MODIFICATION OF THE SHOCK WAVE SHAPE OF A SUPERSONIC LOW REYNOLDS NUMBER FLOW FIELD AROUND A CYLINDER BY A GLOW DISCHARGE IN AIR

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ABSTRACT

This paper describes investigations focused on the shock wave modification induced by a plasma actuator flush mounted on a cylinder in rarefied flow regime. The experimental measurements were carried out in a supersonic low-density wind tunnel and the numerical investigation used a 2D fully compressible Navier Stokes simulation. Experimental observations showed the modification of the shock wave when the discharge was switched on. The numerical simulations show that this modification cannot be reproduced correctly by thermal effects. A theoretical approach was then proposed, in which the shock stand-off distance is written as a function of the ionization degree of the plasma. This approach was confirmed experimentally by measuring electronic properties of the plasma.

1. INTRODUCTION

Weakly ionized gases can be used to control flows when the abilities of traditional methods are close to natural limitations. Electrohydrodynamic (EHD) technologies have therefore been considered to increase flow control effectiveness thanks to their interesting properties such as total electric control, no moving parts and fast response time. For supersonic and hypersonic vehicle designers, plasma actuators are good candidates to reduce wave and viscous drags and heat fluxes, to increase lift, to mitigate sonic boom and to control the boundary layer, turbulent transition or shock wave propagation. However, although extensive research has been undertaken in the past few decades, the plasma effects responsible for flow modifications are still not well understood and remain a controversial issue. The most popular issue is the anomalous shock stand-off distance of a body (generally a sphere) flowing supersonically in a weakly ionized plasma. The anomalous plasma effect results in an higher shock stand-off distance in a plasma than in an un-ionized gas heated up to the plasma temperature and at the same flow velocity [1].

The present work focuses on the modification of the shock position upstream a circular cylinder in a rarefied Mach 2 air flow with a plasma actuator. As the basic phenomena associated with this geometry are relatively well known, the contribution of the plasma to the flow modification should be easier to comprehend. The detached bow shock formed ahead of the body is pushed upstream when the plasma is present. A negative glow discharge is created with a metallic electrode placed on the cylinder surface and connected to a dc high voltage power supply. Numerical and experimental investigations were performed and are compared in the present paper, for a set of plasma discharge conditions.

2. EXPERIMENTAL SET-UP

The MARHy low density facility (formerly known as SR3, Lab. Aérothermique) consists of three parts: the settling chamber, the test chamber, and a third chamber in which a diffuser is installed. The diffuser is connected to a powerful pumping group. The present study was carried out in a low-density supersonic flow at Mach 2 induced with a stagnation pressure of 63 Pa and a test section static pressure of 8 Pa. This last corresponds to a geometric altitude of 67 km. The Knudsen number is 0.019, corresponding to the slip-flow regime (slightly rarefied).

The model under investigation is a circular cylinder made of alumina, with a diameter of $D_{cyl} = 20\,\mathrm{mm}$ and a spanwise length of $80\,\mathrm{mm}$ (Fig. 1), giving a Reynolds number of $Re_D = 160$. An aluminum electrode ($75\,\mathrm{mm}$ long and $3\,\mathrm{mm}$ wide) is flush mounted on the cylinder in the spanwise direction. The plasma is produced with a glow discharge generated by connecting the electrode to a high voltage dc power supply (Spellman SR15PN6) through a resistor. The discharge is ignited in air. The flow around the cylinder ionized by the plasma discharge is analyzed by means of optical diagnostics (see Lago *et al.*[2] for further details on the optical arrangement). An ICCD camera equipped with a VUV objective lens was used to observe the influence of the plasma discharge on the flow around the cylinder. The spectroscopy measurements were carried out with an Ebert-Fastie-type monochromator SOPRA F1500 with a grating of 1800 grooves/mm.

