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STUDY OF AN INDUCTION-TYPE LIQUID-METAL MHD GENERATOR *

by

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General characteristics

The development of a general theory of induction MHD generators with a rotating field was begun in 1960 [ref. #1].

In 1966 a test sample of a three-phase liquid-metal MHD generator using potassium was created for the purpose of experimental verification of theoretical statements assumed in designing the machine.

On the basis of the optimization calculation, basic dimensions of the generator were selected: pole division, number of poles, active length, gap in [along] the liquid metal, number of turns of the helical duct, and transverse internal cross section. In order to reduce losses in the metal wall of the duct, its thickness was assumed to be small—0.25 mm, the material—stainless steel X18H10T.

The electrical circuit contained a three-phase battery of capacitors needed for self-excitation.

After the installation of the generator in the circuit and filling with a working medium, spill tests were made without magnetic field at different temperatures, modes of operation were investigated along with [parallel with] external power network [mains] (in the pump and generator modes) and also modes of autonomous operation with the battery of capacitors at machine and potassium temperatures of 300, 400, 475, and 550°C.

Before and after installation into the circuit, no-load operations were tested in order to distribute the losses. The total operating time of the potassium generators was 152 hours. The pressure differential [drop] limited by the potentialities of the circuit was no greater than 18 atm abs at an absolute pressure of 25 atm at the input, the greatest effective power obtained was 500 watts in the autonomous mode. The measured efficiency of the generator (ratio of electric power to the product of the liquid flow rate and the pressure differential) was 18 per cent.

Construction (figure 1)

The magnetic circuit consists of internal and external parts between which is located a thin-walled helical duct. The magnetic circuit is made of sheets of Permendur [ref. #2]. Slots [grooves] were placed only in the outer portion of the magnetic circuit, they are sealed [covered],

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thus, the thin-walled helical duct is attached to a smooth surface on both sides. The slotted bridge is saturated in the working mode.

A package is tightened with pressure plates that repeat, e.g., the pattern of the tin [plate], the tie pins of the package are made of the same material as the helical duct.

For the three-phase winding an annular type is used [assumed], the winding [wrapping] covers the back of the magnetic circuit on the outside. The use of this type of winding instead of an ordinary two-layer one was determined by the small ratio of the width of the tooth to the width of the slot [groove]; in the case of the two-layer winding, overhangs of the front parts would be excessive.

The helical duct is wound of a rectangular tube with a wall thickness of 0.25 mm. Electrical contact is provided between the adjacent helices so that there is the possibility for the straight-through currents to flow in an axial direction in the liquid metal (in the opposite case, the transverse edge effect would intolerably weaken [attenuate] the electrical power). The very transition resistance of the liquid metal/solid wall interface after wetting becomes insignificant [ref. #3].

The generator has an outer hermetic casing which is filled with argon.

Test installation

A test circuit containing two subsequently included electromagnetic pumps made it possible to smooth increase the pressure differential at the generator to 18 atm. The measuring equipment of the circuit made it possible to measure the pressure at the input and output of the generator by sample [standard] manometers, the volume flow rate per second by means of a conduction-type electromagnetic flowmeter having a permanent magnet. Thermocouples measured the temperature of the liquid metal, the winding of the generator, and the housing that was thermally insulated with [by] asbestos.

The electrical test circuit made it possible to investigate the generator in the parallel operating mode [connected parallel with the external mains] and in the autonomous self-oscillating mode. It contained the following elements:

1. A 50-Hz autotransformer with adjustable voltage and a synchronous generator with adjustable frequency (up to 200 Hz) and voltage that was the external mains for the generator to be tested.

2. A system for autonomous operation consisting of three-phase step-controlled battery of capacitors, a load in the form of rectifiers and adjustable ohmic resistance as well as a preliminary [re]charging mode for the capacitors to provide the start of the self-excitation process.

3. Switching equipment that provided the disconnection of the generator from the mains, the connection of the autonomous load and capacitors, the switching on of the recharging.

4. Measurement equipment that made it possible to measure the currents in the phases, phase voltages, and power, frequency, current and voltage of the load, [and] capacitor recharge voltage. The current and voltage in the phase, [and] the voltage under load were shown on an oscilloscope.

Losses in the generator. The equation of the power balance that is valid both in the pump and the generator modes can be written in the following manner:

$$P_h + P_{net} = P_{mp} + P_{met} + P_{sh} + P_{st} + P_{Cu} + P_{add} \qquad (1)$$

Here P_h is the hydraulic power; $P_h = Q(p_1-p_2)$ where Q is the volume flow rate, p_1 is the pressure at the input, p_2 is the pressure at the output of the machine.

