AIAA Journal
Vol. 36, No. 6, June 1998

Velocity Measurement in Hypersonic Flows Using Electron-Beam-Assisted Glow Discharge

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A new pseudospark-type electron gun has been utilized in the F4 high-enthalpy, low-density, hot-shot wind tunnel at ONERA. The main goal was to perform accurate measurements of the velocity profile across the boundary layer and the freestream through a time-of-flight principle. In these experiments, an intense pulsed electron beam traces the path of a high-voltage, sustained-glow discharge in some 10 ns. A charge-coupled device camera is opened briefly, 5 μs after the electron gun actuation, to image the position of the luminous column convected by the flow.

Introduction

HIGH-ENTHALPY hypersonic flows constitute an especially difficult problem because of their nonequilibrium character. Measurements and modeling are delicate and challenging. Solid probes never render the complex chemistry, and the codes are hard to validate using only pressure and heat flux measurements, which have long been the only quantitative tools available to the experimenter. Visualizations using schlieren and interferometry have provided complementary data about shocks and boundary-layer positions and, rarely, semiquantitative information on density. Laser methods and electron-beam-excited fluorescence have allowed significant progress to be made since the late 1960s.[1] The present paper deals with the peculiar problem of measuring the velocity in short-duration, low-density, high-enthalpy flows, where the local velocity cannot be measured by conventional laser velocimetry techniques. Diode laser absorption,[2-3] exploiting the Doppler shift in the positions of spectral lines, can provide only averaged values along the path of the laser beam crossing the flow. Time-of-flight measurements with electron beam fluorescence (EBF) of N_2 are possible in these low-density flows.[4] However, in the high-enthalpy facility F4 at ONERA,[5] this application was unsuccessful both with a classical filament-based gun and with a high-current, pulsed-electron gun because of the high level of the stray light emitted by the flow.

On the other hand, the low density of the gas allows one to develop various kinds of electrical discharges for investigations of the spatial hypersonic flowfield phenomena. This glow discharge technique has been utilized for visualization of shock waves,[6] streamlines around hypersonic vehicles,[7] hypersonic shock-wave/boundary-layer interaction,[8] etc. Although these methods are very useful for qualitative vizualization, they do not permit accurate measurements of the velocity field or velocity profiles within the flow to be performed. Indeed, such measurements imply that a narrow columnar initial discharge path can be created within the flows by using a needle electrode for initialization of the discharge. According to Nishio,[9] this seems rather difficult when high-velocity flows ($v >$ 1.5 km/s) are concerned. Moreover, the concentration of the electric field attaches one end of the discharge to the tip of the needle. This disturbs the shape of the trace carried by the flow and thus leads to erroneous estimations of the velocity profile near this tip. For high-enthalpy, hypersonic-flow measurements, this would again imply that this initial columnar path remain bright enough to overcome the stray light when convected by the flow.

The aim of this paper is to describe a special device developed to overcome these drawbacks. Based on the concept of the electron-beam-assisted glow discharge, it combines the advantages of EBF and electric discharges techniques. The paper reports how velocity profiles are obtained when using this apparatus at the hot-shot facility F4.

Velocity Measurement Using EBF

In a low-density flow, the use of an energetic electron beam (typically 25–60 keV) induces a complicated set of excitations in the gas all along the beam. For molecular nitrogen, these emissions are mainly from the first negative system N_2^+1N and the second positive system $N_2 2P$. When the density is low, some of the secondary electrons in the plasma have sufficient energy to continue exciting molecules, thus producing radiative emissions that keep the plasma glowing downstream. For a narrow column of excited gas, a high-speed shuttered camera, opened at different known times, can follow the column displacement with the flow. However, with a classical electron gun (filament-heated gun emitting a thin, 1-mm-diam electron beam of energy up to 30 keV and intensity up to 4 mA), the afterglow from a single pulse of a few hundred nanoseconds is not detectable even with an image intensifier of high gain coupled to a sensitive charge-coupled device (CCD) detector array. Image accumulation then has to be achieved with a train of columns induced at regular intervals of time by the pulsed beam and pulsing the opening of the camera at the same frequency as the pulsed beam frequency. Such measurements were done at the Mach 10, medium-enthalpy R5Ch wind tunnel, with only a high-speed shutter coupled to a photographic plate. Images were accumulated over about 40 ms (Ref. 10).

