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Experimental and numerical investigation in flow configurations related to the vacuum systems of fusion reactors

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ABSTRACT

Vacuum flows in various configurations, which are related to fusion reactors are simulated using linear kinetic theory and the direct simulation Monte Carlo method (DSMC), in the whole range of the Knudsen number. In the case of flows through channels of infinite length, even for large pressure differences, the flow is linear (fully developed) and linearized kinetic theory has been applied with considerable success. In the case of flows through channels of finite length, the flow is strongly non-equilibrium and has to be tackled by the DSMC method. In the present work we present a comparative study between experimental and computational results for the case of circular channels of finite length. Experimental data and corresponding computational results are provided for the conductance of channels with different lengths and several downstream to upstream pressure ratios, covering a wide range of the Knudsen number. In addition, a brief review of some recent work related to the case of long channels is presented and general remarks related to the overall flow conditions and characteristics for flows through channels of various lengths and cross sections are stated.

1. Introduction

Vacuum flows are strongly connected to several subsidiary systems of fusion reactors. In particular, there are high vacuum pumping systems for evacuation and maintenance of the needed low-pressure levels in the torus, in the cryostat and in the neutral beam injectors (NBI). The achievable pumping speed in all the prementioned systems is of major importance and therefore a thorough and complete study of the flow conditions is mandatory, in order to the optimum values to be succeeded.

Each of the vacuum systems consists of networks of various channels with different lengths and cross sections. The flow in such channels varies from the free-molecular regime up to the hydrodynamic limit. The scope of the present work is to study on numerical and experimental basis the computed and measured quantities of the mass flow rate and the conductance, for cylindrical ducts, in the whole range of the Knudsen number (Kn).

In the case of tubes with infinite length (i.e. at length over the hydraulic diameter ratios of ($L/D_h \geq 80$), the flow is considered as linear (fully developed) and linearized kinetic theory based on the Bhatnagar–Gross–Krook (BGK) kinetic model has been applied [1]. In this case, kinetic type formulations, based on the Boltzmann equation or on simplified kinetic equations, may take advantage of all flow characteristics and properties and yield a set of simple linearized kinetic model equations, which are solved in a very accurate and computationally efficient manner. Rarefied gas flows in long tubes have been investigated via kinetic theory from the 1960s, implementing semianalytical and numerical schemes. Extended and profound reviews for linearized flows in channels of various cross sections are given in Refs. [2–4]. However, in most cases the results are valid for small up to moderate Knudsen numbers and therefore reliable numerical and experimental results, which cover the whole range of the Knudsen number are limited in the literature.

On the other hand, for the cases of channels with finite length ($L/D_h \leq 5$), the flow is strongly non-equilibrium and the direct simulation Monte Carlo method [5] is implemented. A detailed and comprehensive summary of published works related to rarefied gas flows through capillaries of finite length can be found in the review article [1], while a variety of results for the case of orifices and short tubes can be found in [6–9]. As it is well known, the DSMC method is very powerful in the case of high-speed flows, while it becomes computationally expensive as the flow becomes slower and more rarefied. Therefore, although there is a significant amount of work in the simulation of rarefied gas flows through short tubes, it seems that additional research work is needed in order to provide a more complete data frame for a wide range of geometric and flow parameters.

