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## Experimental study of the gas flows through channels with circular cross sections

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# EXPERIMENTAL STUDY OF THE GAS FLOWS THROUGH CHANNELS WITH CIRCULAR CROSS SECTIONS

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**Abstract.** The experimental setup based on the constant volume technique is developed to measure the mass flow rate through the microtubes under the isothermal flow conditions. Four different gases: Helium, Nitrogen, Argon and Carbon dioxide, and two surface materials (Stainless steel and Sulfinert) are considered. In this study the Knudsen number varies from  $\sim 10^{-4}$  to 0.3. In this range the approach based on the analytical solution of the Stokes equation subjected to the first and second order velocity slip boundary conditions is used. The tangential momentum accommodation coefficient (TMAC) is extracted from the experimental data on the mass flow rate using its analytical expression. The results are summarized in the tables representing the accommodation coefficients for the couples corresponding gas-surface material combinations. The influence of the molecular mass on the tangential momentum accommodation is discussed.

## 1. Introduction

The effect of an interaction between the gas flow and the solid surface increases by the decreasing of the channel size, due to the increasing the surface-to-volume ratio when channel size decreases. For the isothermal gas flow the interaction gas-surface is essentially characterized by the Tangential Momentum Accommodation Coefficient (TMAC). Its value varies in the range  $[0, 1]$ ,  $\alpha = 0$  corresponds to a specular reflexion,  $\alpha = 1$  characterizes a diffuse reflexion. The tangential momentum accommodation coefficient is used in the expressions of the boundary conditions when one uses the continuum or kinetic approaches for the simulation of the flow characterizing by a relatively large Knudsen number. A better knowledge of the mechanism of the gas-solid surface interaction allows us to improve the understanding of the gas flow behavior in the slip and transitional flow regimes and to a better design of the industrial devices which work under rarefaction conditions.

Many researchers carried out different experiments to determine the value of the TMAC for various couples gas-solid surface. The mains experimental techniques used to measure the TMAC were reviewed in [1]. This review shows that generally the accommodation coefficient

depends on large number of parameters such as the type of the gas, the surface material, its cleanliness and its roughness.

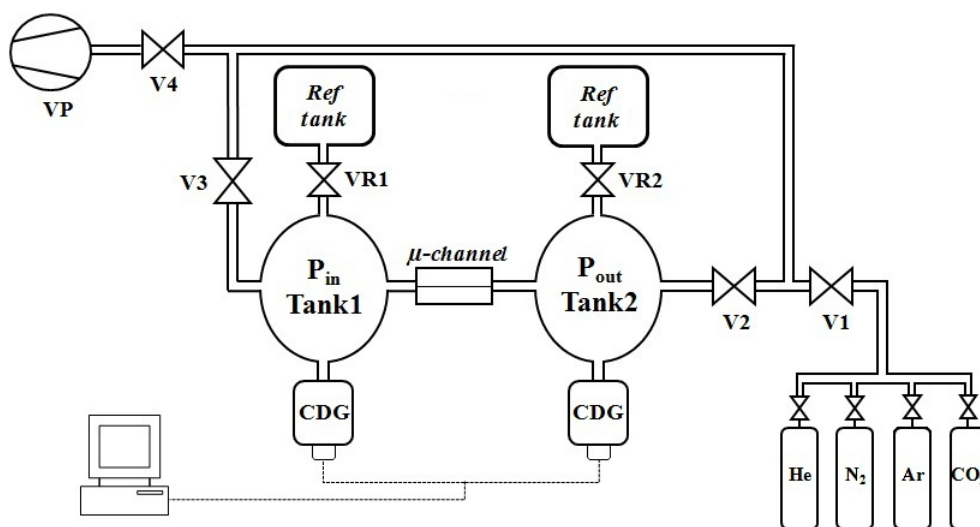
The main experimental techniques proposed in the literature to measure the mass flow rate through the microchannels are [1]:

- The liquid drop method (LD) [2], [3], [4], [5], [6], [7]. This method permits a direct determination of the volume flow rate by tracking in time the interface of oil drop moving in a calibrated tube by a speed camera.
- The accumulate dual tank method was developed by Arkilic and al in [8] and it consists in measuring relative pressure variation between a reference and an accumulation tank. The mass flow rate is deduced from the law of perfect gas.
- The constant volume technique (CV) is used by following authors: [2], [7], [9], [10], [11]. This method is similar to the accumulate dual tank method, but in this case the absolute pressure variation in the tanks is measured. It needs a very high thermal stability.
- An other method is the constant pressure technique [12], [13], [14]. Contrarily to the constant volume technique this method was not used a lot because of the difficulties in measuring the volume variation in time while the pressure is maintained constant.

