VIRTUAL LABORATORY OF VACUUM TECHNIQUE

G.P. Averyanov, V.V. Dmitriyeva, V.L. Shatokhin,
National Research Nuclear University (Moscow Engineering Physics Institute)
Moscow, Russia

Abstract

The report considers the interactive computer modeling of vacuum systems. Operation of real vacuum systems is modeled by simulating computer code. It is possible to assemble virtual installation, to choose the necessary pumps (from the database of low-vacuum and high-vacuum ones), to select the vacuum connecting pipes with the required parameters. The vacuum chamber volume and its internal surfaces characteristics (roughness, types of preliminary processing), defining outgassing from these surfaces are set.

INTRODUCTION

Vacuum Technique virtual laboratory is part of a complex of similar Electrophysics Laboratories, developed at the Department of Electrophysical Facilities (EF) of NRNU MEPhI. Computer modelling and simulation of individual components and entire electrophysical systems is a promising and in some cases the only possible way to replace the full-scale simulation. The creation of computer-based simulators is used in various fields of technology, including nuclear physics field (i.e. nuclear power reactors management simulators). The development of the set of laboratory exercises for Electrophysics solves the following tasks:
- acquire technology skills in assembly and maintenance of various subsystems and systems of EF (as simulator);
- to investigate the structure and the main characteristics of the EF devices and different modes of their work;
- gain experience in EF designing and master the methods of their calculation.

The vacuum system is an essential specialty of any accelerator. In this regard, the "Vacuum Technique" educational laboratory has existed since the founding of the Department of EF. Real vacuum systems of accelerators can have a very large extent, complex structure, and the procedure for their pumping (including heating of system) can take many days. Therefore, the development of computer workshop was a logical continuation of the vacuum practical work, significantly expanding its functionality.

VACUUM SYSTEMS MODELING THEORY

The simulation program algorithm is based on the following basic theoretical principles of vacuum technology [1, 2]. The number of gas molecules in the vacuum system is reducing by means of vacuum pumps, which create a volume flow Q, determined by the speed with which pressure p in the vacuum system of constant volume V decreases with time t:

$$Q = \frac{\mathrm{d}(pV)}{\mathrm{d}t} = V \cdot \frac{\mathrm{d}p}{\mathrm{d}t} \quad . \tag{1}$$

In reality, there is a lower limit of pressure below that pumping of the system is impossible - the ultimate residual pressure p_r. The amount of gas in the vacuum system depends on the ratio of gas flow entering the system - Q_{in} and pumping - Q_p: $Q = Q_p - Q_{in}$. The magnitude of the gas flow entering the system depends on the quality of manufacture of the vacuum system, that is, the values of leakage flow Q_l and outgassing flows Q_{gf} from inner surfaces. When the limit of the residual pressure in the vacuum system is reached mode is set to dynamic quasi-equilibrium: $Q_p = Q_{in}$. Pumped flow is equal $Q_p = Sp$, where S is pumping speed. Equation (1) takes the form:

$$p \cdot S - Q_l - Q_{gf} = V \cdot \frac{\mathrm{d}p}{\mathrm{d}t} \quad . \tag{2}$$

Thus $p_r = (Q_l + Q_{gf})/S$. The result of the solution of equation (2) for the total pressure will be the dependence:

$$p(t) = \frac{Q_\Sigma}{S} + \left(p_{st} - \frac{Q_\Sigma}{S} \right) \cdot \mathrm{e}^{-t/\tau} \quad ,$$

where $Q_\Sigma = Q_{gf} + Q_l$; p_{st} - initial pressure in the vacuum system, $\tau = V/S$. Similar dependences can be obtained for each partial gas component $p_i(t)$. Furthermore, the system pressure cannot be obtained under the pump ultimate pressure. In case of the continues pumping flow $Q = S_p p_p = S_{ef} p$, where S_p and p_p - the pumping speed and the pressure at the pump inlet, S_{ef} - effective pumping speed of the vacuum chamber. The presence of the connecting pipelines leads to the fact that between the vacuum pump and the vacuum chamber arises a pressure differential: $p - p_p = Q/U$, U - the pipeline conductivity. Thus, the pumping of the vacuum chamber is carried out with some S_{ef}, lower than S_p.

Considering these equations, we come to the pumping model determined by the ordinary differential equations with initial conditions (Cauchy problem). The solution to this problem has been realized by the Runge-Kutta method of fourth order.

VACUUM ELEMENTS MODELS

Each of the pumps designed to operate over a certain pressure range with approximately constant pumping speed - S_0. The ultimate pump pressure p_0 determined by

08 Magnetic and vacuum systems, power supplies

the balance between entering and going out gas flows of the pump. Magnitude of the going out flow can be approximately given in this form $Q_{out} = S_0 \cdot p_0$, thus $Q_p = S_0 \cdot p - S_0 \cdot p_0 = S_p \cdot p$. With pressure decrease in the inlet of the pump to a value p_0, pumping flow becomes zero. The dependence of the pumping speed from the inlet pressure expressed by the equation: $S_p = S_0(1 - p_0/p)$. Actual pumping speed dependence is much more complicated and can be found empirically, but this equation quite accurately describes this dependency and can be used in the calculations. The pumping speed at pressures in the pump inlet above the operating range depends on operation principle of the pump.