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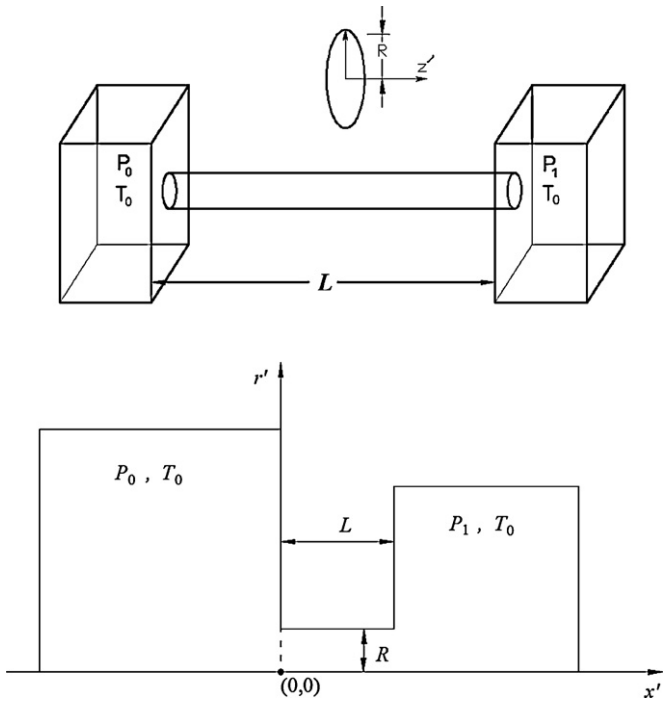

Fig. 1. Flow configuration for circular tubes.

Finally, for the case of channels in the intermediate range of L/D_h i.e. $5 < L/D_h < 80$, developing flow is taken place and the computational cost for DSMC method is high, while linearized kinetic theory cannot be implemented anymore. In this range of the aspect ratios no efficient computational methodologies exist and further research is needed.

2. Flow configuration

The flow configuration presented in this section is general and applies to channels of arbitrary length and cross section. Consider the isothermal flow of a gas at a reference temperature T_0 through a channel of length L and hydraulic diameter D_h, connecting two reservoirs maintained at pressures P_0 and P_1, respectively, with $P_0 > P_1$, as shown in Fig. 1-top.

For the case of tubes with infinite length by taking $L \gg D_h$, the flow is considered as fully developed, and then, end effects at the inlet and the outlet of the channel are ignored. Even more, at each cross section the pressure is constant and varies only along the flow direction z' (Fig. 1-top). For the case of tubes with finite length, we consider a developing flow and the pressure depends on both spatial coordinates (x',r'). Therefore, the complete two-dimensional axisymmetric problem must be simulated. In addition, when the flow is in the transition and continuum regimes, the distribution functions at the entrance and the exit of the capillary are not Maxwellians and therefore the computational domain must include the containers before and after the capillary (Fig. 1-bottom). Consequently, the computational effort for solving flows through tubes of finite length is significantly increased compared to the one required for ducts of infinite length.

The basic parameter of the flow is the Knudsen number, which is defined by the ratio of mean free path λ over the characteristic length of the flow,

$$Kn = \frac{\lambda}{D_h} \tag{1}$$

In the present work the hydraulic diameter D_h is chosen to be the characteristic length of the flow. Instead of Knudsen number the so-called rarefaction parameter δ is introduced, which is defined as [1],

$$\delta = \frac{\sqrt{\pi}}{2}\frac{1}{Kn} = \frac{D_h P}{\mu_0 \upsilon_0} \tag{2}$$

where μ_0 is the gas viscosity at temperature T_0 and $\upsilon_0 = \sqrt{2RT_0}$, with $R = k/m$ denoting the gas constant (k is the Boltzmann constant and m the molecular mass), is the most probable molecular velocity. The use of the rarefaction parameter δ allows a more comprehensive formulation of the model kinetic equations and also it is more convenient to use measurable quantities i.e. pressure, viscosity, for its estimation. The reference pressure P for the case of ducts of infinite length is equal to the average pressure $P = (P_0 + P_1)/2$, while for the case of ducts with finite length $P = P_0$.

The main objective is to calculate the mass flow rate and conductance in terms of geometric and flow parameters, through a well-defined dimensionalization procedure. For the case of tubes with infinite length the reduced (or dimensionless) flow rate G, which depends on the rarefaction parameter δ and the area of the cross section of the duct, is calculated based on the kinetic solution. Then for a specific application with known geometrical parameters of the duct namely, the area of the cross section A, the hydraulic diameter D_h and the length L of the duct and also with known flow parameters as the upstream and downstream pressures P_0 and P_1, respectively as well as the reference temperature T_0, the mass flow rate M can be easily obtained [2].

