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CONTINUOUS ADSORPTION PUMPING

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Absorption pumping is a technical usage of high adsorptivity of some materials such as activated charcoal, silica gel etc.<sup>1</sup> It looks like attractive for experimental situation when it is desirable to avoid injurious effects of conventional pumps<sup>2-4</sup>. Nevertheless, to date, adsorption pumps have not been widely spread in cryogenic technique because of their low realized capacity. The reason is the following.

A scheme of adsorption pumping out suggests two different regimes: isothermal adsorption under temperature  $T_1$  and adsorbent regeneration stage under temperature  $T_2$ . In order to get a suitable "efficiency" of a pump, one tries to enlarge the amount of gas adsorbed during the cycle by increasing both the total mass of adsorbent and the difference  $T_2 - T_1$  which, together with the traditional method of adsorbent heating, increase the necessary time of the operating cycle.

The aim of the present paper is to discuss another approach to the problem based on a new design idea. The approach will be preliminarily formulated, and then a scheme of an "adsorption unit" will be described. To generalize the description, the thermodynamic consideration is to be done. Numerical examples will demonstrate that the obtained analytical expressions can be used as working formulas for calculating the parameters of a continuous adsorption pump.

## Design concept

The continuous adsorption pump (CAP) is suggested to operate with respect to a closed cycle which consists of two isotherms  $T_1$  and  $T_2$  and two isosteres. The working region of each isotherm is that of a maximum slope, the difference  $T_2 - T_1$  being as small as possible. A relatively small amount of adsorbent can be heated by the method excluding the possibility of direct influence on the coolant so that there is no necessity of complete removal of the water. Realization of CAP permits one to obtain fast-acting pumping out facilities.

## Adsorption unit

Let adsorbent (Fig. 1) be glued on an outer surface of a metallic vessel filled with coolant 2. A hermetic volume A is equipped with inlet 3 and outlet 4 valves. The electromagnetic field, exerted inside A, has a maximum of electrical component on the spot of adsorbent 1. The operating closed cycle (Fig. 2) consists of two isotherms 1-2, 3-4 and two isosteres 2-3, 4-1. Point 1 characterizes the adsorbent state of the lowest pressure and the least amount of adsorbed gas. If valve 4 is closed and 3 is opened, the gas comes from the evacuating volume, the state of the adsorbent being changed along the isotherm 1-2. At the point 2 the valve is closed and the electromagnetic field exerted in A (Fig. 1) heats the adsorbent. At the end

of stroke 2-3 the adsorbent is transitted to state 3, the point belonging to the other isotherm. During stroke 3-4 valve 4 is opened and the desorbed gas is evacuated by an outer pump. At point 4 the electromagnetic heating is off and both valves are closed, the state of the adsorbent being changed along 4-1. What is above called CAP is a combination of four units with different strokes carried out at the same time.

The nitrogen adsorption isotherms for charcoal presented in *Figure 2* are calculated on the basis of the appropriate theory confirmed by experimental data <sup>1</sup>.

## Calculations

Let the adsorbent be spread homogeneously enough over surface 1 so that its mass per unit square  $m$  and the depth of layer  $l$  are assumed to be constant. Below the other parameters of the adsorbent such as heat conductivity  $\lambda$  and specific heat capacity  $c$  are suggested to be known.

The total heat flow  $W(t)$  to the adsorbent changes its temperature  $T$  and partly transits to the coolant at the temperature  $T_c$ , thence the heat balance equation is given by

$$Tmc + (T - T_c)\lambda/l = W(t), \quad (1)$$

where  $W(t) = W_h + W_a$ , i.e. it consists of two parts connected with the electromagnetic heating of the adsorbent and the heat of adsorption, respectively.

The specific heat of adsorption  $q$  is usually calculated with the help of the Clapeyron-Clausius equation

$$q = T(v'' - v') \frac{dP}{dT}, \quad (2)$$

where  $v''$ ,  $v'$  are the molar volumes occupied by the molecules of the gas and adsorbed phases, respectively; the derivative of pressure  $P$  with respect to the temperature  $T$  being calculated along the phase equilibrium curve. In the case under consideration  $v'' \gg v'$  and by changing the variables Eq.(2) is transformed to a formula for calculations given by

$$q = -Tv'' \left( \frac{\partial V}{\partial T} \right)_P / \left( \frac{\partial V}{\partial P} \right)_T \quad (3)$$

Numerical values of the partial derivatives of an adsorbant's volume  $V(P, T)$  can be found out from the family of adsorption isotherms, the latter being general experimental information satisfactorily described by the theory.

