INVESTIGATION OF AN INDUSTRIAL DIRECT-CURRENT ELECTROMAGNETIC PUMP

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Following an investigation of the laboratory models of a dc electromagnetic pump operating at elevated voltages [1, 2] we have designed, analyzed, and built two similar industrial models of this machine and designated them as type SN-5. The pumps were installed in a stationary liquid-metal loop as pressure pumps. Unlike the models described in [1, 2] these pumps operate without shunting the power supply by metallic components of the loop (Fig. 1). The pump channels form a bridge composed of four arms with the supply voltage applied to one diagonal of the bridge and the external circuit connected to the other diagonal. At the same time, the short-circuiting straps in each arm are arranged as in [1, 2], i.e., the principle of elevated operating pump voltage is preserved.

Since longitudinal currents in two arms arranged in pairs above each other flow in opposite directions, the armature reaction is compensated. Another distinctive feature of the circuit is that the current conducting busbars are welded to the small side surfaces of the channels. This allows effective utilization of the channel regions to which the electrodes are mounted as they contribute to the total pump pressure.

Each pump is designed to deliver a pressure drop of 10 kgf/cm^2 with flow rate equal to 0.4 liter/sec at a working fluid (potassium) temperature of 600°C. At lower flow rates (about 0.1 liter/sec) the required pressure drop is 15 kgf/cm^2. In view of the relatively high nominal voltage (3.5 V) the moderate current (3000 A), the pumps can be supplied from conventional type VKG 3200 adjustable dc power supplies.

The circulating section of the pump is formed of two rectangular tubes (Kh18N10T material) with an inside cross section of 4.4 × 15.1 mm and 1080 mm long placed on top of each other and soldered together at the ends into common connecting pieces (model with 1-mm-thick

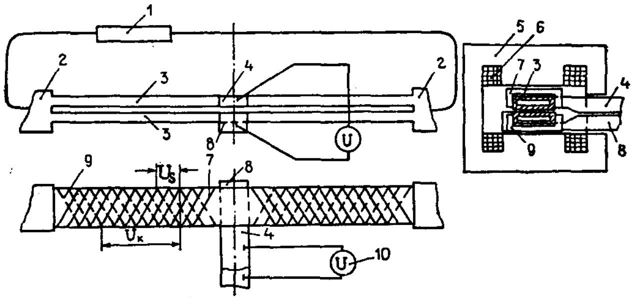

Fig. 1. Direct-current pump operating at an elevated voltage and without shunting the power supply: 1) external components of the loop; 2) collectors; 3) channels of the bridge circuit; 4) upper current conductor; 5) magnetic circuit; 6) excitation winding; 7) upper-channel straps; 8) lower current conductor; 9) lower-channel straps; 10) power supply.

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tube walls). The second model has channels of the same length but is made of tubes with an inside cross section of 4.6 × 16.8 mm and 2-mm-thick walls. To eliminate the effect of current supply on the magnetic-circuit field the 95-mm-wide current conducting busbars, which cross the magnetic circuit on the same side (bifilarly), are soldered with Prs 38 solder at the center of the tubes to their smaller side surface. The busbars pass through a window in the shell-type magnetic circuit. The excitation winding of the magnetic circuit is separated from the hot circulating section by thermal insulation of AGN heat-resistant material and water-cooled panels. Under normal thermal operating conditions the winding provides an induction B = 0.5 T in the gap which is more than required (0.3-0.4 T).

Before being mounted in their permanent position the pumps were tested in a special DU 60 sodium circuit. The purpose of the test was to check the design methods and the obtained pump parameters in the model with relatively thick walls (2 mm in the second version) used to improve reliability, and to investigate the performance of the bridge circuit and the validity of the accepted structural design.

In designing a pump one usually specifies the desired pressure p_a and feed Q, the maximum allowable total channel current I_n (depending on the source parameters), the desired channel efficiency

$$\eta_1=\frac{p_a Q}{I_n U}, \tag{1}$$

the working fluid parameters σ and ρ, and the coefficient

$$\alpha=\frac{Blv}{\gamma U}, \tag{2}$$

whose optimal value is about 0.6-0.8 (all values related to one arm of the bridge shown in Fig. 1).

Also assumed as given is the quantity

$$\xi=\frac{2\Delta_1\sigma_1}{\Delta\sigma}, \tag{3}$$

which is much less than unity so that its error (resulting from the unknown width of the liquid-metal gap Δ) does not introduce a marked error into the design and can be corrected in repeated calculations.

