DSMC Estimate of the Ionic Wind Effect on a Supersonic Low-Density Flow

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Abstract. The present work is devoted to the influence of an electric discharge on the low-density supersonic flow along a flat plate. Simple modifications were applied to the standard Direct Simulation Monte Carlo (DSMC) method to simulate the ionic wind and the energy input due to the discharge. In parallel, experiments were carried out in the facility MARHy of the *Laboratoire d'Aérothermique du CNRS*. The calculations that correspond to the experimental conditions demonstrate that the discharge changes the drag through Coulomb forces rather than through ionic wind. Furthermore, the energy input has a strong influence on the flow profiles, while having only a small influence on the drag.

Keywords: DSMC, electric discharge, ionic wind, flow control
PACS: 47.27.ek, 47.45.-n, 47.85.L-

INTRODUCTION

A number of investigators have observed that creating an electric discharge in a flow could modify the aerodynamic properties of the flow. The topical review by Bletzinger et al. [1] reports how shock waves weaken or even disappear when a discharge is generated in a supersonic flow. A likely interpretation of this observation is a thermal effect : the volumic input of energy increases the temperature of the free stream, with little influence on its velocity. The Mach number is then reduced and the shock waves become weaker. Other authors (e.g., Soetomo [2]) demonstrate how a discharge increases the velocity of the flow along the wall of an obstacle. This was also observed by Léger [3], who carried out experiments in a low-velocity flow along a flat plate with a blunt leading edge. The flowing gas was air at room temperature and pressure, flowing at a velocity of 0.35 $m.s^{-1}$. The Reynolds number based on the plate length was 3750. Electrodes were imbedded in the model wall, perpendicular to the direction of the free stream. The velocity profiles above the plate were measured by means of a Pitot tube and the flow was visualized by smoke. When the plate was inclined by 15 degrees, a separation zone occurred on the leeside in the absence of discharge, whereas switching on the discharge forced the flow to reattach. A possible interpretation of flow acceleration by a discharge is the ionic wind : positive ions created in the discharge are accelerated by the electric field and transfer a fraction of their momentum to the other flow particles through collisions.

The *Laboratoire d'Aérothermique du CNRS* has initiated an experimental study in the wind-tunnel MARHy (previously known as SR3). An electric discharge was created in the vicinity of a sharp flat plate located in a

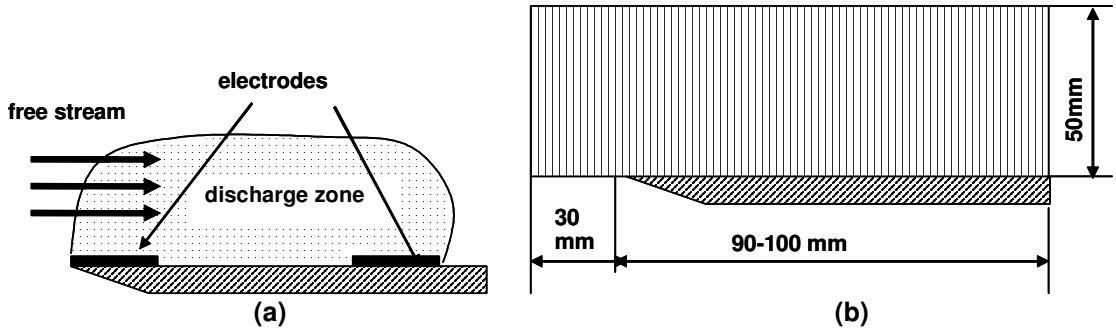

FIGURE 1. (a) Scheme of the configuration (not to scale), (b) DSMC computational domain

supersonic, low-density air flow (Fig.1a). The electrodes were thin strips of aluminum glued on the model. A typical discharge was obtained with a negative DC voltage (-1 kV) applied to one of the electrodes while the other one was grounded. The resulting current was 30-40 mA. The nominal freestream conditions were characterized by a Mach number $Ma = 2$ and a Reynolds number $Re = 780$ based on a plate length $L = 0.1$ m. The Knudsen number based on L was $Kn = 0.027$. Free stream pressure and temperature were $p = 8.05$ Pa and $T = 167$ K, respectively. Another plate with $L = 0.09$ m has also been used. The objective of the study was to evidence (if any) a change in the velocity profiles above the plate and a change in the model drag when the discharge was switched on. A spectroscopic study revealed that the main ionized species was N_2^+. The experimental work has been presented in [4]. In parallel the Direct Simulation Monte Carlo (DSMC) method was applied to the problem and the present paper focuses on this latter point.