For applications in high-enthalpy, short-duration flows, the image accumulation is not effective, as the intense stray light emitted by the flow also accumulates on the camera. The only recourse is in having an initial electron beam with current high enough to achieve a correct measurement from a single shot. This might be obtained with a pseudospark device capable of emitting high-voltage, high-current electron beams in very short pulses of about 20–50-ns duration, as recently used for spectroscopy by Lutfy and Muntz,[11] who demonstrate the feasibility of rotational temperature measurements in the vicinity of a test model.

Pseudospark Electron Gun

The pseudospark was discovered in 1979 at the University of Erlangen in Germany, where research is carried out in the development of electrical switches using controlled pulsed hollow cathode discharges.[12] A pseudospark consists of two electrodes in the form of coaxial disks, each with a central hole, separated by a gap of a few millimeters (Fig. 1). The upper disk forms the cathode, whereas the lower one acts as the anode. Injection of 10^9–10^{10} electrons to the back of the cathode induces the electrical breakdown of the gap between the two electrodes. The standing voltage that can exceed 60 kV for a single-stage apparatus then, typically,[13] collapses to zero

Received June 3, 1997; revision received Feb. 23, 1998; accepted for publication Feb. 26, 1998.

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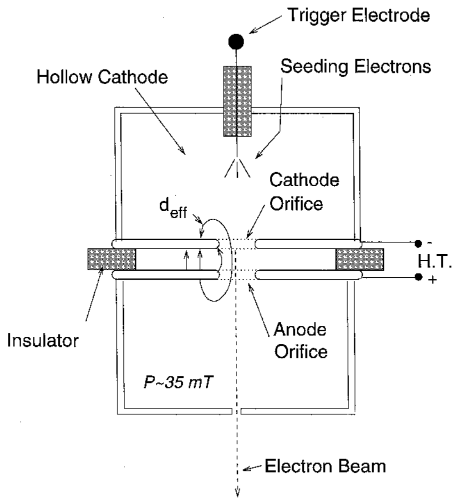

Fig. 1 High-voltage, low-pressure, pseudospark switch.

in 20–50 ns. This is simultaneously accompanied by emission of a very bright pinched electron beam along the axis of the disks. The maximum current is then 300–1000 A, the mean section of the beam is in the square millimeter range, and the electron energy is related to the instantaneous voltage between the electrodes. The fast electrons exit the anode disk orifice and can propagate for a few tens of centimeters in a low-pressure medium. In practice, the pseudospark, which operates in the same gas as the wind tunnel, is provided with its proper gas-pressure control device and communicates with the wind tunnel through a reduced hole of 0.3-mm diameter. This permits one both to achieve a narrower electron beam for the gas ionization trace and to maintain a low pressure inside the pseudospark that remains almost independent from the actual pressure of the flow. Unfortunately, in spite of the high current carried by the pseudospark beam, experiment shows that the luminosity of the afterglow from the plasma column remained far too low to optically trace the convection of the column for velocity of measurements at F4.

Electron-Beam-Assisted Glow Discharge

The other important process resulting from collisions between the fast electrons and the molecules from the flow is gas ionization producing a conductive plasma of ions and low-energy secondary electrons. Because of the initial electrons from the beam, ionization can grow along the preionized path under an electric field that is not large enough to create avalanche breakdown elsewhere in the wind tunnel. Thus, the strategy was to utilize simultaneously the fast-electron emission by the pseudospark, together with its high-voltage breakdown capability, to sustain across the plasma column a supplementary discharge current of much longer duration than the pulsed-electron beam. This induces an intense fluorescence that persists for some microseconds, as long as an electrical current of a few amperes feeds the conductive trace. As the electrodes are carefully designed to not emphasize any peculiar way for the current path, the glowing line is freely convected by the flow along a few centimeters. Figure 2 shows how this is done in the special pseudospark gun devised for the F4 wind tunnel, which operates with the following chronology.

