ᲡᲐᲥᲐᲠᲗᲕᲔᲚᲝᲡ ᲛᲔᲪᲜᲘᲔᲠᲔᲑᲐᲗᲐ ᲔᲠᲝᲕᲜᲣᲚᲘ ᲐᲙᲐᲓᲔᲛᲘᲘᲡ ᲛᲝᲐᲛᲑᲔ, ტ. 3, №3, 2009
BULLETIN OF THE GEORGIAN NATIONAL ACADEMY OF SCIENCES, vol. 3, no. 3, 2009

*Physics*

# Thermophysical Calculation of Cryosorption Pumps

**Guram Dgebuadze*, Leri Tsakadze***

* *I. Vekua Sukhumi Institute of Physics and Technology*

(Presented by Academy Member M. Salukvadze)

**ABSTRACT. A physico-mathematical model of the process of evacuation by means of a cryosorption pump CSP-0.25D is developed. It includes modeling of exchange processes in heat removing elements and adsorption space, mass-exchange processes in the grains of the adsorbent and molecular flows in the canals of the pump.** © *2009 Bull. Georg. Natl. Acad. Sci.*

***Key words***: *cryopump, cryocondenser, adsorption cavity, nitrogen vessel, temperature field.*

For a number of years the work has been conducted in Sukhumi Physico-Technical Institute on the creation of cryogen means of evacuation to obtain and maintain high and super-pure vacuum in experimental radio-physical plants [1, 2].

On the basis of thermophysical calculations, a new model of a cryosorption pump (CSP-0.25D) with cooling agent liquid nitrogen ($LN_2$), in which technical solutions allowing to improve exploitation characteristics of the pump has been created, cryocondenser of a new construction for effective evacuation of water vapours and hydrogen dioxide, also new type of thermal protection of adsorption layers with optically not transparent porous materials are offered. Such structures are able not only to screen adsorbent safely from radiation, but also to protect it from contamination with light-condensed vapours in both viscous and molecular regimes of flowing. Besides, a thick screen prevents penetration of adsorbent dust formed in the process of exploitation into the pumping vacuum, thereby providing high "purity" of the created vacuum. In the final analysis, in basic construction, due to safe protection of the adsorbent from thermal inflows and poisoning substances, low pressure of the residual gas ($10^{-5}$ Pa) will be reached, and which is most important, the life time of the pump will be increased up to 4 months.

Long-term reliability of CSP-0.25D essentially depends on the choice of construction materials. Various physical mechanical and technological properties are juxtaposed with account of pump work. Special demands are set to construction materials as to their temperature coefficients of linear and volumetric expansion, heat conductivity and heat capacity. The lower the value of the coefficient of linear expansion, the easier to ensure heat compensation of the pump construction and in order to ensure minimal heat flows to cryosurfaces over heat bridges the metal should have small heat conductivity $\lambda$ in combination with high strength of $\sigma_b$, i.e. the value of $\lambda/\sigma_b$ must be low.

Taking into account the peculiarity of construction CSP-0.25D (construction exposed to heat cycling) cryomaterials must possess (except the nitrogen vessel) minimal heat capacity. Austenite chromo-nickel steel, 12X18H10T grade, meets all the above-mentioned requirements due to technologically proved economical efficiency and accessibility. This material is used to make the body of the pump, upper cover, bottom, pipe-hangers, branch-pipes and connecting flanges. Aluminium alloys less strong than stainless steel are widely used in cryogen technique due to their good conductivity, reliability and corrosion resistance. Alloys of AD1-H grade are well-deformed, welded, satisfy all the technological requirements in construction of CSP and are used in making a conic cryocondenser.

Besides the above-mentioned materials an important place in construction of CSP-0.25D is held by copper of M0 and M1 grade. The peculiarities of M0 and M1 are high thermoconductivity and heat capacity, which is important for cooling the sorbents. Copper of M0 and M1 grade welds fairly well vacuum-densely, deformed, plastic and can sustain multipte thermocycling. In the pump copper of these grades is used to make the nitrogen vessel, porous screen and thermoconductive inserts.

