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FLOW VISUALIZATION OF GAS FLOWS IN CHANNELS IN THE SLIP REGIME BY MEANS OF MOLECULAR TAGGING VELOCIMETRY

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ABSTRACT

The microscopic mechanisms of interaction between gas molecules and a solid surface have been subject of study for more than two centuries (Maxwell, 1879). In most of the fluid dynamics problems of interest, a no-slip velocity boundary condition at the wall is an enough accurate representation of the macroscopic flow behavior close to the solid surface. However, there are many gas flow problems of great interest, such as gas micro-flows in micro-electro-mechanical systems (MEMS) or gas flows around space satellites or vehicles, in which this simple mathematical representation does not hold anymore and the specific nature of the gas-surface interaction needs to be properly modeled and taken into account. When the frequency of intermolecular collisions inside the gas reduces, the gas mean free path, λ, which is the distance travelled by a molecule between two consecutive collisions, might become comparable or even smaller than the characteristic length of spatial gradients of flow macroscopic quantities, e.g., velocity or temperature. In these conditions, local thermodynamic non-equilibria arise in the gas flow, which is in a state of rarefaction. Rarefaction is usually quantified by means of the Knudsen number $Kn = \lambda/L$, where L is a characteristic length of the system. Higher rarefaction levels correspond to higher Knudsen numbers, which can be obtained by reducing either the system dimensions or the average gas pressure. The onset of rarefaction phenomena takes place in a localized region on the wall surface, where the velocity and temperature gradients are usually the highest ones. For Knudsen numbers in the slip flow regime, i.e., for $Kn \in [10^{-3}; 10^{-1}]$, the continuum representation of the fluid flow is still valid, but the local thermodynamic non-equilibrium at the wall produces macroscopic discontinuities of the gas velocity and temperature fields, for which the usual mathematical no-slip boundary condition cannot be employed anymore.

In the literature, a great amount of theoretical and numerical models of gas-surface interaction have been proposed and provided modified boundary conditions able to correctly describe the rarefaction effects at the wall. Although in different forms and level of complexity, these mathematical models are all based on the introduction of accommodation coefficients, which depend on the gas species, surface roughness and material, and which represent a statistics of the microscopic energy and momentum transfers in the gas-surface molecular collisions. The experimental evaluation of these coefficients is required for the ultimate verification and validation of the proposed mathematical models. However, carrying out direct measurements of the slip

velocity and temperature jump along a solid wall is a difficult task, and most of the experimental studies presented in the literature only indirectly quantify the rarefaction effects by measuring the mass flow rate through micro-channels (Pitakarnnop *et al*., 2010; Silva *et al*., 2016). In this context, this work aims to the application of molecular tagging velocimetry (MTV) technique with the intent of providing novel direct measurements of the gas slip velocity at the wall produced by rarefaction in the slip regime.

MTV is an opto-chemical technique capable of providing local measurements of the velocity field in gas flows. The technique is based on the tracking of suitable tracer molecules that exhibit photoluminescence properties. The low-intrusive feature and the fact of being molecular-based makes MTV the most suitable experimental technique for accurate measurements of small slip velocities characterizing slightly-rarefied gas flows. While various versions of this technique currently exist, this work demonstrates the implementation of 1D-MTV by direct phosphorescence, which is based on the long-lived phosphorescence emission of specific molecules, such as acetone ones, which can be activated by a single UV laser line excitation. An intensified, gated CCD camera is used to capture the tracer light emission. The image acquisition carried out at two different times after the laser excitation reveal the initial and the final positions of the tagged tracer molecules pre-seeded in the gas flows, from which the velocity field can be locally inferred. With the idea of measuring the slip velocity at the wall produced by local thermodynamic non-equilibria, MTV is applied to gas flows in a channel with a rectangular section by using acetone vapor as molecular tracer.

While MTV technique has already been successfully applied in various gas flow systems (Stier & Koochesfahani, 1999; Lempert *et al*., 2002), the application of MTV to the case of confined and rarefied gas flows has been prevented up to now by various technological challenges. First of all, MTV measurements of fluid micro-flows require the adoption of energetic short laser pulses with a beam diameter smaller than the characteristic length of the system. Because diffraction phenomena limit the minimum laser beam waist that can be physically obtained by means of focusing optical lenses to about 30-100 µm, the channel height cannot be smaller than about 1 mm. Hence, in order to reach Knudsen numbers in the slip flow regime, the average pressure needs to be lowered to about 1 kPa. Unfortunately, low average pressures reduce the amount of tracer molecules present in the gas and increase the molecular diffusion of the tracer through the background gas. The combination of these two low-pressure effects makes the light signal to disappear much faster than in high pressure conditions, and makes MTV applications in rarefied gas flows very challenging. In this regard, we recently demonstrated in our previous work (Fratantonio *et al*., 2018) that acetone vapor can provide an enough strong and durable phosphorescence emission in low-pressure slip-regime thermodynamic conditions only if a laser source with an excitation wavelength close to 310 nm is employed.

