# Molecular Tagging Thermometry for near wall measurements of gas flow in rarefied regime

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## Key-words

Microfluidics, Thermometry, Molecular Tagging, Gas micro-flows, Rarefied Gas flows

## Objectives and context

Understanding the phenomena involved in gas micro-flows is of crucial interest for the development of new and innovative microsystems. Gas flows in such systems find nowadays more and more industrial applications in numerous fields such as environment (gas micro-analyzers), electronics (micro-heat exchangers), aerospace engineering (microfluidic actuators for flow control), chemistry (lab-on-chip), and vacuum technology (micro-pumps, pressure and temperature sensors). In gas microsystems, the reduction of the dimensions possibly coupled to a decrease of pressure leads to an increase of the rarefaction. Its effect is characterized by the apparition of thermodynamic disequilibria near the walls, provoking non-linear phenomena resulting in velocity and temperature discontinuities.

The rarefaction level is characterized by the Knudsen number, $Kn = \lambda/L$, ratio of the mean free path of the molecules $\lambda$ over a characteristic length $L$ of the microsystem. In classic microsystems, $Kn$ is frequently between 0.001 and 0.1, which is the range of the well-known slip-flow regime [1]. To describe gas flows in this moderate rarefied regime, the classical continuum physics is still valid far from the wall: the standard Navier-Stokes and Fourier equations can be used to predict the flow behavior but they need to be associated to appropriate velocity-slip and temperature-jump boundary conditions. This is necessary to take into account the presence of the Knudsen layer, a thin layer near the wall in which the gas is in a thermodynamic disequilibrium state (Fig. 1).

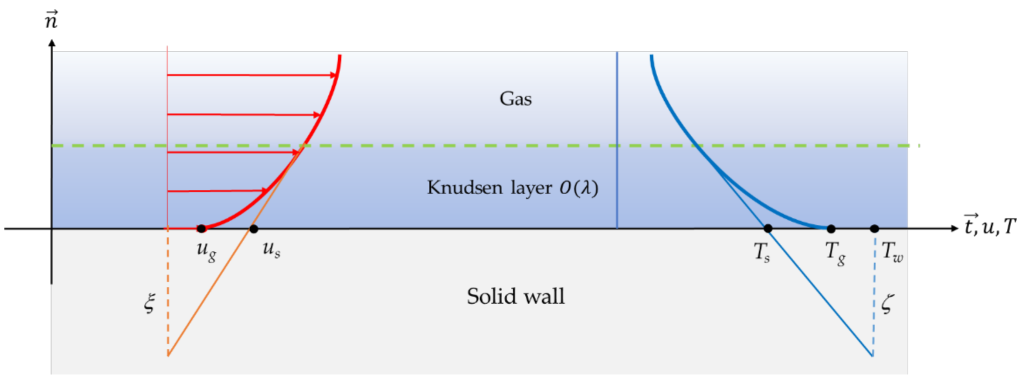


*Figure 1 : Velocity slip and Temperature jump in the slip-flow regime.*
*$U_g$ and $T_g$ : real velocity and temperature conditions at the wall*
*$U_s$ and $T_s$: conditions implemented to simulate the exact behavior out of the Knudsen layer*

In the past ten years, huge progresses have been made on theoretical and numerical studies modeling rarefied gas flows and taking into account rarefaction effects [1-3], but there is still a crucial lack of experimental data in this field allowing to discuss the limits of validity of the developed models [4, 5]. Even if the theory of gas hydrodynamics in the slip-flow regime is now supported by smart experiments, most of these data are only related to micro-flowrate measurements [6-10]. Experimental data on temperature distribution are however not yet available. It is thus necessary to develop techniques able to measure fluid temperatures at small scale in order to accurately design original fluidic microsystems involving gas flow and heat transfer.

