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SYMPOSIUM FOR THE GENERATION OF ELECTRIC POWER BY MEANS OF MHD GENERATORS

Warsaw, 24-30 July 1968

TRANSLATION of PAPER

INVESTIGATION OF A LIQUID-METAL JET MHD GENERATOR

by

K.I. Dmitriyev, E.A. Zotova, I.A. Ivanov, V.S. Presnyakov and F.R. Ulinich

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INVESTIGATION OF A LIQUID-METAL JET MHD GENERATOR

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ABSTRACT

The use of a free liquid-metal jet emitted from an accelerating nozzle with a velocity of ~ 100–150 m/s for converting kinetic energy into electrical energy makes it possible to reduce several times over the friction losses in the generator and to eliminate completely the losses in the conducti_ walls of the duct. However, the extraction of power from a free jet depends essentially on its stability in crossed magnetic and electric fields.

The paper deals with an experimental study on the use of a free jet for MHD energy conversion.

The results are given of experiments with a jet MHD generator employing a liquid-metal sodium circuit under different operating conditions (no-load, short-circuit, various loads).

During the experiments the magnetic field was varied in the range 0–0.62 T and the velocity in the range 0–30 m/s. Each experiment was conducted with a constant magnetic field.

In order to assess the operation of the generator two efficiencies were introduced, for:

(a) The overall efficiency of the generator

$$\eta_1 = \frac{U.I}{\Delta p.Q}$$

where Δp is the pressure developed by the pump,
Q is the flow rate of metal through the circuit,
U and I are the voltage and current under load;

(b) The efficiency of conversion of the kinetic energy of the jet into electrical energy

$$\eta_2 = \frac{U.I}{\frac{\varrho(V_h^2-V_k^2)}{2g}.Q}$$

where U, I and Q are as stated above,

V_h is the nozzle outlet velocity,

V_k is the generator outlet velocity,

ϱ is the density of the metal.

The efficiency values obtained experimentally for different generator operating conditions lie within the limits

$$\eta_2 \approx 10\text{–}40\%$$

$$\eta_1 \approx 5\text{–}25\%$$

The limits of stability for jet generator operation are determined and recommendations are given for increasing the efficiency of generators of this type.

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ABSTRACT

In this paper there are presented the results of experimental investigations of a jet MHD generator employing a liquid-metal sodium circuit in an open-circuit regime and at various loads.

The experiments were conducted under constant and linearly increasing magnetic fields along the length of the generator. Limits were determined for stable operation of the jet generator for both types of magnetic fields.

INTRODUCTION

From the evidence by D. Elliott, the basic principle of liquid-metallic MHD-converters by various investigators has lead to a search for the most suitable scheme for conversion, in general, and for the design of a duct, in particular.

Analysis of various schemes has shown that greatest efficiency may be achieved by utilizing a two-component cycle with separation (Ref. 1). Experiments conducted indicate that if an η_{nozzle} reaches ~90 percent, then the efficiency of two other components of the separator generator schemes are still inadequate in a region of 50 percent along the energy flux (Ref. 2 and 3). In the separator this occurs in consequence of a major loss in the friction of the metal coating on an inclined surface. Losses in the generator accumulate from hydraulic loss (losses in the intake and output ducts and losses in friction of the duct walls) and electrical (terminal losses, losses in the conducting walls, and others).

For increasing the effectiveness of these nodes, it is necessary in the first place, to reduce the hydraulic losses. The best means of separation will be separation due to inertial force when the metal forms immediately in the jet at the nozzle exit. In this case, the hydraulic loss in the friction in the separator is completely eliminated, and the effectiveness may reach high values. However, experimental investigations of such separation devices have only just begun.

More reasonably, from the point of view of increasing the effectiveness of the generator, is the immediate conversion of kinetic energy produced as a result of the separation of the jet of metal to electric energy. In the jet generator scheme, it is possible to completely avoid the two most substantial kinds of loss; i.e., the loss of friction in the duct walls, and the electrical loss in the conducting walls. In addition, ~~terminal~~ end loss may be reduced by either increasing the length of the generator, or by utilizing ~~an~~ insulating partitions at the exit ~~portion in the terminal zone.~~ In this manner, it is theoretically possible to realize separators and generators with high coefficients for energy conversion. A combination of the most effective cycle (a two-component cycle with separation) and equipment elements with minimal loss include:

1. A right-angle acceleration nozzle
2. An inertial separator
3. A jet generator

which may lead to a more reasonable system of liquid-metal MHD converters.