For the MTV acquisitions presented in this work, an OPOlette HE355 LD laser from Opotek Inc. is used for generating laser pulses characterized by an excitation wavelength of 310 nm, a pulse width of 7 ns, and an energy per pulse of about 100 µJ. A 20-cm long channel with a rectangular section 1×5 mm^2 has been equipped with two optical accesses for allowing MTV acquisitions: one for the laser beam entrance and the other one for allowing camera acquisitions of the acetone phosphorescence. A 12-bit *Imager Intense* CCD camera is combined with a gated intensifier relay optics (IRO), which is needed for imaging analysis in low light conditions. A set of optical lenses is mounted on the IRO, which allows a magnification of about 1.7 and a resulting field of view of 5.29×4 mm^2. The gas circuit used for generating the pre-seeded gas flow with the desired thermodynamic conditions through the tested channel is sketched in Figure 1. A mixture of helium and acetone vapor is pre-prepared in a big reservoir located upstream from the tested channel, and a couple of vacuum pumps are used for controlling the gas flow rate. The choice of using helium as main carrier gas for this study is based on the fact that higher rarefaction regime can be obtained at higher pressure because its molecular diameter and mass are the smallest ones among all gases. The drawback of this choice is an increased molecular diffusion of the tracer vapor. The experimental setup has been designed in an open loop configuration in order to satisfy the requirements of acetone chemical compatibility and oxygen free environment. Since oxygen molecules are efficient quenchers of acetone phosphorescence, fresh helium-acetone mixture needs to be introduced in the section investigated by MTV because the tested channel could hardly be made perfectly free from air leakages.

The low phosphorescence intensity of acetone vapor at low pressure requires the integration of multiple laser-excited emission on a single image, and, moreover, the signal-to-noise ratio needs to be increased by averaging multiple images. These requirements elongate the acquisition time needed to produce an exploitable image for velocimetry purposes. In order to maintain the upstream pressure constant for the longest possible duration during MTV acquisitions, a large upstream reservoir volume, about 180 L, has been chosen.. On the other side, the pumping system is used at its maximum power in order to maintain the downstream pressure as low as possible, thus maximizing the flow rate. In this experimental analysis, high flow rates are desired for enhancing as much as possible the gas slip velocity at the wall and the molecular displacement of the tagged line. Capacitive pressure gauges have been placed at the inlet and the outlet of the tested channel to monitor the boundary conditions. The estimation of the average pressure conditions at the center of the channel, where the optical windows for MTV application are installed, has been carried out based on the inlet-outlet pressure measurements and theoretical pressure distributions that take into account of the compressibility and rarefaction effects along the channel (Ebert & Sparrow, 1965).

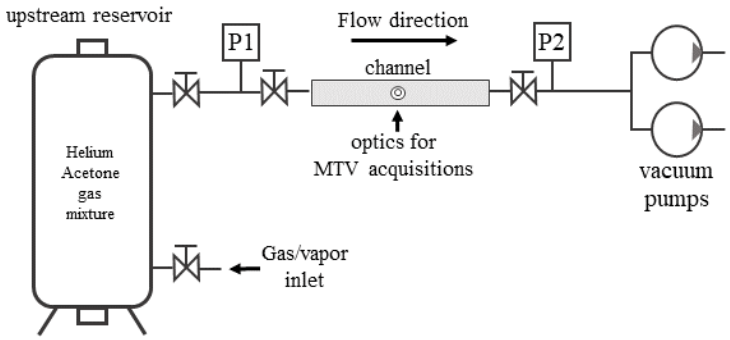

Figure 1: Schematic of the experimental gas system employed for carrying out MTV acquisitions on controlled acetone-helium mixture. P1 and P2 are sensors used for monitoring the inlet-outlet pressures during MTV acquisitions.