## Construction of cryosorption pump.

The proposed cryosorption pump CSP-0.25D has thin-wall construction of cylinder form (Fig.1). The pump is intended for creation and keeping of high vacuum ($10^{-5}$ Pa) in hermetically sealed chambers with volume up to 1 $m^3$, primarily evacuated with any ancillary pump to pressure 10 Pa. As all the other adsorption pumps working at nitrogen temperatures, CSP-0.25D is not intended for evacuation of neon, hydrogen and helium.

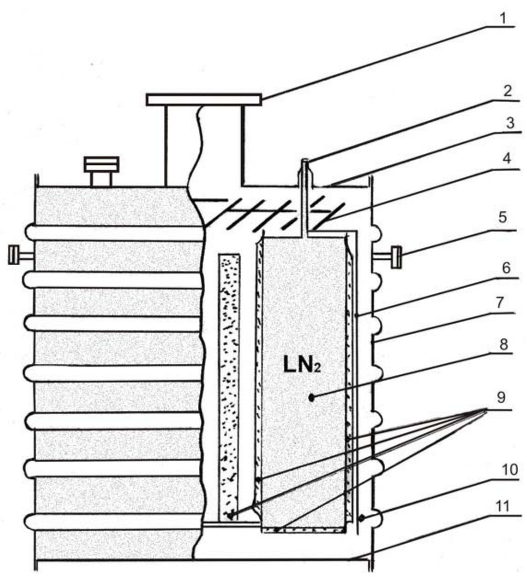


Fig. 1. General view of the cryosorption pump CSP-0.25D
1. Inlet pipe with flange; 2. Tubes for liquid nitrogen filling and vapour evacuation; 3. Pump cover; 4. Cryocondenser; 5. Technological flanges with pipes; 6. Radiation screen; 7. Body of the pump; 8. Liquid nitrogen vessel; 9. Evacuation elements; 10. Vacuum space; 11. Bottom of the pump.

## Physico-mathematical model of the cryosorption pump.

Physical model of the processes taking place in the pump's elements is constructed for the cases of evacuation of pure gases ($N_2$, Ar, CO, $O_2$ and others) or vapours ($H_2O$, $CO_2$ and others).

The model of heat exchange in cryopump is designed for stationary regime with constant gas loading on inlet. It considers molecular regime of gas flow with account of diffusion reflection from hard canal boundaries with constant coefficients of adhesion of gases and vapours on cryosorption surfaces. Adsorption processes in the model are described for quasistationary regime .

## Temperature field of cryocondenser

Cryocondenser is intended for entrapment of easily-condensed vapours ($H_2O$, $CO_2$ … etc.) entering the pump from the evacuated volume. The surface of the cryocondenser is blackened due to which it absorbs radiation entering the pump from the inlet hole. By means of this it decreases heat loading on heat protective screens. To make the molecules desublimate easily on the surface of cryocondenser, its temperature should be close to the temperature of liquid nitrogen. That is why the cryocondenser is in a good thermal contact with the cover of the nitrogen vessel and the cryocondenser is made of material of high heat conductivity.

To evaluate the temperature drops along the generating lines of the cones of cryocondenser the following assumptions were adopted:

1. Mutual radiation of conic surfaces can be ignored compared with the radiation of the inlet hole (average temperature of cryocondenser ~100K, while equivalent of the inlet hole ~300K, i.e. $T_0^4 >> T^4_{cr.c.}$);
2. All the radiation energy, entering the pump from the inlet hole uniformly is distributed on the surfaces of the cones;
3. Vapour flow (we shall call vapour all substances, for which $T_{triple} > T_{N2}$) uniformly desublimates on the surface of cryocondenser. In the case of gas all the heat released when cooling is also uniformly distributed on the surface of cryocondenser.

With the adopted assumptions the equation of the heat balance for the element of cryocondenser (Fig. 2) will be as follows:

$$Q(z)+(W+W_{rad})/F_{cr.c}2\pi\, dz \sin\alpha - Q(z+dz) = 0, \quad (1)$$

where Q(z), Q(z+dz) are quantities of heat entering from outside per unit of time (Watt), W – power of heat release at desublimation of vapour or gas cooling (Watt), $W_{rad}$ – power of radiation from inlet hole (Watt), $F_{cr.c}$ – area of the surface of cryocondenser ($m^2$).

