International Journal of Heat and Mass Transfer 120 (2018) 422–434

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

A time-dependent method for the measurement of mass flow rate of gases in microchannels

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ARTICLE INFO

Article history:
Received 27 July 2017
Received in revised form 29 October 2017
Accepted 29 November 2017

Keywords:
Transient flow
Rarefied gas
Microchannel
Accommodation coefficient

ABSTRACT

Accurate measurement methods are required in the analysis of thermodynamic non-equilibrium effects associated with rarefied gas flows. For example, for the specific case of accommodation coefficients measurements, the quantity of interest is often the mass flow rate along the channel. For this purpose, the following paper presents a new time-dependent version of the well-known constant volume method for the accurate measurement of mass flow rates of gases in microchannels. The technique proposed here is an improvement in respect to the classic technique since it can be used for transient experiments. Moreover, it can be applied to configurations with arbitrary upstream and downstream reservoirs dimensions. Particularly, the proposed method relies on the assumption that the flow conductance varies linearly during the experiments and thus the pressure variations in the reservoirs can be fitted by a well-defined exponential function. Then, the instantaneous mass flow rate through the channel can be determined directly from the pressure fitting coefficients. A great advantage of the time-dependent constant volume method is that the measurements can be obtained from a single experiment for a wide range of rarefaction conditions, since the mean pressure between the reservoirs is allowed to change with time. Moreover, this technique represents a convenient manner to provide raw data of pressure variation with time in the reservoirs and transient mass flow rate in the channel by simply providing the fitting coefficients of the theoretically derived functions. A clear geometric criterion is also presented to determine when such mass flow rate measurements can be considered as quasi-steady, corresponding closely to results obtained under steady conditions, when ideally the channel connects two infinite reservoirs at different pressures. Results for flows of nitrogen through a stainless steel microtube ($L = 92.22 \pm 0.01$ mm and $D = 435.5 \pm 3.5$ μm) were obtained from 118 independent experiments, provided in this work, using two different experimental setups and three different configurations of the system volumes. As expected, no deviation was observed between all experimental campaigns in terms of the reduced mass flow rate. In addition, all results indicate that nitrogen can be considered completely accommodated at the surface of the microtube used, with $\alpha = 0.986 \pm 0.019$ when the diffuse-specular gas-surface interaction model is adopted and $\alpha_t = 0.991 \pm 0.020$ ($\alpha_n = 1$) when the Cercignani-Lampis model is adopted.

1. Introduction

In recent decades, microfluidics has gained considerable attention, especially with the development of microelectromechanical systems (MEMS) for a wide variety of applications [1]. Therefore, many theoretical and experimental studies have been conducted to understand the physical phenomena associated with such flows. Particularly, great effort has been devoted to the analysis of gaseous flows and the thermodynamic non-equilibrium effects resulting from rarefaction, which arise when the molecular mean free path (λ) has the same order of magnitude as the characteristic length of the system (L). These effects depend directly on the nature of the interaction of the gaseous molecules with the solid boundaries, generally characterized by means of slip and accommodation coefficients determined experimentally [2]. These coefficients are of great importance when modeling mass and heat transfer in rarefied gas flows since they give an important indication on the gas-surface interactions at a molecular level, which

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https://doi.org/10.1016/j.ijheatmasstransfer.2017.11.147
0017-9310/

Nomenclature

a	characteristic dimension (m)
A	fitting coefficient of the conductance ($m^3\ s^{-1}$), generic fitting coefficient (–)
B	fitting coefficient of the conductance ($m^3\ Pa^{-1}\ s^{-1}$), generic fitting coefficient (–)
C	conductance ($m^3\ s^{-1}$), generic fitting coefficient (–)
D	diameter (m)
G	reduced mass flow rate (–)
i	index (–)
L	length of the microtube (m)
m	mass of gas (kg)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
M	Mach number (–)
MQ	generic flow quantity (–)
n	number of points, generic exponent (–)
P	pressure (Pa)
P^*	absolute pressure difference with respect to the equilibrium pressure (Pa)
Q	throughput ($Pa\ m^3\ s^{-1}$)
R	specific gas constant ($J\ kg^{-1}\ K^{-1}$)
R^2	determination coefficient (–)
Ra	arithmetic average surface roughness (μm)
Rz	average vertical distance from the highest peak to the lowest valley within five sampling lengths along the microtube inner wall (μm)
s	standard deviation
v_m	most probable molecular speed ($m\ s^{-1}$)
t	time (s)
t_ε	time limit for the isothermal condition (s)
T	temperature (K)
V	volume (m^3)
u	uncertainty