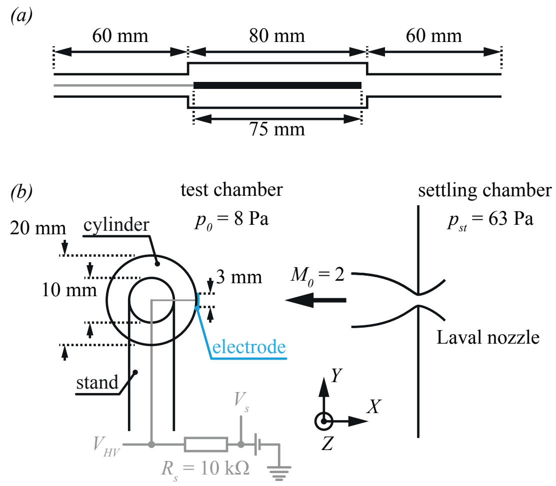

Fig. 1: Schematic representation of the cylinder in the test section: (a) front and (b) side views

The numerical simulations were performed by using a 2D compressible Navier-Stokes in which the boundary conditions were adapted to match with the physical phenomena involved in a rarefied flow regime. The details about the numerical code are given in Parisse *et al.*[3]. In order to simulate the discharge interaction with the flow, two different thermal effects induced by the plasma discharge were simulated separately. On the one hand, the surface heating of the electrode was considered by fixing two temperatures for the boundary condition on the cylinder wall: $T_{w_1} = 500\,\mathrm{K}$ or $1000\,\mathrm{K}$ at the electrode position, and $T_{w_2} = 163\,\mathrm{K}$ for the rest of the cylinder surface. On the other hand, a volumetric heating was simulated by adding a volumetric heating Q_v in the region between the cylinder and the shock in order to heat the flow.

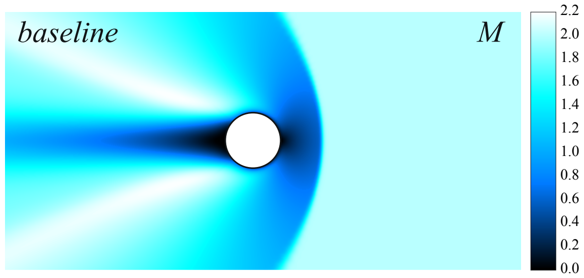

Fig. 2: Mach number field from the WENO simulation of the natural flow. The free stream Mach number is 2

3. RESULTS

The flow field around the cylinder was first simulated without the discharge (i.e., the plasma actuator was switched off). Figure 2 shows the Mach number field of the natural flow around the cylinder, namely the baseline, calculated with the WENO code. The shock wave is readily recognized, enabling the estimation of the shock wave stand-off distance. For the baseline, the numerical simulation gave a stand-off distance of $\Delta = 13.71\,\mathrm{mm}$, which is slightly larger than the experimental value measured with images of the discharge ($12.45\,\mathrm{mm}$). However, these two values are in good agreement with the one ($\Delta_0 = 12.41\,\mathrm{mm}$) found by applying the empirical formulation proposed by Ambrosio and Wortman [4]. In addition, the shape of the natural shock wave is hyperbolic, which corresponds to the empirical shape described by Billig [5].

The discharge was obtained by applying a negative dc potential to the electrode. Figure 3 shows that the discharge current I_{HV} increases linearly with the applied voltage V_{HV}. This behaviour corresponds to an abnormal glow discharge regime. In order to estimate the temperature in the region affected by the discharge, the macroscopic temperature of the gas was deduced from the rotational temperature measured in the plasma region between the shock and the electrode. Two nitrogen systems were observed: the N_2^+ first negative system $\left(B^2\Sigma_u^+\right) \to \left(X^2\Sigma_g^+\right)$ and the N_2 second positive system $\left(C^3\Pi_u\right) \to \left(B^3\Pi_g\right)$. These measurements give rise to a major observation: over the voltage range tested, the N_2 rotational temperature ranges between $350\,\mathrm{K}$ and $400\,\mathrm{K}$ whereas a lower rotational temperature is measured for N_2^+ (slightly below $300\,\mathrm{K}$), meaning the gas is weakly heated by the discharge.

