A MECHANICAL MAXWELL DEMON

By J. L. Costa, H. D. Smyth and K. T. Compton

Abstract

A direct experimental verification of Maxwell's distribution law.—A beam of molecules was directed through radial slits in two disks mounted about 8 cm apart on a common shaft which rotated at a speed from 500 to 6000 rpm. in a highly evacuated enclosure. Those molecules which, because of a favorable relation between their velocity and the speed of rotation of the disks, passed through the slits, fell on the vane of a sensitive radiometer. The variation of the radiometer deflection with the speed of the disks was observed for hydrogen, nitrogen and carbon tetrachloride. The form of the curves varied with the nature of the gas and was in agreement with the predictions of the kinetic theory, thus constituting a rather direct confirmation of Maxwell's distribution law. It is feared, however, that it is not possible at present to develop the apparatus sufficiently to obtain a "velocity spectrum" of the neutral molecules in a gas as was the original hope of the writers.

IT IS a curious consequence of the electrical nature of matter that we can study atoms and molecules more easily when they are ionized than when they are in the normal electrically neutral state. If we are dealing with ions we can control their paths and speed, measure the ratio of their charges to their masses and in general study their behavior as individual particles but when dealing with normal molecules we still have to depend on statistical effects such as pressure, density, and temperature. In many phenomena, however, particularly in gaseous chemical reactions, it would be of great interest if we could determine the exact nature of the uncharged particles present just as we can determine the nature of the charged particles present in a discharge tube by the use of positive ray analysis. An attempt to achieve this end experimentally is described in the present paper. Though it was not sufficiently successful to be used as a method of "neutral ray analysis" it did give an experimental verification of Maxwell's distribution law which is thought to be of interest.

According to the kinetic theory of gases the average kinetic energy of all the molecules in a gas at a given temperature is the same and therefore if some of the molecules are of smaller mass than others they must have greater velocity. Moreover, the velocities of molecules at ordinary temperatures are always of the order of several hundred meters per second, a magnitude not far from realizable mechanical speeds. Long ago Maxwell suggested that molecules of differing velocities might be separated by the intervention of his infinitesimal but highly intelligent "demons." It occurred to the writers that vacuum technique had progressed to the point where a mechanical Maxwell demon might be possible.[1]

[1] Stern (Zeits. f. Physik **2**, p. 49, 1920) had already made a direct measurement of the molecular velocities in the case of a metallic vapor and Tykocinski-Tykociner (Jour. Op. Soc. Am. **14**, p. 423, May 1927) has recently published a plan for an experiment similar to the one described here.

The principle of the experiment may be best understood by reference to the schematic diagram in Fig. 1. Suppose a stream of gas is emerging from the slit S_1 into a highly evacuated space. Some of the molecules will have such velocities that they will pass through the radial slits s_1, s_2 · · · in the periphery of the rotating disk D_1; in particular, a few will continue through the second rotating disk, through the second fixed slit S_2 and impinge on the mechanical detecting system R, a radiometer. The molecules of this group, however, will no longer be of all velocities. Since their time of passage from D_1 to D_2 must be such that they will find a slit in D_2 in front of S_2, the beam will consist of molecules of one or more definite ranges of velocity depending on the dimensions of the apparatus and the speed of rotation of the disks.

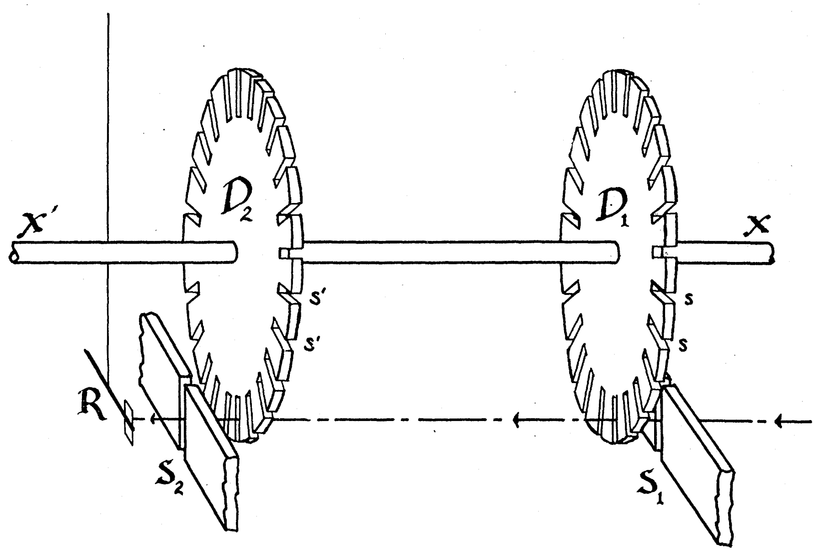

Fig. 1. Schematic diagram of apparatus.