The sought quantities are the arm length l, channel width b, gap Δ, angle of the short-circuiting straps described by the parameter γ, strap resistance r, voltage U, and the induction in the gap B. These quantities can be found from the following relations for p_a, I_n, Q, and Δ supplemented by expressions (1)-(3) [3]:

$$p_a=\sigma UB\gamma\frac{1-(1+r\xi)\alpha}{1+r+r\xi}C_p-\frac{\lambda_0\rho(b+\Delta)lv^2}{4\Delta b}; \tag{4}$$

$$I_n=\sigma U\frac{\Delta b}{l}\left[1+\xi+\frac{\xi n}{1-\lambda_1}+\gamma^2\frac{1+\xi-\alpha}{1+r+r\xi}\right]C_I; \tag{5}$$

$$\Delta=nb;\quad Q=nb^2v. \tag*{(6), (7)}$$

The coefficients C_p and C_I account for space effects [3]. From expressions (1)-(7) one can obtain an explicit expression for t in terms of the given parameters:

$$l=l_0 f(n)\cdot F(\beta), \tag{8}$$

where $l_0=\left(\frac{\lambda_0\rho}{16}\right)^{2/3}\frac{\sigma^{5/3}Q^3p_a}{I_n^{10/3}}$ m is a dimensional term, (9)

$$f(n)=\sqrt[3]{\frac{(1+n)^2}{n}}; \tag{10}$$

$$F(\beta)=\frac{\left\{C_I\left[1+\xi+\frac{\xi n}{1-\lambda_1}+\beta(1+\xi-\alpha)\right]\right\}^{5/3}}{\eta_1^{5/3}\left\{\frac{\alpha C_p}{\eta_1 C_I}\beta[1-(1+r\xi)\alpha]\frac{1}{1+\xi+\frac{\xi n}{1-\lambda_1}+\beta(1+\xi-\alpha)}-1\right\}^{2/3}}, \tag{11}$$

where

$$\beta=\gamma^2/(1+r+r\xi). \tag{12}$$

Let us analyze expressions (9)-(12).

The quantity l_0 depends significantly on the specified feed Q and even more so on the current I_n. Reduction of the specified feed (while preserving the total useful hydraulic power $P_h = p_a Q$) decreases l_0 in proportion to the square of Q. Increasing the allowed current I_n still more (to the 10/3-th degree) reduces l_0.

The pump circuit proposed in [4] also operates without shunting the voltage source and has only two arms with the total feed and one half of the current flowing through each arm. Expression (9) indicates that all things being equal, the total length of the channels in the pump shown in Fig. 1 is one fourth of those in [4], i.e., the size of the pump is much smaller. The dimensionless function f(n) (10) has a flat minimum equal to 1.59 for n = 1, i.e., for a channel of rectangular cross section. Thus, if no other considerations prevail, it is desirable to take n = 1. On the other hand, if the resulting absolute tube cross section turns out to be too small one can make n < 1 (at the cost of somewhat longer l_0).

The function F(β) in Eq. (11) is more complicated. Figure 2 shows this function calculated for several selected efficiency values and for practical values of the parameters $C_I = 1$, $C_p = 0.95$, and $\xi = 0.03$. Expression (11) also contains the small terms $\xi n/(1-\lambda_1)$ and $r\xi$. In calculating the curves in Fig. 2 we have assumed (only for the above small terms) the values r = 1, n = 1, and $\lambda_1 = 0.25$ which are typical of many pumps.

A significant result following from Fig. 2 is that the function F(β) exists for relatively high (for devices such as electromagnetic pumps) efficiencies ($\eta_1 \approx 0.4$). Thus, pumps of this type can have an efficiency similar to that of conventional dc pumps.

The function F(β) has a minimum at a certain β; as the specified efficiency increases, the minimum of this function decreases to some minimum *minimorum* (about 90 for $\eta_1 = 0.15$-0.2) and then increases. For the parameters assumed above the function F(β) exists up to $\eta_1 = 0.56$ (for $\beta \to \infty$). An efficiency $\eta_1 = 0.3$-0.4 can be obtained by making the channel 1.3 to 3 times longer than its minimum value.

After selecting a certain β for the desired efficiency [e.g., near the F(β) curve corresponding to minimum], the strap angle γ can be found from (12). It must be remembered that the quantity r appearing in (12) is a function of γ determined from purely geometric considerations of strap structure [2].

The voltage U can be found directly from (1) and since l is already known the induction B can be obtained from (2). The channel width b is determined on the basis of the input equations considering the value of l obtained before:

$$b=I_n\sqrt{\frac{\eta_1 l}{n\sigma p_a Q\left[1+\xi+\frac{\xi n}{1-\lambda_1}+\gamma^2\frac{1+\xi-\alpha}{1+r+r\xi}\right]C_I}}. \tag{13}$$

The gap Δ and the velocity v are found from (7) and (6) since b is known and n has been chosen.

After the basic pump dimensions and parameters have been determined the calculations must be refined by taking into account hydraulic losses in the end pieces, electric loss in the busbars, and the additional pressure created in the busbar region.

Geometric dimensions of the pumps designed by the above described method and refined in control calculations are listed in Table 1.

The parameters r and ξ include the ratios of the electroconductivities of the liquid metal σ, wall channel σ_1, and strap σ_S, dependent on the channel temperature.

