AiMT Advances in Military Technology
Vol. 6, No. 1, June 2011

The Impact of Critical Flow on the Primary Electron Beam Passage through Differentially Pumped Chamber

J. Maxa[1*] and V. Neděla[2]

[1] Department of Electrotechnology, Faculty of Electrical Engineering and Communication, Brno University of Technology, Brno, Czech Republic
[2] Institute of Scientific Instruments of the ASCR, Academy of Sciences of the Czech Republic, Brno, Czech Republic

The manuscript was received on 22 October 2010 and was accepted after revision for publication on 15 February 2011.

Abstract:

Environmental scanning electron microscope creates new possibilities in the field of examination of various types of specimens and their phases. The article analyses and compares the results of air pumping measurement for selected shapes of the differentially pumped chamber to create vacuum, using the Cosmos FloWorks system.

Keywords:

EREM, CAE, SolidWorks, Cosmos, FEI, Differentially Pumped Chamber

1. Introduction

High pressure in gases (up to 3000 Pa) in the specimen chamber of the variable pressure scanning electron microscope (VP-SEM) sets specific requirements for construction of the microscope and its pumping system. The design of individual construction parts of VP-SEM, mainly the differentially pumped chambers must meet specific requirements for efficient pumping of their interior and minimization of pressure. The specific technological requirements are sufficiently compensated by a wide scope of applications in both the vacuum mode and the high pressure mode [1].

The rather big difference in pressure originating between the specimen chamber (3×10^3 Pa) and around the source of electrons ($10^{-3} \div 10^{-9}$ Pa, according to source type) in VP-SEM, can be maintained only due to the system of differentially pumped chambers, pressure limiting screens (PLA1 and PLA2 in Fig. 2) and an efficient gas

---

* *Corresponding author: Department of Electrotechnology, Faculty of Electrical Engineering and Communication, Brno University of Technology, Technická 10, 616 00 Brno, Czech Republic, phone: +420 541 146 129, fax: +420 541 146 147,E-mail: maxa@feec.vutbr.cz*

pumping system. In the screens there are holes of the order of tens to hundreds of micrometers in diameter that can effectively restrict the gas flow between the individual parts of the microscope, and at the same time allow the passage of electrons from the source to the specimen [2]. The system of chambers and screens is usually integrated in the column of EREM. For pumping, usually a system of rotary, diffusion or turbomolecular vacuum pumps (the interior of the specimen chamber and adjacent differenttially pumped chambers), or possibly ion vacuum pumps (the source of electrons) are used.

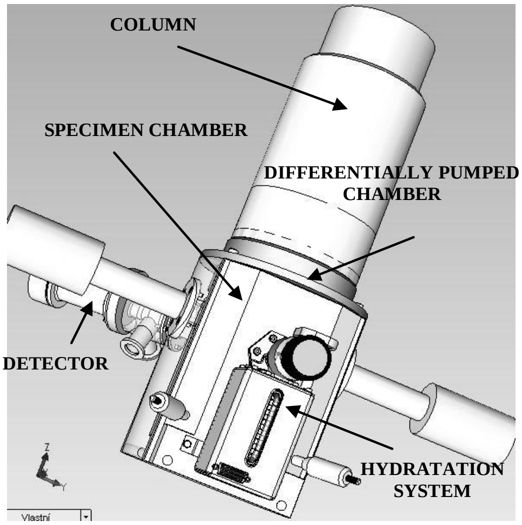

Fig. 1 AQUASEM II [2]

Due to the high pressure of gases in the EREM specimen chamber, there is an increased occurrence of interactions of electrons with molecules and atoms of gases (mainly water vapours). Subsequently the original primary electron beam diffuses. The diffusion of primary electrons increases with increasing pressure, average atomic number of gas, working distance and decreasing accelerating voltage in the beam. The diffusion results in an increased diameter of the trajectory of the primary electron beam. Consequently the signal/noise ratio in the detected signal is less favourable, and the final effect may be a deteriorated resolution of the microscope [3].