Calculation of parameters of pipelines is a separate task. Since the various vacuum components have a rather complicated internal geometrical shape, it is necessary to use Monte-Carlo method for calculation of the conductivity of such element in the molecular or viscose gas flow mode. In a simplified version, pipeline conductance in a wide range of pressures can be determined by the following formula (Knudsen equation): $U = U_v + K \cdot U_M$, where U_v and U_M - conductance in the viscous and molecular gas flow modes respectively; K - coefficient, depending of the pressure in the pipeline.

Leakage occurs in areas with inadequate tightness of the vacuum system. Leakage flow $Q_l = \sigma (p_a - p)$. Here σ - total conductance determining the aggregate bandwidth of all leaks. Valid leakage flow is considered a flow, in which is possible to obtain the desired pressure p in the system: $Q_l \leq p \cdot S$.

The level of initial outgassing rate q_0 and the total surface area A determine the flow rate from the inner surfaces of the vacuum chamber $Q_{gf} = A \cdot q_0 \cdot k \cdot \exp(-kt)$. Value of Q_0 depends on the material and the roughness of vacuum chamber surface. Degassing coefficient k is mainly acquired experimentally. It increases with rising temperature of the vacuum system, which leads to increase the outgassing rate and simultaneously to more rapid decay time $\sim \exp(-kt)$. Therefore, to accelerate the process of obtaining a high vacuum the temperature heating of the vacuum chamber is applied.

THE SOFTWARE STRUCTURE

Virtual laboratory software has a unified structure. In the present representation each software module of Electrophysics laboratory can be represented as interrelated functional blocks, which when necessary may be upgraded independently of each other. The most conservative components of the system (almost independent of the operating environment implementation, etc.) are the configuration file that defines the structure of the system and its mathematical description (mathematical model). All other components of the structure are highly dependent on the level of information technology and tools for their development.

Brief description of the main functional elements.

1) Graphical environment. In the graphic design of any software package that simulates electrophysical facilities and their individual subsystems can distinguish five basic elements:
- Data input element. Used to set the numerical values of a specific physical quantity.
- Graphs display element. The main function of this display is static or dynamic picture of the physical process.
- Elements reflecting an installation diagram.
- Reflection element help (HELP).
- Grouping elements to create pop-up windows, tabs or simply dividing lines.
2) The configuration file. Is a description of the components and their position in the formatted file as an XML document.
3) Mathematics module. Exchange protocol. Mathematical module is a separate executable file, which is called as a system call command.
4) The core is the basic infrastructure of the project, provides a coherent libraries and interfaces that defines communication protocols and the structure of the configuration files.

USER INTERFACE

The structure of the user interface is designed for all virtual laboratories by the same cathedral rules and determined by the main purpose of the laboratory. Assumes the solution of the following main tasks within this laboratory:
- study of the vacuum system and the influence of various factors and components on its characteristics;
- design of the vacuum system (in extracurricular time), its virtual assembly and check for compliance with the technical task.

Laboratories environment consists of two main (working) modules (the window) and a number of additional. The main working window (see Fig. 1) is given the structure of the vacuum system containing the necessary components to ensure high vacuum in the required volume and panels with setting of parameters of the pumping system. This window consist buttons that define the range of parameters of vacuum chamber and pumping unit (based on the manufacturers' data). The characteristics of pumped chamber (material, the quality of treatment of the inner surface, the initial level of surface outgassing) are entered.

