Modification of hypersonic and supersonic rarefied flows with plasma actuators

Romain Joussot[1,2], Viviana Lago[1]
[1]*ICARE, CNRS, 1C av. de la recherche scientifique, CS 50060, F-45071, Orléans cedex 2, France*
E-mail: romain.joussot@cnrs-orleans.fr, viviana.lago@cnrs-orleans.fr

[2]*University of Orléans, CoST, rue de Chartres, BP 6759, F-45067, Orléans cedex 2, France*
E-mail: romain.joussot@univ-orleans.fr

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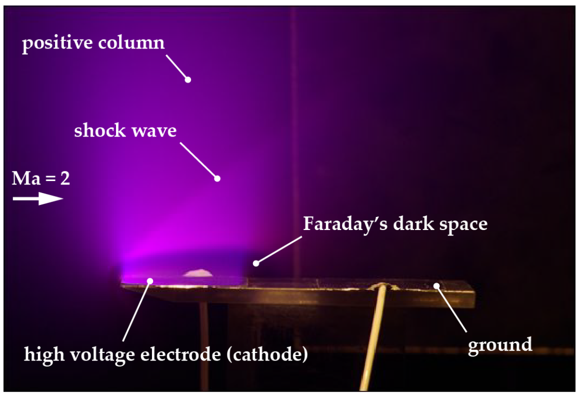
This paper presents experimental investigations focused on modification of high speed flows in the slightly rarefied regime (or slip-flow regime). Modification of shock wave is obtained with a dc glow discharge or a ns-rise high voltage pulsed discharge, in case of supersonic flows (Mach 2 and 4) and hypersonic flow at Mach 20.2. Two model geometries were tested: a cylinder (strong shock wave) and a flat plate (weak shock wave). The main application of such a plasma-based technique is to decrease the velocity of an aerospace vehicle during the rarefied phase of its atmospheric reentry.

Experiments were carried out at the ICARE (CNRS laboratory, Orléans, France) by the FAST team, and were performed with one of the three wind tunnels of the FAST platform. This platform is dedicated to different types of study: rarefied flows and plasma flow control with the MARHy wind tunnel, aero-thermodynamic of models during reentries (Earth, Mars, Titan, etc.) and MHD flow control with the PHEDRA wind tunnel, and shock wave interactions and nozzle vectorization with the EDITH wind tunnel. This paper presents experiments performed in the MARHy wind tunnel, which can be equipped with a wide range of nozzles, allowing the generation of flows from Mach 0.8 to Mach 21 in a large range of Reynolds numbers from 10^2 up to 10^5 ($L_{ref} = 10\,\mathrm{cm}$). These flow conditions simulate most of the reentry vehicles flight corridors from $100\,\mathrm{km}$ to $58\,\mathrm{km}$ of altitude.

In a case of a $20\,\mathrm{mm}$-diameter cylinder in a Mach 2 flow ($8\,\mathrm{Pa}$, $\mathrm{Kn}_D = 0.019$), the shock stand-off distance increases with the discharge power [1]. OES measurements show that the modification of the shock position cannot be induced by thermal effects. It was found that the stand-off distance is directly coupled with the ionization degree of the plasma (ratio of electron density to neutral density) and the thermal non-equilibrium. These plasma effects play also a significant role in the shock wave modification around a $100\,\mathrm{mm}$-long flat plate in a Mach 2 flow ($\mathrm{Kn}_L = 0.004$) (Fig. 1). In this case, surface heating is responsible for roughly 50% of the shock wave angle increase [2] and bulk heating is negligible. It was demonstrated that the remaining 50% is induced by purely plasma effects, resulting from the modification of properties of the incoming flow before it interacts with the flat plate [3]. In particular, decrease in the Mach number is related to a decrease in the isentropic exponent γ. It was found that the drag coefficient rises up to 13% when the plasma actuator is used, compared to only 5% percent with a heating element reproducing only the thermal effects [4].

Recent studies have shown how the Mach number (Mach 2 and Mach 4) as well as the ambient pressure ($8\,\mathrm{Pa}$ and $71\,\mathrm{Pa}$) modify the repercussions of the plasma actuator on the shock wave [5]. It was observed that the shock wave angle increased with the discharge current of +15% for the Mach 2 flow but the increase rate doubled to +28% for the Mach 4 flow at the same static pressure. When studying the effect of the discharge on the Mach 4 flow at higher static pressure, it was observed that the topology of the plasma changed drastically and the shock wave angle was increased by +21% (same discharge current conditions). In the case of an ns-rise high voltage pulsed discharge in an hypersonic flow at Mach 20.2, the effect of the plasma actuation on the shock wave is similar to a modification of the angle of attack of the flat plate (Fig. 1).



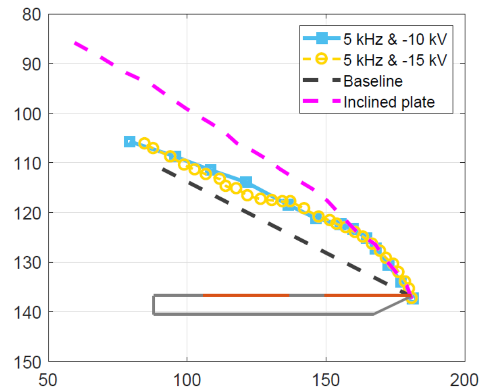


Figure 1: Modification of the shock wave angle: dc discharge in a supersonic flow at Mach 2 and 8 Pa (left panel), pulsed discharge in an hypersonic flow at Mach 20.2 and 0.07 Pa (right panel).

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References

[1] V. Lago, R. Joussot, and J.-D. Parisse Influence of the ionization rate of a plasma discharge applied to the modification of a supersonic low Reynolds number flow field around a cylinder *J. Phys. D: Appl. Phys.*, 47(12):125202, 2014.

[2] R. Joussot, V. Lago, and J.-D. Parisse Quantification of the effect of surface heating on shock wave modification by a plasma actuator in a low density supersonic flow over a flat plate *Exp. Fluids*, 56(5):102, 2015.

[3] R. Joussot, and V. Lago. Experimental investigation of the properties of a glow discharge used as plasma actuator applied to rarefied supersonic flow control around a flat plate *IEEE T. Dielect. El. In.*, 23(2):671–82, 2016.

[4] S. Coumar, R. Joussot, J.-D. Parisse, and V. Lago Influence of a plasma actuator on aerodynamic efforts over a flat plate interacting with a rarefied Mach 2 flow *Int. J. Numer. Method H.*, 26(7): 2081-100, 2016.

[5] S. Coumar, and V. Lago. Influence of Mach number and static pressure on plasma flow control of supersonic and rarefied flows around a sharp flat plate *Exp. Fluids*, 58(6):74, 2017.