All these methods have their own advantages and disadvantages. From the authors point of view, the simplest and the more accurate technique is the constant volume technique (CV) which was adopted in this study.

Various gases: Helium (He), Nitrogen ( $N_2$ ), Argon (Ar) and Carbon-dioxide ( $CO_2$ ) and two materials of the surface (stainless steel and Sulfinert) are used in the present study. The mass flow rate through the microtubes is measured using the constant volume technique under the isothermal conditions. The Knudsen number varies from 0.0002 (hydrodynamic regime) to 0.3 (slip regime). The velocity slip and accommodation coefficients are deduced by using the experimental data of the mass flow rate and the Navier-Stokes model with the first and second order slip boundary conditions.

## 2. Experiment



**Figure 1.** Schematic of the experimental setup

Channel	Material	$D$ [ $10^{-6}m$ ]	$L$ [ $10^{-3}m$ ]
T1	Sulfinert	275.	2000.*
T2	Stainless steel	239.	2013.*

**Table 1.** Dimensions of the microchannels. Indicative values of the diameter was given by provider equal to  $250\mu m$ , these values were corrected using the measurements in the hydrodynamic flow regime, the third column in Table. The length of the microtubes  $T1$  and  $T2$  were reduced to around  $10cm$  for the experiments yield with  $CO_2$  gas\*.

### 2.1. Methodology

The experimental setup is represented schematically in Figure 1. To measure the mass flow rate through the microtubes the constant volume technique was implemented. This technique involves the use of two constant volume tanks connected by a microchannel. The flow through this microchannel is generated by setting a pressure difference between the inlet and outlet tanks. The volume of the tanks has to be much greater than the microchannel volume to guarantee that the flow parameters are independent of time, but remain detectable. The pressure and temperature variation during the experiments are measured and the mass flow rate is deduced from the equation of state. The mass variations occurring in the tanks during the experiments do not call into question the stationary assumption because the pressure variations are maintained less than 2% during the experiments.

The experimental methodology used for the mass flow rate measurements is the following:

- First, the experimental loop (Figure 1) is vacuumed using the vacuum pump (VP) by opening the valves  $V2$ ,  $V3$ , and  $V4$  during a time period (from one to two hours).
- Then, the valve  $V4$  is closed and the system is filled with the working gas from the high pressure tank by opening the valve  $V1$  until having the desired inlet pressure value ( $p_{in}$ ).
- After that, the valves  $V1$  and  $V3$  are closed and the valve  $V4$  is opened again to decrease the pressure in the outlet tank until obtaining the desired value ( $p_{out}$ ).
- Finally, the valves  $V2$  and  $V4$  are closed and the acquisition of the pressure and temperature in both tanks can be started.

The registration of the pressure variations in the inlet and outlet tanks is carried out using two INFICON Capacitance Diaphragm Gauges ( $CDG$ ), see Figure 1, chosen according to their pressure range and connected to the upstream and downstream tanks.

The temperature of the gas inside the system is assumed to be equal to the room temperature. This assumption was checked by the mean of three temperature sensors PT100. Two of them measured the temperature variations in the inlet and outlet tanks and one measured the room temperature variations. The difference between the measurements of the three temperature sensors was less than their uncertainty  $0.3K$ . The relative variation of the temperature during the experimental time length was less than  $0.1K$ . The thermal stabilization is checked before and during each experiment. The purity of the gases was higher than 99.999%.

The volumes of the inlet and outlet tanks are measured using a simple and accurate method. Using a reference tank with known volume the ratio between the measured volume and the reference volume was calculated from the mass conservation. This method is repeated five times and the maximum deviation from the mean value was 0.16%.