On the other hand, for tubes with finite length, the reduced flow rate W is calculated in terms of the parameters L/D, δ and p_1/p_2. The reduced flow rate is defined as $W = M/M_0$, where M_0 is the mass flow rate through an orifice ($L/D = 0$) at the free-molecular limit ($\delta = 0$) [10].

Another quantity of practical interest is the conductance C [l/s], which is expressed as

$$C = \frac{M}{m}\frac{RT_N}{\Delta P} \tag{3}$$

with m denoting the molar mass of the gas and T_N the reference temperature in 273 K. It is noted that the results presented here are presented in terms of conductance, which represents a useful flow quantity especially in vacuum applications. It may be helpful to note that although in dc electrical circuits the connection between current (analogue: M) and potential differences (analogue: ΔP) is expressed in Ohm's law by a resistance, in vacuum practice the link is made by its inverse, the conductance. Thus, conductance is a measure of ease of flow in response to a pressure difference, and the greater the conductance for a given pressure difference, the greater the mass flow rate M [11].

3. Computational scheme

For the case of tubes with infinite length, the problem is simulated based on kinetic theory, where the main unknown is the distribution function, which obeys a kinetic equation. It has been shown that fully developed isothermal pressure driven flows, can be simulated efficiently by the BGK model equation [1]. The discrepancy of the BGK model compared to other kinetic equations including the Boltzmann equation is less than 2%. The corresponding linear integro-differential equation, supplemented by the corresponding integral expressions and subject to the diffuse-specular boundary conditions, is solved numerically. The kinetic equation is discretized properly in the physical and molecular velocity spaces and then its discretized version is solved in an iterative manner. The numerical scheme is not presented here since it has been described, in detail, in a series of previous works [2,3].

For the case of tubes with finite length, the DSMC algorithm, which was recently developed and applied successfully to the simu-

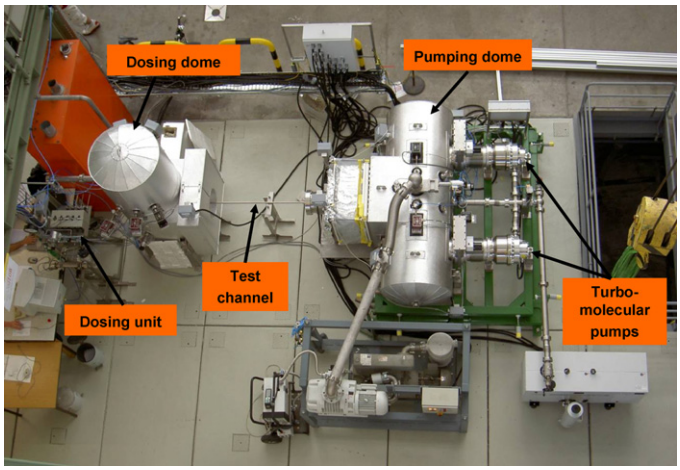

Fig. 2. Experimental facility TRANSFLOW.

lation of rarefied gas flows through tubes of finite length in arbitrary pressure drops ($P_1/P_0 \neq 0$), is used [12]. The code is based on the No Time Counter (NTC) scheme [5]. Since the details of the algorithm are well described and thoroughly explained in previous works [10,12], here only the specific issues related to the present formulation are provided.

The computational parameters have been accordingly chosen to ensure results accurate up to at least two significant figures (statistical error less than 1%). In all cases, the time increment is taken as $\Delta t = 0.01(R/\upsilon_0)$, while the length and the radius of the computational reservoirs before and after the tube are $8R$. The number of model particles is chosen to be 30×10^6 for all cases. Also, the size of the largest cells is $\Delta x/R = 0.05$, while the total number of cells is about 8×10^4. Finally, it is noted that the hard sphere model is used for the simulation of the intermolecular potential, while the reflection of molecules on the surfaces was assumed for both numerical approaches purely diffuse.