In this paper, the first experimental results are given for one node of this scheme - the jet generator.

EXPERIMENTAL TASK

There has been extremely little experimental work on the behavior of a jet in a magnetic field, and there is no data on the extraction of electric power by a jet. The first problem was the obtaining of electric power in a jet generator and observing the behavior of the jet in a constant and linearly increasing magnetic field along the length of a generator at various velocities for the metal, at various loads, and at various geometries of the nozzle and electrodes. In the second stage of the investigation there is a decided interest in the experiment with profiling along the length of the generator by a magnetic field, in a duct with terminal partitions, with profiled electrodes.

EXPERIMENTAL METHOD

In the basic one-dimensional theory of F.R. Ulinich and I.B. Stechkin interesting results were obtained on the behavior of jet incompressibly conducting liquids in a crossed magnetic field with the extraction of power.

Two cases were theoretically examined:

1. A constant magnetic field along the length of the generator B=const
2. A profiled magnetic field, in this case, constant along the length of the generator, the parameter BV=const remains.

The equation for motion for both cases is written as:

$$\rho v \frac{dv}{dx} = -\frac{jB}{c} \qquad \text{(I)}$$

for the initial condition $x=0$, $u=v_0$.

Solving the equation together with Ohm's law $j = \sigma\left(E_y - \frac{vB}{c}\right)$ for the case B=const, a rule for the distribution of velocity produced the following:

$$V = V_0\left(1 - \frac{x}{L_{T0}}\right) \qquad (2)$$

where $L_{T0} = \frac{\rho V_0 c^2}{\sigma B_0^2}$ the length of the braking.

The electrical efficiency of the generator is expressed by the folrmula

$$\eta_{эл} = \frac{3}{2}\frac{u}{V_0} \quad (\text{при } u \ll V_0) \qquad (3)$$

where u is the velocity at the generator output.

In this manner, from the examined equation for $\eta_{эл}$ it can be seen that the effective braking of the jet with high efficiency, when B=const, fails.

When examining the case for a profiled field VB=const a change in velocity along the length of the generator has the aspect of:

$$V = V_0\sqrt[3]{1 - 3\kappa\frac{x}{L_{T0}}}$$

in addition $\quad K = \dfrac{1}{1 - \frac{\delta}{R\sigma\lambda}} \quad$ the load factor

where 2δ - the width of the duct

2λ - the length of the duct

R - resistance of the load.

For electrical efficiency:

$$\eta_{эл} = \frac{K}{K-1} \qquad (5)$$

A justification for utilizing a one-dimensional theory shall be seen from an examination of the experimental data. For the characteristics of the operation of the generator there were two efficiencies introduced making it possible to determine, on the one hand, the effectiveness of the conversion of the kinetic energy of a jet to electrical energy

$$\eta_1 = \frac{uI}{\frac{\rho(V_0^2 - u^2)}{2g}Q} \qquad (6)$$

where U, I - the voltage and current under the load

Q - the consumption of metal through the circuit

ρ - the density of the metal

and, on the other hand, the general effectiveness of the generator

$$\eta_2 = \frac{U I}{\Delta p \cdot Q}$$

where U, I, Q - have the same values as stated above

Δp - pressure generated by the pump.

DESCRIPTION OF THE WORKING DUCT

Experiments were conducted on a sodium circuit, the schematic and description for which can be found in Ref. 4. Installed in the circuit is a jet generator consisting of a body in which electrical insulation is installed for the electrodes and the nozzle for the creation of a jet of liquid metal. After the passage of the working duct, the jet hits the overflow capacity which supports an excess pressure of $\sim$1.5 atm for the security of the stable regime of the centrifugal pump. The body of the generator has a quartz window through which observations are conducted for the behavior of the jet in various regimes. In the experiments there was employed a 3-dimensional pump with an output section, in mm, of:

I) 26x3 ;   2) 20 x 55 ;   3) 26 x 7,2

Electrical energy was removed from the jet through a system of electrodes in the circuit in the capacity of which there were utilized standard bypasses in the current of 500a, 1000a, 2000a, and 5000a.

For determining the characteristic of the generator at various conditions, measurements were conducted of the discharge, the dynamic pressures at the input to the nozzle and at the output of the duct, the current and voltage on the load, and a measurement of the strength of the magnetic field. In Fig. 1 there is shown a change in the linearly--expanded field along the length of the generator at various values of current excitation.