### 2.2. Microchannels characteristics

The two microtubes  $T1$  and  $T2$ , see Table 1, used in this study are made from stainless steel and the internal surface of the microtube  $T1$  is coated with Sulfinert. The Sulfinert coating is the

leading passivation technique for the storage and transfer of low-level organo-sulfurcontaining samples. The Sulfinert layer is applied to the stainless steel surface and is completely inert to organo-sulfur compounds. Typically stainless steel will adsorb or react with sulfur compounds such as hydrogen sulfide. The Sulfinert layer will prevent sulfur compounds from contacting the reactive stainless surface. The roughness of the microtubes is not known. The both tubes were provided from RESTEK company. The details of the fabrication process can be found on the company website. [www.restek.com](http://www.restek.com)

The indicative diameter of the microtubes given by the provider is  $250\mu\text{m}$  and its value was corrected (third column of the Table 1) after comparing the simulated and measured flow rate in the hydrodynamic regime when  $Kn < 0.001$ , see Section 4 for the details.

### 2.3. Mass flow rate calculation

Using the constant volume technique, the mass flow rate through the microchannels can be calculated from the equation of state for ideal gas by assuming steady conditions

$$pV = mRT, \quad (1)$$

where  $V$  represents the volume of the inlet or outlet tanks and  $R$  is the specific gas constant,  $p$ ,  $T$  and  $m$  are, respectively, the pressure, temperature and mass of the gas. If we assume small variation of the gas properties ( $p$ ,  $m$  and  $T$ ) in the tanks, equation (1) can be written as follows

$$\frac{dm}{dt} = \frac{d}{dt} \left( \frac{pV}{RT} \right). \quad (2)$$

As it was shown in [7], [11] the previous relation may be transformed into

$$\frac{dm}{dt} = \frac{V}{RT} \frac{dp}{dt} (1 - \varepsilon), \quad \varepsilon = \frac{dT/T}{dp/p}. \quad (3)$$

If  $\varepsilon$  is small enough compared to 1, then the ratio  $dm/dt$  can be considered as the mass flow rate  $Q_{exp}$  through the microchannel.

As it is clear from equations (3) the constant volume technique requires very high-thermal stability, that means that temperature relative variations during the experiments must be much smaller than the pressure relative variations. In our experimental conditions the deviation of the temperature from the initial value is smaller than  $0.1K$  during the experimental time length. The relative variation of the temperature  $dT/T$  is in order of  $2 \times 10^{-4}$  against  $10^{-2}$  for the relative variation of the pressure  $dp/p$ , therefore  $\varepsilon$  is clearly less than  $2 \times 10^{-2}$  and may be neglected. Thus, the mass flow rate  $Q_{exp}$  can be written under the following form

$$Q_{exp} = \frac{V}{RT} \frac{dp}{dt}. \quad (4)$$

The measurement of  $Q_{exp}$  is affected by a specific relative error of  $2 \times 10^{-2}$  due to the temperature variation.

In expression of the mass flow rate (4) the parameters  $V$  and  $R$  are known and remain constant during the experiments. To calculate the term  $(dp/dt)$  in equation (4) we use the registered recorded data of the pressure variation  $p_i$  at different instants  $t_i$ . This variation is of order of 1% and the data of the pressure can be fitted by the first order polynomial form using the least square method as follows

$$p(t_i) = at_i + b, \quad (5)$$

where the slope  $a$  of the function  $p(t_i)$  is equal to the derivative  $dp/dt$  and it is used in the equation (4) to calculate the experimental mass flow rate. The number of the measured pressure values varies between 40 and 2000 depending on the tanks pressure.

The uncertainty on the measurement of the mass flow rate is evaluated using the following expression

$$\frac{\Delta Q_{exp}}{Q_{exp}} = \frac{\Delta V}{V} + \frac{\Delta T}{T} + \frac{\Delta a}{a}, \quad (6)$$

where the uncertainty on the coefficient  $a = dp/dt$  is estimated from standard deviation following the method used in [7] and its value is less than 0.5%.