1) In about 1 ms, the two capacitors C_1 and C_2 are charged through the resistors R_1, R_2 and R_3; the time constants of the resistor capacitor (RC) circuits are chosen so as to have nearly ground potential for the anode disk.

2) When the C_1 and C_2 potentials come near to a value of -50 kV, electrons from field emission at the filament tip are injected within the hollow cathode, where they multiply as a result of the pendulum trajectories they follow. A conductive plasma is thus created in the vicinity of the cathode hole, which diffuses into the gap between the electrodes. This finally triggers the electrical breakdown between the disks and then short circuits the capacitor C_1 in about 20–50 ns.

3) According to the much longer time constants of the RC circuits, the external electrode of the pseudospark, connected to the anode, rises to the same high negative voltage as the C_3 capacitor.

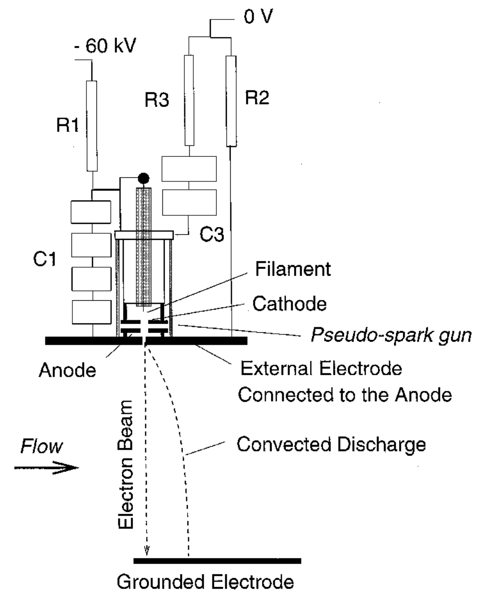

Fig. 2 Improvement of the pseudospark electron gun for velocity measurement.

4) During the same time, an electron beam of about 50 keV is emitted from the pseudospark toward any electrode at ground potential placed in the flow.

The plasma column induced by the beam is a privileged path to form a current loop between the R_3C_3 circuit and ground potential; thus, the capacitor C_3 will maintain a discharge through the plasma column for a time corresponding to the R_3C_3 time constant. This time is chosen to be about 5 μs in the F4 case, allowing the column to be optically detected about 25 mm downstream for velocities of 5000 m/s. During this time, the column is convected and deformed by the flow following the velocity profile that is present.

Pseudospark Gun at the F4 Facility

Figure 3 shows the implementation of the pseudospark gun in the F4 wind tunnel. The gun is placed on top, with the gun exit touching the flow boundary at 350 mm from the nozzle axis. A camera placed outside the test section visualizes the beam at 90 deg (Fig. 4). The camera system consists of a high-speed, high-gain image intensifier coupled, using a macro lens, to a cooled 512×512 array CCD camera (EGG-Princeton). This assembly is protected by a mechanical shutter that prevents stray light from leaking through the image intensifier when the intensifier is not actuated. This shutter is opened a few milliseconds before the intensifier is turned on. The operation of the CCD is controlled by the EGG-Hidris software from a personal computer. The model in the test section is a sphere of 80-mm radius placed on the axis of the flow. It was supposed to act as a grounded electrode, but it is too far away for the beam to propagate to it. Thus, for this purpose, a thin grounded metallic rod is placed, parallel to the flow axis, 170 mm away from the gun exit.

As already mentioned, air is used as the active gas of the pseudospark, but its pressure must be carefully regulated to have proper electrical breakdowns. The pressure in the gun must be kept between 35 and 37 mT for optimal operation at -50 kV. Following the Paschen law, higher pressures in the gun result in lower breakdown voltages and, thus, in lower luminosity for the discharge. Lower pressures delay the time of the electrical breakdown, which occurs in an erratic way without electron beam emission. In this case, the discharge causes only a diffuse glow through the region outside the gun.

