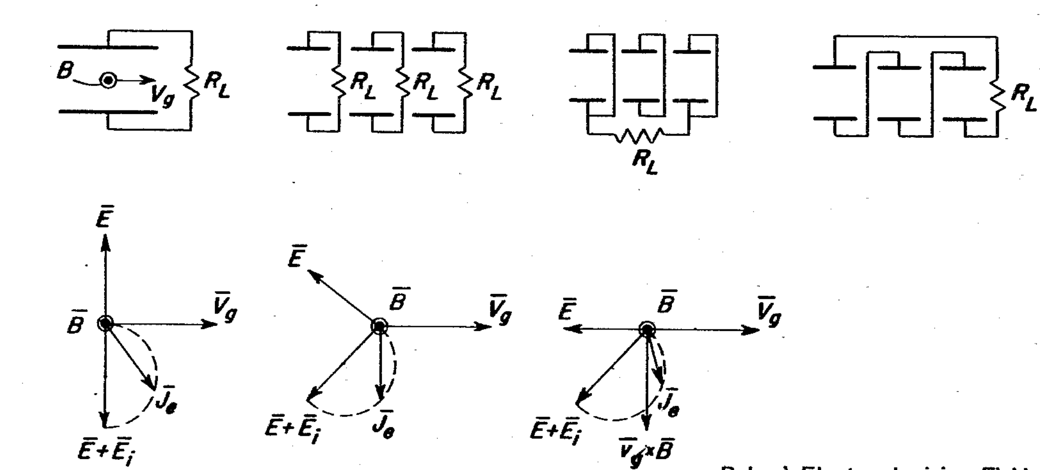
Nov. 28, 1967 E. C. OKRESS 3,355,605
CROSSED FIELD PLASMA DEVICE
Filed Sept. 23, 1963 9 Sheets-Sheet 1

Fig. IA. Fig. IB. Fig. IC. Fig. ID



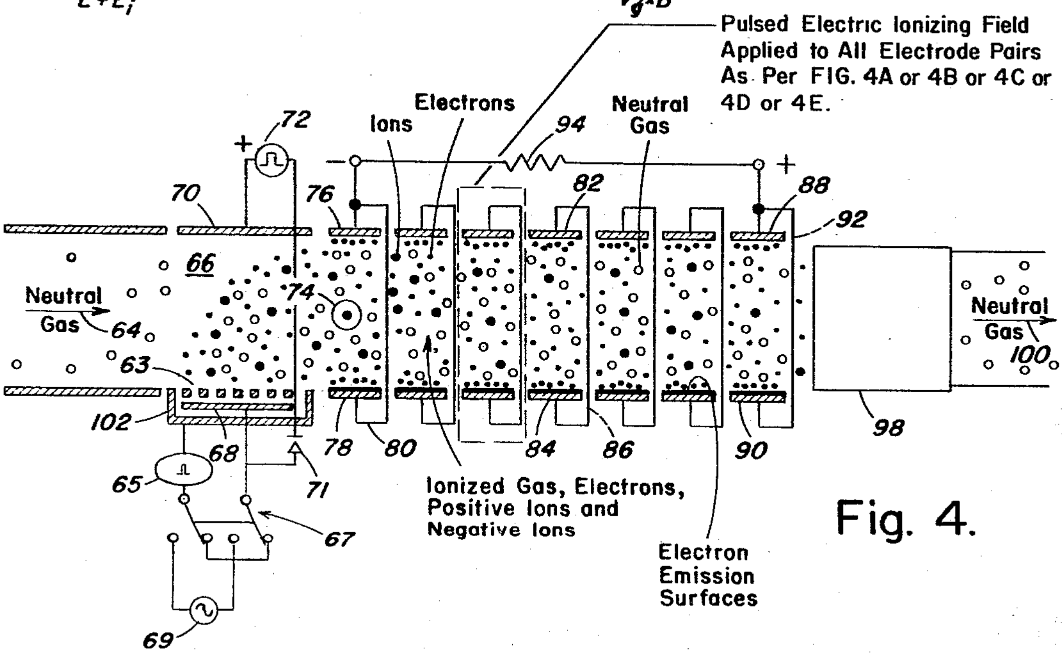


Fig. 4.

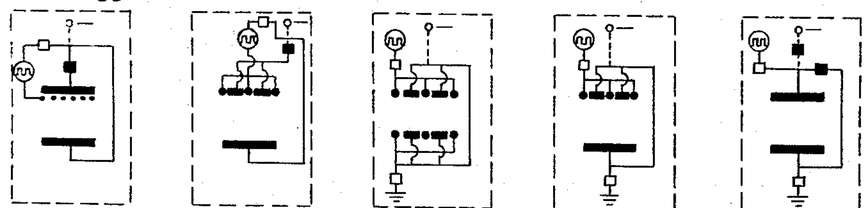


FIG. 4A FIG. 4B FIG. 4C FIG. 4D FIG. 4E

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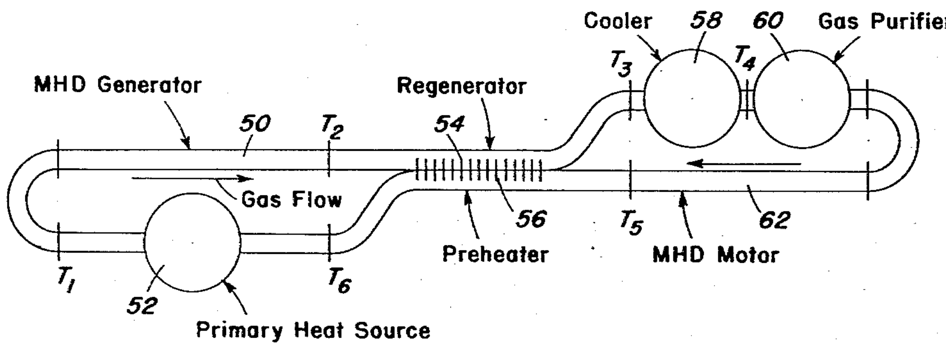

Fig. 2.

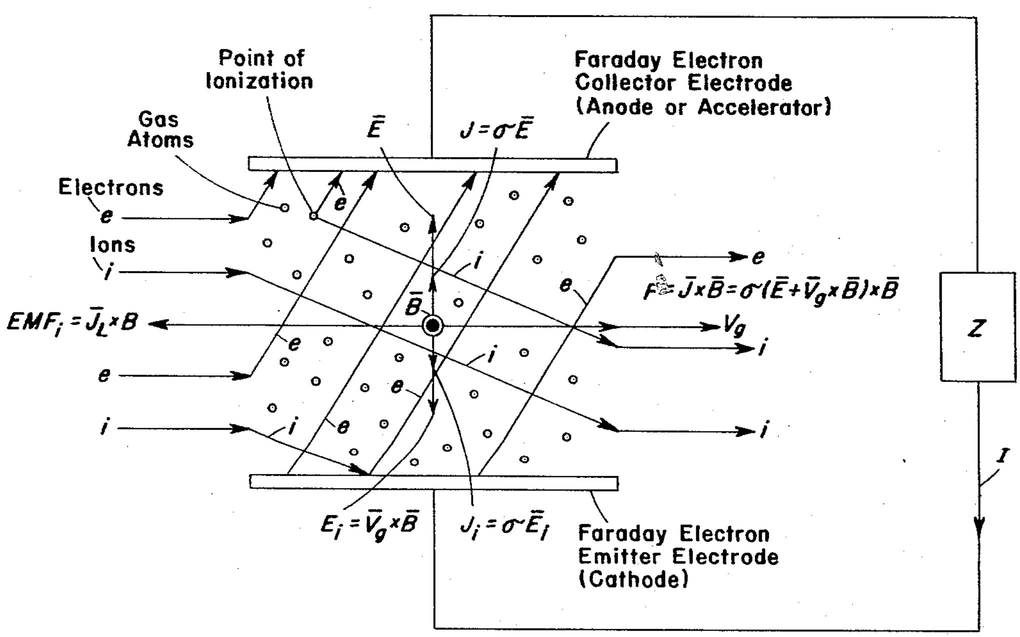

Fig. 3.

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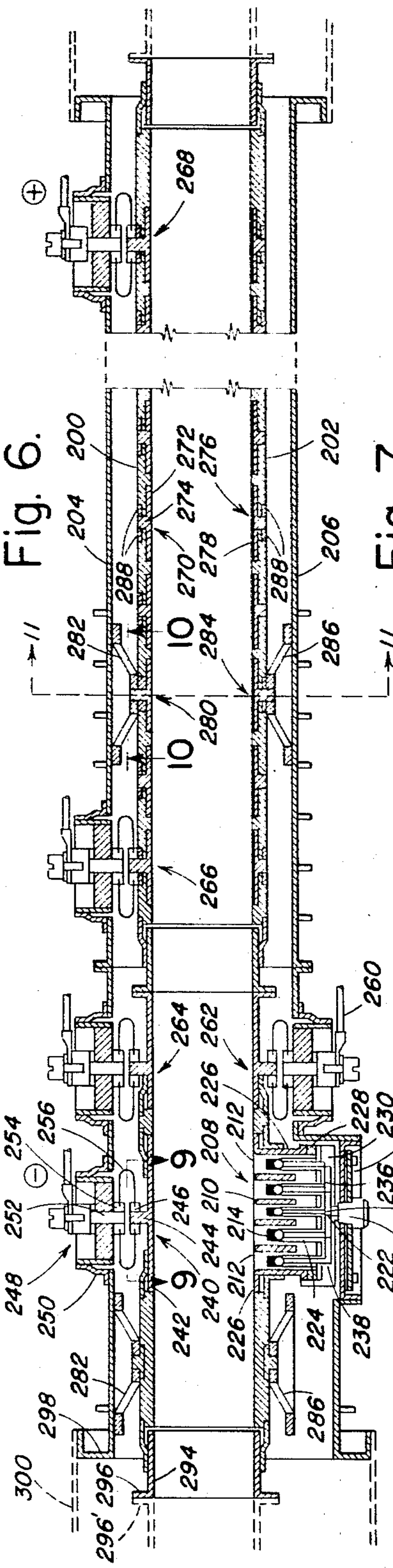

Fig. 6.

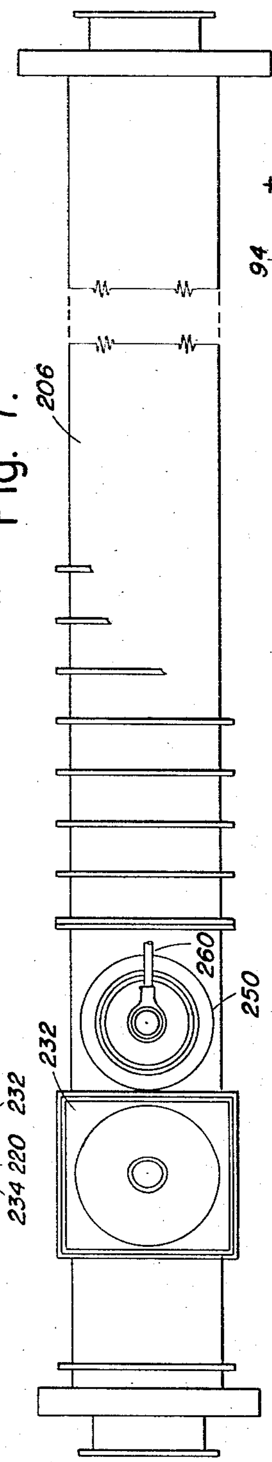

Fig. 7.

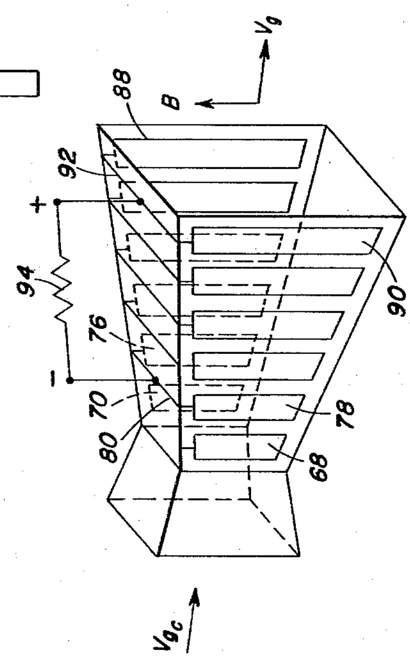

Fig. 5.

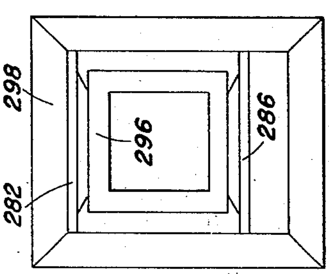

Fig. 8.

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CROSSED FIELD PLASMA DEVICE

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Fig. 14.

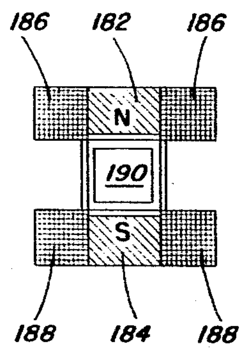


Fig. 11.

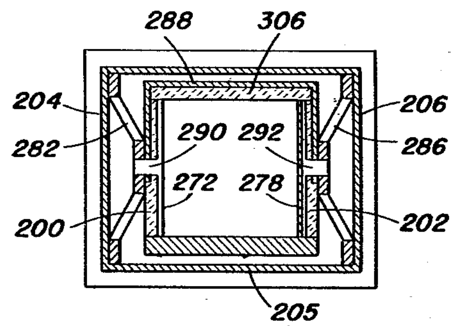


Fig. 13.

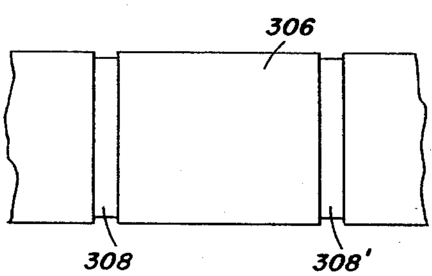


Fig. 10.

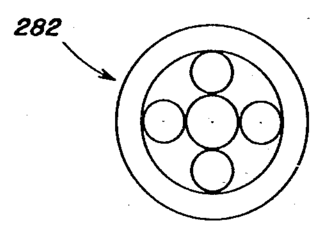


Fig. 12.

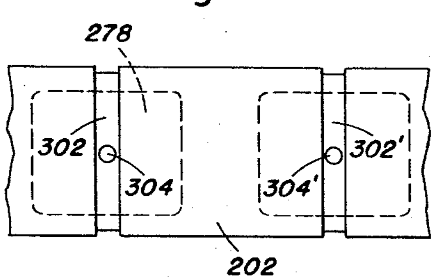
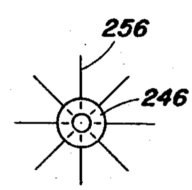


Fig. 9.



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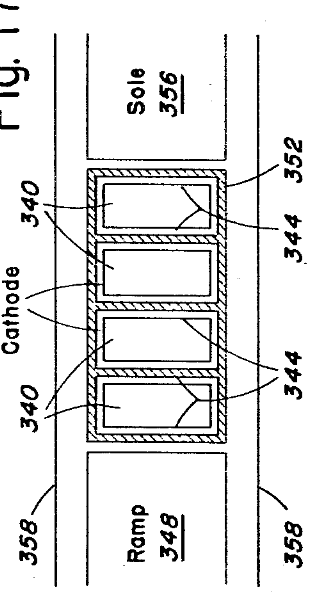

Fig. 17.

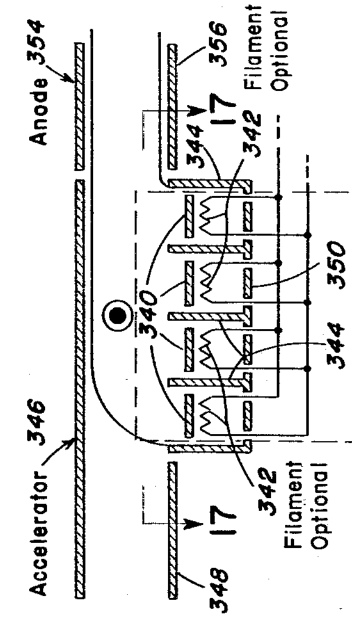

Fig. 16.

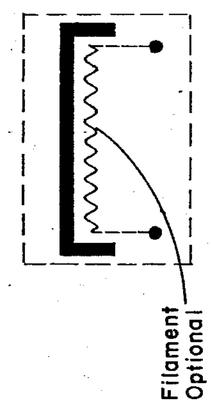

Fig. 16a

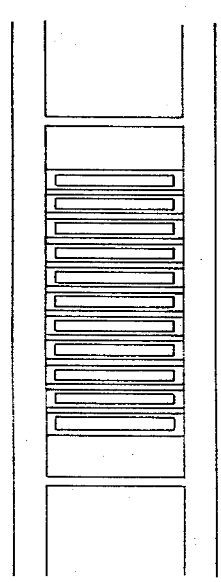

Fig. 19.