Thus, in the generator mode P_h has a plus sign, and in the pump mode a minus sign.

P_{net} is the power taken from or transmitted to the power network [mains] (or in self loading); it is negative in the generator mode, positive in the pump mode. This follows from equation

$$P_{net} = 3UJ \cos \varphi$$

where the angle $\varphi < 90°$ in the pump mode and more than 90° in the generator mode.

P_{mp} is the viscous dissipation; P_{Cu}, P_{sh}, P_{st}, P_{add}, P_{met} are respectively the Joulean losses in copper, in the metal shell of the duct, in the steel of the magnetic circuit and structures, additional losses (associated with the effect of the high harmonics), and in the liquid metal.

The efficiency of the machine in a universal form is

$$\eta = 1 - \frac{P_h + P_{net}}{k_1 P_h + k_2 P_{net}} \qquad (2)$$

where k_1 and k_2 as a function of the sign of P_h and P_{net} can only assume the values 0 (with a negative sign of appropriate power) or 1 (with a positive sign). In the intermediate regime [mode], when $P_h > 0$ and $P_{net} > 0$, the coefficients k_1 and $k_2 = 1$ and $\eta = 0$.

Furthermore, the results of measuring the separate components of the losses in equation (1) are examined.

A. Viscous dissipation

The coefficient of hydraulic resistance λ_0 (without magnetic field) of the Reynolds number Re was measured

$$\lambda_0 = \frac{2Dh(\Delta p)}{L\rho V_{av}^2} = f\ Re \qquad Re = \frac{DhV_{av}}{\nu} \qquad (3)$$

where Dh is the hydraulic diameter, (Δp) is the pressure differential in the helical duct, V_{av} is the mean velocity, and L is the expanded [unfolded] length of the helical line of the duct, equal to 2.1 m. The measurements of the coefficient λ_0 performed in the first series of tests yields satisfactory agreement with the calculation.

However, in the second series of tests, there occurred an increase in the coefficient λ_0 by a factor of 1.5-1.7.

In order to refine and explain this phenomenon, after the hot tests water filling of the generator duct* was conducted with a pressure at the input up to 63 atm.

*The water tests were performed at the Leningrad Polytechnical Institute under the direction of A.V. Tananayev.

Here the hydraulic resistance was reduced from test to test, approaching the initial curve that was obtained in the first test series for potassium. A possible explanation for this may consist in the appearance of deposits in the duct that increased the resistance and were gradually washed away by the water. After these tests, the duct was cut apart. The internal surface turned out to be clean and without dents.

B. Losses in the copper turned out to be greater than calculated due to the increased resistance of the phase.

The increase in the resistance is primarily connected with the engineering necessity of legthening a thinner slotted [grooved] part of the coil [turn] and shortening the length of the opposite [facing] conductors of thicker cross section. It is also connected, to a small degree (5-6 per cent), with the recrystallization and embrittlement of the copper that took place in the sample under study.

C. Losses in the shell of the helical duct were calculated by the formula:

$$P_{sh} = \frac{2p_1\tau\ell\Delta_1\sigma_1\omega^2 k_{att}B_{res}^2}{\alpha^2}\cdot\frac{1+R_m^2}{[1+R_m^2(1-k_{attr})]^2+R_m^2k_{att}^2} \qquad (4)$$

The value of the second fraction in this expression is close to unity at magnetic numbers of $R_m < 0.4$.

Here $2p_1$ is the number of poles, τ, ℓ, Δ_1, σ_1 are respectively the pole division, active length, thickness of one wall, and its electrical conductivity; $\alpha = \pi/\tau$, $k_{att}$and k_{attr} are the coefficients of attenuation for active and reactives powers.

It is possible to show that the resulting induction (amplitude) is

$$B_{res} = kU$$

where U is the phase voltage [voltage of the phase] and k is a constant coefficient.

Using (5) for (4) it is convenient to perform recalculations of the losses in the shell for different voltages.

The performed measurements agree well with the calculation.

D. Losses in steel. Here are included the losses in the charge-calculated magnetic circuit and the losses in the metal structural elements of the design—housing, sleeves, pins, etc. These losses turned out to be subtantially in excess of the calculated value.

The difference is explained both by not taking into consideration in the calculations the losses of the metal structures as wellas the tin plates actually making contact at individual points.