The uncertainty on the temperature measurement is very small but we have to take into account the systematic error made on the stationary assumption previously evaluated at 2% and we affect it to the error on the temperature. The total uncertainty on the experimental mass flow rate is less than  $\pm 4.1\%$  ( $\Delta V/V = \pm 1.6\%$ ,  $\Delta T/T = \pm 2\%$ ,  $\Delta a/a = 0.5\%$ ).

### 3. Analytical solution

The Knudsen number considered in this paper is calculated from the mean pressure between two tanks (upstream and downstream the microchannel) and ranges from  $\sim 0.0002$  to 0.3. This range covers the hydrodynamic and slip flow regimes. Brief presentation of the analytical expressions used for the mass flow rate, the velocity slip and tangential momentum accommodation coefficients is given below.

The continuum approach based on the Navier-Stokes equation has received a particular attention. Its application was extended to the slip regime implementing the first and second order slip boundary conditions for the velocity at the wall [15], [16], [17].

Using the second order slip boundary condition the mass flow rate through microchannel with circular cross section can be expressed in the following form

$$\dot{M} = \frac{\pi D^4 \Delta p p_m}{128 \mu R T L} (1 + 8A_1 K n_m + 16A_2 \frac{\mathcal{P} - 1}{\mathcal{P} + 1} \ln \mathcal{P} K n_m^2), \quad (7)$$

where  $D$  is the tube diameter,  $\Delta p = p_{in} - p_{out}$ ,  $\mathcal{P} = p_{in}/p_{out}$ ,  $K n_m$  is the mean Knudsen number, based on the mean pressure  $p_m = 0.5(p_{in} + p_{out})$  and on the tube diameter  $D$ . In this theoretical frame, the coefficient  $A_1$  and  $A_2$  may be expressed in the form

$$A_1 = \frac{\sigma_p}{k_\lambda}, \quad A_2 = \frac{\sigma_{2p}}{k_\lambda^2}, \quad (8)$$

where  $\sigma_p$  and  $\sigma_{2p}$  are the first and second velocity slip coefficients, respectively,  $k_\lambda$  is the coefficient which depends on the molecular interaction model. The value of  $\sqrt{\pi}/2$  for hard sphere (HS) model [18] is retained in this paper.

Furthermore, the non-dimensional mass flow rate may be deduced from (7)

$$S = \dot{M}/\dot{M}_P = 1 + 8A_1 K n_m + 16A_2 \frac{\mathcal{P} - 1}{\mathcal{P} + 1} \ln \mathcal{P} K n_m^2, \quad \text{where} \quad \dot{M}_P = \frac{\pi D^4 \Delta p p_m}{128 \mu R T L}, \quad (9)$$

here  $\dot{M}_P$  is the classical Poiseuille mass flow rate. Equation (9) may be rewritten in more compact form:

$$S^{theor} = 1 + A_1^{theor} K n_m + A_2^{theor} K n_m^2. \quad (10)$$

The mass flow rate calculated using the analytical expression (9) will be compared with the appropriate experimental values.

Microchannel	T1 (Sulfinert)		T2 (SS)		
	Quantity	Min	Max	Min	Max
Mass flow rate ( $10^{-12}kg/s$ )	2.7	279 000	2.2	403 000	
Inlet pressure (Pa)	147	123 600	173	127 450	
Outlet pressure (Pa)	29	78 700	35.5	80 200	
Average Knudsen number $Kn_m$	$2.2 \cdot 10^{-4}$	0.29	$2.6 \cdot 10^{-4}$	0.30	

**Table 2.** Experimental conditions

Gas	Order	$A_0^{exp}$	$A_1^{exp}$	$A_2^{exp}$	$s_r$	$r^2$	$E_s(\%)$
He	First	$0.995 \pm 0.002$	$10.14 \pm 0.07$	0	0.010	0.998	0.8
	Second	$1.005 \pm 0.004$	$9.16 \pm 0.17$	$6.35 \pm 0.78$	0.023	0.998	1.7
$N_2$	First	$0.997 \pm 0.001$	$11.01 \pm 0.05$	0	0.008	0.999	0.6
	Second	$1.008 \pm 0.004$	$9.42 \pm 0.14$	$16.74 \pm 0.562$	0.021	0.999	1.4
Ar	First	$1.008 \pm 0.002$	$10.99 \pm 0.08$	0	0.011	0.998	0.9
	Second	$1.019 \pm 0.004$	$9.30 \pm 0.16$	$18.57 \pm 0.65$	0.023	0.999	1.5
$CO_2$	First	$1.000 \pm 0.002$	$10.21 \pm 0.08$	0	0.010	0.998	0.9
	Second	$0.999 \pm 0.003$	$10.15 \pm 0.11$	$3.01 \pm 0.45$	0.018	0.999	1.1