When selecting vacuum pumps popup window represent their nomenclature and features. As a result of the choice of an industrial vacuum pump its parameters (ultimate pressure, pumping speed, inlet sizes) are recorded in the right pane of the window (see Fig. 1). Arbitrarily adjustable pump is selectable and its parameters can be varied within wide limits. The panel also contains pumping system parameters (pipelines), which are specified in the design of the vacuum system.
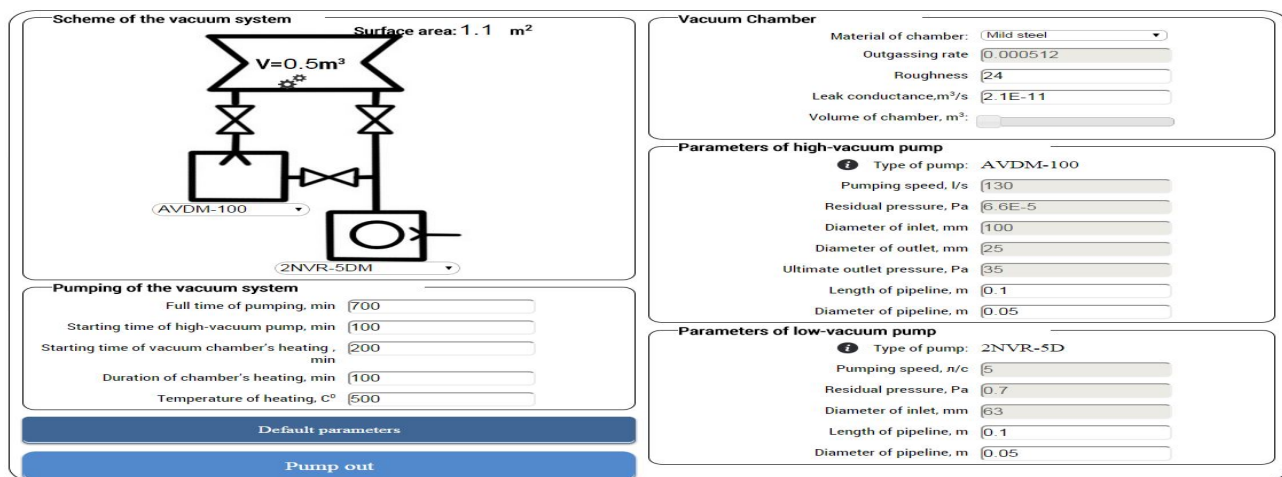
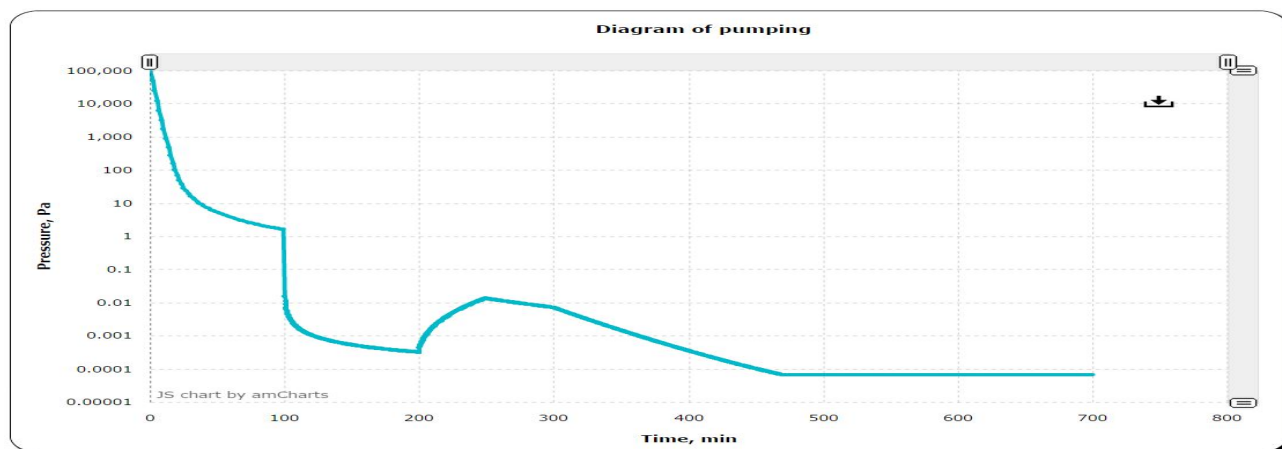Figure 1: Simulation of vacuum system parameters.

Figure 2: Dynamics of vacuum chamber pumping.

In the left pane of the main window (see Fig. 1) "pumping on" and the management of pumping process are performed. Here you set the timing diagram of pumping and all process total time. It's possible to select only preliminary pumping (low vacuum), or connect thermal degassing phase at high vacuum pumping.

The second working window displays the dynamics of the pumping process in time for given characteristics of the vacuum system (see Fig. 2). There is a possibility of a detailed study of the pumping process at different time stages. As a result of the analysis of the results an adjustment of the characteristics of the elements of the pumping system is performed to achieve the desired parameters.

Additional windows contain the traditional set of features of virtual laboratories - theoretical principles of developed topic, guidelines for carrying out the works, individual assignments, and tests for self-control.

CONCLUSION

Developed virtual environment provides a choice of means of pumping and traditional elements of vacuum systems, the choice of material of pumped volume, its pre-treatment, monitoring the process of pumping, registration, analysis of the data and making changes to complete system in order to obtain the desired results. It becomes possible in a short time (with the assessment of real-time) to pass through full cycle of the technologies to reach high vacuum state and to estimate the necessary time. Modeling of vacuum systems significantly expands the functional capabilities of vacuum laboratory.

REFERENCES

[1] L.N. Rozanov, *Vacuum Technique*, (Moscow: V. shkola, , 2007), 391.

[2] K. Demihov et al., *Vacuum Technology. Handbook*, (Moscow: Mashinostroenie, 2009), 590.