At small scale, thermocouples [11, 12], resistance temperature detectors (RTDs) [13, 14] or thermistors [15, 16] are commonly used for thermometry purposes. Unfortunately, all these devices are intrusive: they significantly disturb the flow and the heat transfer and modify the temperature distribution to be measured.

The use of semi- or non-intrusive optical techniques could be an alternative solution. Among these techniques, Infra-Red Thermography (IRT) [17, 18] or Thermosensitive Liquid Crystals (TLC) thermometry [19, 20] are appealing. However, in the case of gas flows, these two techniques only allow the measurement of surface temperatures. Laser Induced Fluorescence (LIF) thermometry has also been widely used [21-23] as well as interferometry [24, 25]. If all these techniques have already been applied at microscale for liquid flows, very few of them have been used for gas flows due to the complexity of their implementation and the low optical signal obtained with gases.

Thus, the Molecular Tagging Technique (MTT) seems to be a good candidate for such measurements. Its principle is based on the luminescence phenomenon [26]: a gas is seeded with fluorescent or phosphorescent molecules (typically acetone or diacetyl) which emit light when they are activated by photons (provided by a UV laser). Typical images of fluorescence and phosphorescence signals can be seen in Figure 1.

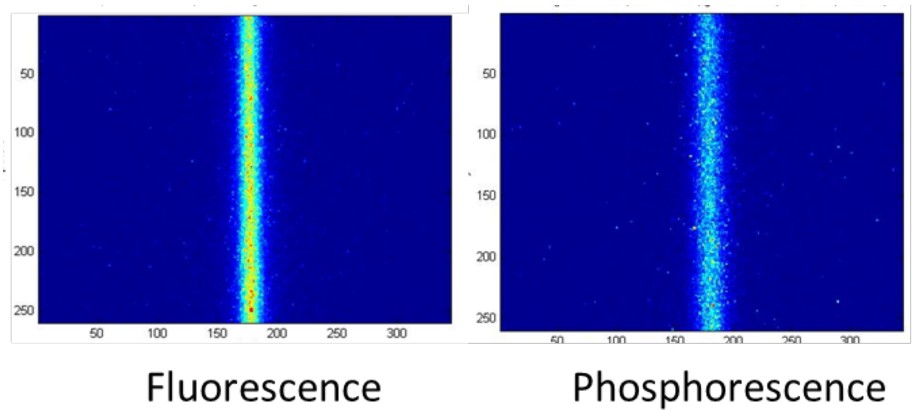


*Figure 2: Fluorescence and phosphorescence signals of argon-acetone mixture at atmospheric pressure*

For temperature measurements, the phosphorescence lifetime dependence on the temperature will be exploited. This phenomenon has already been demonstrated at high temperature and for pressures higher than atmospheric pressure [27, 28] and recently, our research team has obtained results for pressure between 15 000 Pa and 1 000 Pa. As far as we know, MTT technique has only been used once to measure a liquid flow temperature in a channel of millimetric dimensions [30].

The objective of this work is to develop an experimental setup able to simultaneously measure the wall temperature by IRT and the gas temperature near the wall by MTT. The principle is illustrated in Figure 3. The final goal will be to determine the temperature jump when rarefied conditions are reached.

The spatial resolution of the MTT technique is conditioned by the laser beam diameter, of the order of 30 µm at the minimum. Evanescent waves will be then used to illuminate only a thin layer of gas near the wall - typically a slice of 100 nm thickness. This technique has been already successfully used at micro-scale in Micro-Particle Image Velocimetry (µ-PIV) to study liquid behaviour near the wall [31-33]. Here, the challenge will be to couple this technique to MTT in order to excite only the molecules in the illuminated layer, and then to capture and analyse the near-wall signal.