Figure 2a shows the losses in the steel (without housing) as a function of the ratio U/f for different frequencies at a machine temperature of 50°C. The effect of the temperature on the losses is evident from figure 2b where the sum of the losses in the steel (including structural elements) and the shell is plotted along the ordinate axis.

E. Additional losses caused by the effect of higher harmonics turned out to be small.

Oscillograms of the current and voltage in the autonomous mode are nearly sinusoidal. The divergence of the real voltage curve on the oscillogram made it possible to estimate the value of the losses from the higher harmonics. Thus, at a frequency of 50 Hz, the losses in the liquid metal from the higher harmonics are 2.3 per cent of the losses from the first harmonic, the losses in the shell are 3 per cent and the losses in the steel 1.2 per cent respectively.

F. The losses in the liquid metal were determined experimentally from equation (1) where the hydraulic power was defined by the flow and pressure differential, the power of the mains was fixed [established] by wattmeters, the viscous dissipation, the losses in copper, steel, and the additional losses were determined from separate experiments described earlier.

Figure 3 shows the losses found as a function of the flow rate for 2 voltage values at a frequency of 50 Hz. The characteristic feature of the curves is the presence of a loss minimum not equal to zero in a synchronous flow rate corresponding to the given frequency (approximately 0.97 liters/sec) at a mean slip[page] equal to zero. In the case of a solid working medium, this minimum would be equal to zero.

The increase in the Joulean losses in the liquid metal is connected with the unevenness of the velocity profile as a result of which additional electrical currents arise. Thus, by assuming a power [exponential] velocity profile, it is possible to obtain the following analytic expression for the Joulean losses:

$$P_{met} = \tfrac{1}{2}\ell p_1 \tau \rho V_{av}^3 \left[\frac{S^2}{(1-S)^2} + \frac{m^2}{1+2m}\right]\frac{M^2}{Re} \cdot k_{att} \qquad (6)$$

from which it is evident that losses exist when $S = 0$. As a result of this, the complete electrical power is also increased which, in a power profile, is expressed in the form:

$$P_{el} = \tfrac{1}{2}\ell p_1 \tau \rho V_{av}^3 \left[\frac{m^2}{1+2m} - \frac{S}{1-S}\right]\frac{M^2}{Re} k_{att} \qquad (7)$$

Here m is the index of the power in the profile formula, the value of which in the calculation was taken equal to 0.08; M and Re are the Hartmann and Reynolds numbers; k_{att} is the coefficient of attenuation.

However, the minimum value of the losses for $S = 0$ in the experiments was obtained several times greater than the value

$$\tfrac{1}{2}\ell p_1 \tau \rho V_{av}^3 \frac{m^2}{1+2m} \cdot \frac{M^2}{Re} k_{att}$$

In order to refine this problem, a theoretical investigation of the effect of the unevenness [nonuniformity] of the velocity profile was performed both along the z coordinate (depth of flow) at an *arbitrary* profile and along the y coordinate (width of flow). This investigation yields the following expression for complete hydraulic power that includes the viscous dissipation of electrical power

$$P_h = \tfrac{1}{2}\ell p_1 \tau \rho V_{av}^3 \left\{\lambda_0 + \left[C_0 - (1 - C_1)\frac{S}{1-S}\right]\frac{M^2}{Re} k_{att}\right\} \quad (8)$$

and respectively the complete coefficient of resistance

$$\lambda_m = \lambda_0 \left[C_0 - (1 - C_1)\frac{S}{1-S}\right]\frac{M^2}{Re} k_{att} \quad (9)$$

Here C_0 and C_1 are "quasi-constants" that weakly depend on the slippage [a slight function of the slippage] and k_{att} is defined according to the formulas for the solid working medium (homogeneous distribution of velocity).

From (8) it is also possible to obtain an expression for the coefficient of resistance λ'_m which is defined [determined] as N.M. Okhremenko has done [ref. #4] according to the difference in the actually measured pressure differential (power) and theoretically calculated electrical power with the assumption of uniform velocity.

In the case of the solidified working medium $C_0 = C_1 = 0$ and from (8), the electrical power is equal to

$$P_{eP} = \tfrac{1}{2}\ell p_1 \tau \rho V_{av}^3 \left(-\frac{S}{1-S}\right)\frac{M^2}{Re} k_{att} \quad (10)$$

On the basis of (8) and (10), the expression for the above defined coefficient of resistance is:

$$\lambda'_m = \lambda_0 + \left(C_0 \frac{M^2}{Re} + C_1 \frac{M^2}{Re} \cdot \frac{S}{1-S}\right) k_{att} \quad (11)$$

Expression (11) generalizes the formulas suggested by Okhremenko in [ref. #4] by introducing the additional term $C_0 (M^2/Re) k_{att}$ which also exists when $S = 0$.