**Table 3.** Experimental coefficients  $A_0^{exp}$ ,  $A_1^{exp}$  and  $A_2^{exp}$  obtained from the first and second order polynomial fitting for microtube T1 (Sulfinert)

#### 4. Results and discussion

The flows of four gases ( $He$ ,  $N_2$ ,  $Ar$  and  $CO_2$ ) through the microtubes with different surface materials are studied for Knudsen number range  $[0.0002, 0.3]$ . The experimental conditions for both microtubes  $T1$  and  $T2$  are summarized in Table 2. The pressure ratio  $\mathcal{P} = p_{in}/p_{out}$  between upstream and downstream tanks was fixed at 1.5 in the hydrodynamic regime then it was increased to reach the value of  $\sim 5$  in the slip flow regime. It was shown in Ref. [9] that the non-dimensional mass flow rate does not depend practically on the pressure ratio and therefore this change in the pressure ratio does not have any influence on the extracted velocity slip coefficient.

The measured mass flow rate, normalized according to (9), was fitted using a second order in  $Kn_m$  polynomial form, similar to the analytical expression (10), implementing the least square method detailed in [9]:

$$S_f^{exp} = A_0^{exp} + A_1^{exp} Kn_m + A_2^{exp} Kn_m^2, \quad (11)$$

where the coefficients  $A_0^{exp}$ ,  $A_1^{exp}$  and  $A_2^{exp}$  are the least-square method fitting coefficients. From the comparison of the analytical expression (10) and the polynomial fit of the experimental mass flow rate (11), the coefficients  $A_i^{exp}$  ( $i=0, 1$  or  $2$ ) may be expressed under the following form

$$A_0^{exp} = 1, \quad A_1^{exp} = 8A_1, \quad A_2^{exp} = 16A_2 \frac{\mathcal{P} - 1}{\mathcal{P} + 1} \ln \mathcal{P}. \quad (12)$$

The fitting of the experimental data is done with the first order polynomial form in the range of Knudsen number  $[0, 0.1]$  and with the second order polynomial form in the Knudsen number range  $[0, 0.3]$ . The fitting of the experimental data are done without fixing the coefficient  $A_0^{exp}$  to the value one, even if its "theoretical value" is equal to one, see equation (9). The values of the coefficient  $A_0^{exp}$ , obtained from experimental fitting, were used to verify the data of the tube diameter given by the provider. In the hydrodynamic flow regime, when the Knudsen number is very small, the mass flow rate must be equal to the Poiseuille mass flow rate  $\dot{M}_P$ , see (9).

Gas	Order	$A_0^{exp}$	$A_1^{exp}$	$A_2^{exp}$	$s_r$	$r^2$	$E_s(\%)$
He	First	1.000± 0.002	11.09± 0.05	0	0.007	0.999	0.6
	Second	1.002± 0.003	10.82± 0.08	4.12± 0.35	0.012	0.999	0.7
N <sub>2</sub>	First	0.996± 0.002	11.46± 0.08	0	0.013	0.998	1.0
	Second	0.999± 0.005	10.53± 0.17	15.69± 0.70	0.026	0.999	1.6
Ar	First	1.008± 0.003	11.62± 0.09	0	0.014	0.997	1.1
	Second	1.019± 0.002	10.15± 0.09	17.41± 0.37	0.013	0.999	0.8
CO <sub>2</sub>	First	1.008± 0.002	11.04± 0.07	0	0.010	0.998	0.9
	Second	1.012± 0.002	10.46± 0.08	5.80± 0.35	0.012	0.999	0.8

**Table 4.** Experimental coefficients  $A_0^{exp}$ ,  $A_1^{exp}$  and  $A_2^{exp}$  obtained from the first and second order polynomial fitting for microtube T2 (SS)

If we suppose that all other measured quantities in this Poiseuille expression do not have any errors, then the deviation of the coefficient  $A_0^{exp}$  from one may be attributed to an error in the diameter measurements. This technique was used in the present study to adjust the tube diameter measurements given by provider and equal to  $250\mu m$ . The values of the tube diameter adjusted from the Poiseuille mass flow rate are given in Table 1.