PRELIMINARY DSMC WORK

The objective of the DSMC calculations was only to investigate whether the ionic wind or the energy input was sufficient to induce any effect on the velocity profiles and on the drag in the conditions under investigation. The calculations used the DSMC code DISIRAF developed at the *Laboratoire d'Aérothermique*, based on Bird's concepts [5]. This code allows for mixtures of non-reactive gases. The internal energy of molecules consisted in rotational energy only. The nominal experimental conditions were retained for the calculations. A scheme of the computational domain is given in Fig.1b. The computational domain was two-dimensional. Cells had an arbitrary width of 1 m, but the actual position of the molecules in that direction was disregarded.

A preliminary work consisted in simulating the nominal wind-tunnel flow along the plate in the absence of an electric discharge. The gas was considered as a mixture of nitrogen and oxygen. Intermolecular collisions were governed by the VHS (Variable Hard Sphere) model. The total collisional cross-section varies as $\sigma \propto c_r^{-2\alpha}$, where c_r is the relative velocity of colliding particles and α is a constant. The collisional cross-section is defined by a reference value $\sigma_{\text{ref}} = \pi d_{\text{ref}}^2$ associated to an arbitrary temperature $T_{\text{ref.}}$ For a simple gas, the VHS model is consistent with a viscosity μ that depends on temperature as T^{ω} with $\omega = \alpha + 0.5$. For a gas that does not obey a power-law viscosity-temperature relationship, the following approximation is used: ω and d_{ref} are calculated from the viscosity μ at a given temperature T:

$$\omega = \frac{d\mu}{dT} \times \frac{T}{\mu}, \qquad \mu(T) = \frac{15}{8} \times \frac{m\left(\pi RT\right)^{1/2}}{\left(\pi d_{ref}^2\right)\Gamma\left(4-\alpha\right)\left[\left(2-\alpha\right)\left(T_{ref}/T\right)\right]^{\alpha}}. \tag{1}$$

where Γ denotes the Gamma function, m is the molecular mass and R the perfect-gas constant per unit-mass [5].

In the current version of DISIRAF ω must be identical for all species of a mixture. Furthermore, the cross-section for mixed collisions A-B in a mixture of molecules A and B is based on a reference diameter that is the arithmetic average of the reference diameters of gases A and B. The present calculations used

$$T_{\text{ref}} = 300\,\text{K}, \quad \omega = 0.79, \quad d_{\text{ref,N2}} = 4.10\times10^{-10}\,\text{m}, \quad d_{\text{ref,O2}} = 3.93\times10^{-10}\,\text{m}. \tag{2}$$

The computational domain was divided into rectangular cells (Fig. 1b), whose size should be much smaller than the gradient length scale in the direction considered. This ensures that the macroscopic flow properties are nearly uniform within a cell. Values $\Delta x = 1\,\text{mm}$ and $\Delta z = 0.25$ or $0.50\,\text{mm}$ were retained in the axial and transverse directions, respectively. These figures are to be compared with the plate length (9 or 10 cm) and with the displacement thickness of the boundary layer (approx. 13 mm near the trailing edge).

The number of real molecules associated to one simulation molecule (weighting factor) is defined in each cell for each species to ensure the presence of approximately 10 simulated molecules of each species in each cell. The time step Δt of the DSMC simulation was chosen to fulfill the condition $\nu.\Delta t < 1$ for both species in the whole computational domain, where ν is the local collision frequency. A typical value was $\Delta t = 5\times10^{-8}$ s.

The reflection of molecules on the model wall was considered to be diffuse with full accommodation.

The plane $z = 0$ upstream of the plate was considered as a symmetry plane. The number and distribution functions of molecules injected through the upstream and lateral boundaries corresponded to the free stream conditions. If the same conditions are used for the downstream boundary, the number of molecules injected is negligibly small, due to the supersonic nature of the flow. Therefore, no molecules were injected through the downstream boundary. However, this is not correct near the plate, where the local Mach number is small.