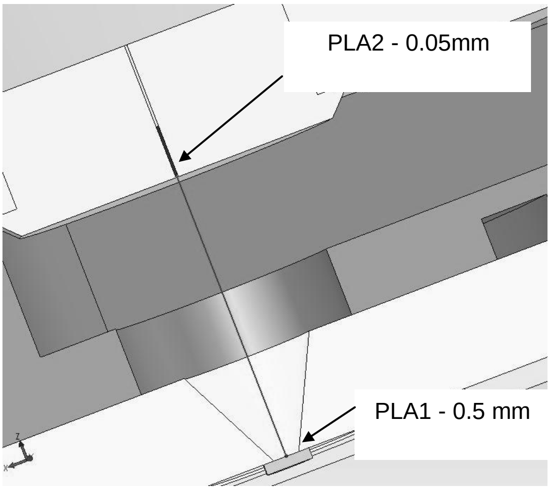

Fig. 2 Electron path leading through the high pressure environment in the differentially pumped chamber of AQUAESM II.

2. AQUASEM

The construction of now fully operating experimental VP-SEM AQUAEM II as a successor of the previous version of this microscope was completed, in cooperation with TESCAN Ltd, in 2007 at the Institute of Instrument Technology, Academy of Sciences in Brno [1]. The key application of the microscope is testing new detection systems operating in conditions of high pressure in gas or vacuum, study of special water containing or non-conducting specimens difficult to monitor and dynamic ‘in-situ’ experiments.

Because of the above-mentioned reasons, an optimal variant of the shape of the differentially pumped chamber was sought as the chamber is the principal construction element for adaptation of the microscope for work in high pressure conditions. Pumping the chamber efficiently is the crucial requirement affecting the qualitative parameters of the microscope, such as the maximal magnitude of gas pressure in the specimen chamber, amount of noise in the detected signal closely associated with microscope resolution, etc. A vital parameter for the final design of the differentially pumped chamber is the minimum gas pressure in the microscope optical axis. In Fig. 2, this trajectory is drawn in red. The area is the same in all variants (see Fig. 3). There are differences in the shape and in the manner of pumping. On the basis of our previous experience, three preliminary shapes were proposed.

Variant 1 (closed) – Gas from the passage area of the primary electron beam through the differentially pumped chamber is pumped in one direction and through the area between the microscope lens and the differentially pumped chamber (Fig. 3A). In this variant, the delimited area for gas passage is constructed in such a way that gas can follow the shortest possible path to the rotary vacuum pump.

Variant 2 (open) – Gas is pumped from the passage area of the primary electron beam through the differentially pumped chamber in one direction, similarly to the first variant C. It passes, however, through the entire area between the microscope lens and the differentially pumped chamber (see Fig. 3B).

Variant 3 (conical) – Gas is pumped from the space for passage of the primary electron beam through the differentially pumped chamber in all directions over the maximal possible free area and it goes away in the same way (Fig. 3C). The gas off take in this variant is identical with variant 2.

The variants were modelled using the SolidWorks system and the Cosmos FloWorks module for analysis of gas flow in seeking an optimal shape.

For calculations executed using the Cosmos FloWorks the following marginal requirements were defined. On the PLA 2 screen with a hole 0.05 mm in diameter, located between the microscope column and the differentially pumped chamber, the static pressure of 0.01 Pa is required. Analogically, in the case of the PLA 1 screen with a hole 0.5 mm in diameter separating the differentially pumped chamber and the specimen chamber (Fig. 2, Fig. 3E), the gradually set pressure values were 200, 400, 600, 800, 1000 Pa. These values are most frequently required for the VP-SEM specimen chamber.

For the pumping hole in the differentially pumped chamber the mass flow of the pumped gas was set at 0.00347 kg/s. in dependence on the selected rotary vacuum pump. In symmetrical objects, Cosmos FloWorks can be used to set computation for only a half of the symmetrical objects, and thus the computing time can be substantially reduced. In real conditions, therefore, the mass flow value is doubled.

3. Pressure in Primary Electron Beam Area in Monitored Variants

In order to select an optimal variant, it is necessary to evaluate the pressure and mainly the density trends directly in the trajectory of the primary electron beam. That is why line C was drawn in the trajectory (Fig. 2) where the system will evaluate pressure and density values and transform them into a table to be used for plotting on graphs.

