POWERFUL DIRECT-CURRENT CONDUCTION PUMP WITH AN INCREASED OPERATING VOLTAGE

V. A. Golodnyak, A. E. Sinel'nikova,
and I. M. Tolmach

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The article describes the design of a powerful dc conduction pump operating on an increased voltage. The pump has a channel with sectional electrodes and is intended for pumping liquid potassium at a temperature of 700°C. The head-discharge characteristic of the pump in the section ($p = 24.5 \cdot 10^5$ N/m^2; $Q = 0.015$ m^3/sec) – ($p = 14.7 \cdot 10^5$ N/m^2; $Q = 0.0296$ m^3/sec) is linear. In the dc regime the supply is 14,870 A, voltage 15.5 V, discharge 0.0296 m^3/sec, head $17.6 \cdot 10^5$ N/m^2, and induction in the gap of the magnetic system 0.27 T. The maximum total efficiency of the pump is 25%. The hydraulic efficiency is 83%. The pump is made up as a bridge circuit, the supply source being connected into one diagonal and the liquid-metal circuit into the other. This scheme eliminates the shunting effect of the circuit and reduces the length of the flow-part of the pump by half. The poles of the magnetic system are shaped so that the "armature" reaction was minimum. The total weight of the pump is 2.5 tons, of which the weight of the magnetic system accounts for 1.9 tons. Also given is a method of comparing the schemes of pumps with sectional electrodes and of a traditional two-electrode pump, which facilitates selecting the pump scheme on the basis of concrete specifications at initial design stages. The method is illustrated by numerical results.

In [1] a scheme was proposed for a liquid-metal dc conduction pump whose distinctive feature is an increased voltage of the supply source with a corresponding decreased value of the operating current. The performance capability of such a machine was demonstrated experimentally [2].

As is known from the theory of a dc conduction pump (KN pump) [3] a part of the current in it envelopes the zone of the strong magnetic field, causing the so-called edge effect. This phenomenon is usually the determining one when evaluating the efficiency of a machine. In the dc conduction pump with an increased voltage (SN pump) the edge effect is absent by virtue of this basic scheme (Fig. 1). However, in such a pump there always exists a considerable longitudinal useless current reducing the efficiency of the machine.

It is expedient to compare both types of machines with respect to efficiency and to indicate the regions of the optimal values of their indices.

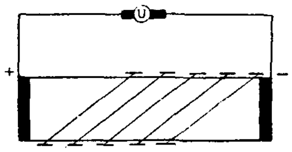

Fig. 1. Diagram of dc conduction pump with increased voltage.

In the present investigation we compared these machines in a pump regime with respect to the reduced electromagnetic efficiency for different volume flow rates (discharge) and heads. It was noted in [3] that machines should be compared not only with respect to the total but also electromagnetic efficiency. This is related with the fact that the total efficiency of a pump consists of the reduced electromagnetic efficiency η_r and hydraulic efficiency η_f:

$$\eta = \eta_r \eta_f. \tag{1}$$

As is known from machine-design experience, the hydraulic efficiency varies very insignificantly and takes on a value of about 0.8-0.9. Thus, for the magnitude of total efficiency

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$$\eta_r = p_r Q/UI, \qquad (2)$$

is determining, where p_r is the reduced electromagnetic head taking into account linear head losses [3]; Q is discharge; U is the voltage of the supply source; I is the total supply current.

The linear head losses are associated with an increase of the resistance coefficient as a result of the effect of the magnetic field, the degree of which is determined by the ratio $n = a/b$ [3], where a and b are the sides of the channel along and across the field, respectively. If for the KN pump $n < 1$, then for the SN pump $n \geq 1$ [4]. Thus, if the resistance coefficient increases in the first case under the effect of a magnetic field, then in the second it, conversely, can decrease.

The electrical diagram of the SN pump does not permit dividing the head losses into linear and quadratic. Therefore, the linear head losses in calculating the hydraulic losses and reduced electromagnetic head of such a pump are not taken into account separately.

The reduced electromagnetic efficiency in the notations of [3] will be equal to

$$\eta_r = (1-q)/(1+K/q), \qquad (3)$$

where $q = Q/Q_k$ is the relative capacity (flow rate), Q_k is the volume flow rate (discharge) of the pump at a zero head, and K is an energy parameter determined by the channel geometry and physical properties of the working body.