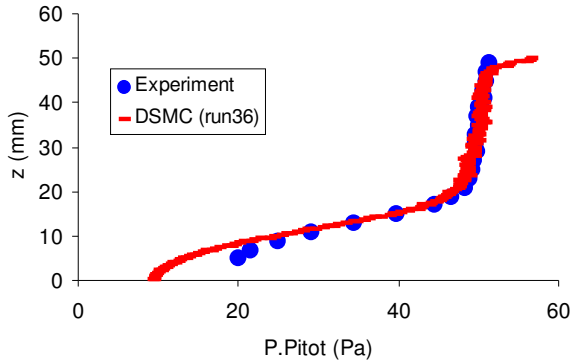

FIGURE 2. Transverse distribution of Pitot pressure at $x = 80$ mm (nominal conditions, no discharge)

A parametric study revealed that a cell size $\Delta z = 0.50\,\text{mm}$ was sufficiently small and that the incorrect downstream boundary condition affected a region at most 1 cm wide along the downstream boundary.

The simulation outputs the space distribution of all flow parameters as well as the dynamic and thermal loads along the model wall and the integrated force exerted to the model (including the drag component).

The DSMC results were compared with experimental data. The flow along the plate in the absence of discharge was investigated experimentally using a glass Pitot probe whose external diameter was 6 mm. Due to the large size of the Pitot probe, the rarefaction effect on the orifice was negligible. The counterpart of this choice was the poor spatial resolution of the probe. The transverse profiles of the Pitot pressure were obtained at different abscissas. At each point of the flowfield, the computed flow parameters were used to calculate the pressure that would be measured by a Pitot tube located at that point (stagnation pressure in a locally subsonic flow, stagnation pressure behind a normal shock wave in a locally supersonic flow). That value was compared with the experimental one. An example of results, relative to the abscissa $x = 80$ mm is plotted in Fig. 2. No corrections have been introduced to account for a rarefaction effect on the Pitot pressure nor for the detachment distance of the shock wave ahead of the tube in the supersonic region. The agreement between both profiles is good except near the plate (due to the poor spatial resolution of the probe) and near the lateral boundary. The latter discrepancy is due to the DSMC boundary condition. Actually, the last points on the profile are not sufficiently far from the plate and they are not located in the free stream but behind the shock wave that originates from the leading edge.

This first calculation gives confidence in the computational method.

DSMC SIMULATION OF THE IONIC WIND

Considering now that a DC discharge has been created in the flow, the ions are accelerated according to the local electric field and may transfer momentum to neutral species through collisions with them. A number of DSMC calculations were carried out to decide whether this process was sufficient to create a change in the velocity distribution and in the aerodynamic drag of the model.

There has been no effort to model the discharge and the process of creation of charged species. The gas was considered as a non-reactive mixture of neutral N_2 and ionized N_2^+. A fixed ionized fraction f was used to define the respective numbers of neutral and ionized particles injected through the boundaries during each time step. In the computational domain, both species were allowed to move independently from each other. The electric field $\boldsymbol{E}$ was considered as uniform all over the computational domain and oriented in the direction of the free stream.

At each time step, the DSMC code moves the particles by a quantity $\mathbf{c}.\Delta t$, where $\mathbf{c}$ is the current particle velocity. To account for the acceleration of ions by the electric field, a small change was introduced in the standard code to replace $\mathbf{c}$ by $\mathbf{c} + \mathbf{E} \times (e/m) \times \Delta t$ before each move of the ions, where e is the elementary charge.