EXPERIMENTAL RESULTS

In Fig. 2-4 the experimental values of η_1 are shown depending on the velocity at the nozzle output and on the deterioration of velocity for instances of constant and linearly-increasing magnetic fields along the length of the generator. Although efficiency reaches values of ~ 60 to 70 percent, in separate regimes, from the illustrations it is clear that at significant braking of the jet, η_1 does not exceed 20 percent for the selected profile field and agrees with formula (3). Total efficiency in the experiment with various loads was basically velow 25 percent. In Fig. 5 and 6 there are presented the dependencies of dynamic pressure, operating in the generator, on the input velocity in a free-running regime for the example of magnetic field. The curves $\Delta p = f(v_0)$ in Fig. 6 make it possible to explain the obtaining of efficiency values of η_1 for various regimes. In Fig. 7 there is presented the dependence of on load during a change in the entry velocity. A zone of unstable regime was discovered for the generator at $\bar{B} = 4000$ gauss for various loads. The experiments conducted made it possible to detect the zones of unstable of generator operation at various values of the magnetic field.

In these instances it happened that the body of the generator was filled with sodium; this was observed through the quartz window. In Fig. 8 there is shown the zone of work of the jet generator for instances of constant and linear magnetic fields.

CONCLUSIONS

1. The effectiveness of a jet generator significantly depends on the profile of the magnetic field.

2. Experimentally obtained efficiency of the conversion of kinetic energy of a jet electrical is on an order of 60 percent.

3. The zones of unstable generator operation were determined at various fields and regimes.

4. A zone of unstable generator operation was discovered through the current at $\bar{B} = 4000$ gauss.

In conclusion, the authors express their gratitude to I.B. Stechkin for his assistance in a discussion of the results, and A.T. Glazov, M.I. Yemel'yanov, and Yu. A. Dodonov for providing the work on the sodium circuit.

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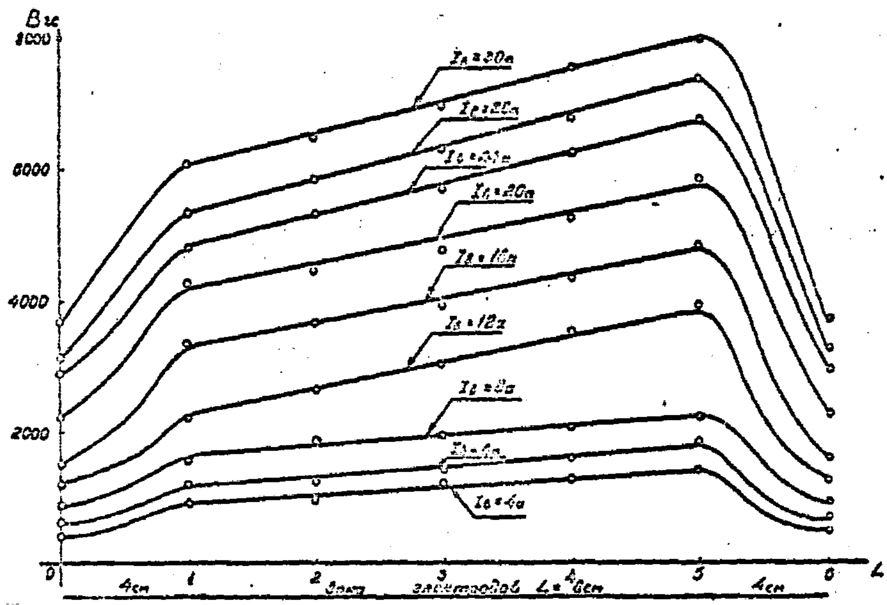

FIG. 1. Change in the linear magnetic field along the length of the generator from current excitation.

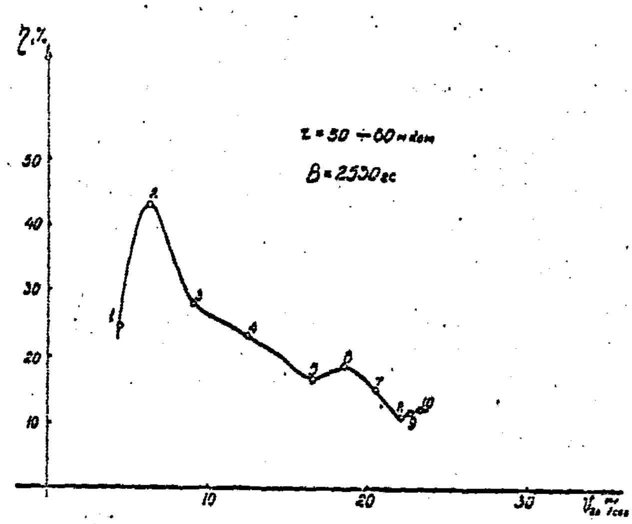

FIG. 2. $\eta_1 = f(v)$ when B = 2530 gauss.

