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STUDIES OF A REPETITIVE LIQUID METAL
SLUG MHD GENERATOR*

by

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Introduction

Liquid metal MHD generators coupled to liquid metal-cooled reactors are very promising as light, compact space nuclear electric power sources. One such concept is the two-phase nozzle proposed by Edwards⁽¹⁾ at Jet Propulsion Laboratory where a mixture of liquid and vapor expands through a nozzle; the expansion energy of the vapor appears as kinetic energy of a high velocity liquid-metal stream which is separated and flows through the generator. An alternative concept being studied at Brookhaven is the repetitive injection of liquid-metal slugs into the head of an MHD channel. The slug seals the channel and provides high conductivity, while the mechanical work of the expanding vapor is converted directly to electricity. The following advantages are possible:

1. High thermal cycle efficiencies (e.g., 20%) at relatively low-liquid velocities (e.g., 50 to 100 ft/sec).

2. An ac power output that can easily be transformed to desired load voltages.

An idealized generator is shown in Figure 1. A pulsating flow feeder, either a rotating valve or intermittent E-M pump, injects the slugs. When the injection pulse ends, high-pressure vapor pushes the slug through the generator. The liquid and vapor then exhaust to a condenser-radiator and after cooling are pumped back to the reactor boiler and generator inlet. Typically, 20 slugs/sec are injected. The generator is light and compact, and with no moving parts should have a long life. The characteristics of a typical 5 MW(e) generator are given in Table I. Four major phases were investigated: (1) cycle thermodynamics, (2) electrical performance and efficiency, (3) slug injection, and (4) slug stability.

Thermodynamics

The cycle is an intermittent-flow, piston-type expansion as shown in Figure 2. If it expanded to the same exhaust pressure as a turbine, it would have the same cycle efficiency, but the generator would be too large. Therefore, a comparative study was made of the thermodynamic efficiency of Rankine turbine and piston devices operating with the same inlet temperature and pressure, but with only partial expansion in the piston. The

expansion is completed by irreversible throttling to the condenser. The details have been published elsewhere⁽²⁾ and only the conclusions are given here. With moderate expansion ratios of $V_{\text{final}}/V_{\text{initial}} = 2/1$, ideal piston cycle efficiencies of 20% are possible (see Figure 3) at boiler temperatures of 2200°F and higher. A turbine would give about 30% efficiency. For a space cycle, however, system weight (which is predominantly radiator weight) is more important, and the piston value is only 5 to 10% greater than a turbine (see Figure 4). Thus the piston competes quite well with a turbine.

Electrical Performance and Efficiency

The problems of slug injection and stability are treated in a later section. Idealizing the equivalent electrical circuit of the generator to that in Figure 5a, the resulting current and velocity of the slug are described by

$$L \frac{di}{dt} + iR_T = vBh, \quad (1)$$

$$m \frac{dv}{dt} = -iBh + \Delta P \cdot A. \quad (2)$$

Solving for velocity, a second order differential equation is obtained:

$$\frac{d^2 v}{dt^2} + \frac{R_T}{L} \frac{dv}{dt} + \frac{B^2 h^2}{mL} v = \frac{A}{m} \frac{R_T \Delta P}{L}. \quad (3)$$

The slug is an electromechanical oscillator with energy stored as kinetic or inductive, and resistance as a damping factor. The transient solution for a slug is,

$$v(t) = v_{\infty} + E \exp(\omega^+ t) + C \exp(\omega^- t), \quad (4)$$

where the natural frequency of oscillation is given by:

$$\omega^{\pm} = -\frac{R_T}{2L} \pm \sqrt{\left(\frac{R_T}{2L}\right)^2 - \omega_o^2} \quad \omega_o^2 = \frac{B^2 h^2}{mL}, \quad (5)$$

and the current is:

$$i(t) = i_{\infty} + \frac{m}{BL} [\omega^+ E \exp(\omega^+ t) + \omega^- C \exp(\omega^- t)], \quad (6)$$