Results in Fig. 4 show that the conical variant is not suitable for our purpose. Important information obtained from Fig. 4 is the fact that the pressure in the specimen chamber has no particular effect on the magnitude of average pressure in the trajectory of the primary beam.

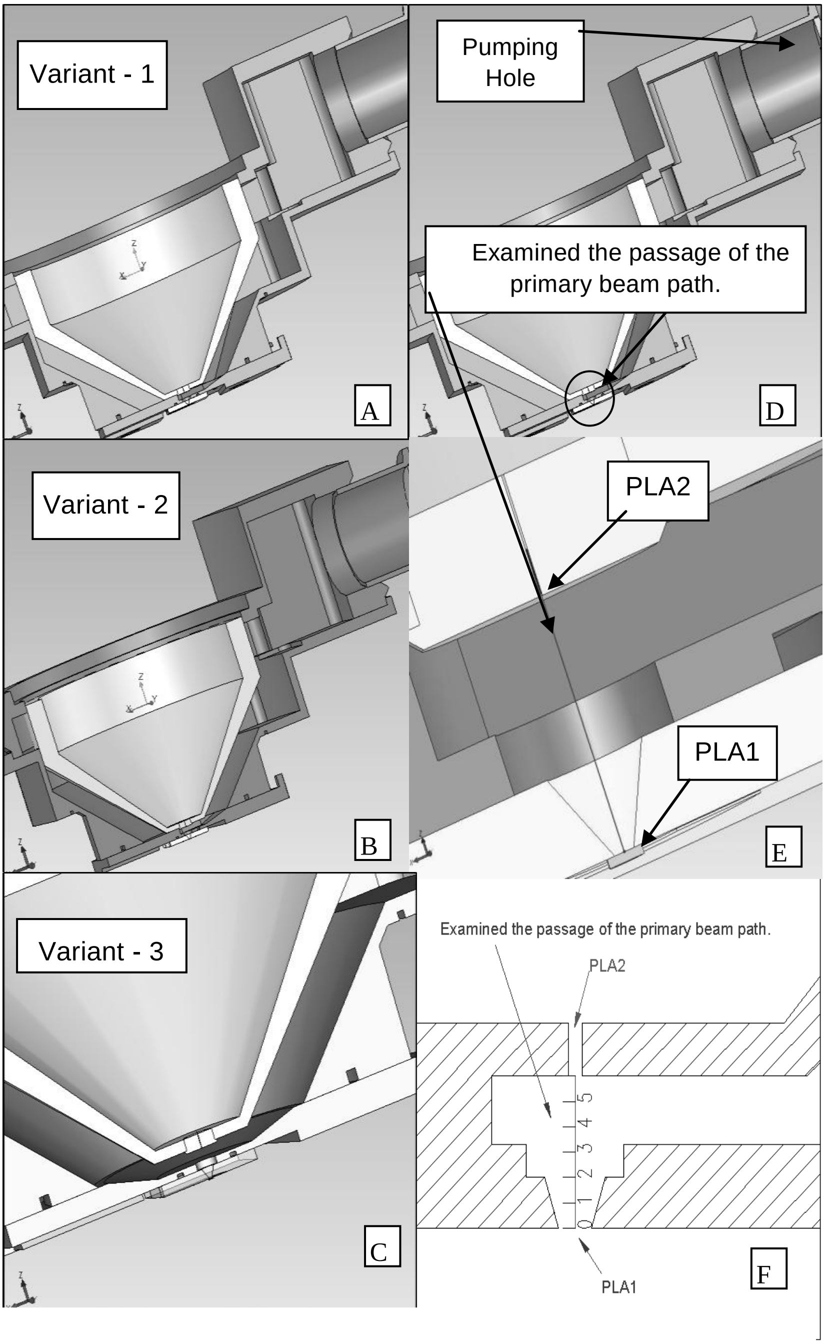

Fig. 3 Variants of differentially pumped chambers

This phenomenon is based on the principle of so-called critical flow originating at the edge of a small dimension hole separating areas of high pressure fall. In our case, it is the fall between the specimen chamber and the differentially pumped chamber on screen PLA 1.