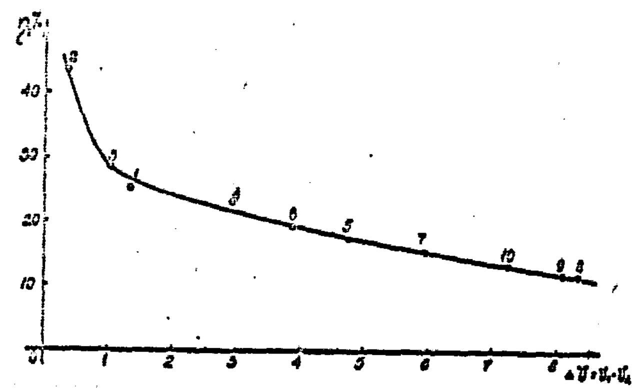

FIG. 3. Dependence of η_1 on the operating velocity at B = 2530 gauss.

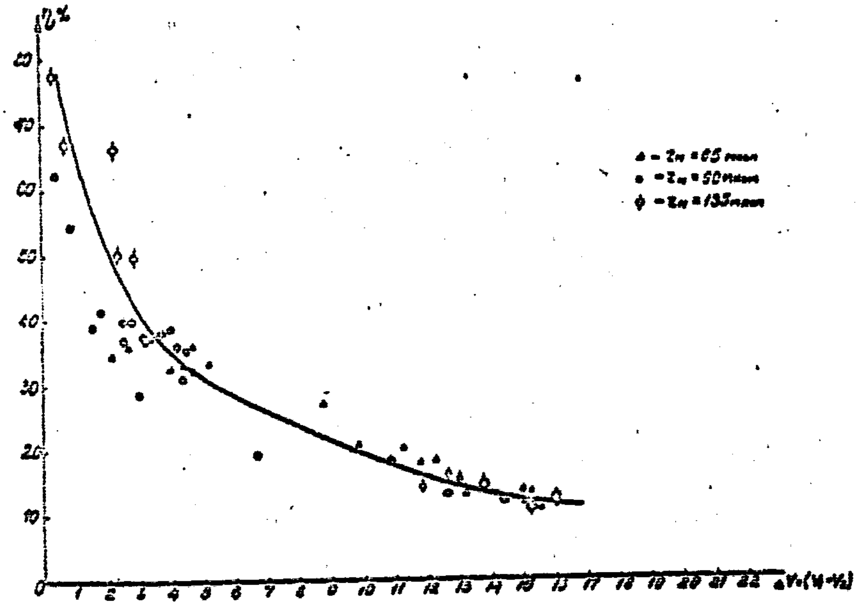

FIG. 4 Dependence of η_1 on the operating velocity in a linear field.

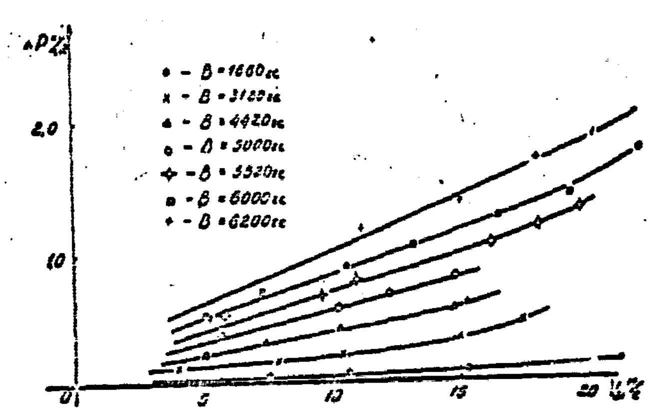

FIG. 5. $\Delta p = f(v_o)$ for B = const in a free load regime.

