Experimental evidence for supersonic ion flow in a low pressure plasma

1972 J. Phys. A: Gen. Phys. 5 1119

(http://iopscience.iop.org/0022-3689/5/7/020)

J. Phys. A: Gen. Phys., Vol. 5, July 1972. Printed in Great Britain. © 1972.

Experimental evidence for supersonic ion flow in a low pressure plasma

R H VAREY and L B KAPP
Marchwood Engineering Laboratories, Central Electricity Generating Board, Marchwood, Southampton, UK

MS received 18 May 1971, in revised form 3 February 1972

Abstract. An experiment is described in which plane Langmuir probes with different orientations with respect to ion flow were used to measure ion velocity in the side arm of a low pressure mercury discharge. The ions appear to be supersonic, a result which confirms recent theoretical predictions.

1. Introduction

Plane Langmuir probes give different characteristics according to their orientations with respect to the direction of ion flow (Varey 1970). The difference increases with the speed of the ions and in this paper we shall use the difference to indicate ion speed.

Recently several workers using fluid models have suggested on theoretical grounds that ions in a collisionless neutral plasma can have supersonic velocities. Stangeby and Allen (1970) have derived a sheath criterion for ions which arrive obliquely at a sheath edge. They show that a necessary and sufficient condition for the formation of a sheath is that the component of velocity perpendicular to the sheath edge should be equal to the ion acoustic speed defined as $(kT_e/m)^{1/2}$, where k is Boltzmann's constant, T_e electron temperature and m the ion mass. The position of the sheath edge was assumed to be known and was not located theoretically. However, the derived condition is independent of any additional velocity component parallel to the sheath edge, which means that in general ions would be supersonic at the sheath edge. Using this criterion as a boundary condition Andrews and Swift-Hook (1971), Swift-Hook and Andrews (1971) and Stangeby and Allen (1971) have obtained numerical solutions to the problem of spherical and cylindrical probes in a flowing plasma. In both cases the ions are shown theoretically to be supersonic close to the probe.

The idea of supersonic ion flow in a neutral plasma is interesting because previous authors (Woods 1965, Kino and Shaw 1966, Forrest and Franklin 1966) have predicted theoretically that when ions reach the sound speed a sheath is formed, so that ions exceed the sound speed only inside a sheath. A similar result is obtained from the classical analyses of Tonks and Langmuir (1929), Harrison and Thompson (1959) and Self (1963).

However, those results were all derived for essentially one dimensional (planar, cylindrical and spherical) situations, whereas the suggestions of supersonic flow apply to two dimensional situations. There is therefore an element of uncertainty as to the conditions under which the theories are applicable. Our measurements with plane Langmuir probes suggest that the ions can go supersonic in a two dimensional plasma flow.

2. Experiment

The measurements were made in the side arm of a low pressure DC discharge drawn from an anchored mercury cathode in a glass T-piece (each arm 75 mm diameter). The ion flow is essentially two dimensional, that is, it cannot be effectively reduced to one dimension by symmetry. Ion trajectories are shown diagrammatically in figure 1. Most of the ions reaching the walls of the side arm are formed in the main part of the discharge. They fall to the walls under the influence of an electric field similar to that in a normal positive column. The problem is to discover whether or not they are supersonic.

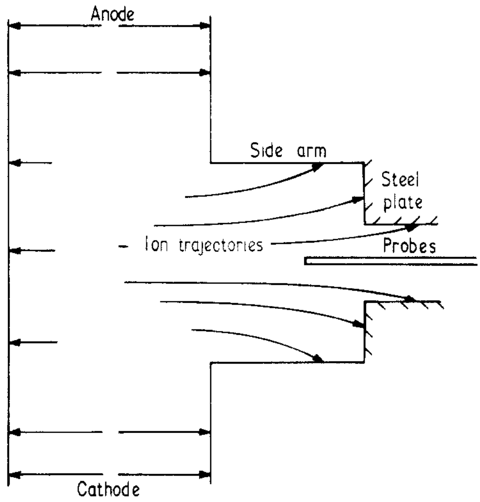

Figure 1. Ion trajectories, side arm and probes, (not to scale).

To do this, two Langmuir probes were placed in the plasma in turn. Both were plane, one with its face perpendicular to the axis of the side arm and the other parallel to it. They were made of 1·5 mm diameter tungsten rod sealed into glass to give a total diameter of about 3 mm (Varey 1970). The experimental arrangement is shown in figure 1. At the end of the 75 mm diameter side arm there was a steel plate with a central hole 12·5 mm in diameter. The cathode temperature was maintained at $-1{\cdot}4 \pm 0{\cdot}2$ °C which corresponds to a mercury vapour pressure of about 0·15 mTorr; the current was 21 $\pm$0·2 A. Both Langmuir probe characteristics gave the same value for electron temperature (22 200 K); this showed no systematic variation along the side arm and was constant to within experimental error ($\pm$ 500 K).