Triggering synchronization between the gun, the camera intensifier and mechanical shutter, and the wind-tunnel operation is an important element during this experiment. The CCD first obtains a trigger signal that opens the mechanical shutter about 500 ms before establishment of the flow. Then, at a chosen time during the flow, the gun receives a trigger to emit a pulse. The electron beam is emitted about 1 ms later, after the capacitors have been charged to the determined voltage. As the jitter for this emission time is too

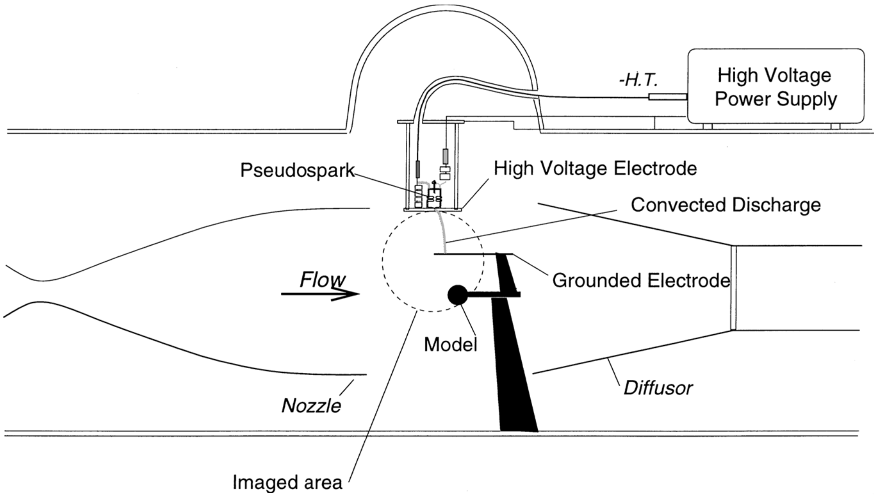

Fig. 3 Mounting of the pseudospark electron gun in the F4 wind tunnel.

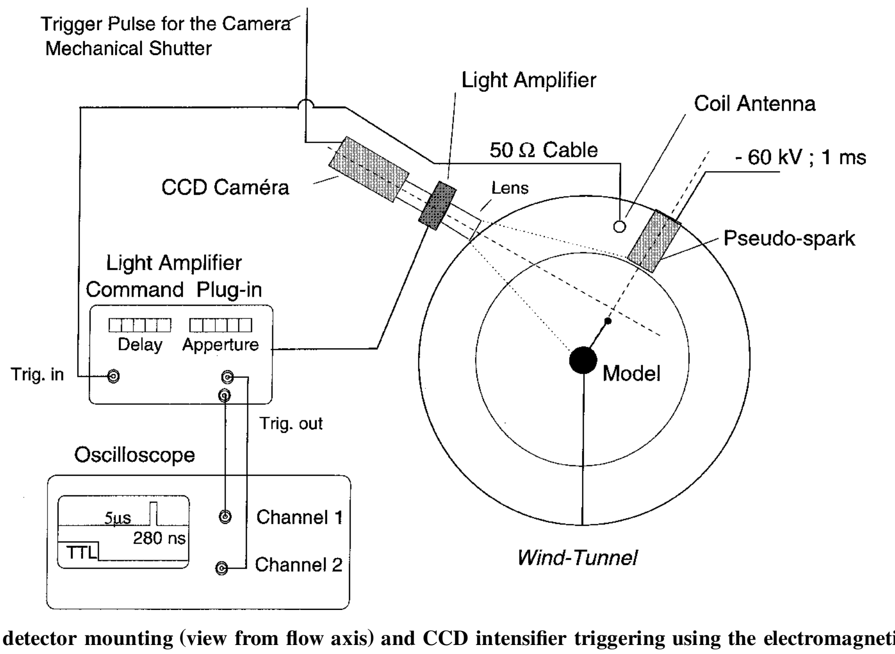

Fig. 4 Pseudospark and detector mounting (view from flow axis) and CCD intensifier triggering using the electromagnetic pulse emitted by the pseudospark electron beam.

large, the optical intensifier opening has to be synchronized to this emission instant and not to a wind-tunnel trigger. A magnetic loop placed inside the test section is used to detect the electrical breakdown in the gun, and its signal, reshaped in proper form, is fed to the module controlling the intensifier. On this module, the exposure time (280 ns) and the delay from beam emission (5 μs) can be set accurately, as required. The finite duration of the exposure time causes a slight broadening of the trace on the detector, which is accounted for in the data reduction.