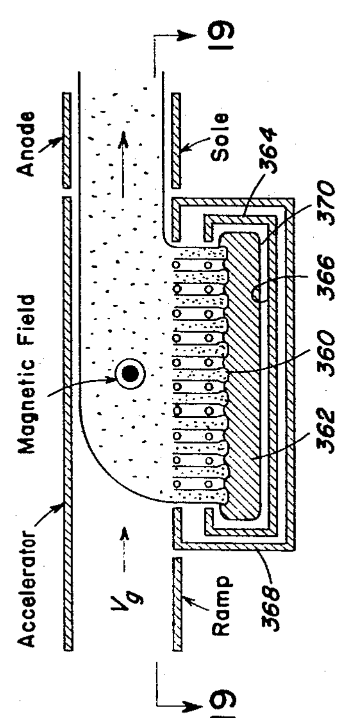

Fig. 18.

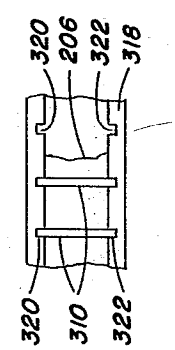

Fig. 15.

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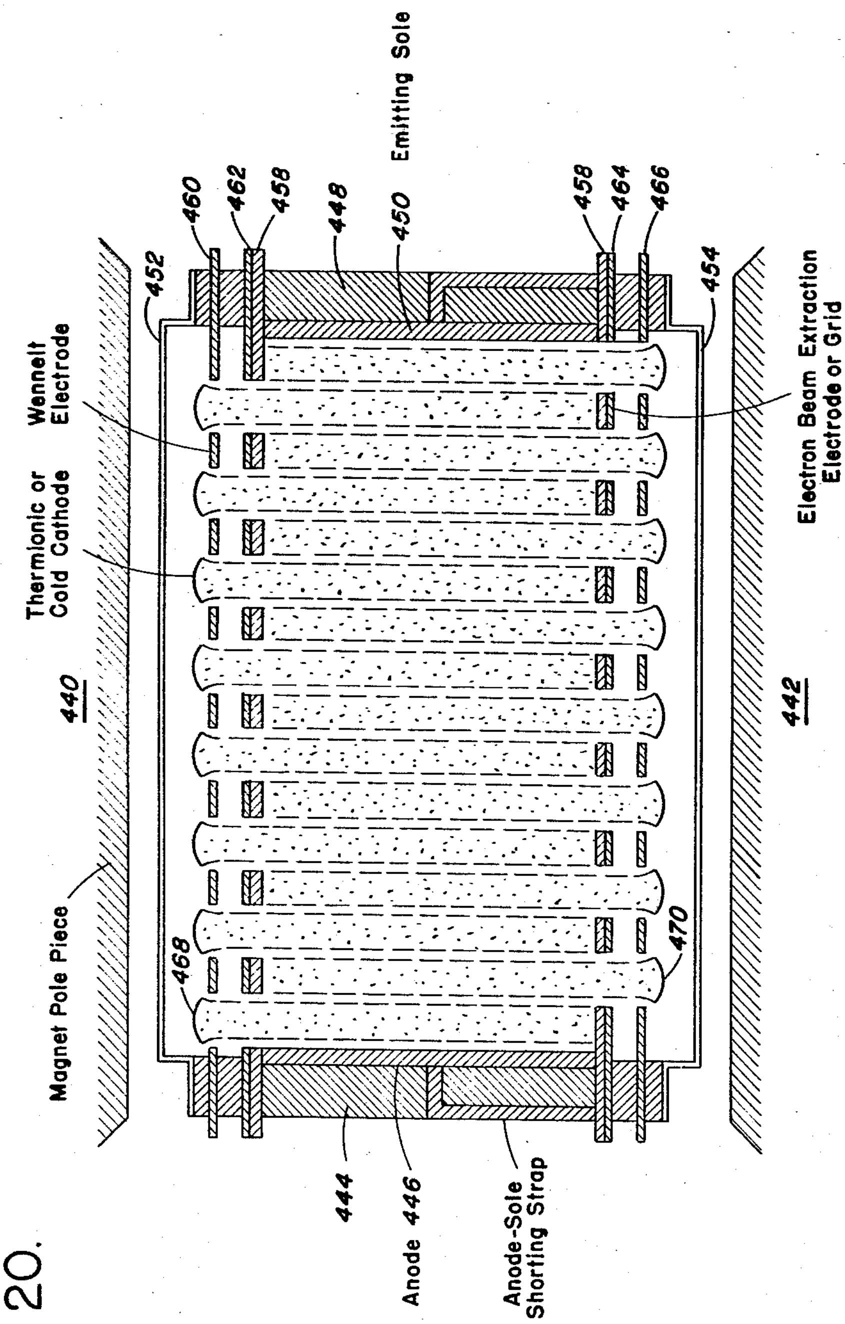

Fig. 20.

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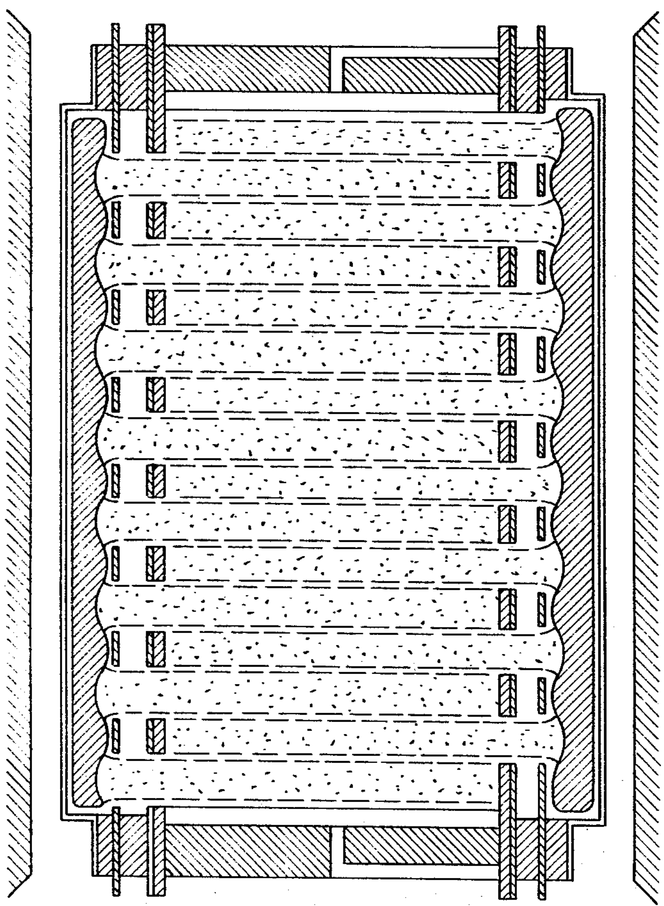

Fig. 21.

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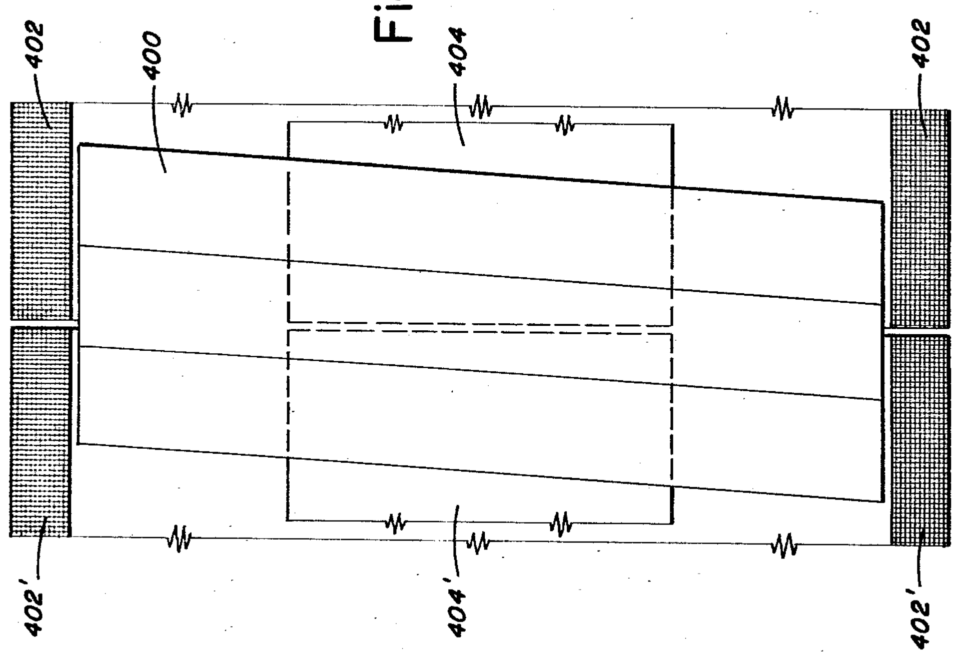

Fig. 22.

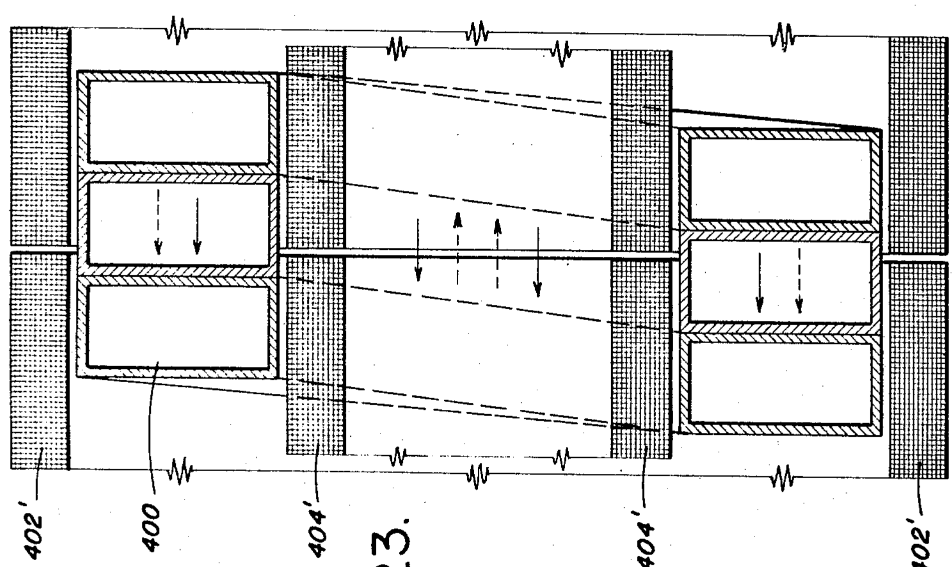

Fig. 23.

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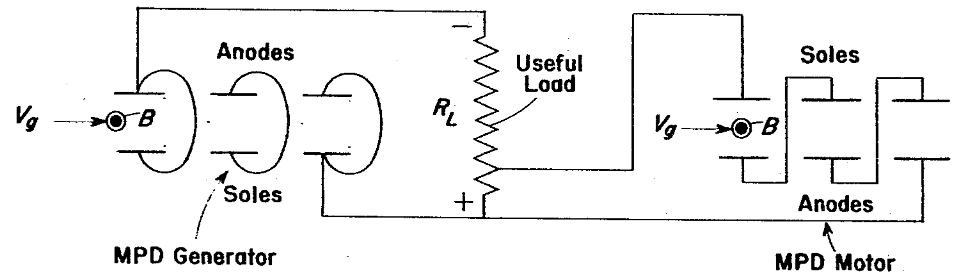
Fig. 25.



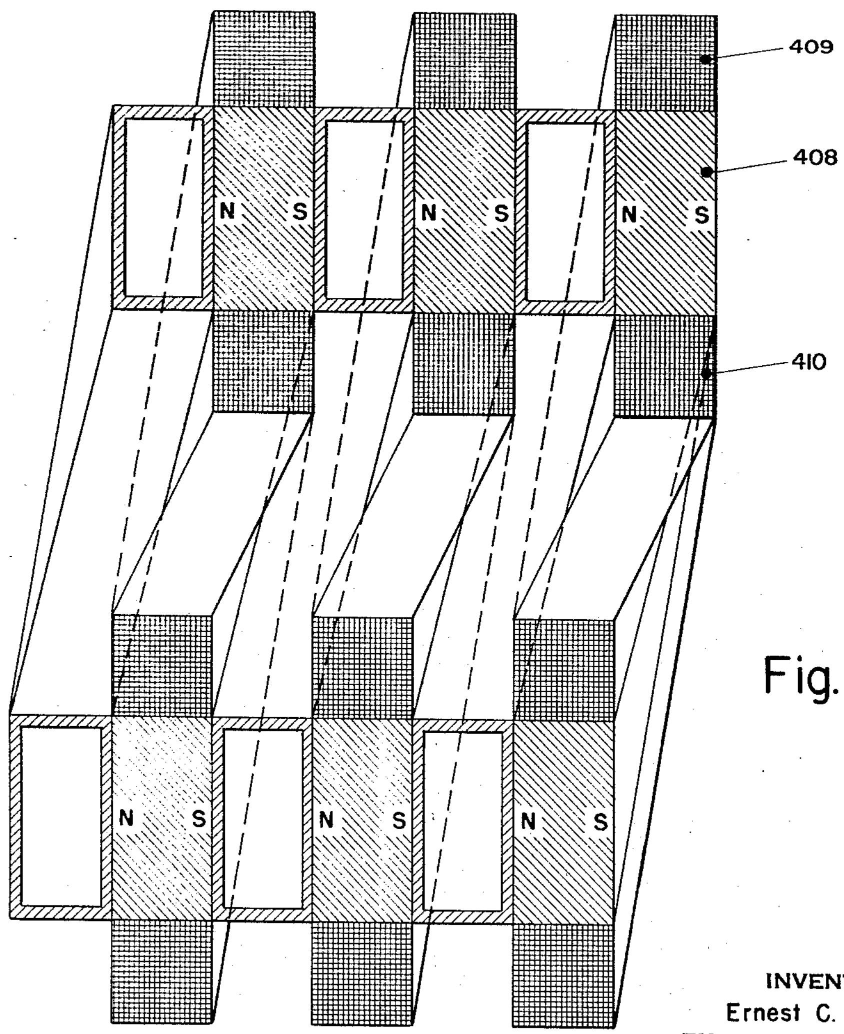


Fig. 24.

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United States Patent Office

3,355,605
Patented Nov. 28, 1967

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3,355,605
CROSSED FIELD PLASMA DEVICE

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Filed Sept. 23, 1963, Ser. No. 310,608
18 Claims. (Cl. 310—11)

This invention relates generally to (thermal to electric) gaseous energy converters and more particularly to a cross field non-equilibrium plasma-type referred to generally as a non-equilibrium magneto-hydrodynamic (MHD) generator.

Common MHD generators utilize thermodynamic equilibrium or thermal ionization of the working medium, which is commonly seeded (combustion) gas in open cycle operation. Because of the extremely high temperature of the working medium which would be required for MHD generator conditions with gas alone (e.g., 5800° F. @ 1 mho/m., 6900° F. @ 10 mho/m. and 8500° F. @ 100 mho/m.) to ionize most gases because of the relatively high ionization potential required to achieve the desired electrical gas conductivity, seeding material (e.g., 1% molar alkali, such as potassium or cesium), which ionizes at a relatively lower gas temperature, is generally added to the gas. Unfortunately, even with seeded combustion gases the temperature is still too high for continuous full (100%) duty and long life operation at MHD conditions (e.g., 3500° F. @ 1 mho/m., 4200° F. @ 10 mho/m., 5100° F. @ 100 mho/m.) when compared with non-equilibrium MHD conditions (e.g., for appropriately seeded nonatomic gas at 2200° F. an order of magnitude higher electrical conductivity can be achieved compared with combustion seeded gas at 5000° F.).