After this first step of the diameter adjustment, the measured mass flow rate was fitted with the first order polynomial form in the Knudsen number range  $[0., 0.1]$  and by the second order polynomial form in the range  $[0., 0.3]$ . The obtained fitting coefficients and the statistical characteristics of the fitting procedure such as the determination coefficient  $r^2$ , the standard error  $E_s$  and the squared residual sum  $s_r$  are given in Tables 3 and 4. The squared residual sum  $s_r$  is defined as following  $s_r = \sqrt{\frac{1}{n-k} \sum e_i^2}$ , where  $n$  is the number of the measured points,  $e_i = S_i^{exp} - S_{f_i}^{exp}$  is the local difference between measured  $S_i^{exp}$ , normalized according to (9), and fitted values  $S_{f_i}^{exp}$  (11),  $k$  is the number of the unknown coefficients of the fitting model,  $k = 3$  for the second order fit. The standard error is  $E_s = \sqrt{\frac{1}{n} \sum e_i^2 / S_m^{exp}}$ , here  $S_m^{exp}$  is the average value of the measured quantities.

As it is clear from the results presented in Tables 3 and 4, that the procedure of the adjustment of the tube's diameter works well: the values of the  $A_0^{exp}$  coefficients are now very close to their theoretical values equal to one. From Tables 3 and 4 one can see that the values of the determination coefficients  $r^2$  are very close to 1. The worst value is obtained for the microtube T2 (SS) and Argon and it is equal to 0.997 which confirms the quality of fitting for both microtubes and for both fits. Whereas, the residual variance  $s_r$  is smaller than 0.026 for both microtubes T1 and T2. The maximum value of the standard error made on the fittings is less than 2%. Therefore, analyzing the statistical characteristics of both fittings we can conclude that the both expressions (of the first and of the second order according to the Knudsen number) represent well the experimental data.

The errors on the coefficients  $\sigma_p$  and  $\sigma_{2p}$  in Tables 5 and 6 derive from the fitting error on the coefficients  $A_i^{exp}$ , see relations (8), (12), and do not take into account the systematic uncertainty coming from the errors on the mass flow rate measurements, see (6), and the errors related to the Poiseuille term (9).

When the slip coefficient is known the accommodation coefficient may be calculated. The authors of Ref. [19] calculated the values of the slip coefficient using the BGK kinetic model and the Maxwell diffuse-specular scattering kernel for different values of the accommodation coefficient  $\alpha$ . After that the authors of [19] proposed a simple expression associating the slip coefficient and the accommodation coefficients. Later, this expression was improved in Ref. [20].

Gas	Molar mass (g/mol)	Order	$\sigma_p$	$\alpha$	$\sigma_{2p}$
He	4.00	First	1.123± 0.007	0.947± 0.003	0
		Second	1.015± 0.019	1.001± 0.010	0.148± 0.018
N <sub>2</sub>	28.02	First	1.219± 0.006	0.903± 0.002	0
		Second	1.044± 0.015	0.986± 0.008	0.378± 0.013
Ar	39.95	First	1.218± 0.009	0.904± 0.004	0
		Second	1.031± 0.018	0.992± 0.009	0.418± 0.015
CO <sub>2</sub>	44.01	First	1.131± 0.009	0.943± 0.004	0
		Second	1.125± 0.012	0.946± 0.006	0.068± 0.010

