Magnetic Densimeter-Viscometer

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trapped plasma without external heating and by sweeping the voltage of a Langmiur probe, the electron temperature is determined to be about 25 eV and equal to the ion temperature. The probe tip is flat and thin to minimize effects of sheath expansion. An estimate of the total number of particles produced by the gun is made by measuring the average density over the cross section of the octopole and multiplying by the containment volume of the machine. This gives 10^{17}–10^{18} particles/shot and is a lower limit since the absolute trapping efficiency of the octopole is not known.

In conclusion we find that this simple gun is capable of producing substantial quantities of interesting plasma and can be used inside plasma physics experiments since it is no larger than other diagnostic devices.

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Magnetic Densimeter–Viscometer*

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A combination magnetic densimeter and viscometer, which essentially simultaneously measures the density and viscosity on 0.3 ml specimens of fluids, is described. A small cylindrical buoy is freely suspended magnetically and coaxially with a larger surrounding cylindrical glass tube which contains the fluid in which the buoy is completely immersed. After calibration, the electrical current in the air core solenoids which magnetically support the buoy measures the density of the fluid while the period of revolution at constant power input determines the viscosity. The density can be measured to the order of magnitude of one part in 10^6 and the viscosity to one part in 10^4.

DENSITY and viscosity are among the most essential parameters for determining the molecular volume and molecular shape of substances in solution.[1] Also, their ratio occurs in an important way in the theory of fluid motion.[2] Usually the density ρ and viscosity η are measured by different experiments separated in time and on different samples of the material. Recently a brief preliminary report was given of a new method[3] with which the density, partial specific volume, and viscosity could be measured with the same specimen of the solution (~0.3 ml) at essentially the same time. The purpose of this paper is to give a more detailed description of the method and its performance.

Figure 1 shows a schematic diagram of the apparatus for magnetically suspending the cylindrical buoy B inside the solution contained in C and Fig. 2 is a block diagram of the

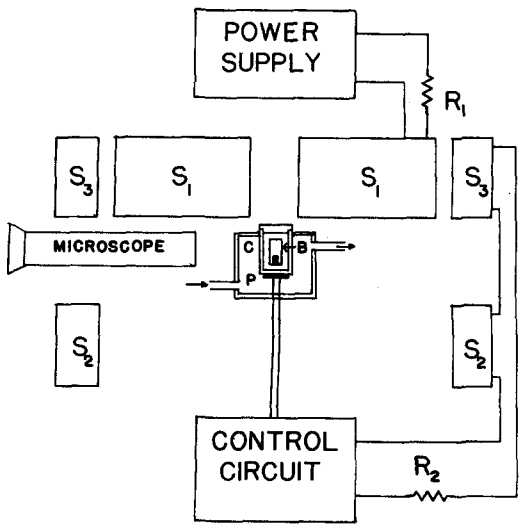

FIG. 1. Schematic diagram of the magnetic suspension densimeter–viscometer.

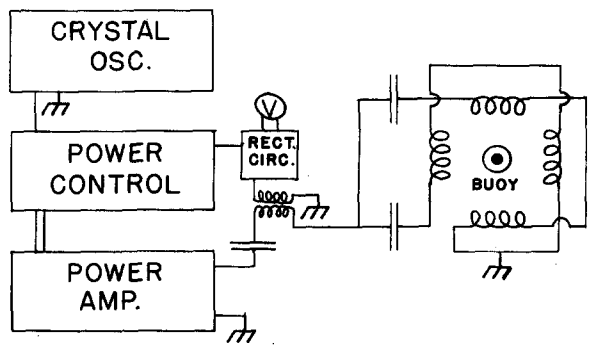

FIG. 2. Schematic drive circuit for the buoy.

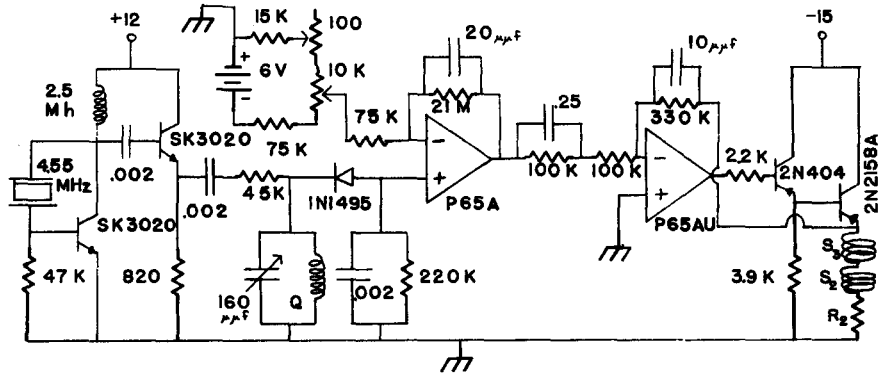

FIG. 3. Diagram of the control circuit.