The purpose of ionization of the working medium is to obtain sufficiently high electrical conductivity for the purpose of achieving optimum MHD generator performance and tolerable MHD generator size—especially with respect to its dominant physical parameter, the electrical conductor or ionized gas duct length. Aside from the problem of recouping of the seeding material, particularly in open cycle operation, crucial material limitations arise because of the high gas temperatures associated with combustion MHD generators which tax the endurance of available (electrode and confining wall) materials to so drastically limit the duty of operation and life of the MHD generator and associated system as to require impractically low values of these parameters. Commercial apparatus is invariably continuous or full (i.e., 100%) duty, relatively high impedance, alternating current type, with generally long reliable life characteristics. Hence, power supplies to be competitive with state of art, must not only approach these characteristics, but must do so reasonably economically in all respects. Consequently, non-equilibrium gas ionization resolves the major problems of MHD generator and associated components of higher electrical gas conductivity and lower gas temperature than is possible with equilibrium or thermal means. Therefore, it offers much better prospects for realizing most of the power source requirements than thermal MHD generators do, in spite of the former's comparative primitive state of development.

As an alternative, therefore, to thermal (i.e., equilibrium) means of gas ionization, a non-equilibrium and in particular novel electrical means are utilized in this invention. Equilibrium vs. non-equilibrium gas ionization denotes whether the ion species temperature is comparable with or higher than, respectively, the gas or more properly the related stagnation temperature (by virtue of the isentropic expansion relation).

It is an object of this invention to provide a device which can operate at continuous or full (i.e., 100%) duty

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and with long life not limited by thermal endurances of available materials.

It is another object of this invention to provide a device which can be continuously or intermittently operated at arbitrary pulse duration and average power, up to and including (100%) duty.

It is another object of the invention to provide a device which can generate either direct current or alternating (i.e., sinusoidal) current component at commercial or domestic frequencies and voltages.

It is another object of the invention to provide a device whose direct current or alternating current output voltage is suitable for operation with commercial distribution systems or transformers, respectively.

It is another object of this invention to provide a device which does not require (condensable) seeding of the gas, but which can be used depending upon the thermodynamic cycle required for a specific application (e.g., Rankine vs. Joule cycle).

It is another object of this invention to ionize the gas by crossed field electron beam injection, at the expense of a tolerable or small fraction of the power output of the MHD generator.

It is another object of the invention to provide crossed field electron beam injection along the interaction duct, especially in sufficiently high magnetic field regions thereof in a convenient and practical manner.

It is another object of the invention to minimize excess ionization especially at electron injection ports by use of controlled cross field electron guns and so minimize recombination energy losses.

It is another object of this invention to supplement the degree of ionization afforded by the crossed field electron guns by periodic electron heating on account of the inherently required pulsed ionizing electric field in the guns sufficiently below the sparking limit to avoid excess ionization. This feature requires extremely short (i.e., order of state of art millimicrosecond) pulse durations, but at corresponding high duty to mitigate the correspondingly rapid recombination rate and so as not to depart significantly from continuous (full duty) operation conditions.

It is another object of this invention to provide a device which is efficient and competitively simple in design, fabrication and operation.

It is another object of this invention to provide a device and associated closed cycle system which is portable in nature.

It is another object of this invention to provide a closed cycle system which has no moving mechanical parts.

It is another object of this invention to provide a device wherein the degree and uniformity of ionization of the gas is under control and independent of the temperature of the gas.

It is another object of this invention to provide a device wherein the gas is ionized in a uniform and continuous manner.

It is another object of this invention to provide a device wherein an MHD generator and an MHD motor (or pump or accelerator) are self-exciting.

It is another object of this invention to provide a device which can start operating practically instantaneously.

It is another object of this invention to provide a device that is not affected by its orientation.

It is another object of this invention to provide a device that is operable on or in the land, sea, air or space.

It is another object of this invention to utilize an electrode configuration best suited to but not rigidly restricted to high Hall parameter operation.

It is another object of this invention to provide a system which can be made to operate open cycle at supersonic or hypersonic gas velocity as an efficient electrical propulsion device for space applications.

It is also an object of this invention to provide a type of cathode such that its non-thermal and thermionic electron yields are adequate and whereby the thermionic portion is derived from cathode heating by the hot flowing gas in the duct.

It is also an object of this invention to achieve the required gas ionization by simultaneous electron beam and periodic ionizing electric impulses and thereby mitigate the dependence on a finite electron supply, tolerance of recombination coefficient and electron mobility which are so inherent in the former means of gas ionization with respect to the latter.

It is also an object of this invention to utilize a Hall (segmented) electrode rather than a Faraday (segmented) electrode configuration due to desire for operation at high Hall effect parameter or high magnetic field, because the Hall configuration requires less control, is more reliable and simpler than the Faraday configuration. Furthermore, the Hall configuration is not subject to the requirement of fixed loading or multiple loads. Finally, the Hall configuration provides a significant reduction in electron retardation or larger electron braking on account of employment of the magnetic field with transverse electric field. Also a high magnetic field, and relatively low gas velocity contemplated, improves the momentum transfer between electrons and gas atoms.

It is another object of this invention to provide gas ionization means which is not an ionizing radiation hazard.

It is another object of this invention to provide a device which can operate at minimum gas temperature consistant with desired thermodynamic (cycle) efficiency and material endurances for full duty long life operation.

It is another object of this invention to provide a MHD motor or pump or compressor or accelerator so as to eliminate mechanical moving parts in the closed system.

Other objects and many of the attendant advantages of this invention will be readily appreciated as the apparatus becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings, wherein:

FIGURES 1A, 1B, 1C and 1D are schematic and vector diagrams of various electrode configurations appropriate for use in MHD generators;

FIGURE 2 is a flow diagram of a closed cycle MHD generator;

FIGURE 3 shows salient MHD quantities involved in the description of MHD energy converter operation;

FIGURE 4 is a schematic representation of an MHD generator or an MHD motor in accordance with the principles of the invention;

FIGURES 4A through 4E illustrate alternate electrode pair means of applying pulsed ionizing voltage to interaction space of the MHD generator or MHD motor illustrated in FIGURE 4;

FIGURE 5 is a perspective view representing schematically a mechanical nozzle or convergent-divergent gas duct with electrodes for an MHD generator of the type shown in FIGURE 1C and FIGURE 4;

FIGURE 6 is a longitudinal sectional view of an illustrative embodiment of an MHD generator in the form of a straight constant cross-section gas duct;

FIGURE 7 is an external elevational view of the device shown in FIGURE 6;

FIGURE 8 is an external end view of the device as viewed in FIGURE 6;

FIGURE 9 is a partial view of an electrical connector of low heat transmission characteristics as viewed along the line **9—9** in FIG. 6;

FIG. 10 is an elevational view of an insulating (e.g., circular) spacer taken as indicated by arrows **10—10** in FIG. 6;

FIG. 11 is a cross-sectional view taken along the line **11—11** in FIG. 6;

FIGS. 12 and 13 are fragmentary views of duct walls grooved and preshaped to receive short-circuiting straps as shown in FIGS. 6 and 11;

FIG. 14 is a schematic showing of an arrangement for applying a magnetic field to a gas duct by means of ordinary (or superconducting) solenoid electromagnet in which wrought iron pole pieces are saturated and, consequently, no yoke is used;

FIG. 15 is a cross-sectional view taken along the line **15—15** of FIG. 16;

FIG. 16 is a schematic cross-sectional representation of a compound crossed field electron gun with strip cathodes and multiple vane control electrodes for injection and modulation (for alternating current operation of the MHD generator) of an electron beam in a gas duct;

FIG. *16a* is a cross-sectional representation of a crossed field electron gun for direct current operation of the MHD generator, this structure being substituted for the electron gun of FIG. 16 when direct current operation is desired rather than alternating current operation;

FIGURE 17 is a schematic plan view taken along the line **17—17** in FIGURE 16;

FIGURE 18 is a schematic cross-sectional representation of a compound crossed field electron gun with multiple plasma-cathodes for injecting an electron beam into a gas duct;

FIGURE 19 is a schematic plan view taken along the line **19—19** in FIGURE 18;

FIGURE 20 is a schematic cross-sectional representation of a dual compound electrostatic electron gun with strip cathodes, for injecting electron beams into a gas duct along the direction of the applied magnetic field in an MHD generator (or motor);

FIGURE 21 is a schematic cross-sectional representation of a dual compound electron gun with plasma cathodes, for injecting electron beams into a gas duct along the direction of the applied magnetic field in an MHD generator (or motor);

FIGURE 22 is a schematic representation of a helically wound gas duct of an MHD generator (or motor) with ordinary (or superconductor) solenoidal windings for providing the required magnetic field, an outer solenoid being partially cut away. Such a structure is more complex than its linear counterpart for sake of compactness;

FIGURE 23 is a schematic representation of the device as shown in FIGURE 22 in longitudinal cross-section;

FIGURE 24 is a schematic cross-sectional representation of a helically wound gas duct of an MHD generator (or motor) with saturated magnet iron pole pieces and ordinary (or superconducting) solenoids disposed between adjacent turns of the helically wound duct. Such a structure is more complex than its linear counterpart for sake of compactness;

FIGURE 25 is a schematic diagram of typical electrical connections suitable for connecting an MHD generator of the type shown in FIGURE 1C to an MHD motor of the type shown in FIGURE 1D.

Similiar reference characters refer to similar parts throughout the several views of the drawings.

Briefly, in this invention thermal energy in a suitable unseeded gas derived from a primary heat source (e.g., fossil fuel, solar energy or gas cooled nuclear reactor) can be directly converted into commercial, direct or alternating current electricity, depending upon the ultimate application. Crossed field electron beam and interdependent periodic ionizing electric field impulse gas ionization means are utilized to provide a device whose gas temperature does not tax the endurance of the associated materials. Thus an MHD device which can operate continuously at full (i.e., 100%) duty and still have a long operating life is provided.

In this invention a suitable gas is nonequilibriumly or electrically ionized to make it optimumly electrically conducting, by crossed field means, involving electron injection, and/or by periodic ionizing electric field impulse means, thereby enabling the device to convert directly a major part of the thermal or kinetic energy, of the gas imparted to it by a suitable primary heat source, directly into electricity.

The rate of extraction of enthalpy from the gas by the MHD generator derives from the usual energy balance, which shows that it depends strongly (i.e., square) on the gas velocity-magnetic field product, for a given efficiency, conductivity, Hall parameter, degree of nonuniformity and ion slip, neglecting heat loss to the exterior and changes in kinetic energy in the gas.

The energy transfer means is in accordance with the equivalent Hall or Faraday generator principle, taking cognizance of the fact that whereas the energy transfer via a metal electrical conductor is by virtue of the positive ions anchored to the crystal lattice, in a gas electrical conductor energy transfer occurs only by virtue of attractive electrical forces and predominately axially directed collisions between (unanchored) ions and (neutral and excited) gas molecules.

This invention is also capable of directly converting electricity to mechanical (directed kinetic) energy of the gas, in accord with the equivalent Faraday's motor principle. The resulting MHD motor or pump, accelerator or compressor does not depend on any moving mechanical parts and, therefore, it eliminates the need for any mechanical components in the whole system. The energy required to operate the MHD motor is derived from a tolerable fraction of the MHD generator output.

Either fossil fuel, direct solar energy or a gas cooled nuclear reactor may serve as the primary heat source for heating the gas or "working fluid" of the proposed energy converter. The electrical power output can be continuous or full (100%) duty (i.e., direct current), or intermittent (i.e., pulsed), or alternating (e.g., sinusoidal) current. In those instances where alternating current or modulation is desired, low drive of a voltage controlled electrode system of the crossed field (or electrostatic) electron gun (used for injecting the electrons into the gas at high efficiency for complete absorption and ionization of the gas) is utilized. In the case of pulsed modulation, various pulse durations and repetition rates can be utilized. In the case of alternating current modulation, various frequencies, including commercial or utility frequencies, can be realized.

The life of the non-equilibrium MHD motor (i.e., pump or compressor or accelerator) is not limited in duty or life by the state-of-art materials of the (metallic) electrodes and confining (dielectric) duct walls. This is a consequence of the fact that highly efficient non-equilibrium electrical gas ionization (i.e., 90%) is utilized, instead of equilibrium or thermal (high temperature) gas ionization and the required doping or seething with easily ionizable material (e.g., potassium, cesium, and the like). However, even with seeding, gas temperature of 3500° to at least 4000° F. are required by thermal or equilibrium MHD generators in obtaining desirable electrical conductivity of the seeded gas. In this invention the temperature of the gas is approximately 2500° F. as it need mainly be adequate for good thermodynamic (cycle) efficiency (e.g., ~45%) and, suitable with respect to duty and life of the primary source of heat, such as a gas cooled nuclear reactor. It is possible to obtain high generator efficiency (i.e., theoretically about 95%) and high cycle efficiency (i.e., ~45% at 2500° F.).

The upper practical limit of the generator efficiency is dependent upon the maintenance of an adequate uniformity and stability, (e.g., avoidance of spark channels) in the plasma. Spark channels and consequently excess channel ionization can be alleviated, especially in the crossed field guns, by resort to periodic (rectangular) impulses of extremely short (i.e., order of a nanosecond) pulse duration and rise time (within state of art capability of a decinanosecond and centinanosecond, respectively) at high duty, so as to mitigate the effects of recombination rate and provide virtually continuous (full duty) operation. In fact, pulse duration somewhat longer than this (e.g., order of a centimicrosecond) serves to substantially supplement the degree of gas ionization afforded by the crossed field electron injection since all the electrons in the gas are involved.

Due to the use of electrical non-equilibrium ionization means, the MHD generator and MHD motor are capable of self excitation and possess rapid starting characteristics. The performance features of the MHD generator, particularly power density and conversion efficiency, are best realized especially with respect to the electron beam gas ionization means alone when the Hall (effect) parameter, $\mu_e B$ (i.e., product of electron mobility, μ_e, and magnetic field B), is dominant. The requirement of high electron mobility, including considerations relative to the primary heat source, as well as to (high) specific heat/thermal conductivity and (low) molecular weight, on account of thermodynamic and aerodynamic condsiderations, are satisfied by using noble gases at low pressure. High magnetic field reduces generator size, reduces losses proportional to wall area and enables quicker extraction of power. There is also a significant reduction in electron retardation (i.e., much larger electron braking) on account of the magnetic field employed with a transverse electric field. Furthermore, a high magnetic field and relatively low gas velocity improves the momentum transfer between electrons and gas atoms. Need for high magnetic field on account of need for high Hall effect parameter calls for a Hall configuration which requires less control, is more reliable and simpler than the Faraday configuration and is not subject to the complexity of multiple loads or fixed loading (constant K type). Low gas pressure contributes toward minimizing the predominant recombination-attachment losses. It also reduces wall heat loss and viscous pressure loss. On the other hand, heat exchange size and non-equilibrium ionization time are increased.

In this invention, electrical non-equilibrium ionization of the gas is efficiently initiated and maintained with negligible, if any, gas flow obstruction or at the expense of magnetomotive force of the magnets. This gas ionization means is achieved dually by crossed field electron beam injection means supplemented by periodic ionizing electric impulse means in the guns and interaction duct. While the former is characterized by a finite number of electrons the latter involves all the electrons in the gas.

The electron beams can be injected into and guided in the MHD generator (or MHD motor) interaction space, for example, by means of an applied (electric-magnetic) crossed field ("short," "long," "space charge," "ramp" or magnetron optic) electron guns, it being understood however, that the electron emitting source is not restricted to a solid state type (e.g., plasma). The term "short" or "long" crossed field electron gun refers to the length of the electron guns' cathode along the electron orbit direction in vacuum. When the vacuum length is less than a half (and in particular a quarter) cycle the gun is termed "short" optic. When otherwise (i.e., several half cycles) the gun is termed "long" or "adiabatic" optic. The electron beam can also be injected electrostatically into the MHD generator (or MHD motor) interaction space, along the (applied magnetic field axis which acts as a beam focusing field). However, this is at the expense of considerable design, fabrication and operational complications and disadvantages and additional magnetomotive force requirement on the part of the magnet. In any case, the electron beam must permeate the gas interaction space completely and continuously, due to the inherently rapid gas ionization decay rate and for sake of uniformity, especially at injection sites. This means provides a finite number of electrons into the gas and so its ability to provide the desired gas electrical conductivity is correspondingly limited.

In contrast, the applied periodic rectangular ionizing electric impulses are applied to all the electrons in the gas since this field is impressed between the electron emitters (i.e., cathode) and electron collectors (i.e., anodes or accelerators) and are of such duration (e.g., order of a centimicrosecond) that, together with the injected electron beams, competitive non-equilibrium and uniform gas electrical conductivity (e.g., >10 to >1000 mho/m.) may be achieved without sparking and consequent excess ionization. This supplementary means is inherent in the operation of the system. It involves essentially imparting periodically a relative low average energy to all the electrons in the gas for such brief intervals (e.g., order of centimicroseconds for typical MHD conditions) so as to sufficiently ionize the gas, but not excessively so as to cause sparking or arcing and energy dissipation. The net energy expended in producing each ion pair decreases as the electron temperature becomes much greater than that of the gas.