For  $W_a$  one can write down the following

$$W_a = \dot{Q}_a = qm\dot{a} + \dot{q}ma, \quad (4)$$

where  $a$  is the number of moles of the adsorbant per mass unit of the adsorbent (see *Figure 2*). As can be shown,  $\dot{q} = 0$  for the isotherms presented in *Figure 2*. For steady isothermal process 3-1 it is easy to obtain from Eq.(1)

$$T = T_0 + (W_h - q_2 ma / t_s) / \lambda \quad (5)$$

and the same for 1-2

$$T = T_0 + (q_1 ma / t_s) / \lambda \quad (6)$$

where  $t_s$  is the time of the stroke and  $q_1, q_2$  are calculated from Eq.(3) for the corresponding isotherm. The equation for the 2-3 and 1-1 strokes is nonlinear in the general case. But when  $q(T)$  is a continuous function inside the region under consideration, there is the opportunity to simplify the task. The approximate equation is given by

$$T(mc + \alpha) + T(\lambda l + \beta) = W_h + T_0 \lambda / l \quad (7)$$

where

$$\alpha = ma(q_1 / T_1 + q_2 / T_2) / 2 \text{ and } \beta = ma(q_2 / T_2 - q_1 / T_1) / t_s.$$

At last the solution of Eq.(7) is expressed as

$$T = \frac{W_h + T_0 \lambda / l}{\lambda / l + \beta} (1 - e^{-\theta t}) + T_0 e^{-\theta t} \quad (8)$$

where  $\theta = (mc + \alpha) / (\lambda l + \beta)$  and  $T_0$  is the temperature of the adsorbent at the beginning of the stroke.

## Numerical examples

For numerical calculations the used reference data are the following

$\lambda_s$ (W cm <sup>-1</sup> K <sup>-1</sup> )	0.03	$q_1$ (J mol <sup>-1</sup> )	7 060
$\lambda_g$ (W cm <sup>-1</sup> K <sup>-1</sup> )	0.28	$q_2$ (J mol <sup>-1</sup> )	14 500
$c$ (J g <sup>-1</sup> K <sup>-1</sup> )	0.14	$\rho$ (g cm <sup>-3</sup> )	0.5

Two limiting quantities  $\lambda_s$  and  $\lambda_g$  are used to take into account different qualities of a heat contact between the adsorbent and the coolant. According to this, the results of the numerical calculations are divided into two groups: the first eight lines of *Table* present the data obtained with  $\lambda_s$  and the lower eight ones are for the data with  $\lambda_g$ . Inside every group four upper and four lower lines show the results obtained with  $m = 0.25$  g cm<sup>-2</sup> and  $m = 0.5$  g cm<sup>-2</sup>, respectively. The specific adsorption heats

for two isotherms are figured by the above-mentioned method;  $\rho$  is a bulk density of charcoal.

The calculation procedure and results are commented stroke by stroke below.

1-2. Isothermic adsorption. From Eq.6 it is possible to estimate  $W_a$ , and then the knowledge of  $Q_a = qma$  makes it possible to calculate  $t_s$ . The inequality  $t_s > \theta$  satisfies the condition of the steady process. The molar flow from the evacuation volume is shown in the 7-th column, the total square of the adsorbent spread being supposed to be of  $100\text{cm}^2$ . The value of  $t_s$  is taken as a constant for all the following strokes.

2-3. Isothermic transit. The only purpose of the stroke is to overheat the adsorbent up to the temperature  $T_2$ . Substitution of  $T_2$ ,  $\beta$ ,  $\theta$ , and  $t_s$  in Eq.8 affords the opportunity to calculate  $W_h$ .

3-4. Isothermal desorption. The feasibility of the stroke is connected with the capacity of an outer pump that is shown in the 7-th column of *Table*.  $W_h$  is calculated from Eq.5.

4-1. Isothermic transit. The corresponding substitutions in Eq.8 allow one to check up that the final temperature of the adsorbent is approximately  $T_1$ .

The CAP, consisting of four identical adsorption units, will have the molar flow of value which is shown in the 7-th column, in the lines for (1-2)-strokes. The outer pump has to provide the molar flow of the same value during the (3-4)-strokes, but the necessary pumping speed becomes  $k$  times as low as in the case of the absence of CAP. As one can judge from *Figure 2*, the compression factor  $k > 10$ .

Increasing or decreasing  $\lambda$  apparently leads to the increasing  $\theta$  and, consequently, to lowering the pump capacity. The molar flow as large as  $0.095\text{mol s}^{-1}$  can be reached when a very good thermal contact ( $\lambda = 0.28\text{W cm}^{-1}\text{K}^{-1}$ ) between the coolant and the thin layer of the adsorbent ( $m = 0.25\text{g cm}^{-2}$ ) is used, but that requires an electromagnetic wave generator with an average output power of about 6kW. The latter can be lowered yet if a thermal contact between the coolant and the adsorbent is changeable. One can see it easily when the contact is off during the (2-3)- and (3-4)-strokes, the necessary heater power is only equal to  $W_a < W_h/2$ . The changeable thermal contact, of course, will complicate the adsorption unit, but the complication is the cost of obtaining a CAP of a very high pump capacity with modest coolant consumption and heater power.

The CAP designed for helium or other gases of interest in cryogenics will have the same pump capacity at proper temperature and pressure <sup>2</sup>.