Figure 4 yields the experimental results of the measurement of the coefficient $\frac{\lambda_m - \lambda_0}{(M^2/Re) k_{att}}$ obtained for the generator in the slip range of 0.11— -0.67 (with transition through 0) at Hartmann numbers up to 530 and Reynolds numbers $(2\text{-}4)\cdot 10^5$. The indicated coefficient was determined experimentally from relationship (17) which is further deciphered:

$$\frac{\lambda_m - \lambda_0}{\frac{M^2}{Re} k_{att}} = \frac{(\Delta p - \Delta p_{mp})Q}{-P_{net}}\left[-\frac{S + (\sigma_1 \Delta_1)/(\sigma\Delta)}{(1-S)^2} - \frac{k_T^*}{Q^2}\right] - C_0 - \frac{S}{1-S}(1 - C_1)$$

In this expression all values of Q, P_{net}, S, Δp, Δp_{mp}, [and] k_T^* are found from the experiment.

A graph is constructed as a function of the argument $\frac{S}{1-S}$, a line passing through the origin of the coordinate defines the electrical power for a solid working medium. These experimental points lie above this line. Processing the data of the experiment in agreement with figure 4 yields a value of approximately 0.054 for C_0, and for $C_1 \approx 0$.

The losses in the liquid metal in a nonuniform profile are expressed in a form which differs from presentation (6):

$$P_{met} = \frac{1}{2} \ell p_1 \tau \rho V_{av}^3 \left[\frac{S^2}{(1-S)^2} + C_1 \frac{S}{1-S} + C_0\right] \frac{M^2}{Re} k_{att} \quad (12)$$

In designing the generator taking into consideration the power profile, the coefficient C_0 was assumed equal to 0.0054, and $C_1 = 0$, actually C_0 turned out to be equal to 0.054 when $C_1 = 0$. Thus, in nominal slip and nominal induction and velocity, the real losses in the liquid metal e.g., exceeded the calculated by 55 per cent. Accordingly, the effective power will be reduced. However, by selecting other values of induction, velocity, and slippage that are optimum under the conditions of a specific generator, no such strong reduction of the effective power can be achieved. We explain the substantial resistance of the coefficient C_0 that occurred in the experiments compared with the corresponding value for the power profile by a bent duct of the test sample [model] where because of this there was apparently a substantial asymmetry in the depth profile due to the appearance of centrifugul forces [ref. #5]. The analytic expression that we obtained for C_0 at an arbitrarily deep velocity profile $V(z)$ and infinite width of flow [ref. #6] is:

$$C_0 = \frac{1}{2\delta V_{av}^2} \int_{-\delta}^{\delta} (V(z) - V_{av})^2 \, dz; \; C_1 = 0 \quad (13)$$

Here 2δ is the depth of the flow, V_{av} is the mean velocity.

Figure 5, on the basis of (13), shows so substantially (tens of times) that the value C_0 can grow on transition from the power 1 to the non-symmetrical profiles 2, 3, 4 which take place in the twisted ducts, although the mean velocity of all profiles is identical.

Measurement of the magnetic field. Figure 6 shows the calculated dependence for 550°C of the amplitude of the resulting induction in the gap on the magnetizing current, and the experimental characteristics for the temperature of the machine at 20, 300, and 500°C (recorded in the absence of the liquid metal). The characteristic [performance] at 20° is found by direct measurement by means of a frame with several turns [coils] located in the gap.

The characteristics for 300 and 500°C are found according to the measured dependences of the applied voltage on the phase current with subsequent recalculation of the induction and the magnetizing currents from the vector diagram. The experimentally obtained inductivities of scattering and no-load path [curve] were used in plotting the vector diagram.

The fairly significant reduction of induction can be explained by the following causes:

1. Somewhat reduced magnetic properties of a specific batch of Permendur, which, along with the extremely loaded teeth and backs along the induction cross section, caused saturation of the latter.

2. By the use of annular winding that covered the back of the magnetic circuit. In this case local saturations of the back are possible especially with an asymmetry of currents in the phases.