where the solution for velocity and current at infinite time are:

$$v_{\infty} = \frac{\Delta P \cdot A \cdot R_T}{B^2 h^2}, \quad (7)$$

$$i_{\infty} = \frac{\Delta P \cdot A}{Bh}. \quad (8)$$

Constants E and C are derived from boundary conditions for i and v at t=0. Figure 6 shows the solution for a slug injected at the head of the MHD channel. The initial values of i and v are assumed zero. Generator parameters are the same as in Table I. Inductance of the channel was assumed the smallest possible value, that corresponding to the return current bus bars

dividing to return on both sides of the channel. Even with the minimum inductance, it takes 10 milliseconds for current and velocity to reach 95% of their infinite steady-state values. During this time the slug travels 10 inches. If the oscillation is excessive, it will be necessary to decrease the channel height. A height of three instead of 6 inches lowers the time to reach 95% of steady-state to 2.5 milliseconds, and also decreases the magnitude of the oscillations.

The velocity overshoot occurs because the current is inductively limited, and this in turn produces a current oscillation. This can easily be smoothed by the load. Probably the main problem is the effect of the higher velocity slug.

After the slug reaches constant velocity, assuming that electrodes are spaced along the channel with a spacing equal to slug length, and that there is perfect commutation, the output will be an ac square wave of frequency,

$$f = \frac{v_{\infty}}{4d} \quad (9)$$

However, since the channel walls between electrodes are not perfect insulators, and the slug leaves a finite film behind it on the channel walls, a short circuit occurs as the slug leaves one electrode pair and touches the next. Some of the current generated in the slug can bypass the load. For example, in

Figure 1, current can exit from the slug through electrode 1A and return through 2B (to which it is connected) without passing through the load. In the more realistic equivalent circuit of Figure 5b, it can be seen that if the wall film has the same resistance as the load, 50% of the generated current will be lost. The magnitude of this effect must be found experimentally. If short circuits are too great, successive electrode pairs must be electrically isolated; i.e., 1A, B, 3A, B... are coupled to one transformer while 2A, B, 4A, B are coupled to another. The wall film will then have a sufficiently high resistance, but the generator requires two transformers and will be heavier.

An experimental single mercury slug generator was constructed and tested. The slug was initially at rest on a fine frit through which gas, but not liquid, could pass. Helium at 30 to 60 psi was admitted to a plenum below the frit by a valve that opened in several milliseconds. The slug accelerated up a channel past successive electrode pairs, generating an ac power output in a pure resistive load which varied from 1 to 10 times slug resistance. The channel was constructed of Lucite with copper electrodes 1 in. long imbedded in it. The electrodes were separated by 2 in. of Lucite insulator. The

generator was 0.75 in. high, 2.5 in. wide, and 22 in. long. Output voltage and current (the latter by a calibrated shunt) were measured, and instantaneous gas pressure was followed by a fast response transducer. Scope pictures were taken and subsequently analyzed. Several hundred slugs were run under a variety of conditions. Results were reproducible, varying about $\pm 10\%$ for the same conditions. Typical results are shown in Figures 7 to 14.

Figure 7 shows the current curve obtained for a 3 in. slug accelerated by a pressure differential of 50 psi in a magnetic field of 12,000 gauss. Total circuit resistance was 5×10^{-4} ohms, 4 times the slug resistance. Note particularly:

1. The pressure drops abruptly as the gas penetrates the slug.
2. Output current is increasing in frequency and magnitude until break-through -- the slug is still accelerating.
3. A true square wave is not obtained. The L/R time constant is 0.3 millisecond, so the current rise is not limited by inductance, but must rather be limited by short circuit currents.