**Table 5.** Experimental accommodation and slip coefficients for microtube T1 (Sulfinert)

Gas	Molar mass (g/mol)	Order	$\sigma_p$	$\alpha$	$\sigma_{2p}$
He	4.00	First	1.228± 0.005	0.899± 0.002	0
		Second	1.198± 0.009	0.912± 0.004	0.092± 0.008
N <sub>2</sub>	28.02	First	1.270± 0.009	0.882± 0.004	0
		Second	1.166± 0.019	0.927± 0.009	0.348± 0.016
Ar	39.95	First	1.287± 0.010	0.875± 0.004	0
		Second	1.124± 0.010	0.946± 0.005	0.387± 0.008
CO <sub>2</sub>	44.01	First	1.223± 0.008	0.902± 0.003	0
		Second	1.159± 0.009	0.930± 0.004	0.132± 0.008

**Table 6.** Experimental accommodation and slip coefficients for microtube T2 (SS)

In the present work we use this improved expression from [20]:

$$\sigma_p(\alpha) = \frac{2 - \alpha}{\alpha}(\sigma_p(1) - 0.1211(1 - \alpha)), \quad (13)$$

where  $\sigma_p(1) = 1.016$  is the slip coefficient for  $\alpha = 1$  calculated first by Cercignani in Ref. [15] using the BGK kinetic model with assumption of full accommodation of the molecule at the wall. The values of the experimental slip coefficients (see Tables 5 and 6) are different from those obtained theoretically in [15] ( $\sigma_p = 1.016$ ), therefore the accommodation is not complete in our experimental conditions.

Analyzing the values of TMAC obtained for both microtubes *T1* and *T2* in the range of Knudsen number  $[0, 0.1]$  we notice that the highest and similar values for two gases, Helium and Carbon-dioxide, and the lowest values for the two other Nitrogen and Argon are obtained. The tendency of the TMAC to increase with the decrease of the molar mass reported in Ref. [21] can be observed in our results if we do not consider the Carbon-dioxide gas. We have to remind that the length of the microtubes *T1* and *T2* was not the same when experiments were carried out for the Carbon-dioxide gas. Its length was reduced by factor 20 and therefore the experimental conditions for this gas were different. The two degree of freedom of the Carbon-dioxide molecule can have also effect on the gas-surface interaction. In general, the values of TMAC obtained for the microtube *T1* (with sulfinert surface) are significantly higher than those obtained for the microtube *T2* (with SS surface), see Tables 5 and 6, which means that the Sulfinert surface tends to be more diffusive than the stainless steel surface.

In the  $[0, 0.3]$  Knudsen number range, the experimental data are fitted with second order polynomial form. The results show that the TMAC increases comparing to the first order analysis for both microtubes, slightly less for the microtube *T2* than for the microtube *T1* (see Fig. 2). The dependence of the TMAC on the molecular mass of the gas for the microtube *T1*

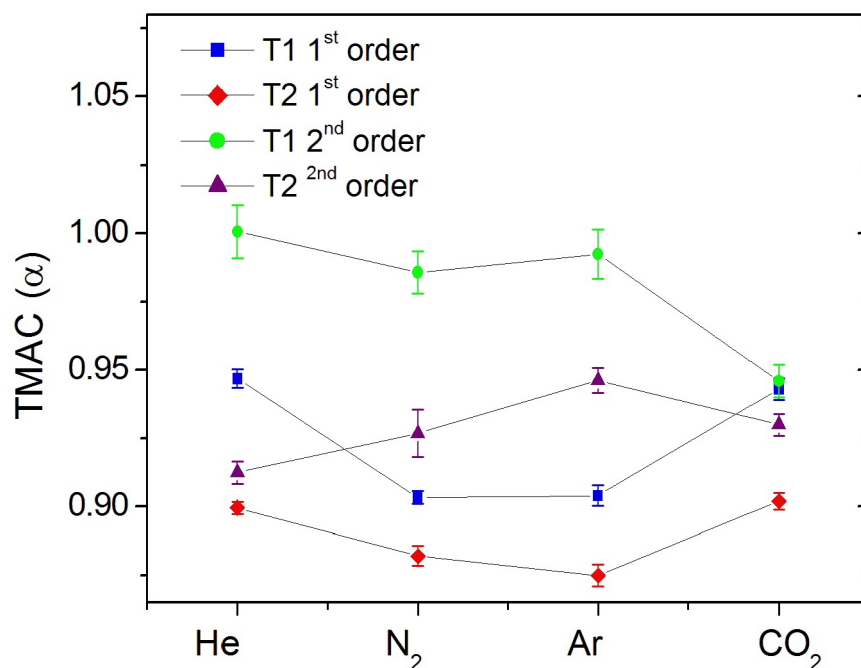
is less observed in this range. The values obtained for the three gases Helium, Nitrogen and Argon (see Table 5) lie in the range [0.985, 1]. In this case the diffuse reflection assumption can be justified for the three gases when the Knudsen number increases. For the microtube T2 the TMAC obtained is in the range [0.912, 0.946]. Considering the error made on the TMAC plus some other eventual errors (on the mass flow rate) we can conclude that the value of TMAC tends to a constant value and does not depend any more on the molecular mass, when the Knudsen number increase. Nevertheless, the dependence of the TMAC on the material surface is also observed in this range. The Sulfinert surface can be considered as diffuse surface for the Helium, Nitrogen and Argon molecules.