F4 Results and Discussion

The system is first tested under static conditions with the test section at a pressure of 100 Pa. This is necessary to tune the adequate pressure in the gun and to obtain reference images to note the initial position of the beam. A calibrated grid was used to determine the magnification of the optics. Figure 5 shows the image acquired 90 ms after the onset of the shot, during a typical run at stagnation conditions, 215 bars and 7.8 MJ/kg. In the upper part, we can see the convection of the deformed discharge beam 5 μs after the initial emission of the electron beam; thermal emission of the gas is seen to radiate near the model in the lower part of the frame. Local velocities can be inferred from the distances over which the discharge was convected. More precision is obtained when

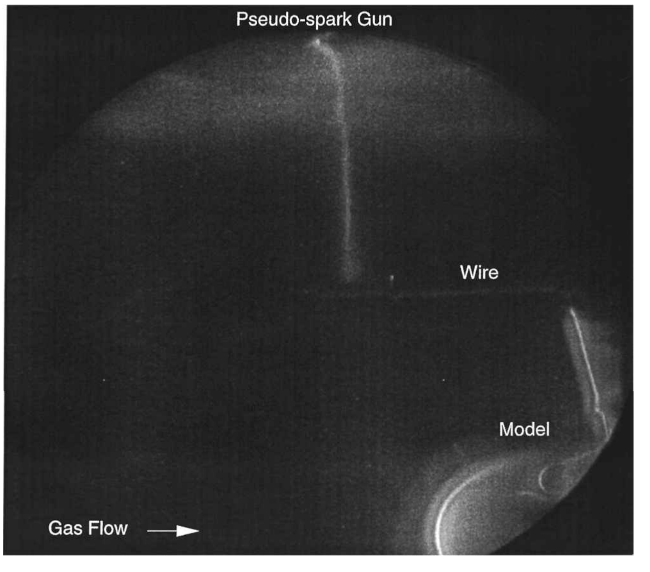

Fig. 5 Typical F4 run, flow at 90 ms, convection imaged 5 μs after beam emission.

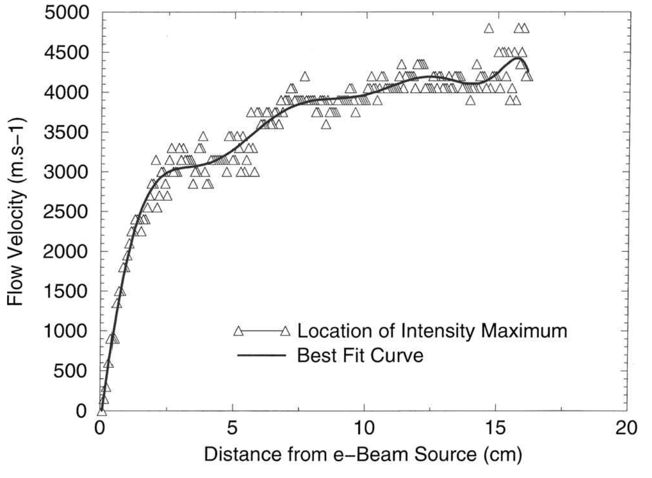

Fig. 6 Velocity profile at 90 ms for run of Fig. 5.

using a specific software that scans the digital frame to recognize the pixels with the maximum intensity. Figure 6 shows the velocity profile deduced from the best fit of the image in Fig. 5. The highest velocity of the profile, viz., 4100 m/s (±5%) at 150 mm from the external boundary of the stream, correlates well with theory. It is slightly higher, about 5%, than what is usually obtained from diode laser measurements on similar runs. This is logical, as the latter gives an average value over the velocity profile of the flow.