At the current peaks, current is within a few % of the value predicted from

$$i = \frac{vBh}{R_T} , \quad (10)$$

where v , B , h , and R_T are independently measured values. Current peaks occur approximately midway in time between current nulls, indicating that the peak corresponds to a slug centered on an electrode. This agrees with the prediction that short circuits in the wall film will be most important when the slug is commutating between successive electrodes, and least important when it has the best contact with a given electrode pair. More evidence of wall film shorting is shown in Figure 8, which compares current traces for a 2 and 5 in. slug. The latter is short circuited for the first few electrode pairs, until it is short enough (2 to 3 in.) that the current is forced to go through the load. In these experiments, a wall film 20 mil thick will short out 50% of the generated current if the slug is 1/2 in. past the electrode. Slug loss rates indicate an average wall film thickness of 40 mil if all the lost liquid remains on the wall, so that short circuits are probably responsible for the deviations from square-wave output. Considering the small dimensions of the generator and the high fluid density, it is remarkable that so little short circuiting occurred. In a larger generator with greater inter-electrode spacing and thinner wall films, it is not likely that short circuiting will be a problem. If it is, then isolated load circuits must be used.

Typical slug velocity curves are shown in Figure 9. Measured velocities are derived from the slope of the position vs time curve. Positions are obtained by assuming that a current null corresponds to a slug midway between successive electrode pairs. Slug acceleration is derived from the pressure vs time trace, and integrated to give a predicted velocity. Agreement between measured and predicted values is within $\pm 10\%$ for most cases. In this experiment, the slug never reaches constant velocity. This implies that most of the work done by the expanding gas goes to kinetic energy of the slug. Maximum slug velocity reached was about 50 ft/sec, or one-half design value.

Typical voltage curves are shown in Figure 10. Measured voltage is defined as

$$V_m = I_{\text{peak}} R_T, \quad (11)$$

where peak currents are used, and predicted voltage as:

$$V_p = V_m B_h. \quad (12)$$

Again, agreement for most cases is within $\pm 10\%$, indicating that short circuiting is minor when slugs are centered on an electrode pair.

Typical power output curves are shown in Figure 11.

Power input is defined as:

$$W_{in} = \Delta P \cdot A \cdot v_m, \quad (13)$$

and is the mechanical work done by the expanding gas. Measured power output is defined as all joule losses in the slug, bus bars, and external load

$$W_m = I^2 R_T. \quad (14)$$

The absolute efficiency is small (10 to 20%) because most of the input appears as kinetic energy of the slug. A better comparison is between measured and predicted power output

$$W_p = \frac{(vBh)^2}{R_T}, \quad (15)$$

which is the maximum the generator can deliver. Here, about 50% of the predicted output is obtained, the rest being consumed mainly in short circuits. When the slug is centered on an electrode pair, the predicted power is obtained, but when it is commutating, much less is generated. A maximum of approximately 2 kW (2000 amp at 1 volt) was obtained with this generator.

Integrated power is shown in Figure 12, and it is again evident that about 50% of predicted output is obtained.

In Figure 13, generator efficiency is plotted vs slug length for two different external loads. Efficiency (the ratio

of measured to predicted power) is constant for slug lengths up to 3.5 in. after which it decreases due to greater short circuiting. This indicates that slug length is not critical in a practical machine, and that it can be safely made 50% greater than the inter-electrode spacing. The reason for the markedly lower external load efficiency with lower external load resistance is not clear. The current is proportionately less as compared to the high resistance cases. Figure 14 shows the effect of driving pressure on efficiency. The low pressure, short slugs have abnormally low efficiency probably because instabilities have much longer to grow, allowing premature penetration of the slug by gas.

Slug Injection

A water model generator was built to test the principle of repetitive slug injection. Up to 5 slugs/sec were injected and blown out of the channel. This was the maximum rate possible, since the pressure available (60 psi) was not sufficient to cycle the liquid column any faster. High speed movies were also taken of single slugs injected into the same apparatus. Since the inertia of the water slug was less, slugs could be satisfactorily injected and then blown out in ≈ 0.1 sec, a rate equivalent to 10 slugs/sec. Faster injection caused excessive

oscillation and turbulence of the slug. This can undoubtedly be reduced by a better injection grid; in this experiment, only 50% of the grid was open flow area. A grid designed to gradually increase porosity to near 100% at the surface, could smoothly decelerate the high velocity injected liquid and prevent jetting.