This invention avoids all of the thermal or equilibrium MHD generator's material problems by using a gas temperature that is substantially lower and below the thermal endurance limitations of materials, consistent with reasonable thermodynamic (cycle) efficiency. With this invention it is not necessary to seed or dope the gas and, naturally, the problem of recouping the seeding material is eliminated. However, it is not here implied that seeding or doping the gas cannot be used, since there may not be need for recouping the seed material in closed cycle operation.

Although the proposed system can be used with various (fossil fuel, gas cooled nuclear reactor or solar) primary heat sources due to the relatively low gas temperature, it is very adaptable for use with an advanced gas cooled nuclear reactor having unclad fuel elements as primary heat source, taking cognizance of the fact that state of art nuclear reactors operate in the vicinity of 1,000° F. Thus, it can be readily seen that it is well suited for remote applications and even for vehicles for land, sea, air or space. In the latter application a Rankine rather than a Joule cycle is indicated, hence a condensible working medium (e.g., Ce) may be incorporated.

As mentioned previously, this invention also embraces an MHD motor or pump or accelerator or compressor having no mechanical moving parts and which is capable of moving gas at velocities from subsonic, to supersonic and even hypersonic magnitudes. While the MHD motor, pump, accelerator or compressor component is used for moving the gas in a closed cycle system for generation of electric power, it can be adapted for use in an open cycle system for providing MHD propulsion of space vehicles.

The normally linear structure of the MHD generator (or MHD motor), for electrical gas conductivities significantly less than about 10 mho/m., can be rolled into a helical structure as a conventional helix delay structure of an appropriate electronic tube (e.g., traveling wave tube) or folded into a meander structure, as an interdigital delay line (of such an electronic tube) in order to avoid unwieldly structures and objectionable and even impractical overall dimensions, while utilizing such length of the gas duct, or electrical conductivity of the gas. In such compact forms, conservation of magnetomotive forces can also be affected in the production of the required uniform magnetic field in the interaction space. The helical structures can be referred to as periodic magnet helix MHD generators (or motors). While the helix (or meander alternative) duct structures are not here considered further, it should be remembered that this invention can also assume these configurations.

In the type of MHD generator configuration disclosed herein (i.e., Hall generator, for the sake of one of the two means of gas ionization—crossed field electron beam injection) the voltage and current or power is taken off longitudinally or axially by appropriate electrodes in the interaction duct, which conveys the electrically conducting gas. The transverse currents provide the necessary physical resistance to the gas flow. In effect, the physical power density expended by the gas flow by pushing against the electromagnet forces is represented by the scaler product $v_g BJ_T$ (where v_g denotes the gas velocity, B denotes the magnetic field and J_T denotes the transverse current density). Substantially similar structural configurations can be used in the MHD generator and the MHD motor or pump or accelerator or compressor, except in the latter case appropriate structural and electrical alterations are dictated and the voltage is applied across the electrodes of the desired configuration, illustrated in FIGS. 1A, 1B, 1C, 1D.

In the MHD generator, the electrically conducting gas is heated to the appropriate temperature by the primary heat source and forced through the magnetic field to generate electric power output in the manner discussed in the text and in accordance with the Hall or Faraday generator principle in which the major current flows perpendicular to the strong magnetic field. Furthermore, it is essential that the energy loss to the duct walls be kept to a tolerable low level compared with the generated or dissipated energy in the volume of the gas. This implies maximizing the gas pressure-cross section product. Finally, it is essential to maintain uniform ionization at an adequate level. In the case of the MHD motor, the Hall or constant K electrode configuration also can be used with appropriate external voltages impressed across the electrodes. It should be mentioned that in the Hall configuration, with respect to motor or generator, non-uniformity has greater influence in reducing the effective gas conductivity and useful range of the Hall parameter. In any event, the electric field so established works with the impressed magnetic field to move the electrically conducting gas along through the duct by cross field interaction at the desired velocity.

The output ends of the MHD generator and MHD motor are combined in a unitary structure to form a regenerative heat exchanger (or regenerator and preheater, respectively), wherein heat from the residual hot gas discharged from the MHD generator is conducted to the colder gas leaving the MHD motor or pump or accelerator or compressor to preheat the gas which is on the way to be reheated by the primary heat source.

It is appropriate to clarify the mechanism involved in crossed field electrically conducting gas interaction in the following manner: Since only electric charges can interact with electric and magnetic fields, an efficient mechanism must exist for transferring the directed kinetic energy from the charged particles to the neutral gas molecules and vice versa. Otherwise, the efficiency of the MHD generator or MHD motor cannot exceed the fractional ionization. The reason for this lies in the fact that most of the kinetic energy in the gas resides in the flowing neutral gas molecules.

Energy transfer in this case can result only from attractive forces and collisions between molecules in the gas conductor. Charges are generally equally divided in number between electrons and ions, therefore, in transferring their energy to an external load they are decelerated at the expense of their directed kinetic energy. However, for the sake of high conversion efficiency, the essentially neutral gas molecules must also be decelerated by transferring energy to the charges. Now, the electron mobility is high relative to that of the ions and hence the electrons are responsible for the major electric current flow. Also, electrons under the influence of an appropriate electric field decelerate promptly, due to their low mass, and form a space charge. This electron space charge exerts electrostatic forces on the positive ions. The latter, because of their relatively enormous mass, compared to that of the electrons, are correspondingly less influenced by the applied electric field. Thus, a positive ion space charge also forms. The electron and positive ion space charges constitute the plasma. Now, the collision cross section of positive ions and neutral gas molecules are similar. Hence, the positive ions by virtue of efficient axially directed momentum, transfer via direct (axially directed) elastic collisions appropriate forces on the neutral gas molecules. Hence, reliance on the electrons alone for transferring energy to neutral gas molecules (being a relatively inefficient mechanism on account of the electrons relatively inferior collision cross section) is dispensed with. Thus, the gas stream, in forcing the charges through the applied fields, is decelerated and, furthermore, continually replenishes these charges. The reduced kinetic energy of flow appears as electric energy at the terminals of the generator in accord with Faraday's generator principle. Furthermore, the effective collision cross section of ions with electrons is enormously greater (e.g., by thousands of times) than that between electrons and neutral gas molecules. Consequently, the electric gas conductivity at about a tenth of one percent ionization may be considered to be effectively equivalent to that at complete ionization. Therefore, essentially three mechanisms of gas retardation or braking by charges may be considered to be as follows: Namely by electrons alone, by positive ions alone and by electrons and positive ions together, with the gas atoms.

The relative collision cross section of electrons and positive ions with gas atoms are such that whereas an enormous (typically 10^3) number of collisions with gas atoms are required in the case of electrons to affect significant momentum transfer, only a few collisions are required in the case of positive ions. Hence electrons alone affect only a marginal braking of the gas even in the case where the magnetic field is high and gas velocity low.

Electrons experience strong interaction or coupling with the magnetic field, and so are promptly braked by it, due to their relatively small mass. In contrast, positive ions experience no relatively significant interaction or braking by the magnetic field because of the strong interaction or coupling between the transverse moving positive ions and the gas atoms by virtue of their comparable masses and collision cross sections. Nevertheless, because of their comparable collision cross sections, positive ions experience strong interaction or coupling with the gas atoms and hence effectively retard the gas atoms by directed elastic collisions. Strong coupling or interaction between electrons and positive ions by virtue of their electrostatic forces serves to join these two mechanisms so as to effectively retard the gas atoms. In any event, little momentum transfer between charges and gas atoms can account for the prevailing MHD power generated since it is such a small fraction ($<1\%$) of the total energy associated with the gas flow. With transverse electric field, a significant retardation of electrons occurs. This dictates shorted electrode pair configuration and hence Hall rather than Faraday type generator. The foregoing may also be viewed with respect to the degree of the Hall current involved. In the case of no Hall current, every time a Hall field develops which couples the positive ions and electrons together, the electrons are responsible for the electric current to the extent of the cathode capacity. The momentum transfer is predominantly through the positive ions and gas atom collisions. In contrast, with Hall current, the positive ions and electrons act independently. The electrons are still responsible for the electric current. The momentum transfer is, however, predominantly through electron and gas atom collisions.

To provide the required optimum electrical conductivity of the gas at a moderate gas temperature (e.g., 10 mho/m. and more at about 2,500° F. for the sake of good thermodynamic performance and generator length) so as not to tax the endurances of the refractory materials, departure from the prevailing thermal ionization practices in several respects is necessary. For the sake of tolerable recombinations/attachment loss the average ion density should be made low. However for the sake of power output density, the electron mobility should be made high. These requirements suggest a low gas pressure and essentially (pure) monatomic noble gas, possessing low molecular weight and high specific heat/thermal conductivity. Polyatomic molecules degrade electron energy by inelastic collisions. To ionize the gas, without experiencing a serious frictional pressure drop and magnetomotive force sacrifices, the (efficient) process of controlled crossed field electron beam injection into the gas is proposed as one of two interdependent gas ionization provisions as the gas enters the cross field interaction space of the MHD generator (or MHD motor). As previously described, this gas ionization means is supplemented by application of periodic ionizing electric field pulses below the sparking limit (i.e., order of decimicrosecond) to ionize the gas to the required degree in order to achieve the desired electrical gas conductivity (i.e., $>>10$ mho/m.). The gas ionization so produced can be made relatively uniform across and along the interaction region to avoid excess ionization (e.g., at electron injection orifices, or by too long ionizing voltage pulse, depending on ionization means) and simultaneously combat the relatively rapid ionization decay rate. The time for ionization to reach the desired level is extremely short ("augenblicklich"), so that for typical MHD generator operation excess ionization and sparking would be expected in the order of a microsecond and inadequate ionization in the order of a nanosecond. Also, the decay of the ionization from its established level is likewise rapid, so that the electrical gas conductivity under typical MHD generator operation can be reduced to such an extent that it is no longer useful in the order of a demisecond. Control of the gas conductivity by the proposed means are such that it can be maintained within an optimum range. That is, not too low, for good efficiency and tolerable generator size (especially duct length) at a given power, and also not too high, so as to avoid severely distorting the cross sectional flow front of the gas stream and severe entropy changes due to excessive Joule heating losses from currents in undesirable paths. Using the crossed field electron guns and periodic ionizing electric field pulses here disclosed, it is possible to achieve uniform ionization and electron injection efficiences approaching high values (e.g., ~ 90 percent).

For the sake of high power density, a high magnetic field is indicated. This measure also reduces the MHD generator (and motor) size, including losses proportional to wall area. Of course, a high magnetic field must be bought at the expense of magnetomotive force across the gas gap, which is a serious problem even for the electrical gas conductivity contemplated. As a matter of fact, the minimum gas electrical conductivity is largely governed by the magnet solenoid regardless of its resistivity, due to cost and weight factors. In any event, both high electron mobility and high magnetic field means a high Hall (effect) parameter. Hence, longitudinal or axial voltage and current or power extraction, without restriction on loading factor, is indicated. The Hall (or H) configuration illustrated in FIG. 1C seems best suited to meet the foregoing requirements. Hence, this indicates the use of segmented electrodes with desirable single high impedance load or voltage operation, suitable for commercial applications. It should be mentioned that non-uniformity is a more significant factor in this type of generator than displayed by the other types mentioned. This restriction tends to reduce the useful range of the Hall parameter and effective gas electrical conductivity. Furthermore, for high efficiency a high electron mobility and high uniformity are required. Hence, ideal performance may be more difficult to achieve as the Hall parameter is increased. Also, at high Hall parameters the ions begin to absorb significant energy and begin to display significant ion mobility or ion slip. In other words, conditions in which the mean free path of the neutral gas molecules becomes large enough so that they begin to pass through the plasma without appreciable interchange of momentum.

Although the gas velocity should also be high, for the sake of high power density and (minimum) generator size (especially duct length), there is the frictional pressure drop and other aerodynamic problems to be considered. As a preliminary compromise, therefore, to reduce this drop to a tolerable level, a gas velocity in the subsonic range is indicated; it being understood, however, that other than subsonic gas velocities can be used.

In this invention, the generator efficiency (i.e., theoretically >90%) and thermodynamic or cycle efficiency (i.e., order of 50%) of energy conversion are correspondingly high. Furthermore, the device is capable of continuous (i.e., 100%) duty operation with long competitive (power station) life, since the materials of electrodes and confining walls are not taxed to or beyond their thermal endurance by the relatively moderate (i.e., order of 2,500° F.) operating gas temperature.

By means of low drive (power) modulation of the control electrode of the crossed field electron gun and periodic ionizing electric field, intermittent (i.e., pulsed) or alternating (sinusoidal) current component power output can be obtained. Continuous (i.e., 100%) duty direct current output is available in the absence of such modulation. As previously mentioned, crossed field gun operation involves pulsing the ionizing electric field at such short pulse duration (e.g., order of decimicrosecond for typical MHD generator operation) that sparking and nonuniformity in gas ionization are not encountered and at such high duty as to mitigate the deleterious ionization decay rate so as to approach full duty operation of the MHD generator.

The required high purity of the noble gas is maintained by effective (physical, chemical and/or electrical) continuous gettering of gas impurities (e.g., polyatomic molecules) in the interaction space of the MHD generator or MHD motor or pump or accelerator or compressor so as not to significantly degrade the electron energy by inelastic collisions. The methods of gettering can include electrical crossed field methods as well as purely physical and chemical methods. Continuous monitoring or measuring of the actual purity of the gas is necessary and can be accomplished by means of magnetron and mass spectrometer, together with appropriate diagnostic determinations of electrical conductivity and other relevant parameters of the plasma associated with the performance of the devices disclosed.

With reference to the FIGS. 1A–1D, there is shown schematically various electrode configurations and associated vector diagrams which can be employed in MHD energy converters. FIG. 1A will be termed the elementary Faraday (E) type configuration. This is a transverse or shunt type, that is, the voltage, current or power extraction in the case of the generator of this type is transverse. The electrodes are continuously conductive along the length of the gas duct and are connected to a single load. The (not necessarily) uniform magnetic field intensity, in the MHD interaction space is indicated perpendicular to the plane of the paper and the gas velocity, v_g is represented by an arrow as directed. This configuration of magnetic field intensity and gas velocity is assumed to be the same in each of the FIGS. 1A–1D.

FIG. 1B will be termed the multi-load-shunt (or π) Faraday segmented type utilizing transverse or shunt power extraction. The electrodes are segmented and each electrode pair is connected to a separate isolated load R_L.

FIG. 1C will be termed the Hall (or H) type. It utilizes longitudinal (or series) power extraction. The electrodes are also segmented and connected to a single load, while the individual opposing electrode pairs are strapped as indicated.

FIG. 1D will be termed the modified Faraday segmented or constant K (or K) type. It also utilizes longitudinal (or series) power extraction. The electrodes are also segmented and connected to a single load in a wave pattern, a cathode of one opposing electrode pair connected to the anode of an adjacent pair, as indicated. The electric field in the interaction space in this type is in a fixed direction, independent of the loading factor, K. The value of the loading factor is restricted to that value which makes the strapped electrodes of equal voltage before strapping.

It can be shown that the performance of each type of MHD converter with respect to power density and efficiency depends upon the Hall parameter both for electrons and for ion-electrons. The Hall parameter for ions is denoted by $\mu_i B$, where μ_i is the ion mobility of the positive ions of the gas and B denotes the magnetic field intensity. The Hall parameter for electrons is denoted by $\mu_e B$, where μ_e is the electron mobility as referred to previously. In the case of $(\mu_i B)(\mu_e B)>1$, the performance of all types is poor. This is because the collision mechanism between positive ions and neutrals is weak.

In the case of $(\mu_i B)(\mu_e B)<1$, the performances of the four types are individually differentiated, depending upon the value of $\mu_e B$. It should be noted that when

$$(\mu_e B)(\mu_e B)<1$$

the E-type has good efficiency for low values of μ_e; the π-type has good efficiency for both high and low μ_e, but not as good as the K type at low values of K. In addition, the performance of the π-type is independent of the value of $\mu_e B$. The efficiency of the Hall type under the condition of $(\mu_i B)(\mu_e B)<1$, is good for high values of μ_e. Therefore, it must operate at peak efficiency. However, it has twice the duct length of the π-type for large $\mu_e B$ and the same efficiency. The efficiency of the K-type is better than that of the π-type for high loading (K<0.5). Its power density under load is the same as that of the π-type. However, as noted above, this type is restricted to a specific value of K. For a particular value of K, the π-type and the K-type work with the same power density and related parameters.