4. Experimental setup

To compare with the calculations and to enlarge the existing and still very scarce data base of transitional flows, a large scale test facility has been set up. The basic principle of the TRANSFLOW test rig (see Fig. 2) (Transitional Flow Range Experiments) is the measurement of the conductance of different channels in the transitional and near transitional flow regime at isothermal conditions. TRANSFLOW is based on the direct dynamic approach, where a constant flow is adjusted and the pressure difference is measured. The constant flow into the test rig is provided by a dosing unit. The temperature and pressure of the injected gas can be measured in the dosing dome, which is directly connected to the dosing unit.

The test channel is following the dosing dome in flow direction. On the downstream end it is connected with the pump dome. The pump dome serves to measure temperatures and pressures at the outlet side of the test channel. It is also equipped with turbomolecular pumps, which are further connected to the forepumps, to maintain the vacuum conditions inside the system. Further details about the TRANSFLOW facility will not be presented, since a thorough description can be found in Ref. [2]. For the present experimental work, the study is focused only in circular pipes with finite and infinite length. More specific, two short test tubes were used for the experiments in the facility. The corresponding lengths and diameters for each short tube are equal to $L = 21.2$ mm, $D = 21.2$ mm ($L/D_h = L/D = 1$) and $L = 21.4$ mm, $D = 5$ mm ($L/D = 4.28$), respectively. In addition, a long tube with $L = 1277$ mm and diameter approximately $D = 16$ mm ($L/D = 80$) was used. The inner surface

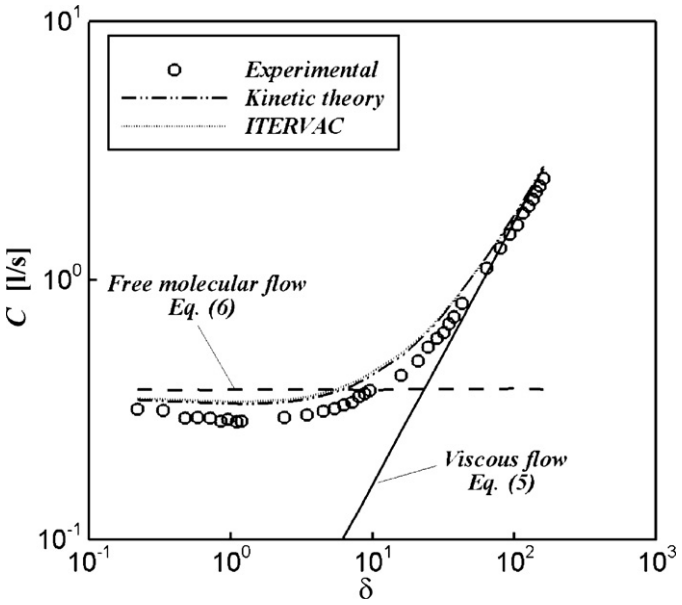

Fig. 3. Experimental and computational conductance in terms of rarefaction parameter δ for long tubes.

of each tube was of standard clean technical quality without special treatment. Gas nitrogen (N_2) was used in average temperature $T_0 = 296$ K.

5. Results and discussion

In this section the comparison between the available experimental and computational results of the conductance and the mass flow rate for tubes under consideration are presented. The results cover a wide range of the Knudsen number from the free-molecular regime all the way up to the hydrodynamic limit. In parallel, numerical results from ITERVAC code [13] are compared with the present experimental data. The ITERVAC code is an essential empirical code, which was developed in Karlsruhe Institute of Technology (KIT) for the validation of proposed design changes to the ITER vacuum systems (neutral beams, torus exhaust, cryostat high vacuum systems and dedicated forepump trains). The main advantage of the ITERVAC code is its simplicity on cost of somewhat reduced accuracy, this means it provides prompt results and is thus a very useful tool for a vacuum designer who wants to judge the impact of a design modification. Benchmarking of ITERVAC was successful in the whole range of gas rarefaction for the cases of channels with infinite length, while there is no corresponding work in the case of short channels. Therefore, for this latter case an investigation is carried out in order to validate and, if needed, to revise and upgrade ITERVAC based on DSMC calculations.

