Modelling of working processes of non-contact oil free vacuum pumps by computational fluid dynamics (CFD) methods

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Abstract. Numerical mathematical models of non-contact oil free scroll, Roots and screw vacuum pumps are developed. Modelling was carried out with the help of software CFD ANSYS-CFX and program TwinMesh for dynamic meshing. Pumping characteristics of non-contact pumps in viscous flow with the help of SST-turbulence model were calculated for varying rotors profiles, clearances, and rotating speeds. Comparison with experimental data verified adequacy of developed CFD models.

1. Introduction

In the end of 20th century semiconductor industry became the main driver of oil free pumping means development [1]. Production of micro- and nano-electronics, photoelectric cells for solar power engineering, flat-panel displays, development and startup of plants for growth of different crystal structures (poly- and mono crystal silicon) required higher level of vacuum pumps production. It concerns reliability enhancement during continuous work and high gas load, tolerance to dust and debris, high productivity and power efficiency in a pressure range from 1000 to 0.0001 mbar [2]. But recently pumping means have been developed in such a way that vacuum oils and other vacuum liquids to be excluded. For a long time oil sealed and oil-vapor vacuum pumps have been supplied with different kinds of traps, but it has not solved the problem of “clean vacuum”. Eventually, production of new oil free pumps was developed, namely, scroll, screw, claw and Roots pumps working in medium vacuum range. They have one common feature – non-contact rotors, which gives the opportunity to get rid of oil. Guaranteed clearances in rotor mechanism enable high rotating speed but non-contact pumps have low pressure ratio due to backward leakage through clearances. That is why the problem of efficiency improvement of non-contact oil free vacuum pumps working process is urgent, and reliable mathematical model of working process must be a basis of it because to manufacture and to test every option of rotor profile with different clearances, rotation speeds, inlet and outlet geometry is a very complicated problem. Moreover, inlet pressure range of such pumps may cover five decades and, consequently, gas flow varies from molecular flow through transient flow to viscous flow with turbulent heat- and mass transfer. Different approaches to working process modelling are used for each flow regime. In [3, 4] for gas flow calculation in slot channels and rotor profile optimization of Roots pumps relationships were used which were obtained by approximation of data obtained by test particle Monte Carlo method for molecular gas flow regime.
2. Problem formulation

In 21\textsuperscript{th} century opportunity of non-contact vacuum pumps mathematical modeling taking into consideration rotors motion appeared due to new computational power and numerical methods.

The most complete information about working process may be obtained with the help of computational fluid dynamics (CFD) methods. It should be noted that numerical modelling of displacement non-contact pumps is much more complex problem than calculation of kinetic (high-velocity) pumps, for example. Variable volume of working chambers connected by very small clearances calls for generation of high quality meshing varying with every step by time. Moreover, different gas flow equations (hybrid turbulence models) have to be combined in one model due to wide range of gas flow regimes (from turbulent in working chamber to laminar or supersonic in clearances).

In this work possibility of working process modelling of screw, scroll, and Roots pumps (figure 1) with the help of software ANSYS-CFX [5] by structured dynamic mesh method in TwinMesh [6] is considered.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Design schemes of pumps under study: a – screw pump; b – scroll pump; c – Roots pump.}
\end{figure}

The whole inner pump volume from cross section of inlet duct to the lower cross section of outlet duct is considered as reference area. Conical section is added at the inlet to stabilize incoming flow.

3. Meshing

Meshing for reference area is one of the main operations when developing mathematical model of working process. Characteristic dimensions of the pump working chamber vary from 200 mm (in the cut off volume) to 0.05 mm (in clearances). High mesh discretisation increases number of cells and makes calculation impossible during reasonable time. Low mesh discretisation does not allow adequate modelling of local effects which may be determinative for process calculation (for example, backward leakage in clearances). Volume of working chamber varies depending on rotor rotation angle; that is why for each time step its own mesh generation is necessary and transition of gas parameters between them.

Customised grid generation (CGG) is realized in TwinMesh. On the first stage 2D O-grid type mesh is generated in the rotor cross section. For Roots or screw pumps inter rotor interface is additionally created which divides working area into two parts. Smoothing algorithm which provides orthogonality, homogenous node distribution, increase of near-wall resolution is used for generating high quality mesh.

Mesh is generated for a number of rotor rotation angles with constant step and grid topology and node distribution remains the same. Then basic mesh is swept along rotation axis and is divided by a given number of elements for generation of 3-D mesh (figure 2).

