

MASS EXCHANGE IN THE HIGH-VACUUM SYSTEM OF CHAMBER—TEST OBJECT—PUMP ASSEMBLY

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Two types of problems on the determination of the local heat and mass exchange characteristics in high-vacuum systems of the chamber—object—pump assembly type are examined.

A high-vacuum system consists of a hermetic vessel, the chamber, within which the test object is located (Fig. 1). The chamber walls are made in the form of a collection of n cavities, cells of a certain geometry. The surfaces of the cells have mass and heat absorbing properties, achieved, for example, by means of a continuously coated, cooled ($T_w \leq 300^\circ\text{K}$) getter film. These surfaces can also have desorption properties simultaneously.

The concept of a quasi-surface, which connects the absorbing cell and the chamber and has important properties needed for the study of the characteristics of high-vacuum systems, was introduced in [1].

An evacuation system with a multielement structure is characteristic for a majority of large high-vacuum systems with cryosorption evacuation. In the particular case of $n = 1$ we obtain the trivial system with one externally located pump. The one-pump system is characteristic for the overwhelming majority of research on technological high-vacuum instruments.

Depending on its purpose the surface of the test object may have a different temperature, with $T_v > T_w$ as a rule, and it has desorption or sorption—desorption properties. The shape and geometry of the test object are quite variable. Examples of a cylindrical system as one of the most widespread combinations of the geometry of chamber—object systems, as well as an evacuation cell—evaporator, are shown in Fig. 1.

Thus, a high-vacuum system consists of a closed combination of desorbing, sorbing and quasi-surfaces which have different sorption—desorption and radiation properties and provide for the organized transfer of mass and radiation for the creation at the surface of the test object of the assigned density fields of molecular fluxes (partial pressures) and temperatures.

A method, based on the use of the fundamental concepts of the mathematical apparatus of the theory of radiation transport in a diathermal medium, is proposed* for the study of mass transport in a high-vacuum system in general form and in the similar form of [2].

In the present report the problem of mass exchange in a high-vacuum system in the presence of a test object is formulated and the solution of this problem is presented for different types of molecular particles. The basic mass transport equations and the basic characteristics of mass exchange in a high-vacuum system are obtained.

It is shown in [1], taking into account certain results of the theory of radiant heat exchange [3], that in a closed high-vacuum system the processes of mass exchange are described with sufficient accuracy by a system of linear integral equations

$$\tilde{M}_c(P_i) - \sum_{j=1}^n R_j \int_{F_j} \tilde{M}_c(N_j) K(P_i, N_j) dF_{N_j} = \tilde{M}_\alpha(P_i), \quad (1)$$

*The method was first presented at the Third All-Union Conference on the Physics and Technology of High Vacuum, Leningrad, October 5-7, 1971.

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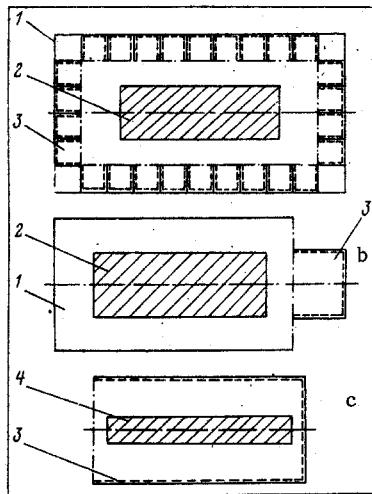


Fig. 1

Fig. 1. Schematic diagrams of high-vacuum systems and their elements; a) pump assembly with multielement structure; b) pump assembly with one vacuum pump; c) system of evacuation cell-evaporator; 1) chamber; 2) test object; 3) evacuation cell with sorbing walls; 4) evaporator of getter particles; solid lines: desorbing surfaces; dashed lines: sorbing surfaces; dash-dot lines: quasi-surfaces.

