TRANSFLOW: An experimental facility for vacuum gas flows

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Abstract.

The TRANSFLOW experimental facility represents a reliable tool for measuring the conductance of 1:1 scale components as typically used in vacuum systems in a wide range of the Knudsen number (e.g. $10^{-4} \leq Kn \leq 10^3$). The main principle of this facility is the dynamic measurement of the pressure difference upstream and downstream of the duct by setting a constant mass flow rate through the test channel. Many experiments on fully developed and developing flows, based on long and short channels respectively, have been already completed and comparisons with corresponding numerical results have been successfully performed. It has been clearly proven that the TRANSFLOW experimental setup provides conductance results with overall uncertainty between 1 to 10% and it could be used as a benchmark facility for any new proposed scientific numerical method in rarefied gas dynamics and in the whole range of gas rarefaction.

1. Introduction

Gas flows under vacuum conditions consist one of the main scientific fields in rarefied gas dynamics with many engineering applications as for instance the vacuum systems of fusion reactors. The main characteristic of such flows is that in rough, medium, and high vacuum conditions, the whole range of the Knudsen number from the free molecular through the transition and slip regimes up to the hydrodynamic limit may be covered. Typical components of vacuum systems are ducts, valves and piping fittings with various lengths and cross sections, where the estimation of overall macroscopic quantities as for instance the mass flow rate, conductance and pressure are of vital importance.

In the above framework, a test facility called TRANSFLOW (test facility for Transitional Flow range experiments) was set up at the Karlsruhe Institute of Technology in 2006. The whole facility is designed for fundamental laboratory research, but sufficiently large to investigate 1:1 scale big vacuum components. It allows the measurement of the conductance for different geometries including ducts, bends and bellows with a maximum length of 1500 mm and a maximum diameter of 600 mm over a wide range of pressure and flow conditions. To the best of our knowledge, TRANSFLOW is the only facility of that kind with sufficiently large size and capable of investigating vacuum components in real scale. This allows generating experimental results, where the wall surface is of
negligible influence and comparisons with results taken in micro-scale experiments, which potentially suffer from a stronger influence of the wall surface on the gas flow, may be performed.

The scope of the present work is to study on experimental basis the measured quantities of the mass flow rate and the conductance for long and short ducts of various cross sections in the whole range of the Knudsen number. In addition, the TRANSFLOW experimental facility, its limitations and the associated measurement uncertainty will be explained and finally some comparisons between numerical and experimental data will be performed.

2. Experimental set-up

2.1. General configuration

The basic principle of the TRANSFLOW test rig (Fig. 1) is the measurement of the conductance in whole range of Knudsen number at isothermal conditions. TRANSFLOW is based on the direct dynamic approach, where a constant flow $Q$ is adjusted and the pressure difference $\Delta P$ is measured (Fig. 2). For completeness purposes the definition of conductance as $C = Q / \Delta P$ is stated. The upstream (dosing dome) and downstream (pump dome) vessels are connected with a test channel. The pump dome is equipped with two turbomolecular pumps, which are further connected to the forepumps, to maintain the vacuum conditions inside the system. For the presented experimental work, indicative results for the case of circular and triangular ducts are demonstrated. More specific, two short test tubes are used with lengths and diameters equal to $L = 21.2$ mm, $D = 21.2$ mm ($L/D_h = L/D = 1$) and $L = 21.4$ mm, $D = 5$ mm ($L/D_h = L/D = 4.28$) respectively (Fig. 3, a and b). In addition, a long equilateral triangular duct with length $L = 1277$ mm and hydraulic diameter approximately $D_h = 16$ mm ($L/D_h = 80$) is used (Fig. 3, c). The inner surface of each duct was of standard clean technical quality without special treatment. Gas Nitrogen ($N_2$) was used at average ambient temperature $T_0 = 296$ K.