Mesh of unstructured tetrahedral and hexahedral elements for undistorted geometry of inlet and outlet ducts (when rotors are rotating) is generated separately in Ansys Meshing.
Working process modelling

System CFD of ANSYS-CFX and TwinMesh makes it possible to create numerical models of pumps taking into consideration channels walls motion and resistance at the inlet and outlet.

Air is considered as working medium in the model of compressible ideal gas. SST turbulence model is used which represents combination of k-ε and k-ω turbulence models. In the area of main volume equations of k-ε model are used and in the vicinity of walls and in clearances equations of k-ω model are used which describe flow pattern rather well at suitable mesh resolution. These models are combined by empirical function depending on distance to the nearest point of solid surface. But when coarse mesh in the clearance is used, SST model based on wall functions gives excess of velocity and mass flow rate, consequently. That is why option «Laminar Turbulent Blend» based on equations of ω-model is used.

Turbulence kinetic energy (k) [7]:

\[
\frac{\partial \rho k}{\partial t} + \frac{\partial \rho U_j k}{\partial x_j} = P_k - \beta^* k \rho \omega^2 + \frac{\partial}{\partial x_j} \left[ \Gamma_k \frac{\partial k}{\partial x_j} \right] + 2(1 - F_i) \rho \sigma_{\alpha_2} \frac{1}{\omega} \frac{\partial k}{\partial x} \frac{\partial \omega}{\partial x},
\]

Specific dissipation rate (ω):

\[
\frac{\partial \rho \omega}{\partial t} + \frac{\partial \rho U_j \omega}{\partial x_j} = \frac{\alpha}{\nu_t} P_k - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[ \Gamma_\omega \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_i) \rho \sigma_{\alpha_2} \frac{1}{\omega} \frac{\partial k}{\partial x} \frac{\partial \omega}{\partial x},
\]

where \( F_i \) – is blending function between k-ω and k-ε, \( \beta^* \), \( \beta \), \( \alpha \), \( \sigma_{\alpha_2} \), \( \sigma_k \), \( P_k \) are model coefficients, \( \rho \) is density, \( \mu_t \) – is turbulent eddy viscosity; \( u \) is velocity.

Opening boundary condition with relevant mass and impulse option and zero gradient of turbulence is given at the input and output. Relevant rotary speed is specified on rotor walls. The conditions of slipping absence and heat exchange absence are specified on housing walls. Conditions of conservation of mass, impulse, turbulence, and heat flow are specified on interfaces between working chamber and inlet and exhaust ducts.

Solution convergence is checked by values of average mass flow rates per one revolution at the inlet and the outlet over time run.

Calculation results

Calculation result is distribution of pressure, temperature and gas velocity in working chamber on every time step. CFD modelling of working process make it possible to obtain mass (volume) gas flow rate in any cross section, indicator power and moment of resistance of gas forces on shafts as integral characteristics.

Calculation of pumping speed of oil free scroll vacuum pump NVSp-12 and Roots pump NVD-200 (manufactured by joint-stock company “Vakuummash”) was carried out [8] to verify CFD model.
It should be noted that working pressure range is from 1 to 105 Pa. When clearances are about 0.1 mm then even at 100 Pa molecular flow in slot channels takes place (Knudsen number is higher than 1). In such conditions CFD ANSYS-CFX cannot be used. That is why calculations were carried out at pressures higher than 200-300 Pa.

Diagrams in figure 3 show parameters of working process in pumps. Moment of connection of cut-off chamber with discharge chamber in NVD-200 is presented in figure 3a. Backward flow through inter rotor channel and eddies in cut off chamber are seen. Pressure ratio can achieve 4.22, that is why gas velocity may reach 700-800 m/s.

Figure 3b shows that in NVSp-12 at inlet pressure 40 kPa the greatest pressure is seen in last but one chamber beginning from the inlet due to gas over compression.

Comparison of obtained calculated data with experimental data [9, 10] was carried out. Calculated and experimental pumping speed vs inlet pressure are presented in figure 4a, b.

**Figure 3.** Velocity field in pumps:

- **a** – Roots pump NVD-200 at inlet pressure 1.3 kPa and rotation speed 3000 rpm;
- **b** – scroll pump NVSp-12 at inlet pressure 40 kPa and rotation speed 1500 rpm.

**Figure 4.** Calculated and experimental pumping speed:

- **a** – NVSp-12
- **b** – NVD-200.
Disagreement between calculation and experiment for both pumps does not exceed 10% which verifies prospect of CFD modelling for non-contact vacuum pumps.

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