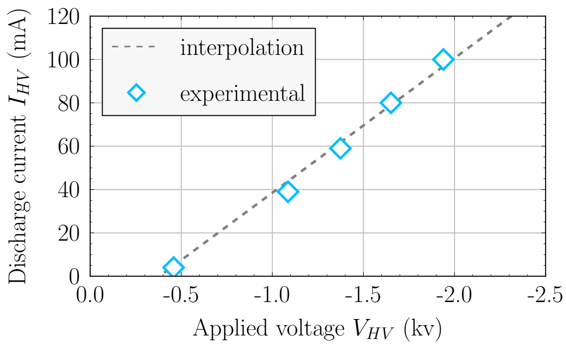

Fig. 3: Current-voltage characteristic of the discharge (Mach 2)

Figure 4 shows the ICCD image of the shock wave modified by the discharge. The plasma changes the position of the shock wave, pushing it upstream the cylinder. The stand-off distance on the stagnation line is estimated from the experimental images using the same post processing method as that applied in the natural case. Figure 5 shows that the shock wave stand-off distance is linearly linked to the discharge current. The higher the applied voltage (or the power), the higher the stand-off distance of the shock wave is.

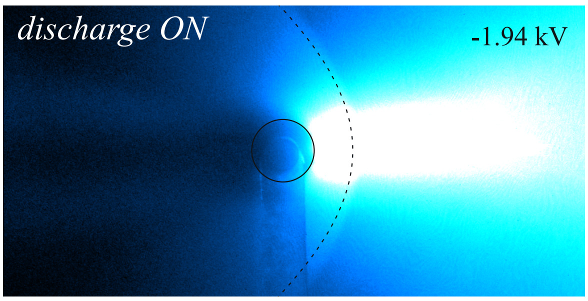

Fig. 4: ICCD image of the flow modified by the plasma discharge (V_{HV} = -1.94 kV, I_{HV} = 100 mA). The black line represents the shock wave shape of the natural flow (Mach 2)

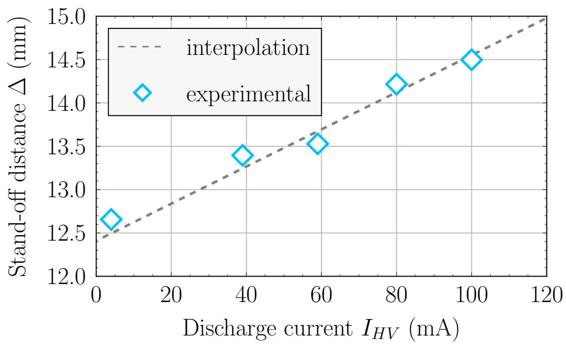

Fig. 5: Experimental stand-off Δ estimated with the ICCD images according to the discharge current I_{HV}

Three types of effects can be considered in order to explain why the shock is pushed upstream: surface heating of the electrode, volumetric heating of the gas where the plasma is present, and influence of the ionization degree. Each of these effects was considered separately in order to aid in discriminating between a thermal-only and a purely plasma effect. The surface heating due to the ohmic heat effect was simulated by fixing the temperature of the cells corresponding to the electrode position on the cylinder surface to a higher temperature than for the neutral case.

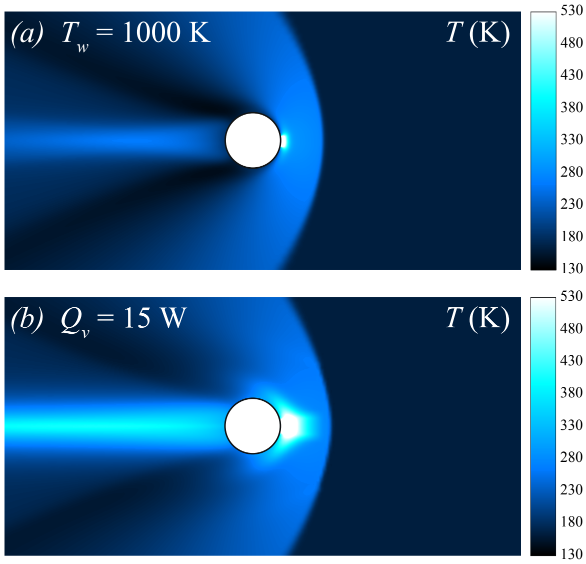

Fig. 6: Temperature fields obtained from the WENO simulations in the case of: (a) a surface heating with T_{w_1} = 1000 K and (b) a volumetric heating of Q_v = 15 W. The Mach number is 2

