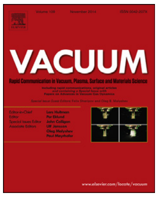
Vacuum 109 (2014) 373–384

Contents lists available at ScienceDirect

Vacuum

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



Computational and experimental study of unsteady gas flow in a dynamic vacuum standard

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ARTICLE INFO

Article history:
Received 28 February 2014
Received in revised form
22 April 2014
Accepted 11 May 2014
Available online 2 June 2014

Keywords:
Unsteady flow
Dynamic vacuum standard
DSMC
Hybrid
Gas expansion
Vacuum gauge

ABSTRACT

A dynamic vacuum standard was developed at the Physikalisch-Technische Bundesanstalt (PTB) to test the response of pressure gauges to changes of pressure from 100 kPa to 100 Pa within one second. It has been validated through a series of comparisons of the pressure and temperature evolution curves between simulations and measurements. On the theoretical side, hybrid continuum-particle and conjugate heat transfer simulations were employed, as well as significant modelling based on the choked flow hypothesis. On the measurement side, fast responding capacitance diaphragm gauges (CDGs) and a micrometre sized thermocouple were used to obtain the experimental data. Three conductance elements and various gases have been considered. The comparisons between simulations and measurements show reasonable agreement, with an average deviation of 13.5% in pressure and 9 K in temperature.

1. Introduction

Several industrial processes, such as leak testing for car rims and switches, CD metallization and coating processes for PET bottles, demand fast changes of several orders of magnitude for the ambient gas pressure. Vacuum load locks are commonly used for such processes, where a medium vacuum may need to be formed within 1 s or less. The productivity of systems is heavily dependent on the reading of vacuum gauges and therefore gauge manufacturers are interested on the ability of their sensors to follow such rapid changes of pressure.

In order to address the industrial need for the dynamic measurement of pressure for such fast processes, the Physikalisch-Technische Bundesanstalt (PTB) has developed a dynamic pressure standard within the framework of the European project EMRP IND12 [1]. This is accomplished by expansion of gas via a calculable conductance and a very fast opening gate valve and allows the investigation of the response behaviour caused by the physical principle of each gauge. Preliminary results had been previously documented in Ref. [2]. The objective of this work is to further validate our experimental facility using both numerical and experimental procedures.

Numerical simulations for steady state configurations are nowadays increasingly used in vacuum applications [3–5]. Important data which would otherwise be unavailable or difficult to measure, such as complete distributions of pressure, temperature and velocity, as well as mass flow rates, may now be extracted. The most important methods are the direct simulation Monte Carlo method (DSMC) [6–8] and the discrete velocity method (DVM) [9–13]. Additionally, hybrid continuum-kinetic methods are also frequently employed [14–19]. Unsteady problems have received less attention but there is an increasing amount of works in the last few years [7,20–23].

The problem of unsteady expansion of a gas into vacuum is a problem of wide application. Despite this fact, it has only been tackled through the use of modelling approximations and complete numerical simulations are rarely encountered for upstream pressures entering the slip or hydrodynamic regime. The reason is that the combination of several flow regimes (rarefied/non-rarefied, compressible/incompressible, choked/non-choked) poses significant challenges in the choice of the appropriate methodology. Moreover, the accumulation of error with time and the span of the problem in several orders of magnitude urge for a method that offers good accuracy in a reasonable computational time. Finally, the possibility of three-dimensional flow and non-trivial geometrical features may pose significant difficulties to current codes based on kinetic theory.

The outline of the paper is as follows: the flow configuration is described in Section 2. Section 3 contains information regarding the

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http://dx.doi.org/10.1016/j.vacuum.2014.05.005
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experimental aspects of this work. Information on the numerical method is given in Section 4. Section 5 contains the experimental and numerical validation of the facility, including the comparison between the two approaches. Finally, further discussion and concluding remarks follow in Section 6.

2. Flow configuration

Our aim is to change the pressure from atmospheric conditions to below 100 Pa within 1 s or less in a predictable manner. This is accomplished by expansion of a test gas at 100 kPa in a small volume via a calculable conductance into a large evacuated volume and should be confirmed by numerical simulations. The expansion is initiated by a fast opening valve [24]. The calibration facility was designed such that it is also possible to generate fast upward pressure changes from 100 Pa to 100 kPa within 1 s. The readings of the vacuum gauge to be tested should be compared with the numerically predicted pressures at time *t* for fast pressure increase and decrease. The facility must be able to capture different time scales by changing the conductance elements, the gas and the flow direction.

An expansion system with two vessels of largely different volumes is preferred over a system with a vacuum pump. In this manner, the expansion ratio is well defined, as the volume ratio is known. Replacing the large volume by a pump or attaching a pump to it bears the risk that the pumping speed is not sufficiently well-known and cannot be characterized for a pressure pulse. Finally, a pressure rise is easier to obtain for a two-vessel system by simply reversing the initial pressure conditions of the two chambers.