Figure 1: Experimental facility TRANSFLOW.
2.2. Dosing and pump dome

The total volume of the dosing dome including adapter flange is 0.6 m$^3$, while both domes consist of stainless steel. For the case of the smaller adjusted flows, which are of the order of $10^{-3}$ mbar.l/s, the facility allows an outgassing rate of the order of $10^{-7}$ mbar.l/s (e.g. this value is high for a cleaned technical stainless steel surface) and it can be assumed as negligible. All connected flanges are high vacuum CF flanges with copper sealing or Swagelok connections. The pump dome is mounted on a movable frame and it can be adjusted to the length and the geometry of the test channel under consideration.

In the pump dome, two turbomolecular pumps MAG W 2800 by Oerlikon-Leybold are attached via a VAT UHV gate valve. They are magnetically levitated and provide a maximum pumping speed of 2.8 m$^3$s$^{-1}$ for nitrogen. The pumping speed of these pumps can be adjusted by the gate valves in 1000 increments (0.1 percent steps). The pump speed can be varied by a frequency inverter between 0 and 475 Hz. The volume of the pump dome is 1.2 m$^3$ and is assumed quite large compared to the volume of the corresponding test channel. As roughing pump, a pumping train consisting of a Pfeiffer Roots blower, type WKP 1000, with a maximum pumping speed of 1070 m$^3$h$^{-1}$ for nitrogen and a rotary vane pump with a maximum pumping speed of 65 m$^3$h$^{-1}$ for nitrogen is used.

Finally, it is noted that the whole facility can be heated for bake-out during the pump down phase to a temperature up to 473 Kelvin (200°C). Therefore 14 heating circuits are available, 6 on the dosing dome, 7 on the pump dome and the remaining one on the test component. The temperatures can be
adjusted within 1 degree, while the temperatures of the dosing dome, pump dome and the test component can be set separately.

2.3. Dosing system

The dosing system consists of total 5 mass flow controllers (MFC, type MKS-647C) in order the injected flow to be effectively controlled. The MFCs are connected via pneumatic valves and via a pressure reducer with an outlet pressure of 1200 mbar, directly to the gas storage. The maximum flow ranges, in nitrogen equivalents, are 1 sccm, 10 sccm, 100 sccm, 1 slm and 10 slm respectively. It is noted that all MFCs are insulated to reduce the effect of changes in the ambient temperature. Finally, it is noted that calibration data is used for obtaining the final uncertainty of each device, which ranges from 0.5 to 2%.

2.4. Pressure measurement

The pressure measurement in the pump and dosing domes is performed by highly accurate pressure gauges. In each dome three capacitance diaphragm gauges (CDG) by MKS, type Baratron® 690 HA, and one hot cathode gauge (HCG) by Granville-Philips, type Stable Ion®, are installed. The operation of CDGs is independent of the used gas and they provide a maximum measurement range of 1000 Torr, 10 Torr and 1 Torr at the dosing dome or 0.1 Torr at the pump dome, respectively. On the other hand the hot cathode gauge provides a maximum measurement range of $10^{-4}$ mbar. For the case of CDGs the obtained uncertainty ranges between 0.003-0.1%, while for the case of HCGs the uncertainty is of the order of 5% especially in low pressure range. It is noted that for all the above pressure gauges calibration data for the estimation of the uncertainty is used as well.

2.5. Control system and data acquisition

The facility is controlled by a SIEMENS S5 programmable logic controller (PLC) including the COROS system as graphical user interface. The PLC controls the vacuum pumps, the valves and the pressure devices. For data acquisition, a Keithley multi-channel voltmeter is installed. The range of the output signal of every device is between 0 and 10 Volt for the pressure and temperature devices and between 0 and 5 Volt for the flow devices, respectively. This range is scaled to the maximum range of the physical values of every device. The sampling rate of every channel is 0.1 Hz and it can be increased to 10 Hz if necessary. The corresponding voltage values for pressure, temperature and injected flow are stored with a resolution of 16 bit to the hard disc of the measurement computer. Almost $10^2$ measurements are needed for averaging, in order to receive experimental results with sufficiently good statistics.

3. Results and discussion

In this section the comparison between the available experimental and computational results of the conductance for the ducts under consideration are presented. The results cover a wide range of Knudsen number from the free molecular regime all the way up to the hydrodynamic limit. In parallel, numerical results from computational fluid dynamics (ANSYS-CFX) are compared with the present experimental data for the solution in the continuum limit.