As can be seen from the results, in both open and closed variant of the differentially pumped chamber at the edge of PLA 1 screen, all values of the set pressures reach the above mentioned critical values of flow. Behind PLA 1 screen, the flow beam first widens in the mode of supersonic gas flow up to a certain distance in dependence on the variant and pressure in the specimen chamber. Then the supersonic flow beam narrows to the point where the beam passes into under sonic gas flow. This fact is of great importance as in the area of supersonic flow the pressure of the environment decreases. The drop of pressure between the specimen chamber and the differentially pumped chamber is directly proportional to the dimensions of the expansion cone of supersonic flow behind PLA 1, therefore the low pressure area is longer. This observation for the studied case is shown in Fig. 5. Fig. 5 shows the expansion cone for the closed variant for the pressure of 200 Pa in the specimen chamber in the left part of the figure, and for the pressure of 1000 Pa on the right. The cone thus eliminates a direct relationship of pressure in the specimen chamber and average pressure in the trajectory of the primary beam in the differentially pumped chamber.

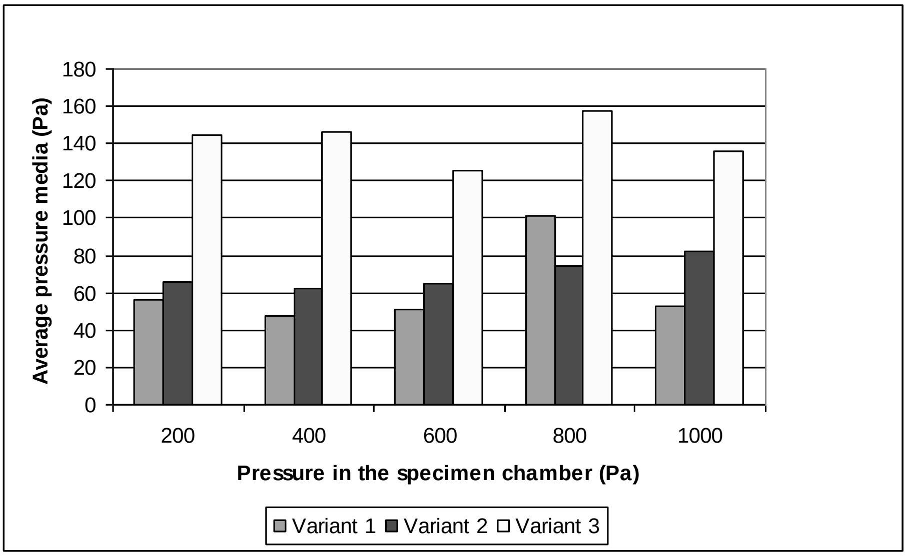

Fig. 4 Average pressure in the trajectory of the primary electron beam

This observation is described in detail in the graph in Fig. 6, where another observation is apparent. In case of large reductions of pressure, there is not only a longer expansion cone but also a certain pulsation – drop and subsequent increase – of flow rate. It is a monitored characteristic of supercritical flow that can be used for more efficient passage of the primary beam through the differentially pumped chamber at a higher pressure in the specimen chamber as it extends the low pressure area.

The flow behind PLA1 screen can be described using Fig. 7. The edges of the output cross section A-A1 cause the turbulence in the output flow. Behind the cross section, the gas flow is affected by pressure in the vicinity of P_{amb}, which is lower than the critical pressure P_{cr}. At this gate P_{cr} changes into P_{amb} and two expansions A-A1-B and A1-A-B1 formed by elementary expansion waves appear. They intersect at point D.

