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Experimental and computational study of gas flow delivered by a rectangular microchannels leak

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ABSTRACT

The gas flowrate through a rectangular microchannels device has been investigated within a collaboration between the Istituto Nazionale di Ricerca Metrologica from Torino and the Institut Clément Ader (ICA) from the University of Toulouse.

The microdevice was characterized with different gas species as He, N_2, Ar, R12, CO_2 and a mixture N_2/H_2 (95/5), in a wide range of pressure, to test its potential use as secondary gas flow standard in terms of ease of use and predictability of gas flowrate.

The measurements of gas flowrates have been carried out in an inlet pressure range between 50 Pa and 100 kPa and with two different outlet conditions: vacuum (10^{-6} Pa up to a few Pa according to the setup) and atmospheric pressure. Furthermore the temperature coefficient has been determined from measurements in a temperature range from 15 °C to 25 °C.

The primary standards of both laboratories were compared and a semi-analytical model was used to predict the molar gas flowrate through the rectangular microchannels in the slip flow and early transition regimes.

1. Introduction

In the framework of the European project EMRP-JRP-IND12 “Vacuum metrology for industrial environments”, the experimental and theoretical study of small gas flows has been approached because of its crucial importance in many branches of industry (cold storage facilities, air conditioning systems whose leak rates have to follow the rules of e.g. DIN 8964 and EN 14091, containment systems for toxic, radioactive and environment polluting substances). The most sensitive, versatile and accurate method for leak measurement is the permanent gas (helium) flowrate measurement through the leak into vacuum. Nevertheless, the leaks usually occur under conditions different from those at measurement: different pressures, temperature and temperature gradients, gas species and mixtures. Research is needed to provide industry with traceability under practical conditions and enabling users of calibrated leaks to predict leak rates under industrial environments [1,2].

Within the framework outlined by EMRP-JRP-IND12, in order to meet this requirement, cooperation between the Istituto Nazionale di Ricerca Metrologica (INRIM) from Torino and the Institut Clément Ader (ICA) from the University of Toulouse allowed to consider a microdevice with well-defined geometry. The microdevice, encased in a suitable box to maintain constant temperature, was characterized by the primary standards of both laboratories with different gas species, obtaining calibration curves referred to atmosphere and to vacuum, in a wide inlet pressure range.

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Afterwards a semi-analytical model was used to predict the molar gas flowrate through the rectangular microchannels in the slip flow and early transition regimes and the results were compared with experimental data.

In addition, the study presented in the paper allowed to test the use of the microdevice as secondary gas flow standard for industrial purpose: the gas flow delivered by the device can be estimated through the developed semi-analytical model, without carrying out several measurements for each gas and in a wide range of inlet pressure.

2. Microsystem leak device

The microsystem T4P leak device consists in a series of parallel rectangular microchannels etched by deep reaction ion etching (DRIE) on a 4 inches diameter silicon wafer and closed by anodic bonding with a 3 inches diameter Pyrex plate.

The characteristics of the microchannels are listed in Table 1. The 575 rectangular cross-section channels with an aspect ratio $a^* = H/W$ equal to 0.0109 are connected to 300 μm deep upstream and downstream reservoirs as shown in Fig. 1. The length and the width of the reservoir channels are respectively 50,000 μm and 1000 μm; considering the dimensions of reservoir channels and microchannels (Table 1), the Poiseuille number P_o for reservoir channels is about 17 and for the microchannels it is close to 24. The hydraulic resistance for a laminar flow (without taking into account rarefaction effects) is proportional to $(P_o\ L)/(S\ D_h^2)$ where $S = WH$ is the cross-section area and $D_h = 2S/(W + H)$ is the hydraulic diameter. As a consequence, the ratio of the hydraulic resistances (one reservoir channel over one microchannel) or the ratio of the conductances (one microchannel over one reservoir channel) is equal to about 3.2×10^{-9}. So, even with more than 100 microchannels in parallel, the pressure loss in the reservoir can be considered negligible.

The depth and the roughness have been measured with a TENCOR P1 profilometer, obtaining a depth of 0.53 μm with a standard uncertainty of 0.01 μm.

The typical roughness at the bottom of the channels has been estimated between 50×10^{-10} m and 80×10^{-10} m. The width has been determined by an optical microscope with an uncertainty of 0.3 μm. The microchannels length which corresponds to the distance between the branches of the reservoirs has been directly deduced from the mask dimension known with an uncertainty of 10 μm. All details on the measurement of these lengths are presented in [3].

Table 1
Microsystem T4P specifications.

Microchannels	Depth, H (μm)	Width, W (μm)	Length, L (μm)	Number of microchannels, n
Value	0.53	50.0	5000	$5 \times 115 = 575$
Uncertainty	0.01	0.3	10	

3. Experimental setups and procedures

The measurements have been focused on three objectives:

(1) Characterization of the microsystem with different gas species in a wide inlet pressure range, from 50 Pa to 100 kPa and with two different outlet conditions: vacuum (10^{-6} Pa up to a few Pa according to the setup) and atmospheric pressure.
(2) Comparison of standards developed at INRIM and ICA laboratories.
(3) Measurements of gas flowrate in a temperature range from 15 °C to 25 °C to determine the temperature coefficient.

3.1. INRIM experimental setup

The quantity generated by the device and measured by a primary standard flowmeter is the molar gas flowrate, defined as the number of gas moles coming out from the device per unit of time.

Two INRIM primary standard flowmeters, based on constant-pressure and variable-volume method, were used. The first one measures the molar flowrate under atmospheric pressure condition in the range

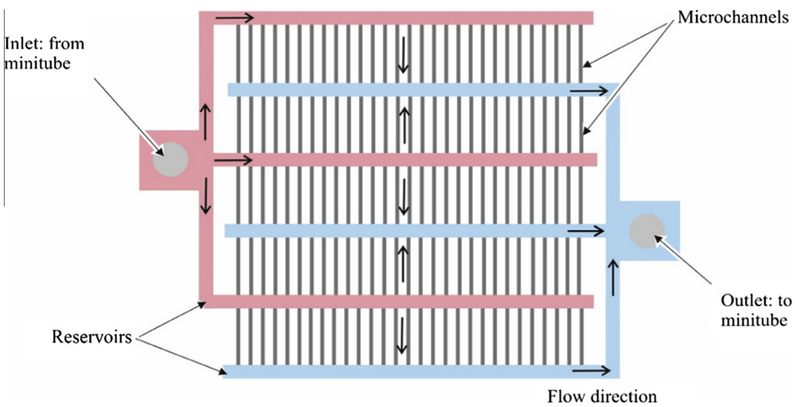

Fig. 1. Schematic of microsystem T4P.