In the case of gas:

$$W=C_p m_{mass}(T_0-T_{N2}), \quad (2)$$

where $C_p$ is average specific heat capacity of gases (J/gK), $M_{mass}$ – mass flow of the evacuated gas g/s, $T_0$ – absolute temperature (K), $T_{N2}$ – temperature of liquid nitrogen (K).

In the case of vapour:

$$W=C_p m_{mass}(T_0-T_{sub1})+m_{mass}W_{sub1}+C_{cond}m_{mass}(T_{sub1}-T_{N2}),(3)$$

where $C_p$ is average specific heat of vapours (J/gK), $T_{sub1}$ – sublimation temperature (K), $W_{sub1}$ – specific heat of sublimation (J/gK), $C_{cond}$ – average specific heat in the condensed state (J/gk).

Radiation power from the inlet hole is equal to

$$W_{rad}=\sigma T^4 F_0, \quad (4)$$

where $\sigma$ = 5.77 $10^{-8}$ W/($K^4 m^2$) is Stephen-Boltzmann constant; $F_0$ – area of the inlet hole surface with temperature T, ($m^2$).

The value of heat flow, entering the pump from the inlet hole makes

$$W_1=W+W_{rad}, \quad (5)$$

where W in the case of vapour is defined by formula (2), and for gas by formula (3).

## Temperature field in heat removing and heat shielding elements of pump.

Effective work of adsorption pump is possible only under condition of good cooling of adsorbent, for which it is necessary to provide good adsorption of heat removal, released in the space, and safe screening of the layers from heat radiation. In the developed construction heat removal and heat shielding of adsorption layers are done optically by not transparent porous screens made of high thermoconductive material (copper M0, M1). To define the temperature field in heat removing and heat shielding elements we shall use a differential equation of heat conductivity with internal heat release [3]:

$$d^2T/dx^2+q_v/\lambda=0, \quad (6)$$

where $q_v$ is heat released per unit of the element's volume ($W/m^3$).

Solution of the equation (6) at constant $q_v$ has the form:

$$T(x)=- q_v/2\,\lambda x^2+C_1x+C_2. \quad (7)$$

The values of the constants $C_1$ and $C_2$ are defined from the boundary conditions. Thus, the ends of the 1st screen are in thermal contact with the nitrogen vessel, that is why $T(x=0)=T_{N2}$ and $T(x=H_{scr})=T_{N2}$. Besides, for the 1st screen

$$q_v=1/\,\delta_{scr}\,F_{scr}\,[W_z + W_{ads}\,m_{mass}/2V_{ads}V_{ads}], \quad (8)$$

where $\lambda_{scr}$ and $H_{scr}$ are thickness and height of the screen, respectively (m); $F_{scr}$ – area of the surface of heat shield ($m^2$); $W_z$ – heat flow (Watt); $W_{ads}$ – heat flow of the adsorbent (Watt); $V_{ads}$ – volume of the adsorption space ($m^3$).

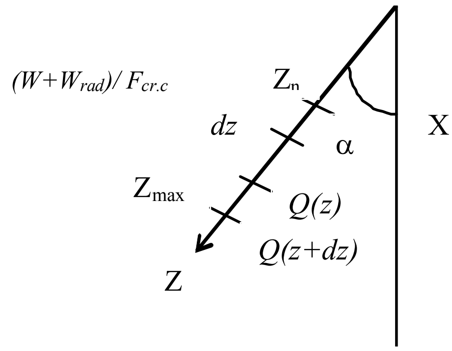

Fig. 2. The scheme of heat flows in the elements of cryocondenser

Coefficient of symmetry ½ in the addend in brackets takes into account the fact that half of the heat released in the 1st adsorption cavity flows to the screen (the second half flows to the nitrogen vessel). Having defined the values $C_1$ and $C_2$ from the above-mentioned conditions for temperature field in the 1st screen we get the correlation:

$$T(x)=- q_v x^2/2\lambda +q_vH_{scr1}x/2\lambda +T_{N2}. \quad (9)$$

The maximal value at the given parabolic law of temperature distribution is reached at the point $X= H_{scr}/2$ (in the middle of the screen):

$$T_{max.scr} = T_{N2}+q_vH^2_{scr}/8\lambda. \quad (10)$$

Analogously, we can find temperature distribution along the other screens, also for diaphragm and insert. The difference is only in the values $q_v$ and the boundary conditions.