Greek letters

α	accommodation coefficient – diffuse-specular model (–)
α_n	energy accommodation coefficient – CL model (–)
α_t	tangential momentum accommodation coefficient – CL model (–)
δ	rarefaction parameter (–)
ε	relative variation of temperature (–)
λ	molecular mean free path (m)
μ	dynamic viscosity (Pa s)
σ_p	viscous slip coefficient (–)
τ	characteristic time (s)
τ_c	time-scale associated with the flow inside the channel (s)
τ_{V_i}	time-scale associated with the pressure variations in reservoir i (s)
$\Psi_{A,i}$	fitting coefficient associated with pressure variations in reservoir i (Pa)
Ψ_B	fitting coefficient (–)
ω	viscosity index (–)

Subscripts

A, B	specific system configurations
i	generic reservoir, index
j	index
m	mean
0	equivalent, reference
1	upstream
2	downstream

Superscripts

0	at initial condition
eq	at equilibrium condition
exp	experimental

Acronyms

CL	Cercignani-Lampis

are directly related to the processes of heat and mass transfer and determine the transport coefficients at the macroscopic level. In most cases, the determination of these coefficients relies on the measurement of mass flow rates in microchannels with simple geometries followed by the comparison of such data with theoretical models [3]. In this sense, accurate methods are required to measure the mass flow rate of gases in microgeometries.

Measurements of mass flow rate in microchannels are generally not possible with flowmeters and high precision flow sensors since these flows can typically be smaller than 10^{-10} kg/s. Consequently, alternative measurement methods must be employed. The three most commonly used measurement techniques are the liquid droplet method, the constant pressure method and the constant volume method. The liquid droplet method is a direct measurement technique in which the volumetric flow rate induced by a pressure difference is determined by monitoring the motion of a liquid droplet flowing along calibrated transparent tubes located at the inlet or outlet of the channel [4–7]. Optical-electronical sensors are frequently used to monitor the liquid droplet displacement. For measurements at low pressure condition, liquids with low saturation pressure must be used to prevent vaporizing effect on the moving surface of the droplet. According to Ewart et al. [7], the implementation of this method is associated with two main difficulties: (i) the precise identification of the droplet-gas interface; (ii) the process of introducing the liquid droplet without perturbing the pressure in the reservoirs or forming several droplets, which may also collapse inside the calibrated tube. Moreover, in order to be accurate, the liquid droplet method requires a correction that takes into account the variation of the volumes of the reservoirs due to the displacement of the droplet as well as the small volume between the droplet and the microchannel [8].

The constant pressure and the constant volume methods are indirect measurement techniques, which use the gas equation of state to relate detectable changes in volume or pressure, respectively, to the mass flow rate in the channel. The constant pressure method consists of keeping the pressure constant in a reservoir located upstream or downstream of the channel by varying its volume while the gas flows through the channel. This change of volume is usually obtained by driving a piston into the reservoir. Assuming isothermal conditions, the mass flow rate through the channel can be related to the variation of the volume with time [9–11]. A drawback of this approach occurs at very low mass flow rates because it requires very slow piston displacements that are difficult to control accurately. In addition, high-integrity seals are necessary to prevent gas leakage [12].

Finally, the constant volume method allows the measurement of the mass flow rate through a channel by monitoring the pressure variation with time in a rigid isothermal reservoir located upstream or downstream of the channel [7,13,14]. The direct application of this technique for flows near atmospheric pressure is