## Conclusion

The working parameters of the continuous adsorption pump - CAP - can be calculated on the basis of the family of adsorption isotherms. The pump capacity of the CAP proves to be comparable to that of Root's pumps, which makes it possible

*Table*

<i>Stroke</i>	$\theta$	$t_s$	$Q_s$	$W_a$	$W_h$	$\dot{N}$
	(s)	(s)	(J cm <sup>-2</sup> )	(W cm <sup>-2</sup> )	(W cm <sup>-2</sup> )	(mmol s <sup>-1</sup> )
1-2	0.58	14	10.1	0.72	0	10.2
2-3	3.27	14	-	1.1	2.76	0
3-4	0.58	14	20.7	-1.48	3.52	-10.2
4-1	1.49	14	-	0.26	0	0
1-2	2.33	56	20.1	0.36	0	5.1
2-3	13.1	56	-	-0.55	1.38	0
3-4	2.33	56	41.3	-0.74	1.76	-5.1
4-1	5.98	56	-	0.13	0	0
1-2	0.06	1.5	10.1	6.72	0	95.
2-3	0.35	1.5	-	-10.25	25.8	0
3-4	0.06	1.5	20.7	-13.8	32.8	-95.
4-1	0.16	1.5	-	2.48	0	0
1-2	0.25	6.0	20.1	3.36	0	47.5
2-3	1.4	6.0	-	-5.12	12.9	0
3-4	0.25	6.0	41.3	6.9	16.4	-47.5
4-1	0.64	6.0	-	1.24	0	0

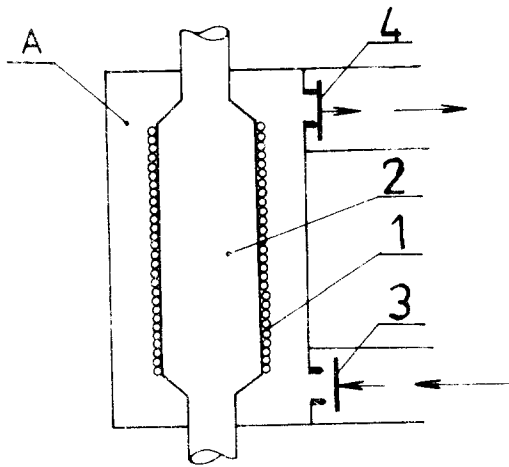


Figure 1. Schematic diagram of adsorption unit.

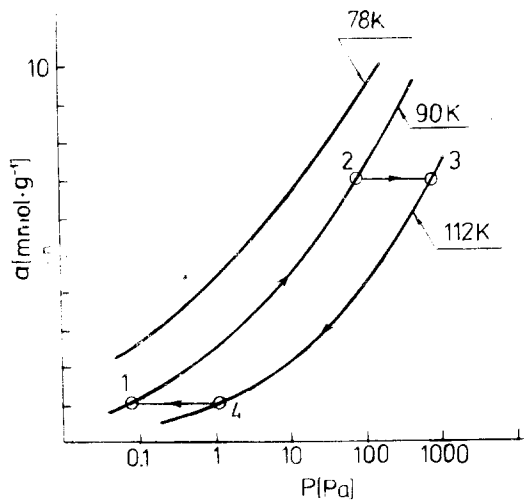


Figure 2. Family of adsorption isotherms.

to use CAP in cryogenic technique. In particular, it is applicable to pumping out the vapour of cryogenic liquids in He evaporation and  $^3\text{He}$  /  $^4\text{He}$  dilution refrigerators inclusive<sup>5,6</sup>.

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Адсорбционная откачка непрерывного действия

Предлагается новая схема адсорбционного насоса. Вакуумный насос работает по строго установленному 4-тактному замкнутому циклу, состоящему из двух изотерм и двух изостер. Показано, что для подробного расчета рабочих характеристик адсорбционного насоса непрерывного действия (АННД) необходимы только общие сведения относительно термодинамических свойств применяемого адсорбента. Некоторые особенности предлагаемого насоса, такие как небольшая разность температур адсорбции и десорбции, размещение адсорбента, а также способ его нагрева, позволяют, как ожидается, достичь с помощью АННД производительности откачки, сравнимой по величине с той, что получают при использовании двухроторных насосов Рутса.

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Continuous Adsorption Pumping

A new scheme of an adsorption pump is proposed. The vacuum pump is supposed to operate with respect to a rigidly determined 4-stroke closed cycle which consists of two isotherms and two isosteres. It is shown that routine information about thermodynamic properties of adsorbent is required for detailed calculation of operating characteristics of the continuous adsorption pump (CAP). Some design peculiarities such as a small difference of temperatures of adsorption and desorption processes, the adsorbent placing and the method of adsorbent heating — all together are expected to provide the pumping capacity of a CAP which is comparable to that of Root's pump.

The investigation has been performed at the Laboratory of High Energies, JINR.

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