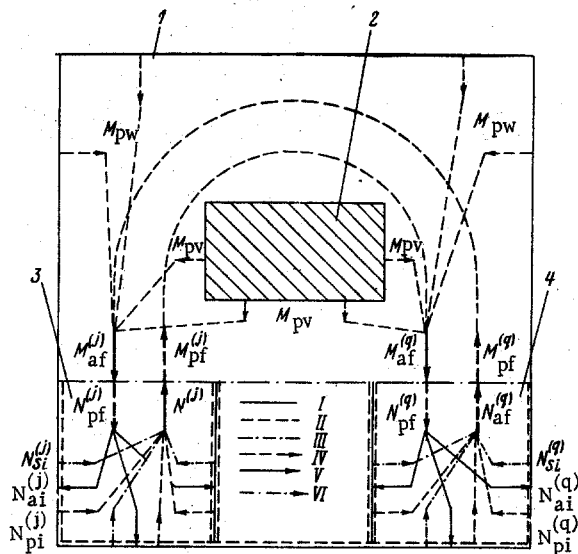


Fig. 2

Fig. 2. Model of interaction of molecular fluxes with surfaces of high-vacuum system: 1) chamber; 2) test object; 3) j-th evacuation cell; 4) q-th evacuation cell; I) desorbing surfaces; II) sorbing surfaces; III) quasi-surfaces; IV) proper (generating) molecular fluxes; V) incident molecular fluxes; VI) reflected molecular fluxes.

where

$$\tilde{M}_\alpha(P_i) = \begin{cases} -\tilde{M}(P_i), & R_i = 1, \delta_i = 0, \\ \tilde{M}_p(P_i), & R_i = 1 - \alpha_m, \delta_i = 0. \end{cases} \quad (2)$$

The coefficient of accommodation α_m is determined differently depending on the specific physical process: for gas particles $\alpha_m = \mu$ (the sticking probability) and for condensing (vapor) particles $\alpha_m = \alpha_c$ (the condensation coefficient). For the quasi-surfaces $\delta_f = 1$, $\alpha_{mf} = 0$, $R_f = 0$.

Two basic formulations of the problem are studied for the analysis of mass exchange in a high-vacuum system:

- 1) a fundamental formulation where the densities of only the proper molecular fluxes are given at all the real sorption and desorption surfaces and at the quasi-surfaces of the system;
- 2) a mixed formulation where the densities of the proper molecular fluxes are given for some of the surfaces of the system and the densities of the net molecular fluxes are given for the other surfaces; a particular case of this formulation is the problem where the densities of the proper fluxes are given at the real surfaces and the densities of the net fluxes are given at the quasi-surfaces.

The solution of both problems makes it possible to determine the local and average values of the densities of the incident, reflected, and absorbed molecular fluxes at the real surfaces of the system, the densities of the incident and net fluxes at the quasi-surfaces, and the local and average characteristics of the pressure field at the surfaces of the object and chamber.

Both formulations of the problem of mass exchange make it possible to study analytically the vacuum characteristics both of a system as a whole and of its separate elements (chamber, evacuation cells, etc.).

It is more convenient to solve the fundamental formulation of the problem in the design of high-vacuum systems. In experimental studies of the characteristics of a system and in the theoretical analysis and calculations of the characteristics of its separate elements it is more practical to use the mixed formulation of the problem.

