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Rapid communication

Experimental study of a rarefied plume impinging on a cylinder-plate configuration

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ABSTRACT

An experimental analysis of the interaction of a rarefied jet plume with a cylinder-plate system is presented. The main goal is to show that the gas rarefaction can change the distribution of pressure between the two bodies quite unpredictably. The geometrical configuration has been proposed as test case to investigate the development of plume that are typically present in complex structures on spatial satellite. The results are qualitatively in a good agreement with analogous experiments and numerical simulations.

Rarefied gas jets are particularly interesting in the spatial environment of complex systems like the Space Station. The generation of plumes due to the expansion of a gaseous jet in a high vacuum ambient and its subsequent impinging on spacecraft bodies or appendices can be the origin of significant problems that span from surface damage phenomena to unwanted distributions of heat loads or disturbing torques, just to cite a few examples. In the past a extensively research has been carried out regarding the analysis of the characteristics of jets impinging on a flat plate [1]. This simple geometrical configuration allows to understand the main peculiar issues of the rarefaction effect and it is easy to realize from the experimental point of view. In so it represents a perfect candidate to carry on benchmark of numerical solutions based on molecular models (*i.e.* DSMC) [2]. In particular Legge [1] examined experimentally the impingement of a nozzle plume over a plate at different angles between the jet axis and the normal to the plate. His experimental results have been then used as reference data for several numerical papers [3,2] in the recent years. Benchmark problems in rarefied gas dynamics have been proposed in the past to many purposes, in particular to test codes and numerical procedures to be adopted subsequently to more complex configurations. Sharipov [4] listed some simple geometrical configurations and pointed out the main requirements of benchmark problems.

In real applications the geometry is usually more complex with a consequent flow field quite difficult to predict. Particularly interesting can be the analysis of the wake behind a body interacting with a plume in fact the characteristics of the flow field can change significantly with the flow regime. Moreover if a surface is located in the wake, the dynamic and thermal loads are strongly related to the wake characteristics.

We report here the results of an experimental campaign concerning the analysis of the flow field generated by a jet impinging on a cross cylinder and its subsequent wake streaming on a flat plate. This geometry has been already considered as a test case in Refs. [5,6] where some experimental and numerical results are provided. Here we show results corresponding to a wide range of the plume density conditions, in so extending the investigation from almost continuum to high rarefied conditions. The main geometrical parameters which drive the problem are the diameters of the nozzle, the cylinder and of the plate. The relative distances between the nozzle and the cylinder and the cylinder and the plate complete the geometrical definition of the problem. The physical characteristics of the flow are given by the values of the mass flow rate, the pressures and the temperatures which are established in the upstream and downstream nozzle ambients and eventually by the gas considered with its properties.

All the experiments have been carried out in the Laboratories of the Department of Mechanical and Aerospace Engineering. Fig. 1 shows a sketch of the experimental apparatus. It mainly consists of an upstream stagnation chamber C_1 connected through the convergent circular nozzle to the downstream chamber C_2 which is kept at a constant low pressure, below 1 Pa, by a vacuum pumps

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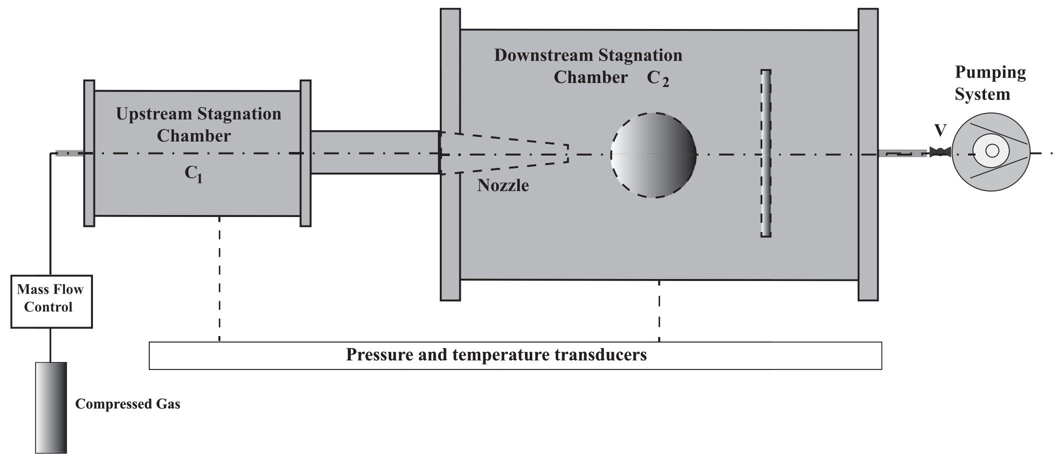

Fig. 1. Sketch of the experimental setup.

system. In particular we adopted both root (UNO 035D) and turbo molecular (TPH) Pfeiffer pumps to deal with all the mass flow rates investigated. The chamber C_1 is fed by Nitrogen through a mass flow meter and controller connected to a high pressure reservoir gas bottle.