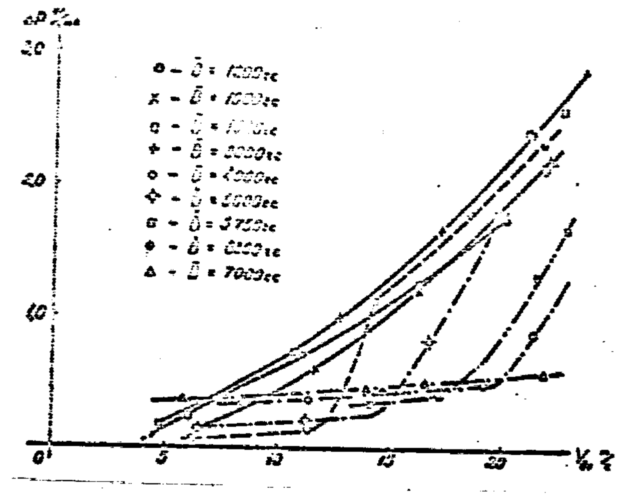

FIG. 6. $\Delta p = f(v_0)$ for a linear magnetic field in a free load regime.

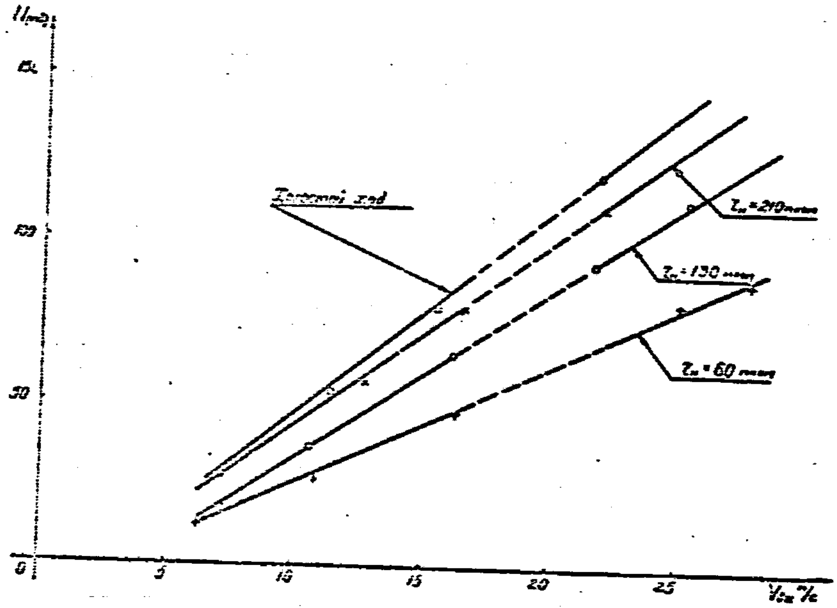

FIG. 7. Change of $U_{(\sim)}$ on load at $\bar{B}$ = 4000 gauss

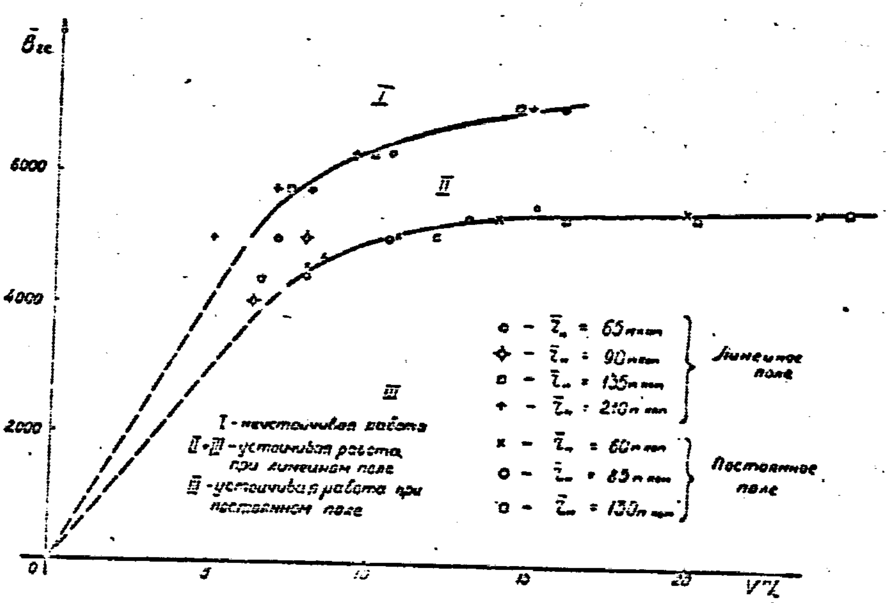

FIG. 8. Change of zone of unstable generator operation from the form of the magnetic field.