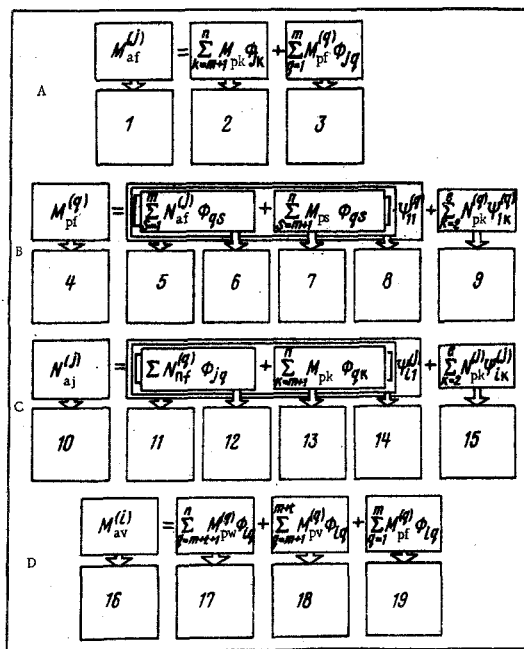


Fig. 3. Phenomenological diagram of interaction of molecular fluxes with surfaces of chamber—object—pump assembly system with allowance for multiple reflections: A) flux incident on quasi-surface of evacuation cell; B) return flux from evacuation cell; C) flux incident on sorbing surface of evacuation cell; D) flux incident on surface of object; 1) density of total incident molecular flux at quasi-surface of j -th cell; 2, 3) density of molecular flux at quasi-surface of j -th cell from all real surfaces of system and from all quasi-surfaces of system, respectively; 4) density of proper molecular flux from quasi-surface of q -th cell into chamber volume; 5) flux density of particles not absorbed by q -th cell and returning again to its quasi-surface; 6, 7) flux density of particles from quasi-surfaces of system and from all real surfaces of system which are not absorbed by q -th cell; 8) total flux density of particles not absorbed by q -th cell; 9) flux density of particles from real surfaces of q -th cell incident on quasi-surface of q -th cell; 10) density of total incident molecular flux on i -th sorbing surface in j -th cell; 11) density of incident flux on i -th sorbing surface of j -th cell from its quasi-surface; 12, 13, 14) flux densities at quasi-surface of j -th cell from other quasi-surfaces, from real surfaces of system, and from all surfaces of system, respectively; 15) flux density at i -th sorbing surface of j -th cell from real surfaces of j -th cell; 16) density of total molecular flux incident on i -th surface of object; 17, 18, 19) flux densities at i -th surface of object from real surfaces of chamber, from other surfaces of object, and from quasi-surfaces of chamber, respectively.

For the unambiguous determination of molecular fluxes let us introduce the continuity condition at the quasi-surfaces in the form of the following equations for the net fluxes:

$$M_{nf}(P_i) = -N_{nf}(P_i) \quad (3)$$

or, which is the same thing,

$$M_{af}(P_i) = N_{pf}(P_i), \quad (4)$$

$$M_{pf}(P_i) = N_{af}(P_i), \quad (5)$$

i. e., the density of the incident flux at a quasi-surface from the volume of one element of the vacuum system (such as the chamber) represents the density of the proper flux for the same quasi-surface into the volume of another element of the system (such as a cell) and vice versa.

The solution of the general problem of mass exchange for a high-vacuum system comes down to the determination of the densities of the incident molecular fluxes at the quasi-surface coming from the elements of the system and is accomplished by the successive completion of several stages, with the fluxes of similar sorbing and condensing particles being considered separately. Several characteristic properties can be distinguished in the chamber-object system:

- a) the system is multizonal;
- b) the number of zones is determined by the number of real surfaces and the number of quasi-surfaces entering into the system;
- c) partial or total shading of the separate zones occurs.

We can determine the molecular flux at the quasi-surface of a cell in the chamber-object system in the form [1]

$$M_{af}(P_i) = M_{ef}(P_i) - M_{pf}(P_i) = \sum_{k=1}^n M_{pk} \Phi(P_i, F_k). \quad (6)$$

The resolving local angular transport coefficients $\Phi(P_i, F_k)$ are determined by the well-known method of [3]. Here it must be noted that the coefficients $M_{p,k}$ which pertain to the quasi-surfaces of the system are not known and are subject to subsequent determination based on the conditions of continuity (3).

The process of exchange of the condensing mass between the chamber walls and the surface of the object is also described by the system of integral equations (1) with allowance for the fact that the condensation coefficient for an overwhelming majority of vapors at wall temperatures of $T_w \leq 300^\circ\text{K}$ is close (or equal) to unity, i. e., multiple reflections of particles from the surfaces are practically absent.