Self-ocoillation mode

As has been mentioned, tests of self-excitation with power output were obtained repeatedly for different values of capacitances [capacities], load and temperature of the liquid metal. The temperature of the machine was maintained close to the potassium temperature. Self-excitation was rigid, i.e., it only occurred in the presence of a preliminary recharge of capacitance up to 30-50 volts, which is associated with the inflection of the no-load curve at its beginning (figure 6). This inflection is caused by the effect of bridges of the covered [closed] slots. One of the self-excitation oscillograms is given in figure 7. In connection with the presence of preliminary recharge, the current of the phase, as is seen from the oscillogram, changes in jumps from zero. In the mechanical test model of an asynchronic MHD generator where the role of the conducting liquid is played by a copper-filled sleeve, self-excitation took place without needing a preliminary recharge of capacitance due to the absence of a small step at the beginning of the no-load curve.

Figure 8 shows the experimental dependences of the complte pressure differential at the generator as a function of the volume flow rate per second Q.

These dependences have the character of nearly vertical steep curves that are limited at the bottom by a dotted line that corresponds to pressure losses in the duct without application of the magnetic field. At a given flow rate self-excitation is possible if the applied pressure differential is greater than the corresponding values of the dotted line.

In this sense, the values of the differential which is defined by the curve of the hydraulic resistance in the absence of a magnetic field are critical.

A procedure was developed for recalculating the effective power, efficiency, and other indices for greater differential taking into consideration the real losses in the machines. Searching for the optimum modes (at a given differential) which assures the greatest efficiency in a specific manufactured machine is also important.

The indicated method of recalculation consists of the following:

Theoretical analysis of the value of the effective power taking into consideration the losses in the shell, the liquid metal, and the winding gives the expression:

$$P_{net} = \tfrac{1}{2}p_1 \tau \rho \ell V_{av}\left[-\frac{S+(\sigma_1\Delta_1)/(\sigma\Delta)}{(1-S)^2} - \frac{k_T^*}{Q^2}\right]\frac{M^2}{Re}k_{att} \qquad (14)$$

The coefficient k_T^* which defines the losses in copper is nearly a constant. In order to calculate the Joulean losses in the steel (charged magnetic circuit), it is possible to increase the value of the coefficient k_T^* to a certain value so that the value

$$\tfrac{1}{2}p_1 \tau \rho \ell V_{av}^3 \frac{M^2}{Re}k_{att}\frac{k_T^*}{Q^2} = P_{Cu} + P_{st} \qquad (15)$$

is developed to the sum of the losses in copper and steel P_{Cu} and P_{st} defined from the experiment for the nominal current of the phase. In other modes, of course, the taking into consideration of the losses in the steel for the constant k_T^* will be less than accurate, nevertheless, this is weakly connected to the values of the effective power due to the small absolute level of these losses.

From formula (8) where the viscous dissipation is presented in the form

$$P_{mp} = \tfrac{1}{2}p_1\tau\rho\ell V_{av}^3\lambda_0 = (\Delta p_{mp})Q$$

it follows that

$$\tfrac{1}{2}p_1\tau\rho\ell V_{av}^3\frac{M^2}{Re}k_{att} = \frac{(\Delta p-\Delta p_{mp})Q}{C_0-(S/[1-S])(1-C_1)} \qquad (16)$$

Here Δp is the full pressure differential at the generator, so that

$$P_h = \Delta p \cdot Q$$

Δp_{mp} is the part of the differential defined from the experimental dependence according to the flow rate Q in the absence of a magnetic field.

Thus, from (14), (15), and (16) it follows that the effective power is

$$P_{net} = -\frac{(\Delta p-\Delta p_{mp})Q}{C_0-\frac{S}{1-S}(1-C_1)}\left[-\frac{S+\frac{\sigma_1\Delta_1}{\sigma\Delta}}{(1-S)^2} - \frac{k_T^*}{Q}\right] \qquad (17)$$

and the internal efficiency is

$$\eta = \frac{-P_{net}}{P_h} = \frac{1-\frac{\Delta p_{mp}}{\Delta p}}{C_0-\frac{S}{1-S}(1-C_1)}\left[-\frac{S\ \frac{\sigma_1\Delta_1}{\sigma\Delta}}{(1-S)^2} - \frac{k_T^*}{Q^2}\right] \qquad (18)$$

The coefficient k_T^* in these relationships is defined on the basis of (15) and (16) as

$$k_T^* = \frac{P_{Cu}+P_{st}}{\Delta p-\Delta p_{mp}}\left[C_0 - \frac{S}{1-S}(1-C_1)\right] \qquad (19)$$

for several experimental fixed values P_{Cu} and P_{st}, Q, S, $\Delta p-\Delta p_{mp}$ after which the mean value is taken [assumed].