In Fig. 3 the conductance in terms of the rarefaction parameter δ for the case of long tube is plotted. It is seen that qualitatively, the conductance remains almost constant near the free-molecular regime and increases as δ approaches the viscous regime. For intermediate δ and especially for δ close to unity the Knudsen minimum is observed, which is however not as pronounced as with the corresponding curves for orthogonal ducts with large aspect ratios [2].

The experimental results are in very good agreement with the corresponding numerical results based on the linearized kinetic theory and ITERVAC calculations. The average relative error, which is defined as $|(C^{comp} - C^{exper})/C^{exper}|$ is of the order of 10% for both numerical approaches. It is noted that close to the hydrodynamic limit ($\delta > 50$) the experimental and numerical results tend

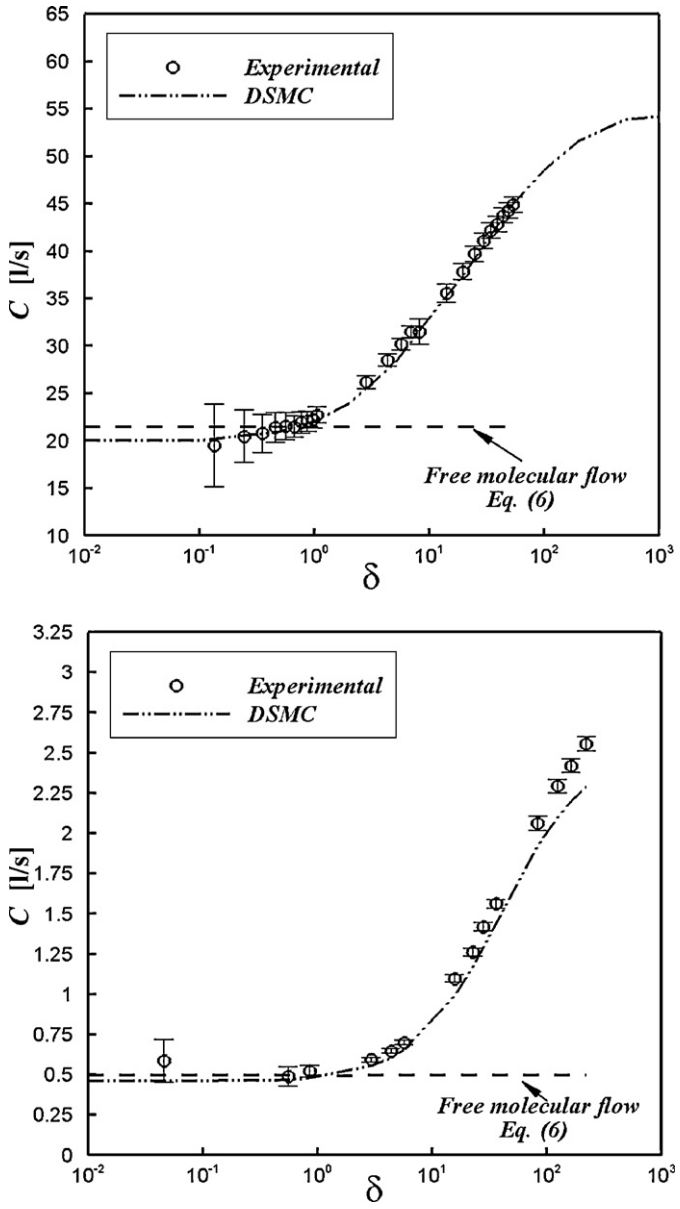

Fig. 4. Experimental and computational conductance in terms of the rarefaction parameter δ for short tubes with $L/D = 1$ (top) and $L/D = 4.28$ (bottom) respectively.