By uncomplicated algebraic transformations for a pump with an increased voltage, we can obtain an analogous expression for the reduced electromagnetic efficiency:

$$\eta_r^* = (1-q^*)/(1+K^*/q^*) \qquad (4)$$

(parameters with an asterisk pertain to a pump with an increased voltage).

The parameters K^* and q^* have the same sense as K and q, but differ in magnitude.

The maximum efficiency occurs when $q = q_0$, determined from the equation

$$\partial\eta_r/\partial q = 0; \qquad q_0 = (K^2+K)^{1/2} - K.$$

When $q = q_0$ the electromagnetic efficiency will be equal [3] to

$$\eta_{r\,\max} = 1 - 2q_0.$$

It is obvious that we can obtain an analogous expression also for a pump with an increased voltage, and then

$$q_k = Q_k/Q_k^*.$$

For the ratio of the reduced electromagnetic heads we can obtain, on the assumption that the heads of both pumps are equal, the expression

$$\eta' = \eta_{r\,\max}^*/\eta_{r\,\max} = (1-2q_0q_k)/(1-2q_0), \text{ where } q_k = q_0^*/q_0. \qquad (5)$$

From the condition of equality of the discharges it follows that

$$p_k = (1-q_kq_0)/(1-q_0). \qquad (6)$$

Here p_k is the ratio of the heads of the conventional pump and the pump with an increased voltage for a zero discharge.

On using Eqs. (5) and (6) we obtain the dependence of the ratio of maximum reduced electromagnetic efficiencies η' on q_0 for the conventional conduction pump for fixed values of q_k and p_k (Fig. 2).

As we see from Fig. 2, if $q_k < 1$ (the discharge at a zero head of the KN pump is less than that of the SN pump), then the efficiency of the pump with the increased voltage is higher. If $q_k > 1$, then the opposite relationship of the efficiency occurs. We recall that both pumps being compared have the same discharge and head at the nominal point.

In the case of equality of discharges Q_k and Q_k^*($q_k = 1$), the ratio of the efficiencies of the pump schemes being compared is equal to unity; i.e., this index cannot be determining, and the advantage of one

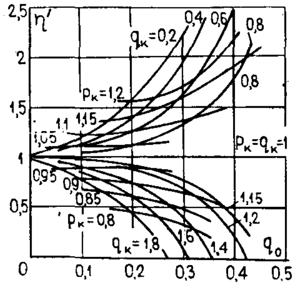

Fig. 2

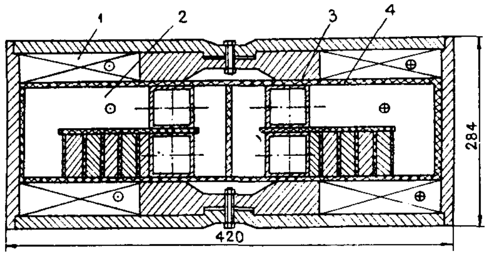

Fig. 3

Fig. 2. Dependence $\eta'(q_0)$ for a KN pump for fixed q_k and p_k.

Fig. 3. Location of the channels in the cross section of the SN pump. 1) Coil; 2) inclined connector; 3) channel; 4) heat insulation.

or the other scheme is determined by such parameters as their current, voltage, weight, etc.

Thus, having calculated the optimal KN pump, by means of Fig. 2 we can indicate for what parameters the SN pump will be more efficient, by how much, and what design requirements it must meet. We can also estimate the magnitude of the supply current and induction.

By means of the method in [4] we calculated the SN pump for the following conditions: working body – potassium at a temperature to 700°C, p(Q) characteristic should pass through point $p = 15 \cdot 10^5$ N/m^2, Q = 0.0296 m^3/sec, $p = 25 \cdot 10^5$ N/m^2, Q = 0.015 m^3/sec.

For the pump channel we used a bridge wiring circuit with symmetric arms. The supply source was connected to one of the bridge's diagonals and the liquid metal flows along two parallel branches. This scheme permits, first, extending the short-circuiting connectors to the sides of the channels and thereby reducing the gap of the magnetic system and, second, eliminates shunting of the source by the liquid-metal circuit, so that the electric current in the presence of symmetry of the arms does not flow out to the output part of the circuit.

The arrangement of the channels in the cross section of the pump is shown in Fig. 3.

The poles of the magnetic system are shaped so as to reduce the distortion of the field by currents in the channels [5]. A special feature of this system is the use of the self-field created by the electric currents in the inclined connectors. This field is superposed on the main field created by the coils. The inhomogeneity of the field over the cross section of the channel is an adverse factor in this scheme. However, as shown in [5], by selecting the form of the pole shoe, the inhomogeneity can be reduced to 15%, which is acceptable.