The E-type performs well with respect to efficiency and power density at values of $\mu_e B<1$, that is, at moderate or small (i.e., $\mu_e B \rightarrow 0$) values of Hall parameter for electrons. The π-type performs well not only at intermediate (i.e., $K\mu_e B<10$) Hall parameters, but in fact at all positive values of $\mu_e B$ (i.e., $0 \leftarrow \mu_e B \rightarrow \alpha$) and so is less restricted than E-type in this respect. The Hall-type performs best when the Hall parameter for the electrons is dominant, that is, when $10<<\mu_e B>10$. All of these three types have high efficiency and high power density in their good performance range.

Closed cycle system

FIG. 2 shows schematically an illustrative example of a closed cycle MHD generator in accordance with the principle of this invention. In this system, monatomic (noble) gas at relatively low gas pressure, (i.e., 10 to 30 pounds per square inch absolute) for the sake of tolerable recombination/attachment loss, is supplied to the MHD generator proper **50** after being heated by a suitable primary heat source **52** such as a gas cooled nuclear reactor, conventional fossil fuel burner, solar heat source, or other means. The hot gas at the exhaust of the primary heat source or inlet to the MHD generator is at maximum system temperature, T_1 typically, in this invention, at about 2,500° F. This gas temperature does not tax the endurance of the associated materials exposed to the hot gas, yet it provides the desired cycle efficiency, typically about 45%. However, this gas temperature does not impart significant ionization to the gas alone to make it an adequate electrical conductor as required, namely about 10 or more mhos/meter.

The hot gas can be directed at subsonic gas velocity, for the sake of tolerable frictional pressure drop, to (a properly convergent-divergent) MHD generator duct, shown schematically at **50**, for simplicity as a straight duct. Here it is electrically uniformally ionized by simultaneous crossed field electron beam injection and periodic ionizing electric field pulses below the sparking limit as previously described. This gas ionization is at the expense of a tolerably small fraction of the MHD generator output.

The MHD generator **50** directly converts physical or axially directed kinetic energy of charged particles and neutral particles (via collisions with positive ions) into electrical energy, by virtue of deceleration of the charged particles (i.e., transfer of their kinetic energy into (induced) electrical energy in the coupled circuit). In particular axial rather than transverse voltage and current or power extraction or coupling is utilized in this system, it being understood, however, that this invention is not limited to this type of power extraction or coupling. In effect, the Faraday generator principle and "Ohms" law apply, providing one takes cognizance of ion slip, Hall effect and the fact that the ions are not longer anchored as in a crystal lattice of a solid electrical conductor.

The gas exhaust of the MHD generator is directed into a heat exchanger or re-generator, **54**, wherein the residual heat of the gas is thermally conducted to a preheater, **56**, which heats the gas that is being returned to the primary heat source, **52**, to repeat the cycle. This measure improves the cycle efficiency or otherwise conserves heat energy. The residual heat of the cooled gas from the re-generator is directed to a cooler or refrigerator **58**, wherein the gas is further cooled to the lowest practical temperature, T_4, in order to obtain the maximum cycle efficiency, regarding the system as a carnot heat engine. From the cooler, **58**, the gas is passed to a primary gas purifier, **60**, wherein the residual gas impurities, other than the chosen gas, may be removed. The cooled and purified gas is passed to the properly convergent inlet of an MHD motor or pump or accelerator or compressor, **62.**

This device can be similar to the MHD generator **50**, except that it is operated as a motor by application of appropriate potentials to its terminals. The gaseous electrical conductor is then electrically forced along its (properly divergent) duct, obtaining supplementary electrical energy needed to return the gas to the primary heat source from the MHD generator, **50**, by connections not shown in this figure, but detailed in FIG. 25 as an example. The discharge from the motor or pump or accelerator or compressor, **62**, is directed to the preheater, **56**, where it is preheated by the exhaust heat from MHD generator, **50**, as aforesaid, before it is returned to the inlet of the primary heat source, **52**, where the cycle is repeated.

In some cases, it may be desirable to substitute another type of pump or accelerator or compressor the MHD type. However, when freedom from moving mechanical parts, absence of lubrication problems, etc., are important considerations the MHD device has decided advantages. Electrical input to the motor, **62**, can if desired, be supplied from any suitable electrical source other than generator, **50**.

The gas purifier, **60**, can be of any suitable type, electrical, physical or chemical or a combination thereof.

FIG. 3, illustrates elementary relations between various components involved in the MHD generator and MHD motor action. In the figure, v_g represents vectorially the gas velocity and B the applied magnetic field, the latter directed perpendicular and out from the plane of the paper. Due to the forcing of charges through the magnetic field by the gas stream via axially directed elastic collisions with them and the electrostatic forces between the electrons and positive ions, an electric field is induced at right angles to both the velocity and the magnetic field vectors shown vectorially as $\overline{E}_i$ equal to $\overline{v}_g \times \overline{B}$. The resulting induced current density is shown as $\overline{J}_i$ and is equal to $\sigma\overline{E}_i$ where σ is assumed (approximately) as a scaler (rather than properly as a tensor) electrical gas conductivity, assuming an isotropic plasma in spite of the magnetic field, for simplicity of illustration. Due to the action of the plasma being forced through the magnetic field an induced EMF $\overline{F}_i$, results equal to $\overline{J}_i \times \overline{B}$ directed parallel but opposite to v_g, as shown.

The figure also shows that in the case of a motor, an applied electric field intensity $\overline{E}$ directed oppositely to $\overline{J}_i$ but orthogonally to $\overline{B}$ and $\overline{v}_g$. The resulting conduction current $\overline{J}$ due to the applied $\overline{E}$ is equal to σE. The net measurable current density through the plasma is consequently $\overline{J}=\sigma(\overline{E}+\overline{v}_g \times \overline{B})$. The action of the current density $\overline{J}$ gives rise to a Lorentz force $\overline{F}$, of value $\overline{J} \times \overline{B}$ or $(\overline{E}+\overline{v}_g \times \overline{B}) \times \overline{B}$. In case $\overline{E}$ is greater in magnitude than $\overline{E}_i$, the device acts as a motor; otherwise it acts as a generator.

The flow of electrons, *e*, and positive ions, *i*, in the interaction space, together with the resulting ionization of the gas is also illustrated in FIG. 3.

For continuous Faraday electrodes and Hall effect a phase angle of currents with respect to the electric fields occurs. The magnitude of this phase angle depends upon the ratio of the electron cyclotron frequency to the collision frequency, whereas the electric fields remain as indicated. For segmented Faraday electrodes and negligible Hall effect, the currents are as shown. With Hall effect, a phase angle departure of electric fields with respect to the currents occurs as shown in the vector diagrams of FIGS. 1A, 1B, 1C.

Longitudinally coupled generator

FIG. 4 shows schematically an elementary embodiment of the MHD generator **50** of FIG. 2. The principle of operation depends upon the Hall effect which is predominant and requires electric coupling of, or power extraction by, longitudinal or axial voltages and currents, as in the Hall-type configuration shown in FIG. 1C, while the transverse currents provide the necessary physical resistance to the ionized gas flow. Neutral gas of high electron mobility characteristics, namely a monatomic or noble gas such as helium or argon at lower than atmospheric pressure, so that attachment/recombination losses are not excessive, enters the generator from the primary heat source at the left, as shown in the figure by an arrow **64**. In an illustrative example, the compromising temperature, taking cognizance of material limitations and good cycle efficiency, of the gas is chosen about 1645° K. (2500° F.) and for the sake of tolerable fractional pressure drop, its speed subsonic, at about 1000 meters/second.

The gas first passes an unobstructing primary crossed field electron gun region **66**, between a cathode assembly, comprising an electron emitter **68**, a Wehnelt electrode **102** and control grid **63** and an accelerator electrode **70** of the electron gun which is shown as a "short" type crossed field electron gun. The primary crossed field electron gun controls the gas ionization by means of controlled electron beam injection and periodic ionizing electric field pulses as previously described so as to minimize excess ionization within it by application of proper ionizing pulse duration and repetition rate and electric gradient at the cathode aperture, to minimize recombination energy loss.

With reference to FIGS. 4 and 4*a* through 4*e*, that the anodes (shown shorted to the emitting soles, for longitudinal coupling) actually perform dual functions. That is, the anode accommodates not only the output power (terminals) and shorted transverse voltage and current (shorting straps), but also independently the pulsed ionizing voltage, with respect to the emitting soles; identically with that applied between the accelerator and cathode of the primary crossed field electron gun.

To avoid interference between these two functions, the anodes are structurally composite and independent or, alternately, blocking or chokes are inserted in the output terminals and shorting straps so as to not only prevent the flow of pulse current through these circuits, but to prevent shunting of the pulse voltage that is applied between each anode and sole pairs.

The composite anode may comprise one set of interdisposed and connected elements for the pulse voltage, and the other set for the output power and shorted transverse voltage and currents. In the alternate means involving blocking or chokes, these can be inserted in the output terminals and shorting straps so that the subject pulsing voltage applied to the anodes behaves as though the output terminal and shorting straps are absent, yet does not interfere with their individual functions.

Thereby, use of appropriate pulse voltage duration (to prevent excess gas ionization and hence sparking and arcing), appropriate pulse voltage amplitude (to raise the electron temperature in appropriate increments), and appropriate pulse voltage repetition rate (to compensate for the ionization decay rate), provides encouragement for achieving a uniform, continuous and adequate gas ionization throughout the effective interaction space.

The subject pulsed electric field gas ionization means supplements that achieved by means of the electron beam. Thus, the two non-equilibrium gas ionization means working together provide promise of attaining the desired range of electrical gas conductivity and other benefits previously mentioned.

Furthermore, working at high Hall parameter enables a corresponding high output (power) impedance so that the cathode current density is very low.

Furthermore, use of secondary electron emitting soles with high secondary electron yield eliminates electron emission problems. These emitters take advantage of the back bombardment characteristic of crossed field operation of emitters.

Various type crossed field electron guns, as illustrated by FIGS. 6 and 17–20 in accordance with the principles of this invention, can be substituted for the type of gun shown. It should be noted that although FIGS. 6 and 17 illustrate primary cathode heaters, this is not necessary since the hot gas is at adequate temperature for the cathodes contemplated, especially since the nonthermal electron emission properties of the cathode are emphasized.

The electron gun in FIG. 4 employs crossed periodic pulsed ionizing electric field and direct current magnetic fields, the periodic pulsed ionizing electric field being provided by means of a source (i.e., MHD generator) of electric potential represented arbitrarily by a keyed battery, **72**, connected between the accelerator, **70**, and the cathode assembly **68**, **63**, **102**. This cathode assembly with or without the control grid, **63**, and Wehnelt electrode, **102**, may comprise (not shown) the emitting soles, **78**, **84**, **90**, if desired.

The magnetic field can be provided by one or more conventional or superconducting solenoids (or by one or more permanent magnets, not shown, which are not likely to be practical due to the high MMF requirements of Hall generators). The magnetic field distribution is generally substantially uniform throughout the MHD interaction space and the electron gun regions of the MHD generator (and MHD motor). However, certain situations may indicate modified (non-uniform) magnetic field distribution at the ends of the electrodes along the flow so as to increase the local charge density. The magnetic field is indicated by an arrow, **74**, shown perpendicular to the paper.

The applied electric field in the electron gun region is governed by Paschen's and crossed field laws. The effects of the former law are mitigated (by utilizing pulse durations of the order of a nanosecond at typical non-equilibrium MHD conditions) and controlled so as to increase the gas conductivity beyond the limit of electron beam injection alone by utilization of periodic pulsed ionizing electric field at appropriate pulse duration (e.g., order of decimicrosecond as previously discussed), and at a repetition rate to mitigate ionization decay rate and for the sake of full (100%) duty operation, and to avoid the deleterious effects of gas discharge and consequent non-uniform gas ionization. Furthermore, the relative intensities of the electric and magnetic fields can be such that only insignificant electron current flows to the accelerator, **70**, and consequently quite modest electron current need by demand of the illustrative periodic pulser, **72**, in energizing the electron gun. Provision against reverse electron current can also be made by means common to the state of the gas discharge art.

A control grid electrode, **63**, is incorporated for alternating current operation. It is used with a Wehnelt electrode, **102**, as shown in conjunction with the cathode, **68**, the electrode, **63**, being appropriately biased, (i.e., with intermittent (pulsed) or alternating potential) with respect to the cathode, by means of a biasing source represented arbitrarily in the figure by modulator **65**. The purpose of the electrode, **63**, is to control the electron beam. Although separate sources for the electron gun are illustrated, these very low power sources of potential are energized by the MHD generator. The cathode, **68**, is a non-thermal and thermal type electron emitter, in the latter case deriving its heat from the hot gas flow in which it is in contact.

Electrons emitted from the cathode, **68**, are drawn away toward the accelerating electrode, **70**, under the influence of the periodic pulsed electric field and direct current magnetic field, by application of appropriate sources mentioned. In addition, modulation of the grid for alternating current operation can be included. Thereupon the electrons, except for any captured by the accelerator electrode, are immediately constrained to move in magnetron paths, due to the combined effect of the orthogonal crossed electric and magnetic fields.

The pulsed electric and continuous magnetic field intensities are preferably adjusted so that the paths of the electrons in the gas starting at the extreme left of the cathode will just barely graze the accelerator plate and will not be substantially collected thereby but will be further constrained to continue substantially parallel to the accelerator plate in accordance with crossed field constraints, before, at, and after passing the throat of the electron gun. The result is substantially a smooth electron flow forming a stream of electrons emerging from the throat of the electron gun, in magnetron paths, all substantially along the plane of the electrodes.

FIGURE 4 shows schematically the electron stream from the primary crossed field electron gun, **66**, as it is injected into the gaseous stream in the interaction space of the generator. In the interaction space, the moving gas passes between a series of electrode pairs anode, **76**, cathode, **78**, anode, **82**, cathode, **84**, anode, **88**, cathode, **90**, etc. of parallel electrodes separated by insulating spaces without plates. The upper plate in each pair, as shown in the figure serves as an anode while the lower plate of each pair serves as a crossed field cathode similar to that of the electron gun and is referred to as electron emitting sole. The emitting soles are non-thermal and thermal or thermionic type (i.e., cermet or dispenser) type-deriving their optimum operating temperature for the thermal or thermionic portion for electron emission from the flowing hot gas with which they are in contact. They can also be, as the cathode of the primary electron gun, indirectly heated to meet any additional heat requirement on account of any inadequacy on the part of the hot gas. The emitting soles are preferably highly productive of secondary as well as primary electrons.

A succession of many short electrodes is employed instead of long continuous electrodes in order to break up the longitudinal circuit and so prevent large axial or longitudinal surface currents which would otherwise flow in the electrodes, due to the Hall effect which is made dominant for the purposes of this invention, a circumstance which would cause large ohmic losses. Furthermore, since at high magnetic fields or high Hall effect parameter, the current density tends to peak at the trailing edges of the electrodes, appropriate design considerations have been applied to minimize erosion thereat.

The emitting soles **78**, **84**, **90**, etc. supply the electrons to the gas or plasma in the interaction space as required to make up for electron loss and those passing to the load. To short circuit the electrodes of each electrode pair, electrical conducting straps, **80**, **86**, **92**, etc., are provided outside the interaction space between the anode and the emitting sole. The axial or longitudinal current, voltage and power are taken off through a load circuit, **94**, connected between the first and last pairs of electrode pairs, as shown. The magnetic field, both in the electron gun and in the interaction space is in the same direction but not necessarily the same magnitude and perpendicular to the plane of the paper and that of the ionized gas flow and electron beam flow. Both the applied magnetic field and the injected electron beam are made as substantially uniform as possible throughout the interaction regions between facing pairs of electrodes. However, there may be an advantage in controlling the magnetic field distribution in the interaction space with respect to the vicinity of the edges of the electrodes to take advantage of the increase in local density of charges thereat and so increase the power output from the MHD generator.

The use of the electrical ionization via electron beam injection, supplemented by periodic pulsed ionizing electric field means as previously discussed for maintaining adequate and uniformly as possible ionization of the flowing gas so that the desired electrical gas conductivity is achieved in the interaction spaces of the MHD generator (and the MHD motor), renders the system as a whole self-exciting and self-starting, as in the case of an electromagnetic machine or self-excited thermionic oscilator. With the gaseous stream forced through the duct, ionization is established immediately upon entering the primary crossed field electron gun portion of the duct. Full MHD generator (or MHD motor) action begins immediately upon the establishment of adequate ionization in the flowing gas, which requires continual and uniform ionization throughout the volume of the duct.

Requirement for continual uniform ionization arises on account of the rapid rate of decay of ionization, due primarily to recombination/attachment loss, which is characteristic of the behavior of the gas. The distribution and energy of the electron stream can be adjusted to accomplish this desired result while at the same time its energy is virtually entirely absorbed in the gas upon reaching the far end of the interaction space and an electron collector and heat regenerator, **98**, which is provided at that point..