to approach the analytical value of conductance (solid line), which is direct proportional to the rarefaction parameter δ. This behaviour is described by the well known Hagen–Poiseuille equation,

$$C_{HD} = \frac{\pi}{256}\frac{D^4}{L\mu}(P_0 + P_1) \tag{4}$$

Using the definition of rarefaction parameter δ from Eq. (2) it is deduced that

$$C_{HD} = \frac{\pi}{128}\frac{D^3}{L}\upsilon_0\delta \tag{5}$$

which corresponds to the solution of the corresponding Navier–Stokes equations for laminar flow through a long tube. On the other hand, for small values of rarefaction parameter δ, close to the free-molecular flow, the experimental and numerical conductance approaches the analytical solution of the conductance (dashed line) given by the following expression [14],

$$C_{FM} = \frac{\sqrt{\pi}}{8}\upsilon_0 D^2 \frac{14 + 4(L/D)}{14 + 18(L/D) + 3(L/D)^2} \tag{6}$$

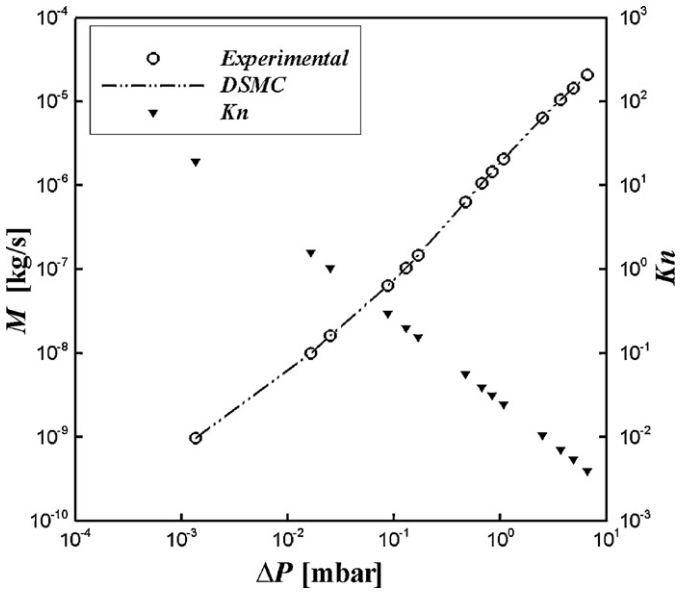

Fig. 5. Experimental and computational mass flow rate in terms of ΔP and Knudsen number Kn for the short tube with $L/D = 4.28$.

It is noted that the Eq. (6) is valid for any L/D ratio and it is also clearly deduced that the conductance in the free-molecular flow is independent on the pressures upstream and downstream of the tube.

In Fig. 4, the corresponding numerical and experimental conductance, in terms of the rarefaction parameter δ, for the case of short tubes with $L/D = 1$ (top) and $L/D = 4.28$ (bottom) respectively, is presented. For the case of short tube with $L/D = 1$ the pressure ratio varies from $P_1/P_0 = 1.2 \times 10^{-2}$ to 8×10^{-2}, while for $L/D = 4.28$ the corresponding pressure ratio varies from $P_1/P_0 = 6.7 \times 10^{-4}$ to 8.7×10^{-4}. It is noted that the numerical results for $L/D = 1$ correspond to $P_1/P_0 = 0$, while for $L/D = 4.28$ the numerical results correspond to the exact pressure ratio given by the experiment. Comparing Fig. 4 with the corresponding Fig. 3, for the case of long tubes, it is seen that qualitatively the behaviour of the conductance thoroughly differs in the hydrodynamic regime, where the conductance seems to reach asymptotically a constant value. A good agreement is observed in specific ranges of δ, especially in the transition and slip regime, where the average relative error is of the order of 10%. Larger discrepancies between experimental and numerical results are observed in small flows in the free-molecular regime, where the accuracy of the measurements is strongly affected by the offset deviation of each flow device. As a result, the lower limit for the experimental facility TRANSFLOW, where reliable results can be obtained, is of the order of $\delta \approx 10^{-1}$ to 10^{-2}. Also it is noted that in Fig. 4 (bottom), for the case of $L/D = 4.28$, the discrepancy between experimental and DSMC results in the viscous regime is due to the fact that DSMC results are based on insufficient number of modelled particles. Furthermore, the corresponding analytical solution for conductance in free-molecular flow has been calculated (dashed lines) using Eq. (6) and it is seen that the numerical and experimental results tend to reach the corresponding analytical values. Moreover, for the case of tubes with finite length there is not a closed form expression for the conductance and as a result no comparisons can be performed for that specific case.