Figure 6*(a)* shows the temperature field calculated with an electrode surface temperature of T_{w_1} = 1000 K, which was an unacceptably high value in regard to the electrode material (aluminum melting point temperature around 933 K). In this case, the stand-off distance was increased by $+5.62\%$, rising from 13.71 mm to 14.48 mm, which is far short of what was obtained experimentally with the discharge. Volumetric heating of Q_v = 15 W was then considered in order to heat a larger region of the flow upstream the cylinder. The effectiveness of volume heating is presented in figure 6*(b)*. The shock stand-off distance determined from the simulation is increased by $+34.9\%$ (Δ = 18.50 mm), which is a value over two times greater than the value obtained with a discharge current of 100 mA ($+16.5\%$). In addition, the local temperature 1 mm upstream the cylinder can reach 700 K, which is inconsistent with the optical temperature measurements, since the temperature of the gas remains below 400 K.

The physical properties of the plasma must be considered in order to explain why the stand-off distance is increased beyond what can be attributed to thermal effects. Mishin *et al.*[1] shown experimentally that the shock stand-off distance for a sphere is greater in a weakly ionized gas than in air heated to the plasma temperature. They explained their observations by the modification of the isentropic exponent, inducing a modification in the speed of sound. A theoretical link between the properties of the plasma and the isentropic exponent was proposed by Burm *et al.* [6] who shown the dependence of γ on the ionization degree α_i. The modification in the speed of sound is induced by an increase in the temperature of heavy particles in the plasma (i.e., the gas temperature) and a lower isentropic coefficient depending on α_i [7].

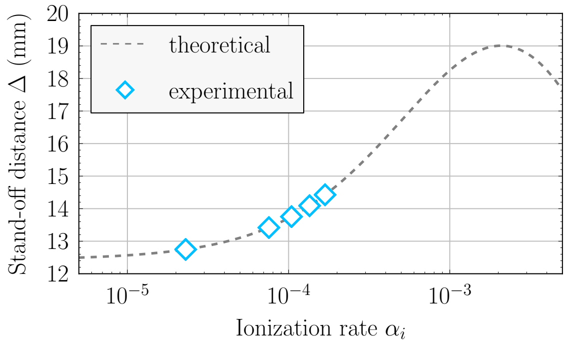

Fig. 7: Stand-off distance for a plasma according to the ionization degree. The line is the theoretical variation and the diamonds are the empirical values for the applied voltages tested experimentally

By using the formulation of Ambrosio and Wortmann [4], the shock wave stand-off distance can be written as a function of the ionization degree α_i. Figure 7 shows the variation in the stand-off distance for a plasma according to its ionization degree. The diamond points correspond to the experimental values of Δ for which α_i was measured with a Langmuir probe. The experimental increase in Δ with the ionization degree is consistent with the theoretical one, meaning that the plasma properties play a major role into the modification of the shock wave around the cylinder.

4. CONCLUSIONS

Experimental observations have shown the modification of the shock wave by the presence of a plasma. It was found that the shock wave is pushed upstream, thus increasing the detachment distance by several mm. The plasma induces several types of effects, such as thermal heating, ionization or thermal non equilibrium. With a heating located at the electrode surface the calculations give underestimated values of the stand-off distance. The volumetric heating was tested and leads to opposite influence compared to those obtained with the surface heating. Measurements of the rotational temperatures shown that only a little heating occurs in the plasma volume, which is inconsistent with the numerical results. The empirical correlation of Ambrosio and Wortman was adapted to plasma conditions in which the ionization degree and the non thermal equilibrium have been taken into account. The results show that the shock wave detachment distance increases with the ionization degree, and the comparison between numerical estimations and experiments is in good agreement.

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