The energy required to maintain the desired degree of gas conductivity by electrical ionization, namely conductivity in the order of 10 mho/m. or more, is moderate; it being of the order of a base percentage the useful power output of the generator. It is known in the art and as has been pointed out previously that the electric power generated is less than a percent of the total energy associated with the gas. That is, the total energy is equivalent to a small fraction of an electron volt at typical MHD conditions. Since the ionization potential of ordinary gases are relatively high, only a few percent of the atoms at the most would be ionized under ideal conditions of the available energy extracted and utilized. Nevertheless, the electrical conductivity of the gas when ionized to the extent of a small fraction of a percent is substantially as high as for the completely ionized gas.

A supplemental means for ionizing the gas with crossed field electron beam periodic pulsed ionizing electric field means, at the expense of a small fraction of the power output of the MHD generator, is also utilized, as previously discussed to achieve the desired electrical gas conductivity.

Only a few of the required representative electrode pairs in the generating portion of the generator, **50**, are shown for illustration in FIG. 4.

The pair of electrodes nearest the electron gun comprises the anode, **76**, and the electron emitting sole electrode, **78**, connected together outside the gas duct by the electrical conductive strap, **80**, which is of negligible resistance. The opposing faces of the electrodes of each pair are parallel to the direction of the magnetic field. An intermediate electrode pair comprises the anode, **82**, and the electron emitting sole, **84**, connected by a like strap, **86**. The pair of electrodes farthest from the electron gun comprises the anode, **88**, and the electron emitting sole, **90**, connected by a like strap, **92**. The output terminals of the generator, **50**, comprise the electrode pair, **76**, **78**, and strap, **80**, which constitute the generator terminal conventionally called the negative terminal, for direct current operation, and the electrode pair, **88**, **90**, and strap **92**, which constitute the positive terminal. The electrical load connected to the generator terminals is represented in the figure by the impedance, **94**.

Electrons emitted by the cathode, **68**, follow, in the simplest case, half cycloidal paths in the region between the cathode and the accelerator. The gun forms an electron beam which substantially permeates uniformally the entire interaction region of the gas duct as previously discussed. The electron beam moves to the right as shown in the figure, while ionizing the flowing gas, moving in the same direction, with the aid of the applied periodic pulsed ionizing electric field between cathode and anode or accelerator. In the interaction portion of the generator, the plasma is subjected to a strong Hall effect, which induces both transverse and axial or longitudinal current and voltage in the plasma. The transverse currents serve to provide the necessary physical resistance to flow. The load, **94**, is coupled through the longitudinal currents and voltages. Thereby, desired high rather than low impedance output characteristics are realized.

The electron beam injection and applied pulse duration, amplitude and repetition rate of the ionizing electric field can be controlled so that the ionization effect of the electron beam and pulsed electric field is substantially uniform and limited to the desired interaction region of the gas duct. After traversing the interaction region the plasma deionizes very rapidly as previously discussed, due primarily to recombination/attachment losses. Residual charges are collected at the ion collection/regenerator **98**, which in a very simple form can comprise one or more plates arranged edgewise to the gaseous stream. The ion collector/regenerator, **98**, primarily serves the purpose of absorbing residual heat energy from the exhaust gas. The neutral gas leaving the ion collector/regenerator, **98**, is in turn exhausted toward the right in the figure as indicated by the arrow, **100**.

To adapt the MHD generator for alternating current component operation, an alternating voltage, represented by a modulator **69**, is impressed between the control electrode, **63**, and the cathode, **68**, as shown schematically in FIG. 4. The action of the electron gun is the same as described previously, except that the electron flow is modulated instead of steady. For direct current operation the periodic pulsed non-ionizing electric field bias voltage, **65**, can be applied, but is optional. Its pulse duration is so short (order of a nanosecond) that no significant gas ionization occurs on its account. The alternating voltage from modulator, **69**, can be superimposed on this for alternating current power output from the MHD generator. As a result, there is a controlled variation of the degree of gas ionization and, hence, of the electrical gas conductivity in the MHD generator. This in turn causes a corresponding modulation of the power output of the MHD generator. The modulation of the power output of the MHD generator is attributable to the fact that the ions of the gas recombine extremely rapidly in the absence of an effective process of continual ionization so that significant variation of the electron output of the electron gun and periodic pulsed ionizing electric field is reflected in corresponding variations of the electrical gas conductivity and hence power output of the generator.

A switch, **67**, is shown whereby the modulator, **69**, can be included in the circuit or not, depending upon whether direct current or alternating current component operation is desired. It will be evident that the modulated or alternating current output from the MHD generator obtainable by use of the modulator can be converted by means of a transformer in conventional manner and that all known intermittent or pulsed or alternating current techniques can be employed in the utilization of the power output of the generator. Direct current operation especially at commercial voltages, is applicable in practice. Alternating current operation could also be obtained, in principle at least, alternatively by modulating the current in the solenoids producing the impressed magnetic field (especially in the case of a superconducting solenoid) but with much more drive required (except in the case of superconducting solenoids) and much less economy compared to low drive voltage modulation of the control electrodes of the primary cross field electron gun and secondary crossed field emitting soles.

Double-walled duct embodiment

FIGS. 6, 8 and 11 show an illustrative embodiment of coaxial ducts, primary crossed field electron guns and electrode structures for use in an MHD generator (or MHD motor) according to the invention. The emitting soles thereof can be replicas of the primary cathode assembly or can be simpler, as discussed previously. The coaxial duct is built on the Dewar principle with two spaced walls and thermal insulating space between the walls to minimize heat loss from the inner duct. The inner duct wall is a suitable dielectric (e.g., ceramic) with matching metal (e.g., tantolium, etc.) inserts on the inside to form the electrodes and joining members of sections. Those electrodes that are cathodes and emitting soles can be directly heated (via the hot flowing gas) or indirectly heated (via an auxiliary heater) "thermionic" and non-thermal electron emitter, as previously described. They can have a coating or a layer or comprise a body of electron emissive material such as a dispenser or cermet type.

Suitable dielectric (or ceramic) spacers are provided between the inner and outer walls at intervals along the duct for the purpose of isolating and supporting the inner duct in the outer one. The outer duct wall is of suitable metal (e.g., stainless steel) with suitable dielectric (or ceramic) inserts at locations where electrical connection is made to an electrode inside the duct. The ducts can be made in demountable setcions which can be welded (e.g., heli-arc) together to make up any required length, and separated (e.g., by grinding off the welds) a number of times and resealed as before as desired.

FIG. 5 shows in three-dimensional diagrammatical form a general convergent-divergent duct or nozzle which involves consideration of the Joule-Thomson (Joule-Kelvin) effect. Such nozzle can be used in practice for converting the random motions of the gas into more axially directed motion within the electron gun and interaction spaces in the gas duct in an MHD converter. In the near vertical wall of the divergent portion of the duct are shown schematically the crossed field electron gun cathode **68** the first sole electrode **78** in the interaction space, for simplicity a few intermediate sole electrodes, and the last electron emitting sole electrode, **90**. Usually in practice, a much larger number of intermediate emitting sole and anode electrodes will be required, depending upon design requirements. In the far vertical wall of the divergent portion of the duct are shown schematically the electron gun accelerator electrode **70**, the first anode electrode **76** in the interaction space, a few intermediate anode electrodes, and the last anode electrode, **88**. The sole electrode of each opposing pair of electrodes in the interaction space in shown strapped to the respective anode electrode of the pair, the first strap **80** and the last strap **92** constitute respectively, the negative terminal and the positive terminal for the load impedance **94** for direct current operation. The relative directions of the gas velocity, v_g, and the magnetic field intensity, B, are shown by arrows in the figure.

FIG. 6 shows a longitudinal or axial cross section of a simple MHD generator. The coaxial ducts therefore, in a central plane perpendicular to the magnetic field. This plane is also perpendicular to the planes of the opposed electrodes. FIGS. 7 and 8 show external appearance at side and one end, respectively. Although a conventional straight duct system is illustrated, in practice, the inner duct may be tapered, for example as illustrated in FIG. 5, so that

$$\lim_{\sqrt{g} \to \sqrt{gf}} B\sqrt{g}C \simeq \text{constant}$$

where C and $\sqrt{gf}$ denote cross section dimension and final gas velocity, respectively. The dielectric (or ceramic) inner duct wall that is uppermost in the figure is designated, **200**, and the lower inner duct wall is designated, **202**. The upper metal duct outer wall is designated, **204**, and the lower, **206**.

The electron cathode assembly of a simpler illustrative type of crossed field "short" electron gun suitable for direct current operation is shown generally at **208**. The cathode of the gun need not have an indirect heater assembly since the hot flowing gas is at adequate gas temperature for optimum thermionic operation. Other electron guns (e.g., those disclosed in FIGS. 17 through 22) for alternating current operation can be substituted for the electron gun shown. A simplified cathode **210** is shown comprising electron emissive material either coated upon a suitable base metal or comprising a cermet or dispenser type unit. The cathode **210** can operate by virtue of heat of the hot (e.g., 2500° F.) inert gas or its own accord, thermionically by means of a suitable integral electrical heat source. It can also be primarily a non-thermal type of emission cathode.

The indirectly heated (optional) cathode **210** is shown in the form of an inverted metal box separated on all sides from the main portion of the inner wall **202** by a gap **212**. Inside the cathode, **210**, are located a plurality of electrically heated heater elements indicated schematically at **214**. All the heater elements **214** are connected in parallel in conventional manner and brought out through an insulating tube **220** to a pair of heater connections **222**. The heaters are held in place by a cover plate assembly **224** through which the tube, **220**, projects.

A Wehnelt electrode, **226**, generally surrounds the sides of the cathode **210**. The electrode **226** comprises a sheet of metal inserted into the wall **202** to the left of the cathode, folded downward over the edge of the wall **202** at the gap, **212**, passing under the cathode and back up opposite the cathode at the right of the cathode to fasten to the wall **202** at the right of the gap **212**. A suitable dielectric (or ceramic) spacer ring **228** permits the cathode to be insulated and supported by the control electrode. An access side duct **230** for cathode connections is inserted in the lower outer wall **206**. The duct **230** is provided with a suitable cover plate **232** and a suitable dielectric (or ceramic) electrode base press **234**, sealing a hole in the plate **232**, through which the heater connections **222**, a cathode connection **236** and a control electrode connection **238** are brought out. The modulator **69** and the biasing voltage **65** can be inserted when required between the cathode connection **236** and the control electrode connection **238** in a manner similar to that shown in FIG. 4 between the electrodes **68** and **63** of that figure.

The accelerator for the elementary "short" electron gun is shown generally at **240**. The accelerator plate **242** is a metal (e.g., tantalum) plate inserted (i.e., brazed) in the upper inner duct wall **200**. The plate **242** extends opposite the control electrode **226** and the cathode **210**. Electrical connection is made to the plate **242** by way of a metallic pin **244**, which can be integral with the plate, the upper end of which makes a suitable engagement with a nut **246**. An access hole in the upper outer wall **204** opposite the nut **246** is sealed by a metal-dielectric (e.g., metal-ceramic) plug assembly **248**, which can be sealed (e.g., heli-arc welded) to a metallic collar **250**. Through the plug assembly **248** extends a shouldered metallic pin **252**, the lower end of which makes a (e.g., set screw) locked engagement with a nut **254** to permit angular orientation of the nut **254**.

Hairpin type electrically conducting "wires" **256** are inserted into holes in, or otherwise secured to the peripheries of the nuts **246** and **254**. A set screw (not shown) is provided in the nut **254** for securing the nut in correct angular position on the pin **252** so as to align the placements or holes for the wires **256**. A plan view of the nut **246**, hairpin wires **256** and without the set screw is shown in FIG. 9. The shouldered end of the pin **252** is provided with suitable means for engaging an external electrical connector **260**.

The metal and ceramic parts are joined in vacuum-tight manner as known in the art, so that the space between the inner duct and the other casing can be evacuated by known means and operated under high vacuum to reduce heat transmission from the inner duct to the outer casing and the ambient medium.

A sole electrode for the electron gun is shown at **262**. It can be an electron emitter or not, depending upon the application. In any event, its construction can be simple for direct thermionic electron emission by means of the hot gas or it can be primarily a non-thermal electron emitter independent of the hot gas. Its form can be generally similar to that shown for the accelerator electrode **240**.

An auxiliary anode electrode for the electron gun is shown generally at **264**. The construction of the auxiliary anode electrode can be substantially the same as for the accelerator **240**. The auxiliary anode electrode is flush with the upper wall of the duct as shown.

An anode electrode, for either an MHD generator or an MHD motor with an electrical connection external to the duct, is shown generally at **266**. The construction of this anode electrode can be substantially the same as shown for the electrode **240**, except for current capacity and because at the high Hall parameter or magnetic field characteristic of the Hall generator (FIG. 1C) the trailing edge of the anodes (and cathodes) with respect to the gas flow must be made more erosion resistant due to the concentration of electric current there. The anode electrodes are inserted into the upper wall of the duct. In an MHD generator, the external electrical termination of anode electrode **266** is used only at the two generator terminals that are to be connected to the electrical load of the generator.

The first of these, from left to right, is the negative terminal of the generator for direct current operation. It is the first anode electrode to the right of the primary electron gun. The second terminal is the positive terminal of the generator and is the last anode electrode shown generally at **268** at the extreme right hand end of the interaction space of the generator, the construction of which is substantially the same as shown for the other anode electrodes that have external electrical connections. In an MHD motor, all the anode electrodes and emitting soles may require external electrical connections.

The electron emitters of the cathode of the electron gun and sole in the MHD generator can be operated either as a non-thermal thermionic emitters, actuated by the passing hot gas stream, or as indirectly heated emitters, actuated by impressed external heat source, shown in the drawings only for the cathode of the primary electron gun.

The magnetic field can be readily supplied by permanent magnets, however, because of the high mmf. requirements it may be desirable to generate the magnetic field by means of electromagnets, conventional or superconducting.

The non-thermal thermionic electron emitters can be refractory dispenser or cermet types, having an operating temperature of about the ambient gas temperature (or 2500° F.). Operating these emitters at their optimum temperature insures long operating life.

An anode electrode that has no electrical connection through the outer duct wall is shown generally at **270**. The structure comprises a metallic plate **272** inserted in the upper inner duct wall **200**. A metallic pin **274** which can be integral with the plate **272** makes electrical contact with the plate **272** on the upper face thereof and extends upwardly to the upper surface of the wall **200** into a strap groove **302** (FIG. 12) for connection to a strap **288**, as will be explained presently with reference to FIG. 11.

An electron emitting sole electrode that has no electrical connection through the outer wall of the duct is shown generally at **276** (FIG. 6). The structure comprises a composite metallic plate **278** inserted in the inner lower wall **202** of the duct. The upper surface of the composite plate **278** can be impregnated or coated with a thermionic or secondary electron emissive material to promote copious emission of electrons as required. The strap **288** lying in a strap groove **302** (FIG. 12) is connected to the plates **278** and **272** as shown in FIGS. 11 and 6.

An anode electrode having no electrical connection through the outer wall of the duct and having a thermal and electrical isolator and spacer spanning the region between the inner and outer walls of the duct, is shown as an example at **280**. The structure is generally similar to that shown for the anode electrode **270**, except that a pin corresponding to the pin **274** extends sufficiently beyond the upper surface of the wall **200** to form a support or axle for a thermal spacer such as a wheel **282**. The rim of the wheel **282** is displaced laterally from the axle to such an extent that the rim bears against the inside surface of the upper outer wall **204**, while the axle bears against the outer surface of the upper inner wall **200**. The spacer or wheel **282** can have a plurality of spokes which extend diagonally between the axle and the rim.

An electron emitting sole electrode, similar in size to the anode electrode **280**, is shown generally at **284**. This electrode is inserted into the lower inner wall **202** of the duct and the thermal spacer or wheel **286** corresponding to the spacer or wheel **282** spans the region between the outer surface of the inner lower wall **202** and the inner surface of the outer lower wall **206**.

FIG. 11 shows a cross section of the duct through the anode electrode structure **280** and the electron emitting sole electrode structure **284**. The view shows the inner and outer walls of the duct in cross-section, together with the thermal and electrical isolators and spacers shown as the wheels **282**, **286**. The view further shows the short-circuiting strap **288**, which corresponds generally to any one of the straps **80**, **86**, **92** shown schematically in FIG. 4 for connecting an anode electrode to an opposing electron emitting sole electrode by an electrical conductive path outside the inner wall of the duct; specifically over the outer surface of the inner wall of the duct. The anode end of the strap **288** is electrically connected to a metallic pin **290** that forms the support for the isolator and spacer wheeel **282**. The strap **288** lies in a groove in the outer surface of the inner wall **200** of the duct, extending upwardly as shown in FIG. 11 and over the top outer surface of the inner wall, and thence downwardly to an electrical connection with the metallic pin **292** that forms the support for the isolator and spacer wheel **286**.