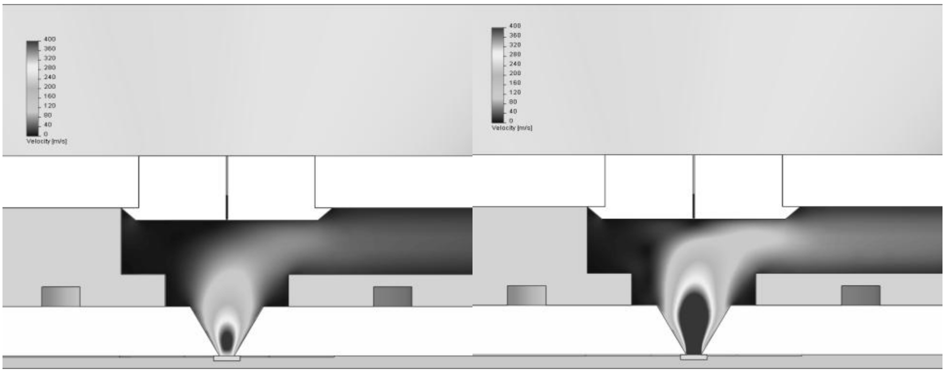

Fig. 5 Expansion of supersonic flow for 200 Pa and 1000 Pa

Further elementary expansion waves falling at the boundary A-B and A1-B1 reflect from it and expansions are transformed into a series of elementary compressions. [4]

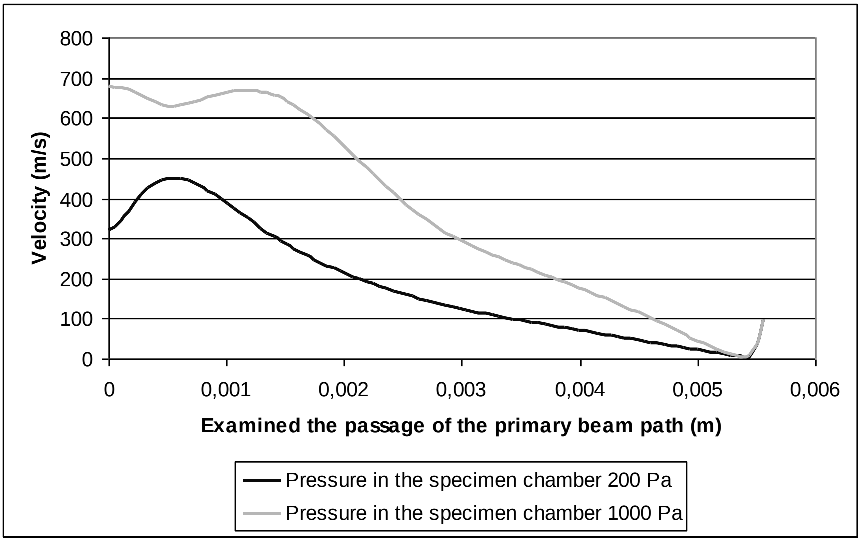

Fig. 6 Flow rate in the trajectory of the primary beam.

The result of this process is the wedge of thinning A-A1-D. Inside it, the pressure is substantially reduced. Then the pressure is lower than P_{amb}. In the second wedge D-B-B1, the pressure increases and in section B-B1 it reaches the value of P_{cr}. Thus the wedge of thinning passes into the wedge of thickening. In this section the reiteration of the cycle starts, then P_{cr} changes into P_{amb} again.

In the mentioned graph the pulsation is apparent in the variant for the pressure of 1000 Pa in the specimen chamber. The graphic representation is in Fig. 8. The results show that in the closed variant pulsation starts at 600 Pa in the specimen chamber, in the open variant at 500 Pa. In the conical variant, due to lower rates, pulsation does not occur.

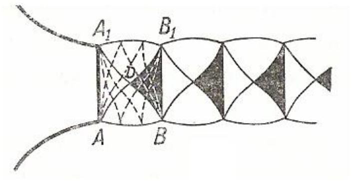

Fig. 7 Expansion waves behind the edge of the jet [4].