The flow part of the pump consists of four square channels with inside dimensions 31 × 31 mm, wall thickness 1.5 mm, and length 3 m, representing all-drawn tubes of steel Kh18N10T. The ends of the channels lying above each other are connected in pairs on the side of the electrical supply through plane diffusers by a collector rotating the flow 180°. Branch pipes in the form of plane diffusers for reducing hydraulic losses are welded at the entry and exit of the pump. The lower channels at the exit are connected by a

TABLE 1

Parameters	SN	KN
Working body	Potassium	Potassium
Temperature of liquid metal, °C	700	700
Velocity of liquid metal, V, m/sec	15,5	30
Operating current I, A	14870	56000
Operating voltage U, V	15,5	3,15
Induction in gap, B, T	0,27	0,9
Useful head p_n, N/m^2	$17{,}61 \cdot 10^5$	$19{,}2 \cdot 10^5$
Hydraulic efficiency η_f	0,824	0,9
Relative volume flow rate q_0	0,367	0,32
Relative head p	0,633	0,68
Head at zero discharge, p_m, N/m^2	$34 \cdot 10^5$	$31{,}2 \cdot 10^5$
Total efficiency, η	0,214	0,324
Reduced electromagnetic efficiency η_r	0,261	0,36

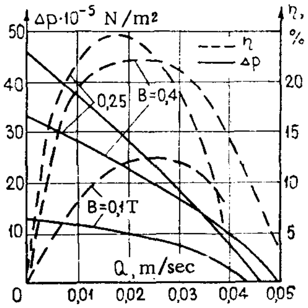

Fig. 4. p(Q) characteristics of SN pump.

short-circuiting bus. To limit unilateral thermal expansion of the pump, the flow part on the entry side is secured by screws to a rigid flange connected with the core of the magnetic system. The flange absorbs and transmits to the core the force from the pipelines of the liquid-metal circuit.

It is assumed that the flow part of the pump together with the short-circuiting connectors has a temperature of the order 700°C and is properly the hot part of the pump separated from the magnetic system by cooling panels. The main purpose of the latter is to protect the exciting coil and magnetic circuit against heat fluxes from the hot part of the pump. Insulation of a special thermostable material is placed between the hot part of the pump and the cooling panels to reduce heat losses. A calculation showed that with such an insulating and cooling system the temperature of the hottest section of the exciting winding does not exceed 80°C, whereas the temperature value allowable for the insulation is 180°. Overheating of the cooling fluid (water) in the panels at an entry temperature of 30° and flow rate of 1-1.5 kg/sec does not exceed 50°.

Table 1 presents the parameters of the SN and KN pumps for equal discharge $Q = 0.0296$ m³/sec and reduced electromagnetic head $p_r = 21.3 \cdot 10^5$ N/m².

The calculation of the conventional KN pump was performed on a digital computer by the method presented in [3].

Figure 4 shows the p(Q) characteristics of the SN pump.

We will give a comparison of the SN and KN pumps according to the method proposed above:

relative volume flow rate of KN pump, $q_0 = 0.32$;

relative volume flow rate of SN pump, $q_0{}^* = 0.367$;

$$q_k = q_0{}^*/q_0 = 0.367/0.32 = 1.15;$$

head at zero discharge of KN pump, $p_m = 31.2 \cdot 10^5$ N/m²;

head at zero discharge of SN pump, $p_m{}^* = 34 \cdot 10^5$ N/m²;

$$p_k = p_m{}^*/p_m = 31.2 \cdot 10^5/34 \cdot 10^5 = 0.915.$$

On the basis of Fig. 2 the ratio $\eta^*_{r\ \max}/\eta_{r\ \max} = 0.725$. The ratio of these same quantities according to the calculation is

$$\eta^*_{r\ \max}/\eta_{r\ \max} = 0.261/0.36 = 0.725.$$

Thus, the calculation of the efficiency of the SN and KN pumps on the basis of detailed designing additionally confirms the permissibility of using simple Eqs. (5) and (6) to facilitate the selection of the scheme at the initial stage of development.

As we see from a comparison of the numerical results, the efficiency of the KN pump was higher than that of the SN pump. However, the operating current of the first (56 kA) is much greater than that of the second (14.8 kA), which hampers considerably the technical realization of the device. Therefore, preference was given here to the scheme of the SN pump.

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