FIG. 10 shows a view of a particular isolator and spacer wheel such as the wheel 282.

Thermal and electrical isolators and spacers will usually not be required at every electrode position along the length of the duct or duct section. They can be placed as far apart as the design of a particular system dictates. Such isolators and spacers, as in the form of disks or wheels, are convenient during assembly of a duct. The inner duct wall with the desired number of thermal insulating spacers or wheels distributed along its length may be rolled into place within the outer duct wall, the spacers or wheels rolling or sliding upon the inside of the bottom outer duct wall 205 (FIG. 11) until the proper location is reached. This construction and assembly procedure is especially suitable for straight ducts, but it is also applicable to tapered ducts as required. For a tapered duct, the spacer or wheel size is appropriately graduated and the inner duct is slipped into the outer duct with the smallest spacer or wheel foremost.

At each end of the section of the duct a short metallic duct terminal section 294 is inserted with its inner surface flush with a suitable inner surface of the inner dielectric (e.g., ceramic) walls as shown. The duct section 294 is formed with a flange 296 all around and brazed or preferably heli-arc welded at the ends to a matching flange 296 of an adjacent section of duct to form a continuous inner wall. At each end of the duct the metallic outer walls of the duct are formed into a flange 298. The outer duct wall can be sealed for example by heli-arc welding or brazing a short length of metallic duct 300 to the flange 298 and to a similar horizontal flange 298 of the adjacent section of duct. It will be understood that thermal expansion joints are to be provided as needed, in accordance with known practice.

The arrangements shown for joining sections of duct are illustrative only and those skilled in the art of fabrication and installation of such ducts can readily devise other arrangements. The internal structure and arrangements of the ducts employed in the systems illustrated herein are evidently adaptable to any desired degree or ease of demountability.

Non-magnetic stainless steel (e.g., American Iron and Steel Institute Type No. 304) is a suitable material for the outer duct walls of the Dewar type duct and for end flange members thereof. For the inner duct walls, electrodes and flanges, tantalum or even molybdenum alloys and matching ceramic ducts can be used.

Grooves for the short-circuiting straps 288 and 288' in the outer surface of the inner wall are illustrated in FIGS. 12 and 13. FIG. 12 represents a portion of the outer surface of the inner wall 202, having strap grooves 302, 302' therein. In this view, holes 304, 304' are shown for passage of the metallic pins such as the pin 274 of FIG. 6. FIG. 13 shows a portion of the outer surface of an inner wall 306 which is to be fastened at right angles to the wall 202 as shown in FIG. 11. The face and edges of the wall 306 are formed with grooves 308, 308' as shown.

The electrodes other than emitters can be made of some suitable metal or alloy, such as tantalum, molybdenum, molybdenum alloys, tungsten, tungsten alloys, etc. Plates of this material are brazed into accurately milled recesses or niches in suitably matching dielectric (e.g., ceramic) wall members, the surface of the plate being arranged or made flush with the inside wall in order to introduce no material resistance to the gas flow due to the presence of the electrodes. It is essential that the thermal expansion characteristics of the metal and dielectric be matched over their operating and fabricating temperature ranges. Normally, ceramics are placed in compressive stress rather than tensional stress, due to their far greater strength in the former. In any event, ceramic-metal seals are presently available which withstand operating inert gas temperatures of the order of 2500° F. for an indefinite period.

FIG. 14 shows in cross-sectional view an illustrative arrangement for applying the magnetic field to a straight duct by means of conventional or superconducting electromagnets. Permanent magnets are rather impractical at the high Hall parameter or magnetic fields contemplated in accordance with Hall generator characteristics. No yoke is utilized since the pole pieces are operated at saturation. Therefore, half the magnetic field in the interaction gap is provided by the pole pieces and half by the solenoids surrounding them as shown. A solenoid winding 186 surrounds the pole piece 182 and another solenoid winding 188 surrounds the pole piece 184.

A plurality of solenoids can be placed along the length of the gas duct so as to break the magnetic system up into a plurality of unit sections energized by separate windings. The windings can be designed according to the Fabry formulae and their extensions and can be wound wild or orthocyclicly, with solid or tubular conventional or superconducting conductors. The windings can also be disk wound or tape wound, with radial or axial cooling means in the case of ordinary conductors. Superconductors (e.g., Nb_3Sn, Nb, Zr, etc.) of course, radically reduce power supply needs (e.g., by a factor of 1000 for small size, and 4000 for large size), weight, and cost of solenoid, but require helium (at 20° K.) as coolant. Regardless of the type of solenoid (i.e., classical or superconducting), it essentially controls the minimum gas conductivity in practice. So, it represents a vital consideration in MHD generator development.

A plurality of reinforcing ribs 310 are shown as metal bands of good magnetic material, fastened to the outer surface of the outer duct wall and spaced apart at intervals along the length of the duct.

Electron guns

In general, the electron beam can be derived from an electrostatic type or crossed field type thermionic or plasma electron gun. The electron beam can be injected into and along the gas stream either normal to the periodic pulsed electric and direct current magnetic fields in the interaction region between pairs of electrodes or along the magnetic field. The latter type of injection increases the magnetomotive force requirements for the magnet; and furthermore, electron guns using this type of injection have to be repeated at each electrode pair or otherwise made continuous along the duct, in either case compounding the complexity of the gas ionizing means. Finally, such an electron gun requires perforating the two walls of the duct thereby contributing substantially to structural problems. These along-the-magnetic-field injection electron gun may, however, be useful under certain circumstances. Illustrative arrangements for electron guns of this type are shown in FIGS. 20 and 21.

The former means of crossed field electron injection, achieved by means of crossed field electron guns, as illustrated by FIG. 6, for direct current operation and FIGS. 16 and 18 for alternating (or intermittent operation or direct current) operation is most satisfactory in many instances. In the design and especially the use of such guns, it is necessary to take cognizance of the fact that the associated electric fields must not act on the gas for longer periods of time than is necessary for the desired degree of ionization (by virtue of the ionizing electric field and acceleration of the electron beam) so as to avoid not only non-uniformity, especially at beam injection, but excessive ionization and energy dissipation due to sparking or channel arcing as well. Such time duration may be of the order of centimicroseconds, which fortunately is relatively common for switching times in circuitry (e.g., by virtue of transistor technology). However, due to the correspondingly rapid decay rate of ionization (e.g., order of dimisecond for typical MHD generator conditions), the repetition rate must match and be high enough for continuous power output, which may be a problem because the difficulty of achieving high repetition rate at such short pulse durations increases substantially, at present state of art. In any event, the crossed field guns perform at least two major functions at comparable efficiencies. They not only create, inject and control the electron beam in the gas, but the associated periodic pulsed ionizing electric field below the sparking limit raises the electron temperature of all the electrons in the gas. Thereby, compound ionization of the gas takes place. Such functions can be repeated at each anode sole electrode pair in the interaction space and not merely limited to the primary electron gun. Furthermore, for direct current operation, the crossed field guns can be quite simple. The additional complication of modulation electrodes in the guns are only required for alternating current component operation as previously discussed.

The simpler of the crossed field guns suitable for direct current operation, is illustrated by FIG. 6. This gun can be further simplified by elimination of the primary heater and reliance placed on a non-thermal and thermionic (by virtue of hot gas) type cathode, together with the periodic pulse ionizing electric field previously described to adequately ionize the gas for initiation and continuance of operation. It is an equivalent conventional high vacuum "short" type crossed field gun, sometimes referred to as the "Charles" gun (when used without any grid). Focussing and acceleration occur quickly over time equal to a fraction of a cyclotron period or equivalently over a spatial distance of a fraction of a cyclotron wavelength of the beam. In other words, the length (along the duct) of the emitter or cathode is a fraction (i.e., half) of an electron convolution from the emitter. A "long" or adiabatic crossed field counterpart can also be used. In this case, the converse applies with regard to focusing and acceleration. The cathode or emitter of the gun can be a non-thermal and a thermionic type electron emitter directly heated to optimum temperature by an indirect heater or by the flowing hot gas.

The purpose of the multiple vane grid control is to achieve effective modulation of the electron beam for the purpose of generating an alternating current component at the output terminals of the MHD generator, with low drive, and yet not obstruct the required electron beam. The purpose of the compound plasma electron cathode is to obtain high electron beam density from a plasma meniscus in accord with known state-of-art plasma physics.

In the multiple vane grid controlled crossed field electron gun as shown in FIGS. 16 and 18, the cathode is subdivided into a plurality of segments **340**, spaced apart and lying parallel to one another substantially in a plane. The cathode segments **340** can be individually heated as by heater units **342** similar to the heater units **214** shown in FIG. 6, or they can be directly heated by the hot flowing gas. The control electrode member is in the form of a plurality of vanes **344** or individual control electrodes interspersed between the cathode elements **340**.

Each vane **344** can be a flat strip of suitable conductive material (molybdenum, trungsten, tantalum, etc.) arranged parallel to and spaced from the adjacent cathode elements **340**. Each element **344** lies in a plane perpendicular to the plane of the cathode elements. The vanes **344** are arranged with parallel edges lying substantially in a plane parallel to and spaced from the plane of the cathode elements **340** toward the center of the duct by a short distance. The accelerator plate **346** for the gun lies in a plane parallel to the edges of the vanes **344** and spaced both from the cathode plane and the plane of the vane edges, on the far side of the duct from the cathode plane. A ramp electrode **348** is provided in the plane of the vane edges and spaced from the nearest vane.

The vanes **344** are connected electrically through an apertured bottom plate **350** and side plates **352** forming with the vanes a box-like structure, within which the heaters and cathode segments can be insulatingly supported in known manner. An auxiliary anode **354** is shown adjacent the accelerator **346** and a sole **356** is shown adjacent the right-hand-most vane **344**. In FIG. 18, the inner wall surfaces of the inner duct are indicated diagrammatically at **358**.

FIGS. 18 and 19 show an illustrative arrangement of a plasma type crossed-field electron gun. The cathode is formed by a plasma meniscus **360** in a plasma region **362** within a plasma reservoir **364**. The latter is a box-like metal structure the bottom and sides of which form an electron emissive surface **366**. Surrounding the plasma reservoir **364** and insulated therefrom is another box-like metal structure or electron extraction and control electrode **368**. The upper surface, both of the plasma reservoir **364** and of the electrode **368**, is perforated with aligned small openings through which a plurality of electron beams are directed into the gas duct, the upper surface of the electrode **368** being preferably flush with the inner surface of the gas duct as shown.

Gas from the gas duct permeates the entire interior both of the plasma reservoir **364** and the electrode structure **368**. In the operation of the gun, electrons emitted from the surface **366** form a sheath region **370** next to the emitting surface and produce a plasma or ionized gaseous region within the sheath which forms the meniscus **360** from which electrons are extracted in beams by the action of the applied periodic pulsed (e.g., order of monoseconds) non-ionizing electric field on the electrode structure **368**. The electron beams enter the crossed field region of the gun where they are deflected in the direction of the gas flow as in the case of the other crossed field guns illustrated.

FIG. 20 shows an electrostatic segmented dual electron gun for injecting electron beams into the interaction space of the gas duct along the direction of the applied magnetic field. The view shows a cross section of the magnetic pole pieces and the gas duct, the plane of the cross section being perpendicular to the direction of gas flow. The magnetic pole pieces are shown at **440** and **442**. An insulating duct wall **444** is shown supporting an anode **446**, and an opposite insulating wall **448** is shown supporting an emitting sole **450**. The duct is closed off at the top by a metal wall **452** and at the bottom by another metal wall **454**. The portion of the gas duct which contains the rapidly flowing gas is limited at the top by a perforated insulating plate **456** and at the bottom by another perforated insulating plate **458**. The perforations in the top plate **456** are staggered with respect to those in the bottom plate **458**.

A Wehnelt electrode **460** and an auxiliary electrode **462** are provided at the top and an auxiliary electrode **454** and a Wehnelt electrode **466** at the bottom. These electrodes can be in the form of metal plates insulated from each other and having openings registering with the openings in the adjacent perforated insulating plates **456**, **458**. The openings and the resultant electron streams passing therethrough are preferably very closely spaced in order to permeate the interaction space with electrons all traveling essentially parallel to the applied magnetic field. The electron beams originate in electron emission from upper cathodes **468** and lower cathodes **470**. Electrons from a cathode **468** are controlled by the periodic pulsed non-ionizing (e.g., order of monoseconds) electric field applied to the Wehnelt electrode **460** and similar electric field applied to the auxiliary electrode **462**, and electrons from a cathode **470** are controlled by Wehnelt electrode **466** and auxiliary electrode **464**.

FIG. 21 shows a plasma-type cathode gun similar in all respects to that shown in FIG. 20 except that the electron source is a plasma reservoir instead of a plurality of distinct cathode segments.

Controlled electron beam injection into a gas provides, aside from the periodic pulsed ionizing electric field below the sparking limit, not only a very effective utilization of energy devoted to ionization but also provides a relatively uniform distribution of ionization both across and along the interaction region. This is desirable because of the very rapid recombination/attachment loss of electrons and ions.

The electrical gas conductivity should be controlled by means of the electron beams and pulse duration and repetition rate of the ionizing electric field so that it is maintained in an optimum range, neither too low, for the sake of reasonable size and efficiency, for a given power capacity, nor too high, in order to avoid distortion of the cross sectional flow front to avoid excessive entropy changes due to Joule heating losses from extraneous currents. The controlled electron beam injection and periodic pulsed ionizing electric field process are well suited for achieving these requirements at common efficiencies in the neighborhood of 90 percent.

Since power density in the MHD generator (or MHD motor) is a function of the electrical conductivity of the gas and its electron mobility (for a given magnetic field, gas velocity and loading factor) it is desirable to use high electron mobility, high magnetic field intensity, low gas pressure (for the sake of low recombination/attachment loss) and minimum gas temperature (for the sake of not taxing endurance of materials of electrodes and duct) for full 100%) duty, long life operation, consistent with the desired conversion efficiency.

An effective means of achieving high electron mobility, is to use a noble gas with high specific heat and low molecular weight such as, for example, argon and helium as the plasma means. While argon is characterized by order lower electron collision cross section and recombination coefficient and very large relative Hall parameter and relative power density, helium provides better thermal conductivity, higher gas velocity, lower gas pressure and the like. High electron mobility and high magnetic field intensity promote the desired strong Hall effect, which in turn implies longitudinal rather than transverse current and voltage or power extraction, which results in relatively high load impedance or output voltage.

Additionally, the plasma means can also be composed of a gas-vapor or vapor of an easily ionizable material such as, for example, cesium can be used.

The use of the highly efficient electron beam means of gas ionization, supplemented by equally efficient periodic pulsed ionizing electric field means of gas ionization eliminates the need for extremely high gas temperatures characteristic of thermal equilibrium ionization in achieving the desired or same order of electrical conductivity of the gas. Simultaneously this avoids taxing the endurance of materials of electrodes and duct walls. Hence, operation is not limited to intermittent or pulsed service at low duty.

In summary, regarding ionization in accordance with this invention, ionization is initiated and maintained at adequate level and at maximum efficiency by entirely nonequilibrium and in particular electrical means. The means utilized is a crossed field electron beam injection into the flowing gas and/or supplemented by periodic short pulse ionizing electric field impressed on all electrons in the gas so as to raise the electron temperature to the desired degree.

The electron guns used to provide the electron beam are characterized by the fact that the accelerating and beam forming periodic pulsed ionizing electric direct current magnetic fields of the gun do not interfere with the gas flow nor do they modify significantly the field conditions in the interaction space of the MHD converter. The crossed field type of gun is non-obstructing to the gas flow and the non-magnetic electrostatic type of gun is adapted to external injection but considerably more complicated and costly.

Compact duct configurations

FIGS. 22 and 23 show one arrangement suitable for gas electrical conductivities where the duct length is of undesirable length. In such an arrangement a duct length of many meters can be formed into a compact helix and conveniently supplied with the requisite magnetic field. A duct **400** is shown surrounded by an outer solenoid **402**, the upper half of the solenoid **402** being shown cut away in FIG. 23 to reveal the helical duct within. An inner solenoid **404** is shown coaxial with the helical duct.