In Fig. 4 the conductance in terms of the upstream pressure $P_0$ for the case of a long equilateral triangular duct (e.g. Fig. 3c) is plotted. For small values of $P_0$ the flow belongs to the free molecular
regime, while for large values of $P_0$ the viscous regime is being approached. It is seen qualitatively that the two conductance limit cases - a constant value in the free molecular limit (according to [1,2]) and a direct proportionality to $P_0$ in the viscous limit (according to [2]) - are properly described. For intermediate pressures ($P_0 \approx 1$ Pa) the Knudsen minimum is observed, although it is very weak (as expected in such a long channel) and not as pronounced as with the corresponding curves for orthogonal ducts with large aspect ratios [3]. The experimental results are in very good agreement with the corresponding numerical results based on the linearized kinetic theory [1]. The obtained average relative error, which is defined as $(C_{\text{comp}} - C_{\text{exp}}) / C_{\text{exp}}$, between corresponding presented experimental and numerical results, varies between 3 to 10%.

In Fig. 5, the corresponding numerical and experimental conductance, in terms of $P_0$, for the case of short tubes with $L/D=1$ (left) and $L/D=4.28$ (right) (e.g. Fig. 3a and 3b) 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 $8 \times 10^{-2}$ with $P_1$ to range between $10^{-4}$ and $10^{-1}$ Pa, while for $L/D=4.28$ the corresponding pressure ratio varies from $P_1/P_0=6.7 \times 10^{-4}$ to $8.7 \times 10^{-4}$ with $P_1$ to range between $10^{-4}$ and $10^{-1}$ Pa as well. It is noted that the numerical results for $L/D=1$, for simplicity purposes, are based on the assumption of $P_1/P_0=0$ (expansion into vacuum), while for $L/D=4.28$ the numerical results correspond to the exact pressure ratio given by the experiment. The influence of the assumption of expansion into vacuum (i.e. $P_1/P_0=0$) has been proven to result in a negligible impact on the obtained results. Comparing Fig. 5 with the corresponding Fig. 4, 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 in the case of the short ducts. A good agreement is observed in specific ranges of gas rarefaction, especially in the transition and slip regime, where the relative error as defined above is within 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 mass flow controller. As a result, the lower limit for the experimental facility TRANSFLOW, where reliable results can be obtained, is of the order of $P_0=0.1$ Pa. Also it is noted that in Fig. 5 (right), for the case of $L/D=4.28$, the discrepancy between experimental and DSMC results in the viscous regime [4,5] 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 (dashed lines) has been calculated based on available results presented in [3]. It is seen that the numerical and experimental results tend to reach the corresponding analytical values.

**Figure 4:** Conductance in terms of upstream pressure $P_0$ for a long equilateral triangular duct with $L/D=80$. The gas is nitrogen at ambient temperature.
4. Concluding remarks

From the above analysis it is clearly seen that the TRANSFLOW experimental facility is proven to be a very reliable experimental setup, where results with overall uncertainties between 1 to 10% can be obtained for test channels or industrial components. The main advantages of the facility are the flexibility in terms of the 1:1 scale of the installed components, where the influence of the wall surface can be assumed negligible, the wide range of achievable gas flows and pressures in isothermal pressure driven flows and finally the ability of measuring thermal driven flows due to the installed heating system. Such a scientific device could be used as a benchmark facility for any new proposed scientific numerical method in rarefied gas dynamics for the whole range of the Knudsen number. Currently, a research plan is under development for the extension of the applicability of the TRANSFLOW in “micro” applications and more specific in the investigation of thermal creep flows, transient flows and flows through conical micro channels.

5. Acknowledgments

This work has been supported by the European Community under the contract of Association EURATOM/KIT. The work of S. Varoutis has been carried out within the EFDA-Fusion Researcher Fellowship, while the work of V. Hauer and C. Day has been carried out within the framework of the European Fusion Development Agreement.

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