The correct variation in plasma density is given when the probe face is parallel to the direction of ion flow (Varey 1970), that is, to the axis of the side arm. The variation of plasma density measured along the axis in this way is shown in figure 2(*a*). The plasma density given by the characteristics of the other probe was also found, and the ratio of the two values is shown in figure 2(*b*). It is this ratio which gives an indication of ion speed.

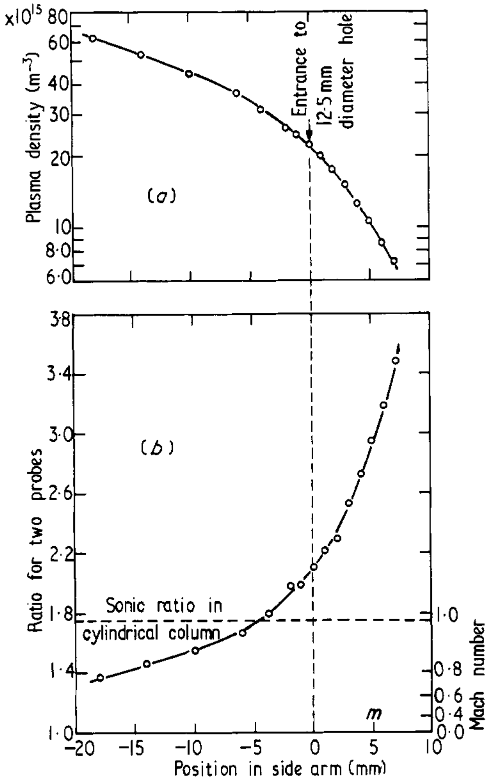

Figure 2. (*a*) Plasma density on axis of side arm; probe face parallel to axis. (*b*) Ratio of densities given by two probes and corresponding Mach number in a cylindrical column.

A separate experiment has been carried out previously (Varey 1970) in a cylindrical positive column where the ion velocity is known as a function of radial position from the theory of Tonks and Langmuir (1929). There, the ratio of the values for plasma density given by the probe perpendicular to and facing the ion flow and by that parallel to it increases with the velocity of the ions. On the axis, where the ion drift velocity is zero, the ratio is one and close to the wall where the ions are sonic the ratio is 1·7–1·8. By comparing the ratio of probe readings with the ion velocity corresponding to their radial position the relationship between ion velocity and the ratio of probe readings can be found. This is shown in the lower half of figure 2(*b*), the figures on the right being the Mach number of the ion flow and those on the left the ratio of the probe readings. The points plotted in figure 2 are the results of the present experiment in the side arm of a discharge. It can be seen that the ratio reaches values much higher than 1·7–1·8, particularly in the 12·5 mm diameter hole where it goes to twice that number.

Now the velocity scale corresponding to various plasma density ratios has actually been established only for a cylindrical positive column. For other ion velocity distributions it may not be strictly correct to assume the same correspondence, and the ions may not reach the speed of sound at exactly the same ratio. However, the shape of the ion velocity distribution in the side arm will not be very different from that in the positive column so a ratio as high as 3·4 is a strong indication that the ions are going faster than the speed of sound. The point at which the ions become supersonic is probably close to the mouth of the 12·5 mm diameter hole. There the ratio is 2·1 which is close to the sonic ratio in a positive column (1·7–1·8).

Hence, plane probes facing in different directions indicate experimentally that ions can be supersonic in a two dimensional plasma thereby confirming the theoretical predictions.

Acknowledgments

This work was carried out at the Marchwood Engineering Laboratories and is published with the permission of the Central Electricity Generating Board.

References

Andrews J G and Swift-Hook D T 1971 *J. Phys.* A: *Gen. Phys.* **4** 142–57
Forrest J R and Franklin R N 1966 *Br. J. appl. Phys.* **17** 1061–7
Harrison E R and Thompson W B 1959 *Proc. Phys. Soc.* **74** 145–52
Kino G S and Shaw E K 1966 *Phys. Fluids* **9** 587–93
Self S A 1963 *Phys. Fluids* **6** 1762–8
Swift-Hook D T and Andrews J G 1971 *J. Phys.* A: *Gen. Phys.* **4** L21–4
Stangeby P C and Allen J E 1970 *J. Phys.* A: *Gen. Phys* **3** 304–8
—— 1971 *J. Plasma Phys.* **6** 19–32
Tonks L and Langmuir I 1929 *Phys. Rev.* **34** 876–922
Varey R H 1970 *J. Phys.* D: *Appl. Phys.* **3** 1107–12
Woods L C 1965 *J. Fluid Mech.* **23** 315–23