Consider a simple case. Suppose the gas emerging from S_1 consists of two kinds of molecules of differing mass but in temperature equilibrium. Then there will be molecules of two velocity groups corresponding to the Maxwell distribution around the mean velocities for the two kinds of molecules. Let the number of molecules passing through S_2 be studied as a function of the speed of rotation of the disks. If there is only one slit in each disk a maximum should occur corresponding to the movement of the slit in D_2 in front of S_2 in the time of passage of each type of molecule from D_1 to D_2. The total number of molecules passing through S_2, however, will be very small and difficult to detect. On the other hand if there were a large number of slits in D_2 then at such a speed that the fast molecules get through the first slit s_1' coming in front of S_2, the slow molecules get through the second or third and the maxima are obscured. However, since this effect is calculable and the chief difficulty to be feared is that of insufficient intensity the latter case seems to offer a better chance of success.

Apparatus and Procedure

The drawing in Fig. 2 represents the apparatus as realized. Inside the cylindrical bronze casting B are set two flanges F_1 and F_2 in each of which is a sapphire bearing accurately aligned along the axis of the cylinder. These bearings carry the shaft A on which are mounted two duralumin disks with radial slits cut in their peripheries. Also on the shaft A is the rotor R of the electromagnetic driving system. It is actuated by the stator M. The glass window W_1 gives a view of the rotor from outside, thus allowing the

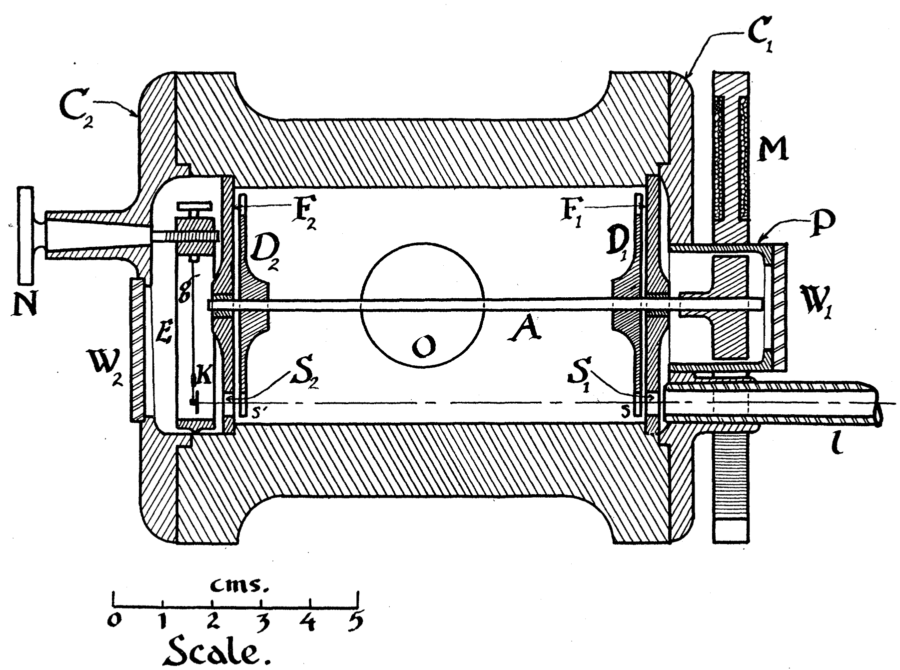

Fig. 2. Diagram of apparatus as realized.

speed to be measured. Gas is fed in through the glass tube l to the slit S_1 and evacuation is through O by big tubing to a rapid diffusion pump. E is the radiometer mount with suspension z and the delicate movable system k. This system carried a small mirror which was illuminated through the window W_2. A radiometer, rather than some other detector of the molecular beam, was chosen principally because of its insensitivity to the action of stray molecules not included in the primary beam coming through the slits. The movable system weighed between one and two mg, was supported by a delicate quartz fiber, was rendered conducting by sputtering in order to eliminate electrostatic disturbances, and was given a slight magnetic control in virtue of unavoidable magnetic properties. The whole apparatus was constructed with a view to solidity and freedom from vibration and was bolted down to a concrete pillar.

Varying the speed of the rotary converter which supplied the current to M made it possible to vary the speed of R between 500 and 6000 r.p.m.

The procedure in an actual experiment was to observe the deflection of the radiometer as a function of the converter speeds, the latter then being reduced to speeds of rotation of the slit system by a stroboscopic calibration. Small deflections due to secondary causes and varying with the speed of the rotating system were measured and allowed for in the experiments.