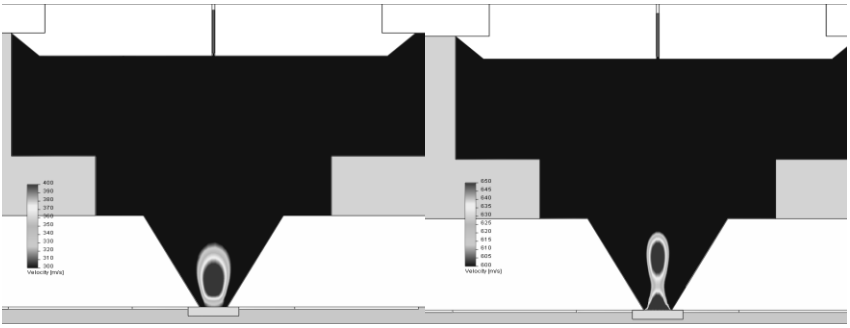

Fig.8 Double expansion wave in the 1000 Pa variant.

The given characteristics of the critical flow are used in the design of the differentially pumped chamber as they substantially affect the density of the medium in the trajectory of the primary beam, as it follows from elementary equations. One-directional flow of an ideal gas in a tube of a variable flow diameter can be described by equation:

$$p = r\rho T \tag{1}$$

and three laws:
law of conservation of mass:

$$Q_m = \rho v A = const. \text{ [kg/s]} \tag{2}$$

law of conservation of motion:

$$e = \frac{v^2}{2} + \frac{\kappa}{\kappa - 1}\frac{p_o}{\rho_o}\left(\frac{p}{p_o}\right)^{\frac{\kappa-1}{\kappa}} \text{ [J/kg]} \tag{3}$$

and law of conservation of energy:

$$e = \frac{v^2}{2} + c_p T = const. \text{ [J/kg]} \tag{4}$$

with P – static pressure, r – universal gas constant, ρ – density, T – temperature, A – area, v – *velocity*, Q_m – mass flow, e – internal energy, κ – Poisson constant, c_p – specific heat.

The average values of medium density in the trajectory of the primary beam, as well as the average values of the pressure, show that the conical shape of the chamber is absolutely unsuitable, mainly because of the low flow rates, which means that the physical laws associated with critical flow in the medium behind a small hole, in our case PLA1screen, are not taken into account.

The results for the remaining two variants are very similar, though on the whole, the closed variant is the more acceptable one.

Tab. 1 Results for the density of secondary electrons on the track in the detector

PRESSURE IN THE SPECIMEN CHAMBER (Pa**)**	**ARITHMETIC MEAN OF MEDIUM DENSITIES (**g/m^3**)**		
	VARIANT 1	**VARIANT 2**	**VARIANT 3**
200	0.75	0.81	1.73
400	0.63	0.92	1.68
600	0.84	0.88	1.60
800	0.79	1.05	2.20
1000	1.10	1.20	1.52

4. Conclusions

On the basis of the above analyses, we could evaluate also those spots in sections of the differentially pumped chamber where gauges for experimental measurements cannot be placed, however information on flow conditions is indispensable for construction.

Results of analyses offer new possibilities for modifications of construction of the differentially pumped chamber.

References

[1] NEDĚLA, V. and AUTRATA, R. Environmental Scanning Electron Microscopy (in Czech). *Československý časopis pro fyziku*, 2005, vol. 55, no. 3, p. 251-251. ISSN 0009-0700.

[2] NEDĚLA, V., MAXA, J. and AUTRATA, R. Environmental Scanning Electron Microscope Aquasem II – the Design and Applications. In *Proceedings of 10th Seminar Recent Trends in Charged Particle Optics and Surface Physics Instruments*. Brno : Institute of Scientific Instruments of AS CR, 2006, p. 55-56, ISBN 80-239-6285-X

[3] NEDĚLA, V. and MAXA, J. Hydration System for Environmental Scanning Electron Microscopes (in Czech). *Jemná mechanika a optika*, 2006, vol. 2006, no. 11-12, p. 329-332. ISSN 0447-6441.

[4] DEJČ, ME. *Technical Dynamics of Gases* (in Czech). Praha : SNTL, 1967.

Acknowledgments

This work was supported by the project No. GAP102/10/1410 of the Czech Science Foundation, the faculty project FEKT-S-10-14, and the project No. MSM0021630516 of the Ministry of Education, Youth and Sports of the Czech Republic.