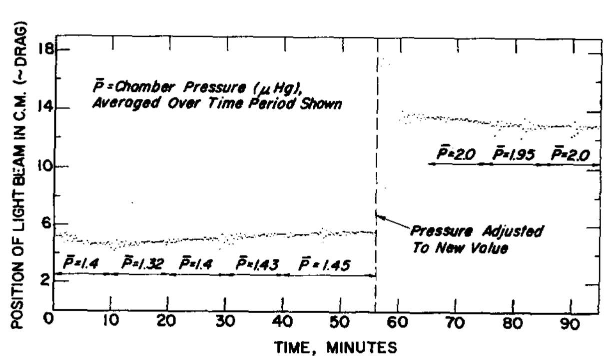

FIG. 2. Results of two typical data runs.

Table I. The average value of σ was found to be 0.97, with a maximum scatter of $\pm 2.5\%$ about this value. As a check on the result, the drag data reported in Ref. 7 for argon were substituted into Eq. (1). The σ value thus obtained agrees within $\pm 2\%$ with the present result, lending confidence to the operation of the apparatus and the data obtained.

The tangential momentum accommodation coefficient data reported here were all taken at pressures below 0.01 Torr to ensure free molecule flow in the experiments. However, the calibrations were performed at pressures as high as 760 Torr where $Kn \ll 1$ and the gas could be treated as continuum. The results obtained at those higher pressures indicate that the device is not limited to low pressures, but can be used over a wide pressure range.

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A Phasemeter for Photoelectric Measurement of Magnetic Fields

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Magnetic fields are sensed by means of the Faraday effect. Corresponding electrical signals in phase quadrature are generated. An auxiliary oscillator is used to obtain a phase modulation proportional to the magnetic field to be measured. Demodulation is performed by a phasemeter described in detail. This phasemeter keeps track of multiples of 2π by digital accumulation and performs linear analog interpolation with an accuracy of $2\pi/1000$. The hybrid digital/analog output has an arbitrarily wide measuring range. In addition, a purely analog output is provided combining the count of increments of 2π with the interpolation. The sampling rate of 40 kHz insures fast measurement response. Results of an experimental magnetic field sensing system incorporating the phasemeter as demodulation unit are presented.

INTRODUCTION

SIGNALS in phase quadrature at the outputs of photodetectors are generated in many instruments such as interferometers and optical shaft encoders. Usually reversible fringe counting is limited to increments λ/n where $n \leq 8$. Several interpolation schemes to achieve higher resolution have been described.[1–4] A radio engineering technique can be used to transform the signals at the photodetector outputs into phase modulation of an auxiliary carrier frequency.[2] Various methods for demodulation of the phase modulated signal have been suggested. One technique intended for high resolution interferometry is based on separate detection of increments corresponding to half-fringes directly from the output signals of the photodetectors and determination of fractional fringes beyond half-fringes by means of digital time interval measurement of the phase modulated signal described above. In order to avoid ambiguity in correlating the integral fringe count with the interpolation, special circuits have to be provided.[2] In another method the phase modulated signal is frequency demodulated and subsequently integrated. This method as described by von Willisen[4] is limited to periodic optical modulation. Since there is no digital fringe counting incorporated, the measurement range and resolution are limited by the analog signal processing.

The present phasemeter does not depend on the output signals of the photodetectors directly but rather on the transformed, phase modulated carrier signal. Therefore it can be considered a general phasemeter for dynamically changing phase differences exceeding 2π. Phasemeters with such characteristics have already been described.[5] The phasemeter reported here is particularly suited for a specific magnetic field measuring system intended for sensing fields varying in frequency from 0 to 500 Hz. Measurements nearly independent of electric potential are of importance as magnetic fields in the proximity of a conductor at high potential are of interest. In this system