## Temperature field in adsorption space

The parameters of the temperature field in the adsorption space strongly influence the vacuum characteristics of the adsorption pumps. They, in turn, depend on thermophysical properties and forms of the grains. In the layers of grained adsorbents heat exchange is effected by heat radiation contact and molecular heat conductivity of the residual gas. In high vacuum area the mentioned mechanism of heat exchange can be ignored. Besides, due to poor thermal contact between grains and nonmetallic adsorbents contact heat conductivity can be ignored as well. Thus we can conclude that in the layers of grained adsorbents the dominating mechanism of heat exchange is radiant heat transfer; moreover, because of high level of blackening (for carbon adsorbents $\varepsilon > 0.9$) grain filling is characterized by a low coefficient of radiant energy attenuation.

Proceeding from the above-mentioned, adsorption space can be presented as a multilayer system [4], in which the number of layer-screens is equal to $n_{layer}=\delta_{ads}/R_{grain}$. The distance between the screens is taken to be equal to average size of the grain, and taking into account radiation properties, the level of blackening of screen layers is equal to one. Besides small thickness of the adsorption space compared with its diameter allows to consider the screen layer flat.

Assuming that evacuated gas is uniformly absorbed with all adsorption capacity, heat balance in stationary regime of work in the *i*-th screen-layer can be expressed in the following form:

$$Q_{layer}+ Q_{i-1\to i}+ Q_{i+1\to i} =0, \quad (11)$$

where heat release in *i*-th layer of $j^{th}$ adsorption screen equals:

$$Q_{layer}=W_{ads}m_{mas}V_{ads}/V_{ads}n_{layer}, \quad (12)$$

where $n_{layer}$ is a number of layers.

Inserting the values of $Q_{i-1\to i}$ and $Q_{i+1\to i}$ into (11), we obtain the equation:

$$Q_{layer}+\sigma F_{layer}(T^4_{i-1}-T^4_i)+ \sigma F_{layer}(T^4_{i+1}-T^4_i)=0. \quad (13)$$

As the calculations show the total value of heat inflows makes 33.4W, while the main part of heat radiation power comes from the inlet hall (8.3W) and side surface (17.2W). The first of these components is mainly absorbed by blackened cryocondenser and maximal temperature drop in this element does not exceed 0.5K. Such high level of isothermality of cryocondenser is provided by good heat conductivity of the material and enough thickness of the plates. Heat radiation from the side surface is accepted as heat-shield surrounding the first (the most capacious) adsorption space according to calculations, parabolic temperature distribution with maximum in the centre of the screen is established along the screen, reaching 80.5K. Thus, average temperature of the screen differs from the nitrogen by 1.5-2K that points to high effectiveness of the applied in the pump scheme of heat protection of adsorbent.

From the above values of the power of heat inflows we see that its value mainly influences on the discharge of liquid nitrogen, at the same time almost not distorting the constant temperature field in the heat shield elements. The quantity of liquid nitrogen, used by the pump in the process of work is chief energy index of the