After the pumps were fitted into the test loop they were pressurized at 18 kgf/cm² and 22 kgf/cm², respectively. The loop was then charged with liquid metal at 300°C which was kept

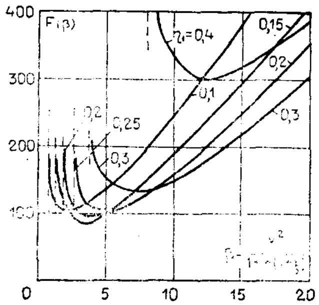

Fig. 2

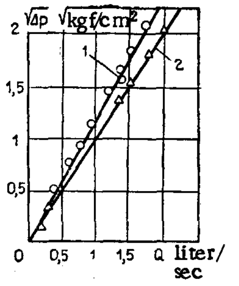

Fig. 3

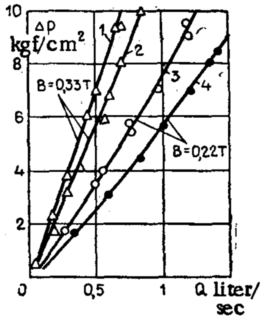

Fig. 4

Fig. 2. Function F(β) for certain given efficiency values.

Fig. 3. Hydraulic characteristics of channels in the absence of current and magnetic field: 1) 2-mm walls; 2) 1-mm walls.

Fig. 4. Hydraulic characteristics of channels without current but with magnetic field applied (choke operation): 1, 3) 1-mm walls; 2, 4) 2-mm walls.

under circulation for 24 h by means of an external pump to ensure good wetting. Before being charged the pump channel was heated for two hours to 200°C by passing a current through the magnetic circuit excitation winding.

Figure 3 shows the feed rate of the channels without current and magnetic fields. Figure 4 shows the feed rate without current but with the magnetic field applied (choke operation).

The p(Q) characteristics obtained for the first model of the pump for channel heating currents 2000 and 3000 A and an induction B = 0.334 T are shown in Fig. 5. Figure 6 shows the p(Q) characteristics of the second pump model for 2000 and 3000 A and three induction values.

The efficiency of the first model (1-mm-thick walls) was 9% and that of the second model (2-mm-thick walls) about 7%. This is equal to the efficiency of conventional machines taking into account the low hydraulic power (400 W) and relatively thick walls.

The shunt currents were zero to within experimental accuracy thus confirming the efficiency of bridge circuits.

During the experiment we measured the voltage drop across one of the straps U_s and across a certain channel section U_k (Fig. 1). The results were processed in BQ/U_s, and U_s/U_k coordinates and are shown in Fig. 7. Comparison of experimental results with theoretically plotted curves shows good agreement indicating that the design approach is correct.

To check the results theoretical p(Q) characteristics were plotted and compared with experimental ones. The value of the hydraulic resistance coefficient used in calculations was determined experimentally, while the hydraulic resistance of compensation loops at the channel input and output was calculated theoretically and taken into account in computing the loss in the active pump space proper.

In calculating the pump characteristics we have also taken into account the pressure developed by the current conducting busbars. Their contribution was determined from expressions obtained for a conventional two-electrode conduction pump to which a correction factor, less than unity in the given case, was introduced. The value of this coefficient was determined as an average of the values obtained in several operating conditions.

TABLE 1

Pump model	Δ_1 mm	b mm	Δ mm	n	λ_1	γ	r	ξ
I	1	15,1	4,4	0,291	0,4	1,6	$0{,}1892\frac{\sigma}{\sigma_1}+4{,}434\frac{\sigma}{\sigma_s}$	$0{,}454\frac{\sigma_1}{\sigma}$
II	2	18,6	4,6	0,247	0,4	2,0	$0{,}307\frac{\sigma}{\sigma_1}+4{,}88\frac{\sigma}{\sigma_s}$	$0{,}87\frac{\sigma_1}{\sigma}$

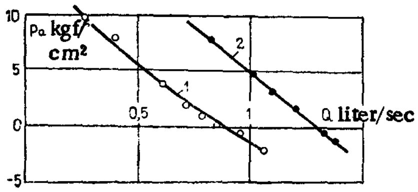

Fig. 5

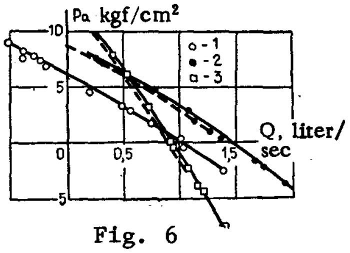

Fig. 6

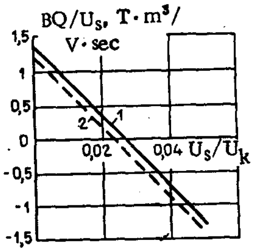

Fig. 7

Fig. 5. Experimental p(Q) characteristics of first model of the pump (1-mm wall channel) for an induction 0.335 T in the gap and channel current 2000 A (1) and 3000 A (2).

Fig. 6. Experimental p(Q) characteristics of second model of pump: channel current 2 kA, B = 0.024 T (1); 3 kA, B = 0.224 T (2); 3 kA, B = 0.443 T (3).

Fig. 7. Comparison of theoretical and experimental values of BQ/U_s as a function of U_s/U_k: 1) averaged experimental curve; 2) theory.

The theoretical p(Q) characteristics are shown by the broken curve in Fig. 6. A comparison with experimental curves discloses good agreement which confirms the validity of the design techniques as applied to relatively thick walls and bridge circuits [1, 2].

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