For the present calculation, the molecular parameters retained were $\omega = 0.77$, $d_{\text{ref,N2}} = 3.73 \times 10^{-10}$ m, $d_{\text{ref,N2+}} = 5.87 \times 10^{-10}$ m at $T_{\text{ref}} = 1000$ K. For nitrogen, the reference diameter was determined as explained

before. For the ion, it was adjusted to yield the correct estimated collisional cross-section for mixed collisions $(N_2 - N_2^+)$. The latter was estimated from the viscous collision integral Ω_{22} for mixed collisions by

$$\pi\left[\left(d_{\mathrm{ref,N2}} + d_{\mathrm{ref,N2+}}\right)/2\right]^2 = \sigma_{ref}\left(N_2 - N_2^+\right) = \sigma_{ref}\left(N_2 - N_2\right)\times\left(\Omega_{22}\left(N_2 - N_2^+\right)\Big/\Omega_{22}\left(N_2 - N_2\right)\right), \qquad (3)$$

where the values of both Ω_{22} integrals were taken from Refs.[6] and [7] at the temperature of 1000 K. The resulting value of $d_{\mathrm{ref,N2+}}$ is not realistic for $(N_2^+ - N_2^+)$ collisions, that are governed by long-range Coulomb interactions. However, for the present problem, it was considered that simulating correctly mixed collisions was more important than simulating correctly collisions between ions.

The DSMC calculations included two free parameters, namely f (ionized fraction of the gas injected through the boundaries) and E (intensity of the electric field). These parameters were varied in the present parametric study.

Based on the DC voltage and on the distance between electrodes, the electric field E in the experiment was expected to be of the order of 30 $\mathrm{kV.m^{-1}}$, resulting in an acceleration of 10^8 $\mathrm{m.s^{-2}}$. This value would lead to a considerable increment of velocity at each time step (typically 5000 $\mathrm{m.s^{-1}}$), even larger than the free stream velocity (518 $\mathrm{m.s^{-1}}$), which is clearly unacceptable.

The ionized fraction f is difficult to estimate. Based on the current measured between the electrodes and on the mobility of electrons, the concentration ratio between electrons and neutral particles was estimated to be of the order of 10^{-8}. The concentration ratio between ions and neutral particles is probably larger, but still very small compared with unity. The large difference in the concentrations of N_2 and N_2^+ would cause problems for DSMC.

Therefore, the computations used larger values of f and smaller values of E compared with the realistic ones, while keeping the product $E \times f$ in a reasonable range (Table 1). The value of E was sufficiently small for the velocity increment during Δt to be smaller than $u_\infty / 100$.

TABLE 1. Parameters and results for the simulation of the ionic wind.

Run	f	E ($\mathrm{V.m^{-1}}$)	f x E ($\mathrm{V.m^{-1}}$)	Friction Drag ($\mathrm{N.m^{-1}}$)	Coulomb force ($\mathrm{N.m^{-1}}$)
34	0	0	0	0.125	0
27	10^{-4}	30	3 x 10^{-3}	0.128	-0.01
29	10^{-3}	30	3 x 10^{-2}	0.130	-0.1
32	10^{-2}	30	3 x 10^{-1}	0.162	-1
40	10^{-3}	300	3 x 10^{-1}	0.156	-1
Exper.	>10^{-8}?	3000-30000	3 x 10^{-5}-3 x 10^{-3} ?		

Velocity profiles resulting from the computations have been plotted in Fig.3. The reference situation corresponds to the first curve. A change in the velocity profile is hardly visible for $E \times f = 0.003$, while it is clearly visible for $E \times f = 0.03$ (Fig.3, left). The ions pass momentum to the neutral particles. Profiles obtained for other values of x