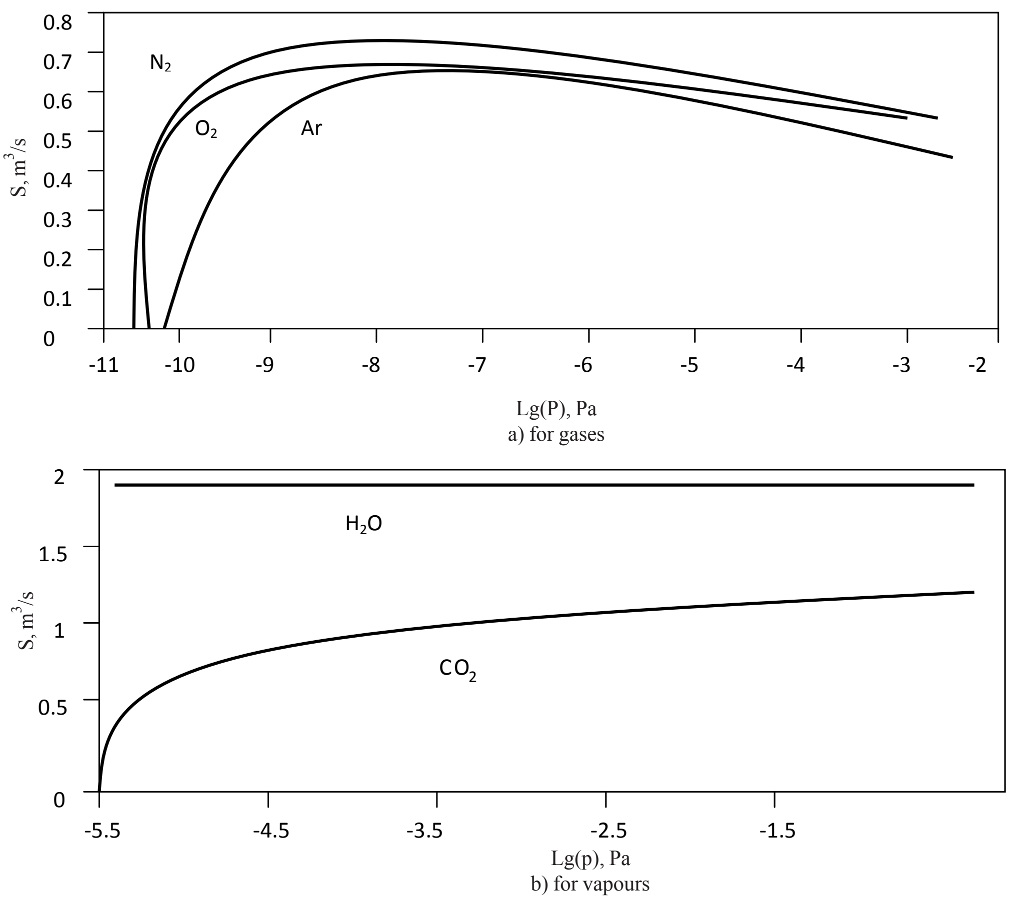


Fig. 3. Pumping speed dependence action on pressure

plant and is fully determined by the value of heat inflows.

In Fig. 3 the main characteristic of the cryosorption pump CSD-0.25D, obtained by means of calculation – dependence of action speed on pressure at the inlet - is presented. As is see from the diagram the speed of the pump's action in the high vacuum area with respect to gases equals 0.6-0.7 $m^3/s$. Note that for adsorption pipes the dependence S=S(P) is not constant and the diagrams in Fig. 3a correspond to the starting period of evacuation. In the course of time, due to the absorption of new portions of gas (implying that the pump is constantly loaded with gas flow) the pressure in the chamber will fall, i.e. the diagrams in Fig. 3a will shift to the right.

The work was supported by the Project GNSF/ST08/4-417.

*ფიზიკა*

# კრიოსორბციული ტუმბოების თბოფიზიკური გაანგარიშება

## გ. დგებუაძე*, ლ. წაქაძე*

** ი. ვეკუას სოხუმის ფიზიკა-ტექნიკის ინსტიტუტი*

(წარმოდგენილია აკადემიკოს მ. სალუქვაძის მიერ)

**ნაშრომში მოყვანილია კრიოსორბციული ტუმბოს CSP-0.25D ამოტუმბვის პროცესის ფიზიკა-მათემატიკური მოდელი. ის შეიცავს თბოარინების ელემენტებსა და ადსორბციულ სიღრუეებში თბოგადაცემის პროცესების, ადსორბენტის მარცვლებში მასური გაცვლისა და ტუმბოს არხებში მოლეკულური დინებების მოდელირებას.**

## REFERENCES

1. *G.N. Dgebuadze*, Bulletin of the Georgian Academy of Sciences, v.158, No.3, 190-192p., 1998.
2. *G.N. Dgebuadze*, High Performance Cryosorption Pump. Cold Facts, The Magazine of the Cryogenic Society of America, Inc., v.15, No.3, Pages 8, 9, 28, Summer 1999.
3. *F. Krate, U. Black* (1983), Osnovy teploperedachi. M., 210 p. (in Russian).
4. *S.S. Filimonov, B.A. Khrustalev, U.M. Mazilin* (1990), Teploobmen v mnogosloinykh i poristykh teploizolyatsiyakh. M., 184 p. (in Russian).

*Received June, 2009*