Formulas (17) and (18) containing the experimental values C_0, C_1, k_T^*, Δp_{mp} make it possible to determine rapidly the optimum values of the flow rate and slip which provides the most power for the greatest efficiency at a given differential Δp.

Figure 9 shows some experimental dependences of the effective power on the flow rate when Δp = 7.7-18 atm in a self-excitation mode. The dotted curve in the graph corresponds to the calculation following (17) for Δp = 12 atm and shows good coincidence with the direct experiment.

In these experiments the constant full pressure differential and the constant frequency of the self-oscillation corresponding to the synchronous rate Q_{syn} = 9.7 liters/sec was maintained along each curve. Therefore, for each flow rate there is found a corresponding slippage

$$S = 1 - \frac{Q}{Q_{syn}} \qquad (20)$$

and then P_{net}

The optimum values of the flow rate and slippage found for a specific generator are actually provided by the selection of the corresponding [appropriate] values of capacitance C and resistance of load (per phase). These values are calculated in the following manner.

Angular frequency

$$\omega = \frac{\pi Q}{F\tau(1-S)} \qquad (21)$$

where F is the cross section of the helical duct.

By uncovering in (16) the expressions for the M and Re numbers, it is possible to obtain the following for the amplitude of conduction in the gap defined by the current in the winding:

$$B_m = \sqrt{\frac{(\Delta p - \Delta p_{mp})\ H^2 \cdot 2\delta}{[C_0 - \frac{S}{1-S}(1-C_1)]\,\ell p_1 \tau Q \sigma k_{att}}} \qquad (22)$$

Here H is the width of the turn of the duct, 2δ its gap in [along] the liquid metal.

The current and voltage of the phase are defined by the known relations (for example [ref. #7]):

$$J = \frac{4K_E p_1 \delta K_{pr} B_m}{3WK_{ab}\mu} \qquad (23)$$

$$U = J\sqrt{\left[r_1 + \frac{3(WK_{ab})^2\tau\ell\mu\omega}{2\pi\sqrt{2}K_E p_1 \delta K_{pr}}\ \frac{R_m}{1+R_m}k_{att}\right]^2 + \left[X_s\ \frac{3(WK_{ab})^2\tau\ell\mu\omega}{\pi\sqrt{\ }K_E p_1 \delta K_{pr}}\left(1 - \frac{R_m^2}{1+R_m^2}k_{att}\right)\right]} \qquad (24)$$

The sought resistance of phase (at ohmic loading) is

$$r_{load} = \frac{-P_{net}}{3J^2} \qquad (25)$$

The power of the battery of capacitors is obviously equal to

$$P_{kvar} = \sqrt{(3UJ)^2 - P_{net}} = 3U^2\omega C \qquad (26)$$ [kvar = kilovoltampere reactive]

The testing of the machine in the pump mode with power from the mains yielded the following results: head [pressure] 4.6 atm, flow rate 1.15 liters/sec, phase voltage 160 V, frequency of mains [power network] 77 Hz, efficiency 20.5 per cent at a temperature of 300°C. In the other mode— 7 atm, 0.78 liters/sec, 160 V, 50 Hz, temperature 300°C, efficiency 18.5 per cent. An increase in the potassium temperature to 500°C reduced the defferential to 4.4 atm in the same mode.

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8.

Figures

1. Overall view of the experimental model of a liquid-metal MHD generator.

2. (a) Dependence of the loss of steel on the ratio of phase voltage to frequency.
(b) Dependence of complete loss in steel by a bent duct and additional (losses) on temperature with a constant phase voltage (curves 1,2,3,4,5,6,7,8,9,10,11, and 12 correspond to 160V, 150V, 140V, 130V, 120V, 110V, 100V, 90V, 80V, 70V, 60V, and 50V).

3. Dependence of Joulean loss in metal on flow rate.

4. Dependence of the coefficient $\dfrac{\lambda_m - \lambda_o}{\frac{M^2}{Re} k_{att}}$ on the parameter $S/1 - S$

5. Influence of the velocity profile on the value for the constant C_0 leading to the coefficient for resistance λ_m.

6. Dependence of the amplitude of the resulting induction in the gap on a magnetizing current.

7. Self-exciting generator oscillogram.

8. Dependence of complete pressure drop on flow rate for various generator temperatures operating during constant capacity in a no load regime.

9. Dependence of effective power on the resistance of the load and flow rate at a constant pressure drop in the generator.