circuit used for slowly rotating the buoy. The method of measuring the density of the solution is similar to that previously reported[4] but is sufficiently improved to require a brief description. The buoy B is an accurately made and carefully balanced cylinder. It consists of an inner solid ferromagnetic (Carpenter Hy Mu 80) cylinder, 0.2 cm long and 0.1 cm diameter, surrounded by a Kel-F hollow cylinder 0.7 cm long, 0.28 cm diameter with wall thickness of 0.02 cm. The ends are 0.05 cm thick. The container C is an accurately made glass cylinder and holds approximately 0.3 ml of solution. The buoy B is freely suspended inside the solution contained in C, by the air core solenoids S_1, S_2, and S_3. The three solenoids S_1, S_2, and S_3 have a common vertical axis with B and C. The solenoids S_2 and S_3 are identical and are spaced at a vertical distance equal to their radii in a manner similar to Helmholtz coils and also each is at an equal vertical distance from B as shown in Fig. 1.

The air core solenoids are Reynolds Foil Coils which are made of a single layer of aluminum foil covered with a thin layer of insulation. S_1 has 2500 turns and S_2 and S_3 each have 500 turns. In order to support B a constant current I_1 is passed through S_1 which is not quite large enough to raise B off the bottom of C. Next, a current I_2 is sent through S_2 and S_3 which are connected in series so that at the desired vertical position of B their magnetic fields cancel but their magnetic field gradients dH/dz add, where H is the magnetic field and z is the vertical coordinate. The upward force on the buoy B due to the solenoids is MdH/dz where M is the magnetic moment of the buoy and dH/dz is the resultant of the field gradients produced by S_1, S_2, and S_3. In general, $M=M_0+f(H)$ where M_0 is the permanent magnetic moment and $f(H)$ is the induced magnetic moment in B due to the magnetic field. Since the current I_1 in S_1 is held constant to one part in 10^6 by a carefully regulated constant current power supply and the resultant magnetic field due to the common current I_2 through S_2 and S_3 is zero, the magnetic moment M remains constant during a series of measurements. On the other hand, if I_2 is in the proper direction, dH/dz increases as I_2 increases and the upward force on B increases. If now the current I_2 is regulated by the sensing coil P and the control circuit, the buoy B is automatically held at the desired height as determined by the nonferromagnetic microscope. The up and down motion of the buoy is less than 0.1 wavelength of light and the microscope can detect a drift of 10^{-4} cm if such is present. Since the resultant axial magnetic field of the solenoids is a maximum along their common vertical axis, B is held firmly on the axis. Equating the forces on the buoy B,

$$F_1+MdH/dz=m_Bg-V_B\rho g=V_{B}g(\rho_B-\rho), \qquad (1)$$

where F_1 is the constant force on B due to S_1, dH/dz is the resultant gradient of the magnetic field due to S_2 and S_3, m_B, V_B and ρ_B are the mass, volume, and density of B, respectively, and ρ is the density of the solution contained in C. Since M is constant and dH/dz is exactly proportional to I_2,

$$F_1+KI_2=V_{B}g(\rho_B-\rho). \qquad (2)$$

Consequently, the value of the density ρ is a linear function of I_2, since all the other quantities in the equation are constant, and can easily be evaluated by calibration with liquids or solutions of known density such as water or standard sucrose solutions. I_2 is determined by measuring the potential across a standard resistance R_2 by a recording potentiometer or similar device and is constant to about one part in 10^6. The temperature is maintained to $\pm$ (0.002°C) by a cooling bath surrounding the chamber so that the density of the solution can be determined to the order of magnitude of one part in 10^6. On the other hand, for most cases, at present, it is only necessary to measure the density ρ to one part in 10^5 which is carried out routinely. The fact that the buoy is essentially stationary means all wall effects, etc., are zero, so that the volume of the container and hence the volume of the substance required for a measurement can be made small. This makes the ratio of surface area to volume large which in turn allows B and C to come to temperature equilibrium quickly. In practice, with aqueous solutions it reaches equilibrium in 2 or 3 min and the container C may be filled and a measurement of ρ made to one part in 10^5 in 5 min.