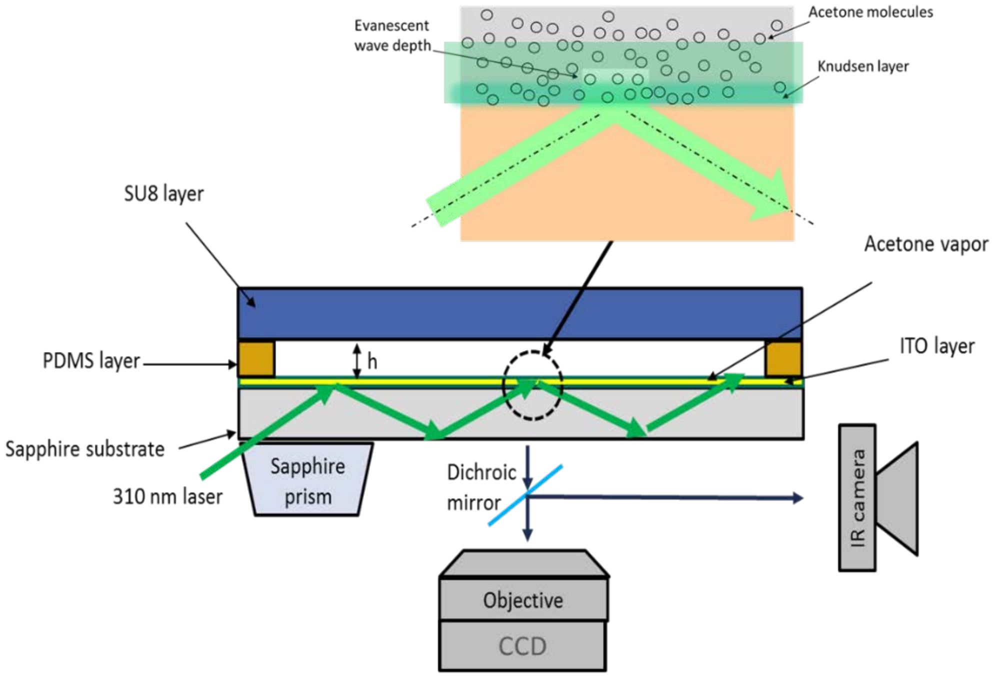


*Figure 3: Principle of expected experimental setup*

**Methodology - Material**

An experimental setup devoted to Molecular Tagging has been developed at Institut Clément Ader (ICA) for velocity measurement (MTV) and is being adapted for two years for thermometry (Figure 4). The UV light is generated by a laser and images are recorded with a camera coupled to an intensifier. This setup, associated with specific signal processing methods taking into account diffusion effects to reconstruct velocity profiles [34-36] allowed original works concerning the measurement of velocity in gaseous flows [37, 38]. The first slip-velocity measurements by MTV have been obtained a few months ago (PhD Thesis – Fratantonio).