Conclusion

The work described here with the improved pseudospark gun proves that this apparatus is very helpful to measure locally the freestream and boundary-layer velocity profiles in low-density hypersonic flows. More work is to be performed, simultaneously with diode laser and spectroscopic measurements, to evaluate the whole potential and measurement accuracy of this new technique.

Acknowledgments

The authors gratefully acknowledge the input of B. Porcheron, S. Gaultier, and M. Grave on the software that scans the frames from the charge-coupled device camera.

References

[1]Bonnet, J., Chanetz, B., Henry, D., Larigaldie, S., Lefebvre, M., Mohamed, A. K., Pigache, D., Pot, T., Rosier, B., Taran, J. P., and Gorchakova, N., "Optical Diagnostics for Hypersonic Flows," *Proceedings of the ICMAR'96, International Conference on Methods of Aerophysical Research* (Novosibirsk, Russia), Russian Academy of Sciences, 1996, pp. 624–632.

[2]Arroyo, M. P., Langlois, S., and Hanson, R. K., "Diode-Laser Absorption Technique for Simultaneous Measurements of Multiple Gasdynamic Parameters in High-Speed Flows Containing Water Vapor," *Applied Optics*, Vol. 33, No. 15, 1994, pp. 3296–3307.

[3]Mohamed, A. K., Rosier, B., Henry, D., Louvet, Y., and Varghese, P., "Tunable Laser Diode Measurements on Nitric Oxide in a Hypersonic Wind Tunnel," AIAA Paper 95-0428, June 1995.

[4]Bütefish, K. A., and Vennemann, D., "The Electron-Beam Technique in Hypersonic Rarefied Gas Dynamics," *Progress in Aerospace Science*, Vol. 15, edited by D. Kuchemann, Pergamon, Oxford, England, UK, 1974, p. 217.

[5]François, G., Ledy, J. P., and Masson, A., "ONERA High Enthalpy Wind Tunnel F4," *Proceedings of the 82nd Meeting of the Supersonic Tunnel Association*, TP ONERA 1994-150, Wright–Patterson AFB, OH, 1994, pp. 1–13.

[6]Nishio, M., "Qualitative Model for Visualizing Shock Shapes," *AIAA Journal*, Vol. 30, No. 9, 1992, pp. 2346–2348.

[7]Nishio, M., "Methods for Visualizing Streamlines Around Hypersonic Vehicles by Using Electrical Discharge," *AIAA Journal*, Vol. 30, No. 6, 1992, pp. 1662, 1663.

[8]Nishio, M., "Visualization of Hypersonic Shock-Wave/Boundary-Layer Interaction by Electric Discharge Method," AIAA Paper 97-2288, June 1997.

[9]Nishio, M., "Methods for Visualizing Hypersonic Shock-Wave/Boundary-Layer Interaction Using Electrical Discharges," *AIAA Journal*, Vol. 34, No 7, 1996, pp. 1464–1467.

[10]Mohamed, A. K., Pot, T., and Chanetz, B., "Diagnostics by Electron Beam Fluorescence in Hypersonics," International Congress on Instrumentation in Aerospace Simulation Facilities, ICIASF'95 Record 95-CH3482-7, 14.1, Wright–Patterson AFB, OH, July 1995.

[11]Lutfy, F. M., and Muntz, E. P., "Initial Experimental Study of Pulsed Electron Beam Fluorescence," *AIAA Journal*, Vol. 34, No. 3, 1996, pp. 478–482.

[12]Christiansen, J., and Schultheiss, C., "Production of High Current Particle Beams by Low Pressure Spark Discharges," *Zeitschrift für Physik*, Vol. A290, 1979, pp. 35–41.

[13]Larigaldie, S., "Study of the Breakdown Phase in a Pseudospark Switch: Part I—Basis Experiments and Crude Model, Part II—Ultrafast CCD Cameragrams Using HE^{+} Spectral Line Emission," *IEEE Transactions on Plasma Science*, Special Issue on Physics and Application of Pseudospark Discharges, Vol. 23, No. 3, 1995, pp. 362–374.

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Associate Editor