Slug Stability

Two processes tend to destroy the slug: the Rayleigh-Taylor instability, and film left on the wall by friction drag. In the first, the body force on the slug (either acceleration or JXB) equivalent to a gravitational force directed towards the free surface between liquid and driving vapor. Any perturbation on this surface grows with eventual penetration by the vapor. The low pressure surface is stable; any perturbation will die out. Solving the linearized hydromagnetic equations for an arbitrary perturbation of amplitude and wave number K , we assume an exponential growth constant n where

$$\xi(t) = \xi_0 \exp(iKx + nt), \quad \xi \leq K^{-1}. \quad (16)$$

The ordinary hydrodynamic dispersion solution is found for wave vectors perpendicular to the field as

$$n = (gK)^{\frac{1}{2}}. \quad (17)$$

For K parallel to the field and the condition $\frac{\sigma B^2}{\rho n} \gg 1$, a hydromagnetic dispersion relation is found:

$$n = \frac{g^{2/3} K^{2/3} \rho^{1/3}}{B^{2/3} \sigma^{1/3}} \quad (18)$$

For displacements $\xi \geq K^{-1}$, a non-linear solution is found,

$$V = \frac{d\xi}{dt} = (g/K)^{1/2}, \quad K \perp B, \quad (19)$$

$$V = \frac{d\xi}{dt} = \frac{\rho g}{\sigma B^2}, \quad K \parallel B. \quad (20)$$

If K is at an angle with B the effective component of B in equations (18) and (20) is $B \cos(\text{angle})$.

Figure 16 shows the penetration velocities as a function of displacement for a slug subject to a 2000 g body force, a generator field of 20,000 G, and a perturbation of 12 in. wavelength, the largest and fastest growing that can exist in the generator.

This analysis indicates that unless the perturbation wave vector is parallel to B , vapor will penetrate the slug. A real disturbance will be two-dimensional in character, and it may be sufficiently restrained by the field. In the single slug generator tested, a 4 in. slug travelled 20 feet before breakup (see Figure 17), lasting longer than predicted either by the hydrodynamic or hydromagnetic models. In tests on the

Rayleigh-Taylor instability it was observed that initial perturbations of wavelength much shorter than channel dimensions grew at rate within $\pm 20\%$ of theory, but these disturbances were ultimately wiped out by one of wavelength comparable to channel size. One of the shorter wavelength perturbations grew horizontally as well as vertically, destroying all other perturbations until it encountered the wall. It then grew at a rate of $< 1/4$ that predicted by theory, probably because of the restraining wall friction.

Experiments were carried out on single water slugs accelerated at 150 g. High speed movies showed that 80% of the slug loss (Figure 18) was due to wall film and only 20% to the short wavelength instabilities. A 6 in. slug would have travelled 4 ft before breakup, and with a slug of smaller surface volume ratio characteristic of a 5 MW(e) generator, 20 ft.

Vapor Condensation on Slug

An additional problem, is of a practical nature, that the slug must be at condenser temperature if it is not to boil on the low pressure surface. This means that vapor will tend to condense on the high pressure surface since it is colder than the boiler temperature, and on the walls cooled by passage of the slug. A pure condensing vapor would cause too

great a thermal loss. This can be held to a reasonable amount by adding a small amount (e.g., 2%) of a non-condensable gas like argon to the vapor. Figure 19 shows the losses that can be expected for diffusion through a thin argon film. The minimum loss, 3 MW(th), or about 10% of the available energy occurs for a film 0.5 mil thick, which be hydrodynamically stable. Losses considered were: diffusion through the gas film, condensation necessary to establish the film, and pumping power for the argon.