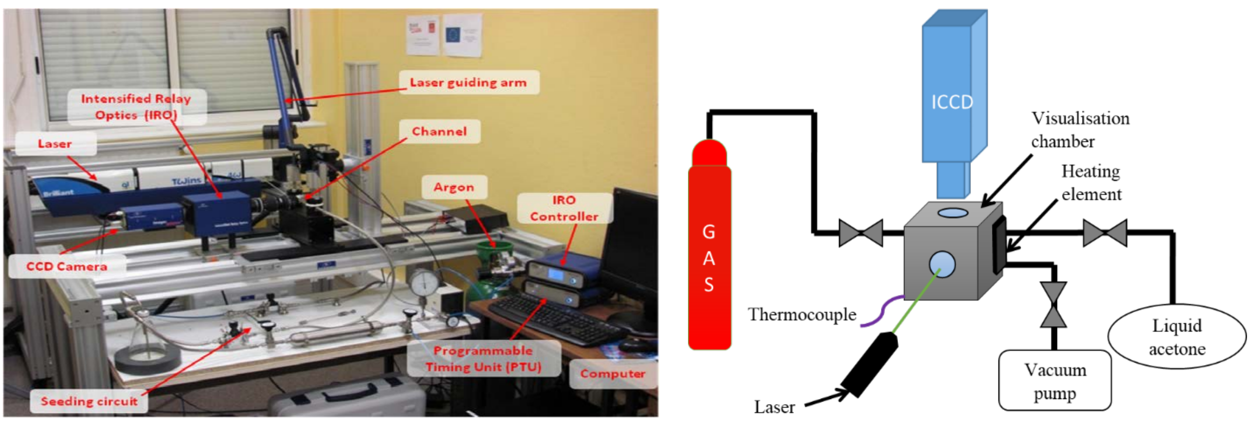


*Figure 4: MT experimental setup developed at ICA for velocimetry (left) and thermometry (right)*

A first design of the experimental setup dedicated to MTT has been built and has permitted to obtain preliminary results on the dependency of phosphorescence on gas temperature, showing that MTT could be used for temperature measurements in rarefied gas flows.

The planed steps for this project will consist in:

1- Improving the implementation of MTT for gases. New developments with improved accuracy should be proposed in order to complete and reinforced the conclusions given by preliminary results,
2- Designing a test cell for the implementation of evanescent waves and make temperature measurements in the illuminated layer,

3- Studying the influence of the experimental parameters on the phosphorescent signal (acquisition parameters, gas conditions parameters such as pressure, and thickness of the illuminated zone),
4- Designing the experimental setup (cellule and optical path) allowing simultaneous measurements of temperature by IRT and MTT,
5- Comparing the experimental data to results obtained with other techniques,
6- Developing numerical models of the experiments, based on the Direct Monte Carlo Simulation (DSMC) technique, in order to have a better understanding of the dependency of the luminescent signal on various flow parameters (temperature, pressure…),
7- Proposing an experimental methodology for the implementation of MTT technique in gas flows and proposing an analysis of the obtained experimental data. Discussing on the validity of assumptions used in analytical models and numerical simulations of gas flows in the slip-flow regime.

**Expected results**

Obtaining accurate data on the temperature distribution is a major challenge in the study of gas micro-flows. The data obtained during this project will allow a real discussion concerning the validity of the different slip-flow and temperature-jump models, as well as their domain of applicability.

Thus, MTT measurements will be compared to data obtained with various numerical models. They could be completed by experimental data obtained with other thermometry techniques.

Our team was pioneer in providing preliminary measurements of velocity slip at the wall by MTV. The next step will be now to obtain similar results with temperature jump at the wall. The final objective is to obtain an experimental tool able to provide simultaneously measurements of the velocity and temperature fields in gaseous microsystems, including in the near wall regions.

**Requirements**

- Master-level degree in Mechanical Engineering, Process Engineering, Physics or similar,
- Excellent communication skills and good written/verbal knowledge of the English language, good presentation skills,
- A good background in fluid mechanics and/or heat transfer,
- Experience in experimental techniques and/or knowledge on lasers would be helpful.

**Collaborations**

This project will take place at ICA (Institut Clément Ader www.institut-clement-ader.org), in Toulouse. The microfluidics research group of ICA has an internationally recognized experience in experimental analysis of gas microflows [2, 3, 14]. It has already designed original experimental setups and provided accurate data on the hydrodynamics of gas microflows [3].

The PhD project will be co-supervised by Prof. Stéphane Colin (http://institut-clement-ader.org/author/scolin/) and Dr. Christine Barrot (http://institut-clement-ader.org/author/cbarrot/).

The candidate will benefit from the experience gained within the European Networks GASMEMS and MIGRATE (details at http://www.gasmems.eu and http://www.migrate2015.eu). The proposed project will be conducted in the framework of already active international collaborations with the following Universities: the University of Limerick-Ireland for complementary experimental approaches (µ-interferometry), the University of Bologna-Italy for the development of heat transfer models at microscale, the Karlsruhe Institute of Technology-Germany for the fabrication of experimental micro-devices including pressure and temperature sensors and Politecnico Milano-Italy for molecular simulation by the Direct Monte Carlo Simulation method.

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