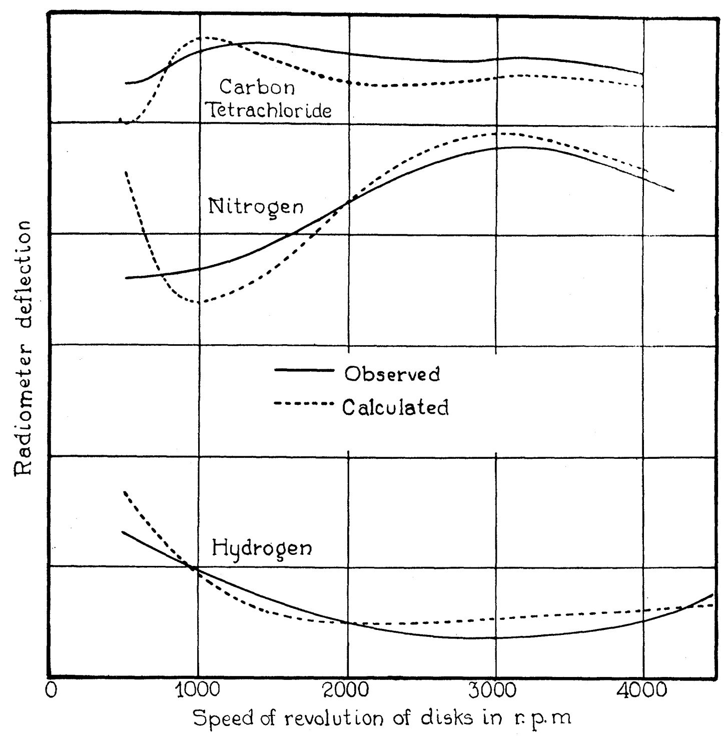

Fig. 3. Variation with speed of the disks of the radiometer deflections.

Results

It was found that when a pure gas was used quite consistent and reproducible results were obtained and that the form of the curves varied with the nature of the gas. This may be seen from Fig. 3 where the experimental curves are averages of several runs. At first sight the comparative flatness of the maxima was disappointing but a theoretical analysis of the situation showed that the curves predicted by kinetic theory were actually in good agreement with the observations.

The calculations involved are a little tedious but quite straightforward and need not be reproduced here. First the probability of a molecule getting through to the radiometer is calculated as a function of the speed of the molecule. As it will depend on the speed of rotation of the disks as well as the distribution of the slits in the periphery and the other dimensions of the apparatus, we need to calculate curves for various speeds of revolution. Then for every molecular speed we multiply this geometrical probability by the kinetic theory probability of a molecule having that speed and by the speed itself. This gives numbers proportional to the numbers of molecules of various speeds passing through to the radiometer. Again this calculation must be repeated for various speeds of rotation of the disks. Up to this point the only assumption made is that the molecules have a Maxwellian distribution of velocity.

In order to find the torque produced in the radiometer by the impact of these molecules on its vane it is necessary to make an additional assumption. Two possibilities suggest themselves. First that the molecules are not reflected or are reflected with a velocity proportional to their velocity of impact. This means that they contribute to the vane an amount of momentum proportional to their velocity and we obtain a number proportional to the total torque on the radiometer at a given speed, by multiplying the number having a given velocity by that velocity and integrating over all values of the velocity. It was by this procedure that the theoretical curves in Fig. 3 were obtained.

The second possibility is that the molecules are reflected with Maxwell distribution of velocity characteristic of the temperature of the vane. This would mean a contribution to the torque proportional to the number of molecules striking in addition to the part of the torque proportional to the product of the number striking and their velocity. This more complicated case has not been worked out in detail but has been considered sufficiently to conclude that it would simply cause a slight flattening of the maxima in the theoretical curves obtained in case 1.

In considering the agreement between the experimental and theoretical curves in Fig. 3 several points should be mentioned. At the low speeds, the difficulty of controlling the speed accurately is greater and the theoretical large torque would also be obscured by the simultaneous increase in stray effects. At all speeds there is an unknown amount of periodic deviation of the induction motor from exact synchronism ("creeping") which would tend to blur the maxima. Finally the radiometer had to be used at nearly the limit of its sensitivity which made the observations difficult.

It is thought therefore that the agreement is as good as could be expected and constitutes a rather direct confirmation of Maxwell's distribution law although not distinguishing between the two mechanisms of reflection suggested above. It is feared, however, that it is not possible at present to develop the apparatus sufficiently to obtain a "velocity spectrum" of the neutral molecules in a gas as was the original hope of the writers.

Woonsocket, R. I. (J. L. C.)
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