In Table 7 a comparison of the accommodation coefficients calculated by other authors [22], [21], [23] with our results is given. The authors of these papers did experimental investigation on TMAC in microtube with silica surface. The following differences between our experimental conditions and those of Refs. [22], [21], [23] are:

- The ratio  $L/D$  is more than 4 times larger for our microtubes.
- The diameter of the microtubes are different: Ref.[22]  $D = 100\mu m$ , Ref. [21]  $D = 25\mu m$  and Ref. [23]  $D = 50\mu m$ .
- The material of the microtube's surfaces are different: glass in Ref.[22] and silica in Refs. [21], [23].

The treatment of the experimental data was also different in Refs. [22], [21] and [23]:

- Only [0,0.1] Knudsen number range was considered in Ref. [22] and the accommodation coefficient was calculated without taking into account the influence of the Knudsen layer.
- The Variables Hard Sphere model was used in Ref. [23] in the definition of the molecular mean free path.



**Figure 2.** Comparing of TMAC for the microchannels T1 and T2

	Helium	Nitrogen	Argon
Porodnov and al [22]	0.895± 0.004	0.925± 0.014	0.927± 0.028
Ewart and al [21]	0.986± 0.009	0.981±0.041	0.942±0.017
Perrier and al [23]	1.00± 0.019	0.961±0.005	0.954± 0.010
present results ( <i>T1</i> )	1.00±0.010	0.986±0.008	0.992±0.009
present results ( <i>T2</i> )	0.912±0.004	0.927±0.009	0.946±0.005

**Table 7.** The tangential momentum accommodation coefficient (TMAC) obtained from the present experiments (in the [0, 0.3] Knudsen number range using the second order fitting) and in Refs. [22], [21] and [23].

In Table 7 the accommodation coefficient obtained from the second order polynomial fit in the Knudsen number range [0, 0.3] is presented. A good agreement of the TMAC values found for the microtube *T2* with the results of Ref. [22] may be observed from Table 7. It is well shown that the TMAC depends on the material of the surface. The roughness of the surface may play important role in determining the TMAC. But unfortunately the value of the roughness for the tubes used in the experiments is not known, therefore no conclusion on its role can be made. The decrease of the TMAC with the increase of the molar mass of the gas is observed in the experiments of Refs. [21] and [23], while in our results and the results of Ref. [22] the opposite behavior is observed. Nevertheless, considering the error on the TMAC values (Table 7) one can see that the influence of the molecular mass is not very significant.

## 5. Conclusion

The experimental investigations on the flow through circular microchannels are presented. The constant volume technique was used to measure the mass flow rates of the gases (Helium, Nitrogen, Argon and Carbon-dioxide).

The continuum approach (Navier-Stokes equations) with first and second order velocity slip boundary conditions was used in the slip flow regime to obtain the experimental velocity slip and tangential momentum accommodation coefficients associated to the Maxwell diffuse-specular boundary condition.

The effect of the materials surface on the interaction gas-solid surface was highlighted by comparing the values of the accommodation coefficients of two surface materials (Sulfinert and stainless steel). It appears that Sulfinert gives more diffuse reflection and tends to make insignificant the influence of the nature of gas interacting with the wall.

The results of the slip and accommodation coefficients were compared to the results obtained by other authors.

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