The experimental run methodology is based on the possibility to assign a constant value of the mass flow rate and to measure the correspondingly values of the pressures in the experimental chain. All the results here reported are obtained for steady conditions, in fact for each value of the given mass flow rate we waited a sufficiently time Δt to reach a constant value of the pressure in both the two chambers C_1, C_2. The typical values of the Δt spans from tenths of minutes for flows in continuum conditions to some hours when the mass flow rate corresponds to rarefied flows.

The circular convergent nozzle has a diameter $D_n = 8 \times 10^{-4}$ m and lets the jet to discharge in the chamber C_2 that has a diameter $D_2 = 9 \times 10^{-1}$ m and length $H_2 = 1.5$ m. The upstream stagnation chamber has $D_1 = 6 \times 10^{-1}$ m and $H_1 = 0.8$ m. Both the two chambers are equipped with pressure transducers and thermocouple sensors. In particular one thermocouple is located in the upstream chamber C_1 approximately at its center. In the downstream chamber C_2 we adopt two sensors. The first is positioned between nozzle and cylinder, 10 cm off the axis, while the second is located between cylinder and plate, at the same distance from the axis. The main goal of the temperature measurements is to monitor any possible changes between temperature ahead and after the cylinder. The upstream temperature was, in all the cases investigated, equal to the ambient one, *i.e.* $T_{amb} = 300$ K. In the second chamber C_2 the two temperatures were both equal to $T_{c_2} = 295$ K.

In Table 1 the characteristics of the instruments adopted are listed.

Table 1
Instruments and Pumps characteristics. The accuracy refers to the full scale value. Mass flow rates are expressed in sccm (standard cubic centimeters per minute), where 1 sccm $\approx 2 \cdot 10^{-8}$ kg/s.

Instrument/device	Product	Range/flow rate	Accuracy	Manufacturer
Mass flow meters/ controllers	MFC5850S	0–5 sccm	0.7%	Brooks Instr.
Mass flow meters/ controllers	MFC5850E	0–200 sccm	1.0%	Brooks Instr.
Mass flow meters/ controllers	GFG-2107	0–1000 sccm	2.4%	Dwyer
Thermocouples	KMQSS-010-12	250–500 K	1%	Omega
Absolute pressure transducer	MKS-627	10^{-2}–10^{2} Pa	0.1%	MKS Instr.

Note that often the performance of the mass flow rate controllers adopted in the vacuum technology is given in terms of *standard liter per minute (slm)* or *standard cubic centimeter per minute (sccm)*. This “apparently” volume flow rate unit represents actually a measurement of a mass flow rate. In fact by taking into account that 1 standard cubic centimeter per minute of gas is the amount that flows in a minute at the reference temperature and pressure of 273 K and 101,325 Pa, respectively, it is straightforward to obtains the value in kg/s. In case of Nitrogen (density $\rho = 1.234$ kg/m^3 at reference conditions) we obtain 1 sccm $\approx 2 \cdot 10^{-8}$ kg/s.

Inside the chamber C_2 the system cylinder/plate is accommodated. As shown in Fig. 2, the cylinder is located between the nozzle and the plate with its axis perpendicular to the jet axis. The distances between nozzle and cylinder and cylinder and the circular plate are L_1 and L_2, respectively. All the results here presented are carried out with $L_1 = L_2$. The diameter of the cylinder is $D_c = 8 \times 10^{-2}$ m $= 100D_n$. The circular plate has the same diameter of the cylinder.

Both the cylinder and the circular plate are equipped with pressure tabs. On the cylinder we measure the pressure at the windward stagnation point A and at the point B, located at the opposite leeward side (see Fig. 2). On the plate the pressure was

