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Gas viscosity sensing based on the electrostatic pull-in time of microactuators☆

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ABSTRACT

A new principle for gas viscosity sensing using electrostatic pull-in and its implementation using a microstructure are presented in this paper. The sensor is based on viscosity-dependent pull-in time measurement. A nonlinear dynamic analysis of pull-in demonstrates the influence of damping conditions on the pull-in time of devices that are operated at meta-stability (requiring specific damping and electrostatic actuation conditions) with a squeeze-film damping coefficient at low frequencies directly proportional to viscosity. Therefore, the fundamentals of pull-in behavior suggest that pull-in can be used for the implementation in a gas viscosity sensor.

Capacitive parallel-plates MEMS structures with squeeze-film dampers have been fabricated and pull-in time measurements have been performed for different gas media. Both pure gases (H_2, CH_4, CO_2, CO and N_2) and mixtures (H_2—N_2, CH_4—N_2 and CH_4—N_2—CO_2) have been tested, with viscosity values in the range between 9 and 18 μPa s. The results show a sensitivity of 2 ms/(μPa s), which can be further increased by manipulating the actuation voltage. Further efforts are necessary to reduce the device sensitivity to external vibration, which translated to a significant amount of noise in the measurements.

1. Introduction

Viscosity is the main parameter characterizing the flow behavior of fluids. For gases the viscosity is an important parameter where flow behavior is important, such as in nozzles of burners and pumps. The dynamic or absolute viscosity coefficient for Newtonian fluids is defined as the ratio between the shear velocity and the shear rate [1], and is expressed in the units Pa s (Pascal second) or Poise (10 μP = 1 μPa s). Some instruments measure kinematic viscosity, which is the ratio between viscosity and density (units are m^2/s or Stokes). Sometimes viscometer manufacturers also provide specifications in terms of acoustic viscosity, which is defined as absolute viscosity × density [2]. Viscosity measurement tools are widely used in industry for quality control of liquids, pastes and gases, dealing with products such as paints, lubricants, adhesives, fuels or food [3–6].

1.1. General viscosity measurement techniques

There are many types of viscometers available for liquids. These are generally classified by the actuation method, such as capillary, orifice, high temperature shear rate, rotational, falling ball, rising bubble, moving piston, vibrational or ultrasonic viscometers [7]. Equipment on the market is usually a laboratory instrument, since samples have to be prepared and processed manually [1].

The viscosity of a gas is generally much lower as compared to liquids, as the forces involved are small. Therefore, at the moment only a few measurement techniques developed for liquids viscosity sensing are capable of measuring viscosity in a gas. As a consequence, the use of on-line gas viscosity sensing equipment is still not widely spread. Gas viscosity measurement is much more difficult due to the much lower viscosity of gases, which is typically in the range $\eta = 10^{-5}$ Pa s, as compared to 10^{-3} Pa s for water and 10^{-1} Pa s for oil. Only a few measurement techniques, such as the capillary tube [8], the vibrating wire and the moving-piston principle have been used in commercial gas viscometers [9]. As an example, the Cambridge Viscosity Inc. VISCOpvt moving-piston viscometer modified for gases has a measurement range of 10^{-4} Pa s to 10^{-3} Pa s with an accuracy of 1% [9]. In [10] a modified perturbation viscometer has been used to measure the gradient of viscosity in non-ideal binary gases mixtures as function of composition, but

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obtaining the absolute viscosity requires prior knowledge of the viscosity of one of the components.

The small value of the viscosity imposes a huge challenge in the design of gas viscometers. The use of new technologies, such as MEMS (micro-electro-mechanical systems) techniques may enable new opportunities for gas sensing because they are more suitable to measure the small frictional forces involved.

1.2. Viscosity measurement based on MEMS techniques

Most of the work reported in literature on gas viscosity measurements employing microsystems use vibrating beams. There are a few exceptions that focus on the measurement of flow and pressure gradient to obtain viscosity. Characteristic parameters, such as resonance frequency, quality-factor and phase-shift depend on pressure and viscosity of the trapped gas and thus can be used for sensing these gas properties [11].

In [12], gas viscosity measurements using damping of a microstructure are demonstrated. The method uses the phase lag between the motion of a microstructure and its actuation signal to measure the damping of a gas. The effective viscosities (normalized to the free gas viscosity) of some gases, with viscosities ranging from 8 to 22 μPa s, were measured in the molecular and transitional flow regions, with an accuracy of 1% [12]. In this study, only the ratio between viscosities is measured, not allowing the measurement of absolute values.

In [13] a micromachined two-dimensional resistor array has been used to measure a temperature distribution, allowing measurement of flow velocity of heated gases and kinematic viscosity. Argon, carbon dioxide and nitrogen were used in the experimental validation, yielding an accuracy in the order of 5%.