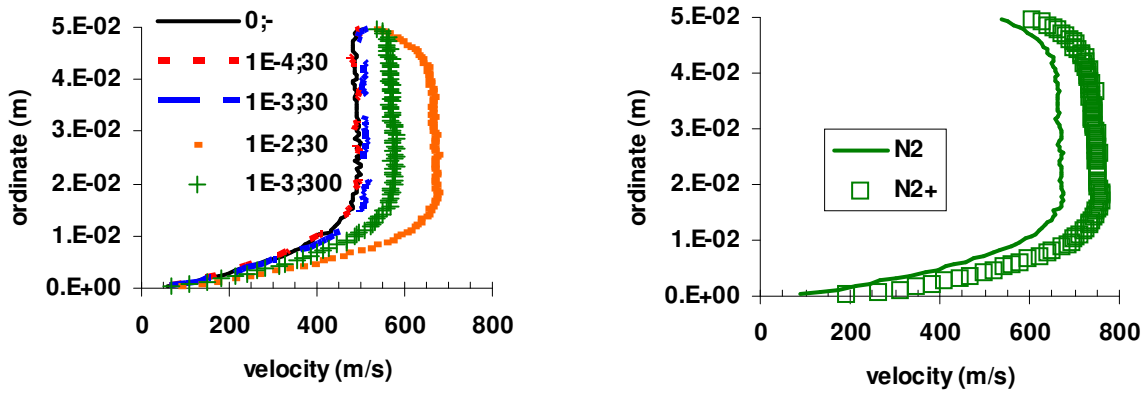

FIGURE 3. Transverse distribution of velocity at x = 79.7 mm. Left: velocity profiles of N_2 for different values of parameters f and E - Right: velocity profiles of N_2 and N_2^+ for f = 10^{-2}, E = 30 $\mathrm{V.m^{-1}}$.

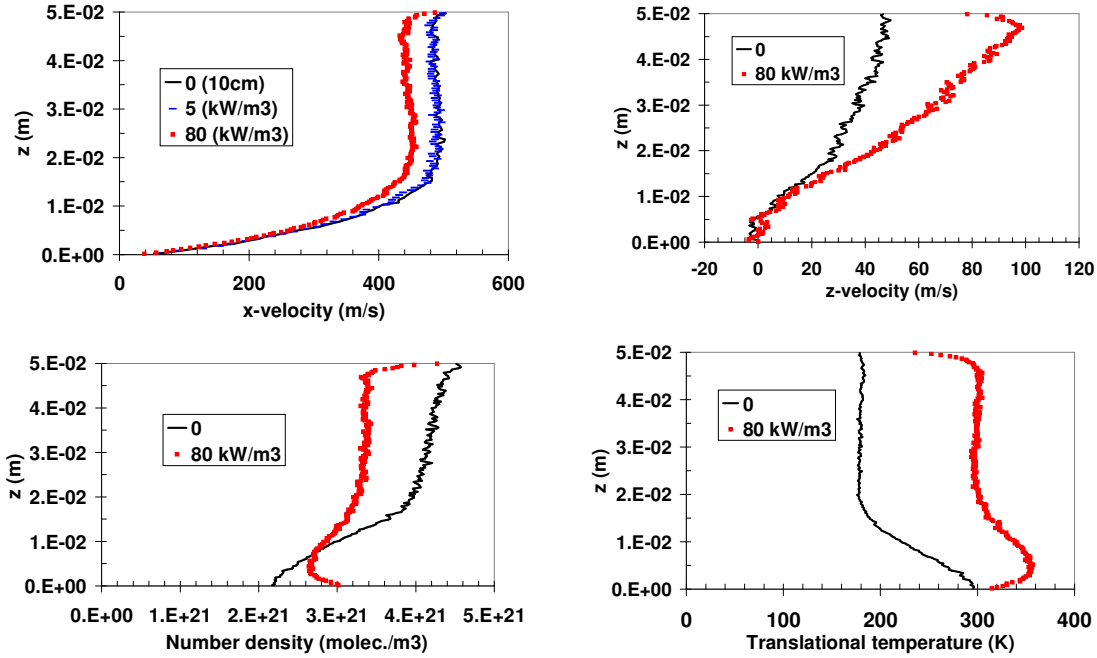

FIGURE 4. Influence of energy input on transverse distribution of flow parameters at x = 79.7 mm.

indicate that this effect increases as the distance from the leading edge increases. However, in contradiction with the expectation, the governing factor is not the product $E \times f$ (compare the curves corresponding to runs 32 and 40). The dominant factor is f. Thus the present calculations, based on an underestimated electrical field and an overestimated ionized fraction, overestimate the ionic wind effect at a given value of the product. The present results demonstrate that a realistic value of both E and f would induce negligible changes in the velocity profiles. However this conclusion relies on a crude estimation of the ionized fraction and on a simplified uniform electric field. It should be re-examined after the experimental flowfield will be investigated with an electrostatic probe for confirmation of the ionized fraction and after a more realistic electric field (e.g., deduced from the electrostatic equations applied to the geometry of the plate with its electrodes) has been introduced in the computation. For the most favorable case computed, ions and molecules exhibit clearly different velocity profiles. The difference of velocity is consistent with that estimated from considerations on the mobility of ions.