Finally, in Fig. 5, the computational and experimental results for the mass flow rate in kg/s in terms of pressure difference ΔP and rarefaction parameter δ, for the short tube with $L/D = 4.28$, are presented. Each experiment is characterized by a pressure difference $\Delta P = P_0 - P_1$ and by a reference Knudsen number, which is based on

the upstream pressure P_0. For each pair (Kn, ΔP) the corresponding computed (dashed dot line) and measured (cycles) mass flow rates are shown. It is seen that again the agreement is very good.

6. Conclusion and outlook

In the present work comparisons between experimental and numerical results for the case of long and short tubes are performed, for a wide range of Knudsen number. The computational approach for long tubes is based on the BGK kinetic theory subject to Maxwell diffuse-specular boundary conditions, while for the case of short tubes the DSMC method has been applied. The experimental work has been performed at the vacuum test facility TRANSFLOW at KIT. The computed and measured flow rates and conductances are in most of the cases in very good agreement. The discrepancies are within 10%. In addition, the present work can be extended to the study of different cross sections and of a range of L/D_h ratio, which covers the intermediate range of $5 < L/D_h < 80$.

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References

[1] F. Sharipov, V. Seleznev, J. Phys. Chem. Ref. Data 27 (1998) 657–706.
[2] S. Varoutis, S. Naris, V. Hauer, C. Day, D. Valougeorgis, J. Vac. Sci. Technol. A 27 (1) (2009) 89–100.
[3] F. Sharipov, J. Vac. Sci. Technol. A 17 (5) (1999) 3062–3066.
[4] S. Naris, D. Valougeorgis, Eur. J. Mech. B/Fluids 27 (2008) 810–822.
[5] G.A. Bird, Molecular Gas Dynamics and the Direct Simulation of Gas Flows, Oxford University Press, Oxford, 1994.
[6] H. Shinagawa, H. Setyawan, T. Asai, Y. Yuichi, K. Okuyama, Chem. Eng. Sci. 57 (2002) 4027–4036.
[7] A.K. Sreekanth, Proceedings of the 6th International Symposium on Rarefied Gas Dynamics, 1969, pp. 667–680.
[8] T. Fujimoto, M. Usami, J. Fluids Eng. 106 (1984) 367–373.
[9] L. Marino, Microfluidics Nanofluidics 6 (2009) 109–119.
[10] S. Varoutis, D. Valougeorgis, O. Sazhin, F. Sharipov, J. Vac. Sci. Technol. A 26 (2008) 228–238.
[11] A. Chambers, Modern Vacuum Physics, CRC Press Company, 2005.
[12] S. Varoutis, D. Valougeorgis, F. Sharipov, J. Vac. Sci. Technol. A 27 (6) (2009) 1377–1391.
[13] C. Day, V. Hauer, G. Class, D. Valougeorgis, M. Wykes, Proceedings of the 21st Fusion Energy Conference, Chengdu, China, 2006.
[14] K. Jousten, Handbook of Vacuum Technology, Wiley-VCH, Weinheim, Germany, 2008.