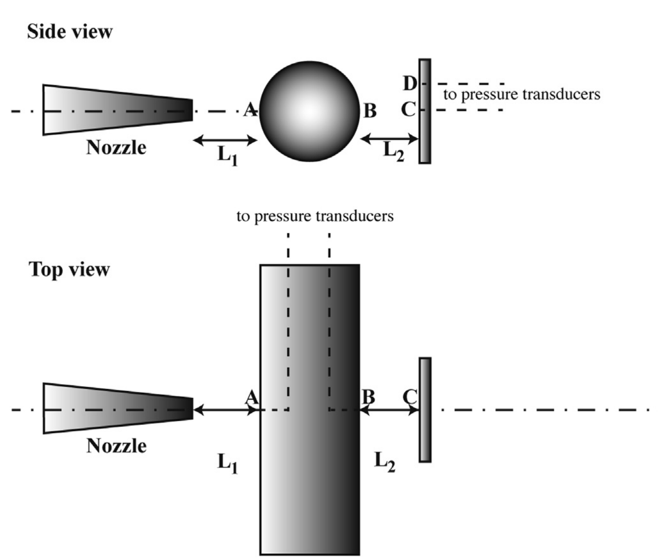

Fig. 2. Cylinder-plate arrangement views.

measured on the axis line of the jet (point C) and at a distance $\Delta R = 2 \cdot 10^{-2}$ m off the axis (point D).

To be more precise the level of rarefaction has been evaluated in terms of the Knudsen number of the gas molecules at the pressure p_0 values obtained in the upstream stagnation chamber C_1 of the experimental setup.

We remind that the Knudsen number is defined as the ratio of the mean free path λ of the molecules and a reference length L_{ref}, *i.e.* $Kn = \lambda/L_{ref}$. We adopted the nozzle diameter D_n as reference length and for λ the expression $\lambda = 1/(2\pi n d^2)$, where n is the number density and d is the molecule diameter [7]. In order to avoid the presence of the molecular diameter, the mean free path can be related to the gas viscosity through the expression $\lambda = (16/5)\sqrt{mk_BT/2\pi}(\mu/p)$ where m is the molecular mass, k_B the Boltzmann constant, p the pressure of the gas and μ the gas dynamic viscosity [8]. As an alternative to the Knudsen number, the rarefaction parameter $\delta = pL_{ref}/\mu v_m$, with the most probable speed $v_m = \sqrt{2k_BT/m}$, can be used to describe the rarefaction level [9]. Obviously the rarefaction parameter δ is inversely proportional to the Knudsen number.

Preliminarily we show in Fig. 3 the distribution of the Knudsen number Kn and the rarefaction parameter δ as a function of the mass flow rate. As expected by increasing the value of the mass flow rate, the equilibrium pressure in the upstream chamber increases monotonically. We observe that a different experimental procedure, which is equivalent to our approach, is represented by imposing a prescribed difference of pressure between the two stagnation chambers and measuring the corresponding mass flow rate, see *i.e.* Ref. [10]. Furthermore in Fig. 3 we show the error bars and we observe that it is almost negligible. For the sake of clarity it will be omitted in the following results.

Fig. 4 shows the ratio between the pressures p_A and p_B on the cylinder. Two different values of the distances L_1, L_2 have been considered and it is possible to observe that the ratio p_A/p_B decreases as the rarefaction increases, for both the two cases. The effect is analogous to that reported in Ref. [5] and agrees with a change of behavior of the wake with the level of rarefaction of the gas. In the continuum regime, *i.e.* at low Knudsen number values, it is known that the ratio p_A/p_B assumes high values. In fact the complete separation of the flow on the cylinder surface let the pressure p_B on the leeward side to be sensibly lower with respect to

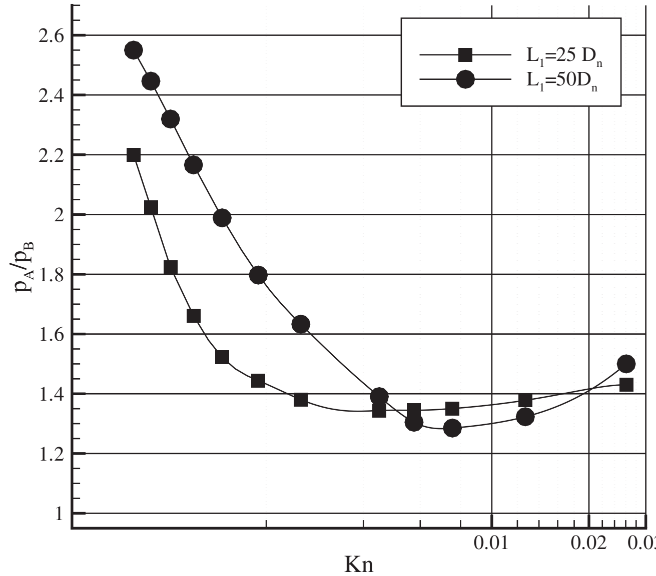

Fig. 4. Ratio of the pressures p_A/p_B between the windward side A and the leeward side B of the cylinder *vs* the Knudsen number Kn of the jet.

the windward side p_A. As soon as the molecular effects become appreciable ($Kn \geq 10^{-2}$) p_A/p_B decreases and reaches a minimum value. From a physical point of view this non linear behavior recall the Knudsen minimum observed in rarefied gas flows through tubes [9]. Also in this configuration we observe almost a minimum in the distribution of p_A/p_B and, if the pressure of the jet could further be reduced toward free molecular conditions, we should face to an increase of p_A/p_B due to the progressive depletion of molecules in the wake of cylinder.