The experimental facility and its schematic representation are shown in Fig. 1. The DN40 gate valve opening time was estimated to be 4.6 ms [24]. The exchangeable conductance element can be easily replaced by a different type of duct, whose geometry can be chosen quite flexibly, or even completely removed to provide the smallest time constant of pressure decrease in our system. The pressure “step” in this case has a time constant of less than 1.3 ms for our system (pressure reduction to 37% of the initial value) and is referred to in this text as the “full opening” configuration.

Either vessel can be filled with the test gas up to 100 kPa. Therefore, an expansion may be realized in any direction, i.e. from the small vessel to the large one and vice versa. The design was such that inner parts and complex geometries were avoided, in order to ensure that the pressure could be theoretically predicted as a function of time.

3. Experimental method

3.1. Volumes and expansion ratio

A view of the flow domain is given in Fig. 2. The volume of the small vessel (V_1), determined by the manufacturer drawings, was estimated to 0.08745 L, while the one of the large vessel (V_2, not shown in Fig. 2) was 185.4 L. Part of the fast opening valve and the tube leading to the large volume are shown in Fig. 2 (denoted as V_2'). It is important to note that other volumes also need to be taken into account. A dead volume, geometrically estimated to be about 0.033 L, exists between the orifice plate and the fast opening valve plate (V_1'). This is taken as an offset correction in the following calculations, assuming instant redistribution of this amount of gas as soon as the valve has opened. Furthermore, a volume of 0.10 L needs to be included in the large vessel volume due to the inner structure of the fast opening valve. The two CDGs and the dosing valve also increase the small vessel volume, thus reaching 0.13570 L ± 0.00073 L (confidence interval 95%) including the dead volume. This value has been measured by gas expansion into a calibrated volume and measuring the pressure with a calibrated gauge. The additional volume of the CDGs and the dosing valve has been taken into account in the simulations by slightly increasing the dimensions of the small volume and the gauge side ports and the final dimensions used in the simulations are included in Fig. 2. Thus, the final pressure assuming high vacuum downstream is 1/1368 of the initial one, i.e. about 73 Pa for an initial pressure of 100 kPa. Small variations may occur by exchanging the orifice with other conductance elements or by completely removing it.

3.2. Channel geometries

The conical orifice described in Ref. [2] has been mounted between the two volumes. It can be seen in Fig. 2 between V1 and V1′. The nominal diameter of the conical part was reduced from 8 mm to 3 mm within a thickness of 2.5 mm and it was followed by a thin cylindrical part of 3 mm diameter and 0.1 mm thickness. The

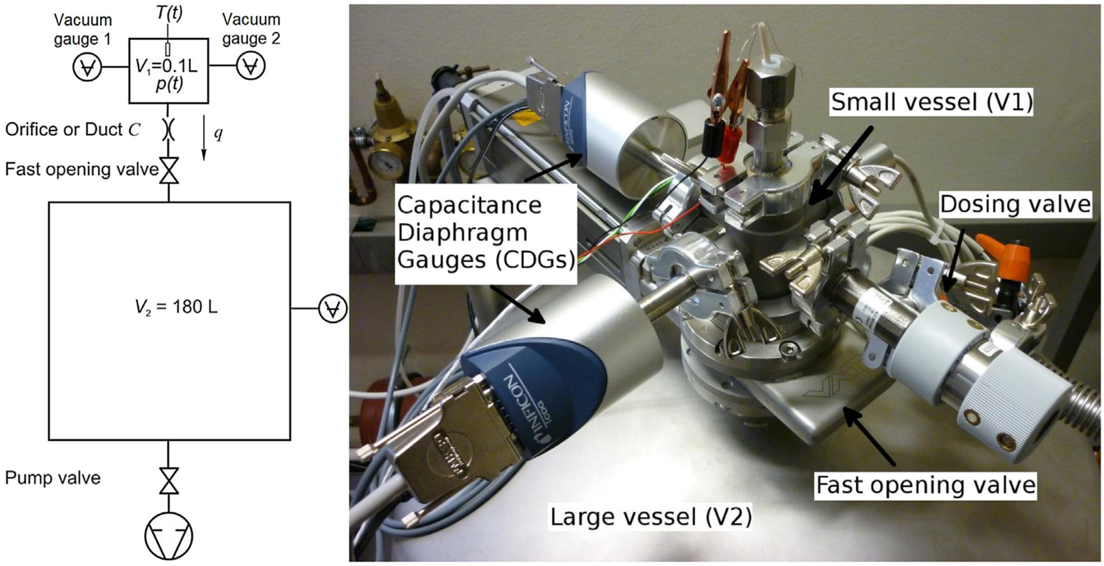

Fig. 1. Scheme (left) and picture (right) of the small volume of the dynamic expansion standard.