If the density ρ is measured as a function of the concentration the partial specific volume $\bar{V}$ of a substance can be found since

$$\bar{V}_0 = (1/\rho')[1-(\partial\rho/\partial C)_m{}^0], \quad (3)$$

where ρ' is the density of the solvent and $(\partial\rho/\partial C)_m{}^0$ is the slope of the plot of ρ vs C where the molality of each of the other components in the solution is held constant and the concentration C is extrapolated to zero. The concentration measurements are only accurate to about one part in 10^3, so that $\bar{V}$ is good to one part in 10^3. On the other hand, changes in $\bar{V}$ of the order of one part in 10^6 may be observed. If the buoy is slowly rotated by a rapidly rotating magnetic field surrounding the buoy, the power input to the buoy is a function of the viscosity of the solution. Figure 2 shows a schematic diagram of this drive circuit. A 50 W af power amplifier is driven at 10^4 Hz by a piezoelectrically controlled oscillator. The feedback circuit automatically maintains the power input constant to the drive coils which surround the rotor. The power input to the rotor itself is so small that the heating of the buoy is negligible. B is rotated uniformly and slowly enough to avoid Taylor vortices, etc. The time for one revolution of B is usually greater than 1 min and if timed for 20 or more complete revolutions can be measured with stop watches to about one part in 10^4. The power amplifier and circuit are over designed to reduce heating and drift. Figure 3 is a wiring diagram of the control circuit of Fig. 1. It consists of a 4.5 MHz piezoelectrically driven (Q coil) sensing detector P, rectifier, operational amplifiers with feedback, derivative circuits, and power stage. The current in the sensing coil is made so small that heating and mechanical forces on the buoy are completely negligible. Figure 4 shows a typical calibration curve in which the potential drop across the precision standard resistance R_2 is plotted vs the density of specially purified NaCl solutions. It will

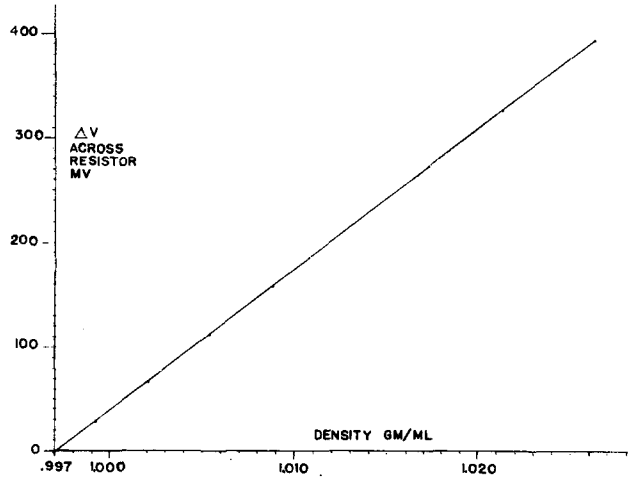

FIG. 4. Calibration curve of density vs potential drop across the resistance R_2 with aqueous solutions of NaCl.

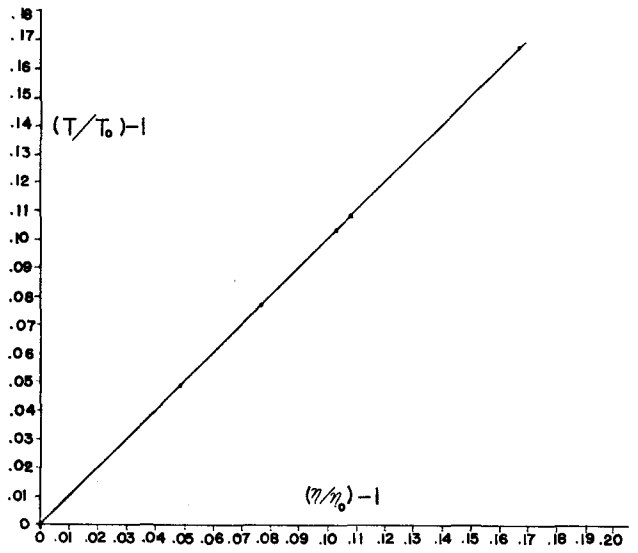

FIG. 5. Comparison of data taken with present magnetic densimeter-viscometer and that reported by Jones and Fornwalt[5] for D_2O–H_2O solutions. η_0 is the viscosity of pure water, η is viscosity of the solutions, T_0 is the period of a revolution of the buoy with pure water, and T is its period with the solutions at constant power input. The temperature was 25°C.

be observed that within the limits of the accuracy with which the densities of the solutions are known, the line is straight which shows that Eq. (2) is satisfied and ρ is linearly proportional to I_2. Similar plots of potential drop across R_2 vs the density of sucrose solutions also were linear within the limits of the known densities of the sucrose solutions. Figure 5 shows a plot of (η/η_0-1) vs (T/T_0-1) for D_2O–H_2O mixtures at 25°C where η_0 is the viscosity of pure water, η is the viscosity of the mixture, T_0 is the time of a revolution of the buoy with pure water, and T is the time of revolution of the buoy with the mixture with constant power input. It will be observed that the points fall on a straight line which shows that the values of the viscosity measured by the apparatus described above are in excellent agreement with those reported by Jones and Fornwalt[5] using other methods. The same type of results were obtained with aqueous solutions of NaCl and with sucrose. It is clear that the solenoid S_1 may be replaced by a permanent magnet if desired and that the container C and buoy B may be located above instead of below S_1 as shown in Fig. 1, if this is more convenient.

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