We observe that interestingly the Knudsen number evaluated by using the pressure p_A and the diameter of the cylinder D_c as reference length, assumes almost the same values of those calculated through p_0 and D_n. In fact the expansion of the gas to lower pressure is compensated by the higher diameter and so the level of rarefaction of the flow around the cylinder is comparable to its condition at the nozzle exit.

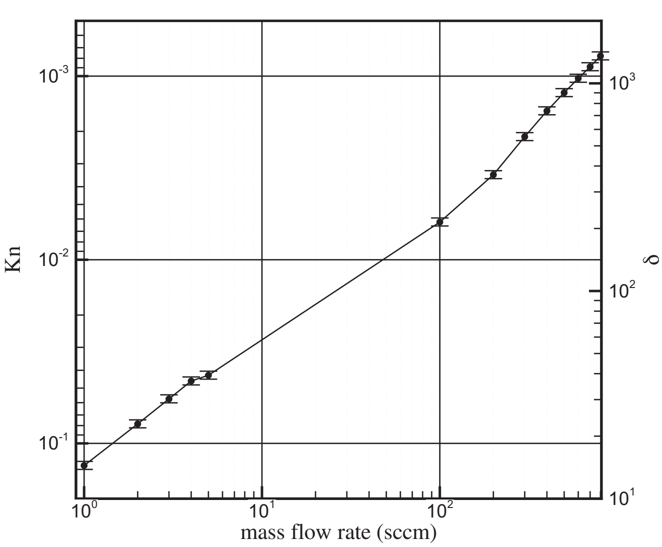

Fig. 3. Knudsen number Kn and rarefaction parameter δ distribution *vs* the mass flow rate (sccm).

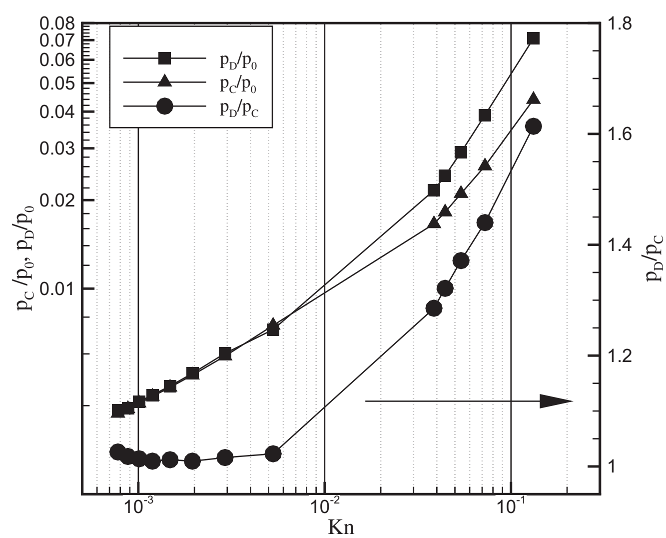

Fig. 5. Pressures p_C, p_D on the plate surface. ■ and ▲ data (left axis) refer to upstream stagnation chamber p_0. ● refers to the ratio p_D/p_C (right axis).

A further insight about the behavior of the flow can be obtained by observing the distribution of the pressure on the circular plate located behind the cylinder. In Fig. 5 we show the ratio between the two pressure p_C, p_D on the plate surface. In the range of Knudsen corresponding to more continuum conditions, p_C/p_D is almost unitary, confirming so that the wake of the cylinder is quite wide and the plate is largely shaded by the cylinder. When the Knudsen number increases the pressure off the axis p_D increases relatively to p_C. This change is coherent with the behavior described before where, in transition regime, the boundaries of wake are less defined and the presence of a higher relative molecules density brings to a greater value of the pressure.

The same effect can be recognized if the pressures p_C and p_D are referred to p_0. The two distributions are reported on the same Fig. 5 and display an appreciable difference for $Kn > 10^{-2}$, as for p_D/p_C.

In conclusion we observe that the behavior of the cylinder's wake impinging on the circular plate is significantly dependent on the rarefaction level of the plume. The almost complete shading of the plate, typical of continuum or complete free molecular flows, is not observed in the transition regime and the practical consequences on the spatial structure is the possibility of unpredictable molecular fluxes on surfaces and additional dynamic and/or thermal loads.

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