Summary and Conclusion

With a relatively small generator, an ac output 60% of that predicted by theory was obtained with slugs that travelled about 2 ft under a net driving pressure of 50 psi. Short circuits at commutation were probably the cause of the low output. In a larger generator, this should not be a problem, but separate load circuits can be used if necessary. A larger generator and magnetic field should considerably extend the slug travel distance. An equivalent slug injection frequency of 10/sec was satisfactorily demonstrated, as compared to the 20/sec for a typical design. Better grids should permit higher injection frequency.

This generator concept seems quite promising but more

experiments are needed, particularly with alkali metal in a larger, say 20,000 G field, in larger channels.

REFERENCES

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2. Chang, P. C. and Powell, J. R., AIAA Journal 3, p. 754 (1965).

NOMENCLATURE

A	Area of channel.
B	Magnetic field.
d	Inter-electrode spacing.
g	Equivalent gravitational field.
i	Current in slug.
J	Current density.
K	Wave number.
h	Width of channel.
L	Self-inductance of channel.
m	Mass of slug.
n	Exponential growth constant in Rayleigh-Taylor instability.
ΔP	Driving pressure for slug.
R_i	Internal resistance of slug.
R_L	External load resistance
R_ω	Resistance of channel wall.
R_{film}	Resistance of wall film.
R_T	Total resistance of circuit.
t	Time.
v	Velocity.

V Voltage.
 ξ Displacement.
 ρ Density.
 σ Conductivity.
 ω_0 Undamped oscillation frequency of slug.
 ω' Damped oscillation frequency of slug.

TABLE I

TYPICAL GENERATOR PARAMETERS USING POTASSIUM

OPERATING CONDITIONS

Output	5 MW(e)
Ideal cycle efficiency	20%
Real cycle efficiency	16%
Generator efficiency	80%
Vapor inlet temperature	2400°F
Vapor inlet pressure	430 psi
Vapor volume expansion ratio	2/1
Final pressure	200 psi
Condenser pressure	15 psi
Condenser temperature	1400°F

GENERATOR

Height	0.5 ft
Width	2.0 ft
Length	5.0 ft
Electrode length	0.5 ft
Inter-electrode spacing	0.5 ft
Number electrode pairs	4

TABLE I - Continued

SLUG

Height	0.5 ft
Width	2.0 ft
Length	0.5 ft
Mass	20 lb
Velocity	100 ft/sec
Injection frequency	20 slugs/sec
Injection time	25 milliseconds
Transit time	50 milliseconds

ELECTRICAL PARAMETERS

Magnetic field	24,000 gauss
ac output frequency	42 cycles/sec
Internal resistance	$5.2 \times 10^{-5} \Omega$
External resistance	$2.6 \times 10^{-4} \Omega$
Wall resistance	$3 \times 10^{-3} \Omega$
Developed voltage	43 volts
Current	1.4×10^5 amp
Slug kinetic energy	4200 joules
Slug inductive energy	2000 joules
Natural frequency	100 cycles/sec
Generator weight	~0.5 lb/kW(e)

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Fig. 1 Repetitive liquid metal slug MHD generator.

Fig. 2 PV plot of potassium vapor expansion in piston generator.

Fig. 3 Thermal cycle efficiency vs boiler temperature for piston and turbine expansion of potassium vapor.

Fig. 4 Radiator weight vs boiler temperature for piston and turbine potassium vapor cycles.

EQUIVALENT ELECTRICAL CIRCUIT FOR GENERATOR

A. IDEALIZED

B. ACTUAL

Fig. 5 Equivalent electrical circuit of generator.

Fig. 6 Electromechanical oscillations vs time of slug in generator.

Fig. 7 Typical current output vs time of experimental generator.

CURRENT OUTPUT VS SLUG LENGTH FOR MHD GENERATOR-SINGLE SLUG OPERATION

Fig. 8 Current output vs time for two different slug lengths in experimental generator.

Fig. 9 Measured and predicted slug velocity vs time.

Fig. 10 Measured and predicted voltage output vs time.

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