A gas density and viscosity measurement system has been developed in [14], using flow and pressure gradient measurements. It comprises a commercial differential pressure sensor, a laminar flow rate MEMS sensor (micro hot wire anemometer chip) and a bi-cylindrical flow channel. Air and carbon dioxide have been tested with an uncertainty of less than 3% [14].

The work reported in [11] uses squeeze-film damping to measure the viscosity of gases. Satisfactory experimental results are however not available. Since measurements were performed at low pressures, the authors concluded that in these conditions the changes in quality factor and resonance frequency were gas independent.

More recently, quartz tuning fork resonators (32.768 kHz resonance frequency) have been used to measure simultaneously the density and the viscosity in gases at a measurement frequency (density/viscosity sampling frequency) of 1 Hz, using a frequency tracking method (measuring motional resistance due to viscous damping and resonance frequency shift due to mass loading) and fitting data in an equivalent circuit model [15]. The deviations/errors obtained in the viscosity measurements were less than 2% for densities above 3 kg/m^3 (achieved by performing the measurements at high pressures).

The resonating beams used for measuring viscosity reported in literature can be fabricated in the same technology as the device presented here. However, low gas damping is required for operation of these structures in resonance, and low damping cannot always be achieved at atmospheric pressure levels, when designing large capacitances, required for increased signal levels. Moreover, at higher frequencies, the effects of compressibility and inertia of the gas become significant and the relation between viscosity and damping force becomes non-linear. Resonance operation, at standard conditions in most gases, is generally only possible in very small microstructures. In general, these devices operate at a much higher motion frequency than the microsystem described here. The proposed method presented here is based on the electrostatic pull-in of capacitive parallel-plates microstructures. This approach consists of measuring the pull-in time in over-damped conditions. The overall pull-in time duration depends on the damping coefficient and, as the operation frequency is low, the damping coefficient is directly proportional to viscosity.

The viscosity measurement technique based on pull-in introduced here has several advantages. First, the critical pull-in displacement of a lateral comb microstructure is well defined, since it depends mainly on the geometry of the structure. Second, pull-in operation enables the largest possible displacement of the structure, which is an advantage in relation to conventional electrostatic actuators where pull-in is avoided and displacement is limited to 1/3 of the total gap and is also an advantage in terms of readout capabilities (larger sensing capacitance). Third, the large increase of the displacement signal when pull-in occurs enables the accurate detection of the pull-in time of the structure and, thus, the measurement of the damping. Finally, as the operating frequency is low, for the gap dimensions used and viscosities measured, the gas inertia (and gas density) plays a negligible role (frequencies much lower than the inertial cut-off frequency).Therefore, absolute (not kinematic) viscosity is measured.

1.3. Application areas for gas viscosity sensors

Knowledge of the rheological characteristics of a gas is valuable in predicting the flow and pumpability of gas distribution systems or the flame properties and performance in the nozzles of gas burners. Viscosity gas sensors can therefore be used for monitoring the quality of combustible gas e.g. in burners. Another challenging application is the detection of the composition of a gas mixture by the measurement of viscosity and several other physical parameters of the gas mixture. Quality control of natural gas is another target application for composition measurement using viscosity sensors. Conversely, if the gas temperature and composition is known, the gas density can be calculated from the measured viscosity coefficient [16]. New applications can arise if small, portable and low-cost systems are developed.

2. Gas viscosity fundamentals

The simplest version of the kinetic theory of gases (molecules treated as solid spheres of diameter d_m) allows a qualitative analysis of the viscosity coefficient. It can be shown that the viscosity coefficient is proportional to both the mass density ρ, the mean free path λ and the mean velocity, $\bar{u}$, of the atoms in a gas [17,18];

$$\eta = \tfrac{1}{3}\rho\bar{u}\lambda \tag{1}$$

The mean velocity is defined as

$$\bar{u} = \sqrt{\frac{8k_BT}{\pi M_m}} \tag{2}$$

where M_m is molecular mass. The mean free path is defined by the same model as [19]

$$\lambda = \frac{k_BT}{\pi\sqrt{2}p{d_m}^2} \tag{3}$$

where k_B is the Boltzmann constant (at pressure p and temperature T). By combining these three expressions, the viscosity of an ideal gas can be rewritten (using the ideal gas equation $pV = nRT$ and the definition of density $\rho = \frac{nN_AM_m}{V}$):

$$\eta = \frac{1}{3}\rho\sqrt{\frac{8k_BT}{\pi M_m}}\frac{k_BT}{\pi\sqrt{2}p{d_m}^2} = \frac{2\sqrt{M_mk_BT/\pi}}{3{d_m}^2\pi} \tag{4}$$

From (4), viscosity is independent of pressure. Experimentally this behavior has been confirmed up to approximately 1 MPa, above