Under these conditions the solution of the problem for the flux of condensing particles at a quasi-surface has the form

$$Q_{af}(P_i) = \sum_{j=1}^n Q_{jp} \varphi(P_i, F_j) \quad (i = 1, 2, \dots, n). \quad (7)$$

If the flux of condensing particles from the surface of the object is absent or is negligibly small the corresponding terms in (7) are reduced to zero.

The process of mass exchange in an arbitrary absorbing cell is also described by the system of equations (1). The solution of the problem of determining the density of the incident flux of sorbing particles at the quasi-surface of the j -th cell has the form

$$N_{af}^{(j)}(P_i) = \sum_{k=1}^l N_{pk}^{(j)} \Psi^{(j)}(P_i, F_k) \quad (i = 1, 2, \dots, l). \quad (8)$$

We assume that the zones in the cell are counted starting from the quasi-surface having the first number. Then the condition (5) is written as follows:

$$M_{af}(P_j) = N_{pf}^{(j)}(P_1), \quad (9)$$

$$M_{pf}(P_j) = N_{af}^{(j)}(P_1) \quad (j = 1, 2, \dots, m).$$

As applied to the given cell the solution of the problem for the condensing particles has the form

$$G_{af}^{(j)}(P_i) = \sum_{k=1}^l G_{pk}^{(j)} \psi(P_i, F_k) \quad (i = 1, 2, \dots, l). \quad (10)$$

With allowance for the one-sided direction of motion of the getter particles through the quasi-surface the condition (9) is written in the following form:

$$G_{af}^{(j)}(P_1) = G_{pf}(P_j). \quad (11)$$

For the condensing particles from the chamber the condition of fitting is analogous to (9).

To derive the calculating equations of mass transfer in the chamber-object-pump assembly system it is necessary to fit the solutions obtained in (6)-(10) on the basis of (5).

We carry out the fitting of the solutions in the average form based on the conditions of congruence of the resulting fluxes at the boundary of separation of the chamber-cell system, i. e., at the quasi-surface. A model of the interaction of the molecular fluxes in the system is shown in Fig. 2 and a phenomenological and analytical representation of the interacting fluxes in the chamber-object-pump assembly system is shown in Fig. 3.

The density of the proper flux from the quasi-surface of the q-th cell with allowance for the mass emission of all the real surfaces of the chamber-cell system and for multiple reflections can be determined, using the equations indicated above, in the form

$$M_{pf}^{(q)} - \sum_{s=1}^m M_{pf}^{(s)} \Phi_{qs} \Psi_{11}^{(q)} = S_q \quad (q = 1, 2, \dots, m), \quad (12)$$

where

$$S_q = \sum_{s=m+1}^n M_{ps}^{(s)} \Phi_{q,s}^{(q)} \Psi_{11}^{(q)} + \sum_{k=2}^l N_{pk}^{(q)} \Psi_{1k}^{(q)}. \quad (13)$$

The matrix of the system of equations obtained is nondegenerate since its determinant is not equal to zero.

Substituting the solution of the system of equations (12) into (6) we obtain the incident flux density at the quasi-surface of the j-th cell with allowance for the mass emission of all the surfaces of the system and for multiple reflections of particles in it. The coefficients lacking in Eq. (8) are determined analogously.

NOTATION

$\tilde{M}(P)$	is the density of molecular fluxes in system;
$M(P), N(P)$	are the densities of molecular fluxes in chamber and evacuation cell;
$Q(P), G(P)$	are the flux densities of condensing particles in chamber and evacuation cell;
$\Phi(P_i, F_c), \Psi(P_i, F_c)$	are the resolving local angular transfer coefficients in chamber-object system and in evacuation cell;
$\varphi(P_i, F_c), \psi(P_i, F_c)$	are the geometrical local angular transfer coefficients in chamber-object system and in evacuation cell;
n	is the number of zones in system;
m	is the number of quasi-surfaces in system;
l	is the number of surfaces in evacuation cell;
δ	is the transmitting capacity.

Subscripts

a	denotes the incident;
e	denotes the effective;
n	denotes the net;
p	denotes the proper;
f	denotes the quasi-surface;
v	denotes the test object;
w	denotes the chamber.

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