The influence of an electric discharge on the flow along a flat plate may result in a change in the aerodynamic drag of the plate. Typically, if the discharge accelerates the flow, it increases the slope of the velocity profile at the wall, and increases the friction drag. This is confirmed by the drag obtained from DSMC calculations (Table 1). Simultaneously, the electric field exerts a Coulomb force to the ions in the flowfield. The force received by the gas is equal to $E \times f \times e \times n$ per unit-volume, where n is the local number density. This force, integrated over the whole ionized volume, is also a force exerted by the gas to the electrodes and contributes to drag reduction. An estimation of this Coulomb force is given in Table 2, assuming free stream values for f and n. It is clear that the contribution of the electrostatic force to drag reduction, considering only positive charges (no electrons), is much larger that the drag increase due to a change in velocity profiles. As electrons are not considered in the present calculation, this discussion ignores the Coulomb force exchanged between the electrodes and the electrons. However, due to their larger mobility, electrons have a much lower concentration than ions in the vicinity of the model and the above conclusion should remain valid.

DSMC SIMULATION OF ENERGY INPUT

The discharge consists also in an input of energy to the flow. In the experiment, the power based on the voltage applied to the electrodes and on the electrode current is in the range 30-40 W. Considering the control volume defined by the plate width and the boundaries of the computational domain (Fig.1b), the energy input is 62-83 $kW.m^{-3}$. This is not small compared with the total enthalpy that enters the same control volume, based on free stream conditions (105 W). Therefore one can expect a purely thermal influence of the discharge.

DSMC calculations with energy input were carried out for pure nitrogen. The standard DSMC code was modified to increment the internal (i.e. rotational) energy of each molecule at each time step by an amount

$$\Delta E = \left(\frac{\text{Discharge power} \times \Delta t}{\text{Number of cells}} \right) \times \frac{1}{N_c \times W}, \quad (4)$$

where N_c and W denote the actual number of simulated molecules and their weighting factors in each cell. Thus the energy was distributed uniformly over the computational domain. Although energy was input as rotational energy, it was rapidly distributed among translational and rotational modes. This is because for all calculations rotational-translational exchanges were governed by the Larsen-Borgnakke model, with all collisions considered as inelastic. The results confirm that the translational and rotational temperatures were very close to one another.

The calculations were carried out for values of the energy input P = 0, 15 and 80 kW.m^{-3}. For the largest value, that corresponds approximately to the experimental conditions, significant changes were observed on the profiles of axial and transverse velocities, density and translational temperature (Fig.4). The friction drag increased slightly from 0.125N m^{-1} to 0.135 N m^{-1} when P increased from 0 to 80 kW.m^{-3}.

CONCLUSION

The flow of air above a flat plate has been computed by DSMC for conditions that correspond to experiments carried out at the *Laboratoire d'Aérothermique du CNRS*. The potential influence of an electric discharge on the flow was investigated first by estimating the influence of the ionic wind. In the case of a "favorable" electric field, the transfer of momentum between accelerated ions and the neutral species is not sufficient to influence any flow profile. However, the Coulomb force exchanged between the ions and the electrodes contributes significantly to drag reduction. This conclusion should remain true even if the (smaller) Coulomb force due to the electrons is taken into account. Although the product of electric field E by the ionized fraction f is clearly the governing parameter for the Coulomb forces, it is not the governing parameter for the ionic wind (f has more influence than E).

The input of energy due to the discharge induces considerable changes in the distribution of flow parameters. However, the effect on drag remains small. The calculations were carried out for a constant wall temperature. In practice, the discharge heats the plate, which has an indirect effect on flow profiles and drag.

Further work is planned on the following items:

- It is desirable to get a better estimate of the ionized fraction, either from theory or from experiment.
- DSMC calculations should be repeated with a non-uniform electric field, based, e.g. on a solution of the electrostatic equations.
- The wall temperature should be monitored during the experiments by Infrared thermography.
- Direct measurement of drag by an aerodynamic balance are also planned.

ACKNOWLEDGMENTS

One of the authors (EM) was supported by a Ph.D grant from the regional authorities (Conseil Régional *Centre*).

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