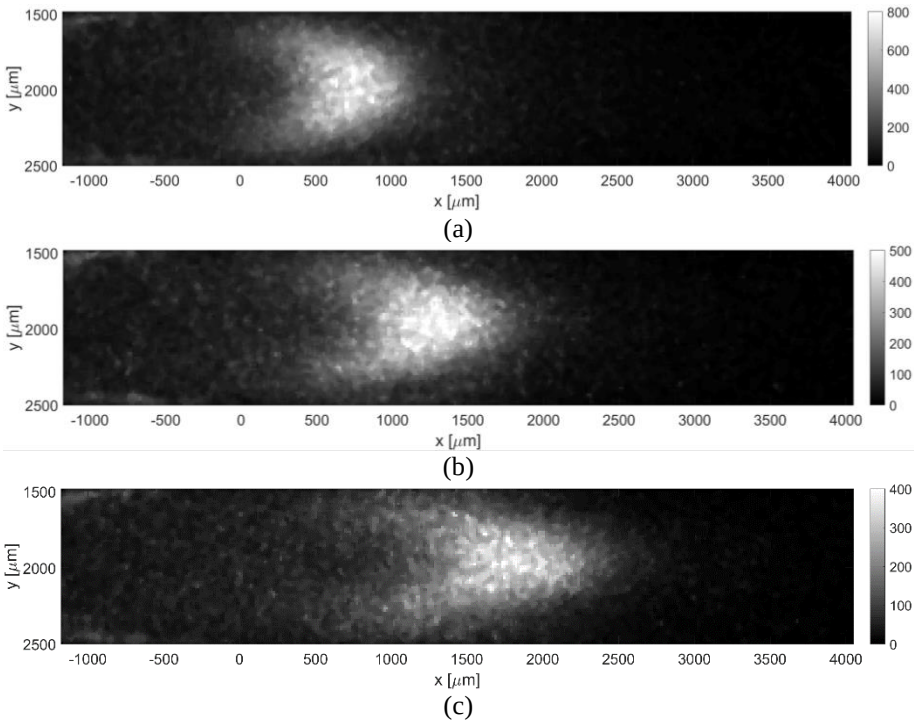

Figure 2: MTV acquisitions of helium-acetone mixture flow in a channel with a rectangular section. The mixture is composed by 20% acetone molar fraction. The average pressure and temperature are p = 1580 Pa, T = 298 K, and the inlet-outlet pressure difference is Δp = 1800 Pa. The three images represent the tagged acetone molecules position at three different times after the laser excitation: (a) t = 20 μs, (b) t = 30 μs, and (c) t = 40 μs.

Figure 2 shows MTV results for the case of a 80% helium – 20% acetone mixture flow at an average pressure of 1580 Pa. This thermodynamic condition corresponds to a Knudsen number of about 4×10^{-3} which is a slightly-rarefied condition in the early slip flow regime. The three images represent the time evolution of the molecular positions of the tracer 20, 30, and 40 µs after the laser excitation. The high pressure difference of 1800 Pa maintained at the channel inlet-outlet provides a mass flow rate of $\dot{m} = 1.7\times10^{-6}$ kg/s and a mean flow velocity of 40 m/s.

The observed high molecular displacement at the wall is not produced only by the gas slip velocity, which has been estimated to be about 1.6 m/s by using a Maxwell slip boundary condition, but mainly by the Taylor dispersion, a diffusion-advection mechanism that makes the gas molecules close to the wall move forward in the flow direction, even if no-slip velocity is present (Si Hadj Mohand *et al*., 2017). This physical phenomenon prevents from deducing the velocity profile as a simple homothetic transformation of the tracer displacement profile. In this context, Frezzotti *et al*. (2015) developed an algorithm based on the diffusion-advection equation describing the motion of the tracer molecules in the carrier gas and capable of reconstructing the velocity profile from the deformed tagged line analysis. This reconstruction method has been successfully applied for extracting velocity profiles from numerical experiments generated by Direct Simulation Monte Carlo (Fratantonio *et al.*, 2018) and from MTV experimental data of non-rarefied channel gas flows (Samouda *et al*., 2015). However, the application of the reconstruction method to the data of Figure 2 does not provide very accurate measurements of the velocity profile. Further investigation is required to developed a better post-processing algorithm for local velocity measurements in gas flows that are strongly affected by Taylor dispersion. Nevertheless, the MTV results presented in Figure 2 are first of their kind, as they are the very first flow visualizations of the gas molecular displacement in a slightly-rarefied and confined gas flow.

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