FIG. 22 represents a cross section through the axis of the helix. For clarity, only the outer wall of the duct is represented in the cross section. The disk or orthocyclic wound solenoids **402** and **404** can be ordinary or superconducting. They are excited in such relative polarities that the magnetic flux inside the inner solenoid is directed oppositely to the magnetic flux inside the outer solenoid, with the result that the flux returning to the inner solenoid by paths outside the inner solenoid passes through the duct in the same direction as the flux generated within the outer solenoid. If desired, the inner solenoid **404** can be omitted. Multiple solenoids **402, 404, 404′, 402′**, can be employed instead of single continuous solenoids, to constitute a periodic system of solenoids.

FIG. 24 shows a helical duct **406** wound in similar fashion to duct **400** shown in FIGS. 22 and 23, but leaving space between adjacent turns for a helical iron (e.g., Armco wrought iron) system, as shown. These magnetic poles **408** are operated at saturation so that the adjoining solenoids **409, 410** each contribute to half the required magnetic field in the ducts **406**. The magnetic field is produced by solenoids **409** and **410**, as shown, each of which is a section of a helix. The magnetic poles can be all alike. Each magnetic pole may be torodial in shape and can be rectangular in cross section. The magnetic poles are at the surfaces shown. In the assembly, as shown in FIG. 24, the horizontal sequence of the magnetic pole is alternately north and south, i.e., periodic. A system using magnets of this type is, therefore, designated as a periodic magnet system MHD generator (or MHD motor). The ducts employed in accordance with the invention can be designed in such shapes and with walls of such dimensions that they can be formed into compact forms of reasonable dimensions as will be evident to those skilled in the art.

FIG. 25 shows schematically, plausible and illustrative electrical connections between the MHD generator and the MHD motor for use either in a closed cycle as in FIG. 2 or for use where the MHD motor is operated in open cycle, e.g., as an electrical MHD propulsion engine. It will be assumed that the exhaust gas stream from the MHD generator is fed directly into the inlet of the MHD motor for open cycle operation, or through a cooler and a gas purifier for closed cycle operation of FIG. 2. The gas velocity, v_g, and the magnetic field vector, B, are shown in the figure both for the MHD generator and for the MHD motor. The positive side of the load R_L, of the MHD generator is shown connected to the last anode of the MHD motor in a constant K connection, FIG. 1D, back to the first sole which latter is connected across a suitable portion of the load. In this connection the MHD generator furnishes the MHD motor with the necessary power to develop a force in the direction of v_g as required. Appropriate design features differing from that of the generator are indicated for MHD motor or MHD propulsion operation.

Determination of salient MHD model generator parameters

An ideal one dimension flow model suitable for estimating numerical values of salient parameters of an illustrative embodiment or model will now be given, with special reference to a generator with a useful power output of the order of 10 kw. or higher, continuous (i.e., 100%) duty operation, for which typical numerical results will be given. The affects of the various losses (i.e., ohmic heating (major); end and eddy current; boundary layer; anode and cathode voltage drop; Hall current; solenoid; etc.) are assumed tolerable with justification.

The maximum carnot cycle efficiency of the system, for closed cycle operation including the MHD generator, the MHD compressor, the heat regenerators, and the gas cooler is according to classical thermodynamics;

$$\left[\eta_G-\left(\frac{T_4}{T_1}\right)\eta_M\right]\Big/[\eta_G+(T_2-T_6)/T_1]$$

where η_G, η_M denote thermal efficiencies of the generator and motor T_1, T_2, T_4 and T_6 denote, respectively, the gas temperatures between; the primary heat source exhaust and MHD motor inlet; and the preheater exhaust and primary heat source inlet. The gas temperatures in the respective portions of the closed system of FIG. 2 are designated at T_1 through T_6 in the figure.

It will now be assumed that the MHD generator and the MHD motor both have the same efficiency of conversion between mechanical energy and electrical energy, which efficiency is designated as $\eta_M\eta_G$ and will be assumed to be about 80%. Taking into account the less than complete conversions of energy into useful form in the generator and in the motor, an estimated overall efficiency can be obtained, which efficiency will be designated as η_C. In making this estimate, the thermal efficiency of the generator is to be multiplied by η_{MG} to account for loss of useful energy in the MHD generator, and the thermal efficiency in the MHD motor or pump or accelerator or compressor is to be divided by $\eta_M\eta_G$ to account for loss of useful energy therein.

Thus, using the values of N_M and in terms of the gas temperature T_1, T_2, T_4 and T_5,

$$\eta_C=\frac{\eta_{MG}\left(1-\frac{T_2}{T_1}\right)-\left(\frac{1}{\eta_{M,G}}\right)\left(\frac{T_4}{T_1}\right)\left(\frac{T_5}{T_4}-1\right)}{\eta_{M,G}\left(1-\frac{T_2}{T_1}\right)+\left(\frac{T_2-T_6}{T_1}\right)}$$

where T_5 denotes the gas temperature between the exhaust of the MHD motor and the preheater inlet.

It will be further assumed that in the generator and in the motor the general thermodynamic ideal condition holds so that:

$$\frac{T_1}{T_2}=\left(\frac{P_1}{P_2}\right)^{(k-1)\eta/k}=\frac{T_5}{T_4}=\left(\frac{P_5}{P_4}\right)^{(k-1)\eta/k}$$

where $N=1$ for reversible adiabatic process, and the p's denote the corresponding gas pressure, and k denotes the ratio of specific heat.

In the heat regenerators, the relations of inlet and outlet temperatures are given by

$$T_2-T_6=T_3-T_5$$

where T_3 denotes the temperature between the regenerator exhaust and the cooler inlet.

$$\eta_C=\frac{\eta_{M,G}\left(1-\frac{1}{(P_1/P_2)^{(k-1)/k}}\right)-\left(\frac{1}{\eta_{M,G}}\right)\left(\frac{T_4}{T_1}\right)\left[\left(\frac{P_1}{P_2}\right)^{(k-1)/k}\right]}{\eta_{M,G}\left(1-\frac{1}{(P_1/P_2)^{(k-1)/k}}\right)+(T_2-T_6)/T_1}$$

or, alternately,

$$\eta_C=\frac{\eta_{M,G}\left(1-\frac{1}{(P_5/P_4)^{(k-1)/k}}\right)-\left(\frac{1}{\eta_{M,G}}\right)\left(\frac{T_4}{T_1}\right)\left[\left(\frac{P_5}{P_4}\right)^{(k-1)/k}\right]}{\eta_{M,G}\left(1-\frac{1}{(P_5/P_4)^{(k-1)/k}}\right)+(T_3-T_5)/T_1}$$

From these assumptions and by assigning a desired arbitrary value to T_2-T_6, a consistent set of operating temperatures for the closed cycle can be determined. Here, cycle efficiency, η_C, is maximized with respect to the pressure ratio, P_1/P_2 or P_5/P_4, by determining the appropriate pressure ratio in the usual way of differentiating and equating to zero. For helium as the gaseous medium, with a value of 1.666 for k, this maximization process gives a value for $P_1/P_2=P_5/P_4$ of about 2.1.

Finally, as above noted, the temperature of the gas at the inlet of the generator, T_1, is taken to be 2,500° F. (1,645° K.) to avoid deterioration of ducts and electrodes state-of-art refractory materials by excessive temperatures and hence for the sake of full (100%) duty operation and long life, and for the sake of the limitations of the primary heat source previously cited. The temperature of the gas at the cooler exhaust or at the inlet to the motor, T_4, the coldest part of the system, is taken in accord with prevailing technology to be 125° F. (325° K.) assuming the use of a suitable state-of-art cooler.

From the classical thermodynamic relations, the exhaust gas temperature from the MHD generator (or input gas temperature to the regenerator), T_2, is found from the given exhaust gas temperature from the heat source (or inlet gas temperature to the MHD generator), T_1, that is from $T_1/T_2=(p_1/p_2)^{(k-1)/k}$. The value of the gas temperature from the MHD motor exhaust (or input to the preheater), T_5, from the given value of the exhaust gas temperature from the cooler (or input to the MHD motor), T_4; that is $T_5/T_4=(p_5/p_4)^{(k-1)/k}$. The cycle efficiency equations, η_c, may be solved simultaneously for the exhaust gas temperature from the regenerator (or inlet to the cooler), T_3, and exhaust gas temperature from the preheater (or inlet to the primary heat source), T_6, using the equality between T_2-T_6 and T_3-T_5. The value found for this ratio, being cognizant of the fact that $p_1/p_2=p_5/p_4$, can then be used to obtain T_6 from the now known values of T_2 and T_1 (that is, from

$$(T_2-T_6)/T_1=\text{constant})$$

and to obtain T_3 from T_5 and T_1 (that is, from $(T_3-T_5)/T_1$, which is equal to the same constant).

The results of such calculations are shown in the following set of illustrative temperatures:

TABLE I

Temperature:	Gas temperature, ° K.
T_1 (assumed) ....(2,500° F.)..	1645
T_2	1224
T_3	536
T_4 (assumed) ....(125° F.)..	325
T_5	437
T_6	1125

The corresponding maximum thermodynamic (Carnot regenerator or cycle) efficiency (η_c) maximum of the closed cycle system as given above is computed for the determined pressure ratio, 2.1, and the gas temperatures, Table I. The results are tabulated as a function of the MHD generator or MHD motor efficiency $\eta_{G,M.}$ in Table II, from which it is found that in the present case (η_c) max.=45%.

TABLE II

MHD Generator (or MHD motor) Efficiency, $\eta_{M,G}$, percent	Maximum Thermodynamic (or Cycle) Efficiency, (η_c) max., percent
50	5.0
60	20.0
70	33.5
80	44.5
90	53.0
100	58.5

For a maximum cycle efficiency and a useful power output of 10 kilowatts, the required power capacity, P_R, of the primary heat source can be estimated tentatively as 25 kilowatts. Thus, the total electrical power output P_T, at maximum cycle efficiency of 45% is $P_T=(\eta_c)$ max. $P_R=11.25$ kw. It can be estimated further that the maximum auxiliary power, P_A, required for the electron gun magnets, or the like, is at least of the order of a tenth of the total electrical power output. That is, $P_A=(0.10) P_T=1.125$ kw. Then, the net electric power output is $P_O=P_T-P_A=10.125$ kw. Hence, the net system thermodynamic (cycle) effieciency is $(\eta_c)_n=p_0/p_R=40.5\%$, which agrees closely with the tentative estimate just made.

The working fluid is circulated in a closed cycle, and requires only a limited volume of material. It is chosen for favorable properties relative to:

(1) The primary heat source.
(2) Thermodynamic cycle.
(3) Maximum electron mobility.
(4) Maximum specific heat.
(5) Minimum molecular weight.
(6) Minimum working pressure.
(7) Maximum subsonic gas velocity.

The properties of interest for the indicated (noble) gases are given in Table III.

TABLE III

Element	Molecular Weight	Specific Heat, c_p	Thermal Conductivity σ_e	Ionization Potential, ϵ_I
Argon	40	0.125	0.009	15.7
Helium	4	1.25	0.082	24.5
Neon	20	0.25	0.027	21.5
Krypton	84	0.06	0.005	13.9
Xenon	131	0.04	0.003	12.1

In Table III, the specific heat given was specific heat at constant pressure, measured at 70° F., in engineering units; the thermal conductivity given was measured at 32° F., in engineering units; and the ionization potential was in electron volts.

Table III shows that helium is superior to the other noble gases with respect to molecular weight and specific heat. With regard to helium, argon displays two orders of magnitude lower recombination coefficient and very large relative Hall parameter and, consequently, very large relative power density. Therefore, in the computations, helium has been taken as a representative working fluid.

The gas flow velocity (i.e., Mach number) is assumed subsonic (i.e., Mach number «1) so that the frictional pressure drop, due to boundary layer losses, is at least tolerable so that for a first order approximation the pressure drop is neglected. With more sophisticated computations, this boundary layer loss can be accounted for, if warranted, depending upon the Mach number and cross section of the duct.

Actually, a too low (electrical conducting) gas velocity is not desired for various reasons, predominant among which is the duct size and particularly the duct length, since the latter varies inversely with gas velocity. Now, energy loss associated with viscous boundary layers can be important indeed, depending upon Mach number, in viscous dissipation, flow separation and space effects in any gas engine. However, in the magnetohydro dynamic converter, the equivalent Reynolds number will be much larger. Hence, those losses will be correspondingly smaller. Furthermore, the presence of the magnetic field and electrical conducting gas will also reduce the friction coefficient by thickening the boundary layer. The nonuniform velocity profile, however, essentially does not cause electrical losses. The reason for this is that the power generated depends only upon the mean velocity and mean electrical conductivity averaged over the cross section of the duct.

Tentative assumption of constant cross section of the gas duct is also a first order approximation in accord with no complete initial optimization of parameters. Assuming lossless conducting electrodes and no energy extraction other than electrical output, then for constant cross section gas duct and inlet flow subsonic, the local Mach number will increase along the flow while the gas temperature decreases. Then electrical power extraction is limited by the fact that the exhaust Mach number cannot exceed unity as a sonic barrier. In fact, as the flow approaches a critical Mach number, choking results. In effect, supply of heat or dissipated electrical energy would force the Mach number toward unity so that "choking" would result. Whereas, if the energy is supplied reversibly with the flow, current and magnetic field mutually orthogonal, the Mach number is forced away from unity, so that choking only occurs when energy is extracted.

If the inlet flow is initially supersonic, the local Mach number will decrease along the stream and a shock wave may result, so that the sonic barrier still limits the power extraction. The shock may lead to saturation in power extraction or even current reversal, depending upon the strength of the shock or to zero current extraction as asymptotic approach to zero current density occurs, in which the gas is in quasi-steady state or "metastable state" hovering between generator and motor action. As a consequence of the foregoing considerations, the cross sectional area of the duct can be increased along the flow. Indications of the degree of pitch are afforded by the conventional axial flow turbines, since the salient aspects of the two flows are similar.

In the case of an MHD motor or pump or accelerator or compressor electrical energy is supplied to a gaseous plasma in a duct. More motor action will result if the energy is supplied approximately reversibly, propelling the gas by subjecting the transverse current to an orthogonal magnetic field instead of simply dissipating the energy to merely heat the gas. For a given flow rate and applied power, the smaller the entropy rise of the gas, the greater is the motor action. The parameter which determines the degree to which energy can be supplied reversibly is proportional to the scalar product of electrical conductivity of the gas, the square of the gas velocity and magnetic field, and to the reciprocal of the applied power density.

A sophisticated analysis of the MHD generator and motor, especially with respect to optimization of parameters, includes considerations relative to ohmic heating losses of the gas due to its relatively low electrical conductivity; eddy current losses, as the flow passes into and out of the magnetic field; electrode voltage drop losses; Hall current losses, due to segmented electrodes; and end losses, due to shunting action of the ionized gas at the inlet and exhaust, can be taken into account.

From the foregoing gas temperatures, there can be deduced the relationship between the power P_G, which the MHD generator must produce and the power P_M, required by the motor, which from an appropriate temperature-entropy diagram may be shown to be:

$$P_G/P_M=(T_1-T_2)/(T_5-T_4)=3.76$$

Since the power, which it is desired to have available for the load, P_T, is the difference between the P_G and P_M, the power which the generator must develop is:

$$P_G=P_T/[1-(1/(P_G/P_M)]=1.36\ P_T$$

Thus to produce $P_T=11.25$ kw required in the illustrative case, the generator must develop $P_G=15.3$ kw.

The power, P_M, required by the MHD motor or pump or accelerator or compressor then comes out as:

$$P_M=P_G/(P_G/P_M)=4.07 \text{ kw.}$$

It may be noted that on the basis of the calculated temperatures, the mean gas temperature in the MHD generator is

$$T_M=|T_1-T_2|/=1434° \text{ K.}$$

The significance of the inlet and outlet temperatures in the MHD generator can also be assessed in terms of Mach numbers. Using the classical relation for the velocity, v_s, of sound in a gas $v_s=\sqrt{gkRT}$ where g is a conversion factor (=32.2 in engineering units), k the ratio of specific heats, C_P/C_V of the gas, R the universal gas constant (386.2 in engineering units), and T absolute temperature in degrees Rankine. The Mach number, M., which is the ratio of the gas velocity to the velocity of sound in the gas, at the specified temperature, can be determined with the results given in the following Table IV, for an assumed subsonic gas velocity of 1,000 m./s., representing tolerable threshold for frictional pressure drop;

TABLE IV

Gas temperature:	Mach number, M
T_1=(1645° K.) 2960° Rankine	0.418
T_2=(1224° K.) 2200° Rankine	0.483

Table IV shows that the gas velocity, both at the inlet and the outlet of the generator, is well below Mach One. Since higher Mach numbers decrease directly the size and particularly the length of the MHD generator, a compromise will be necessary with respect to tolerable frictional pressure drop and cross section of duct.

Calculations are continued by assuming a set of values of certain starting parameters, using these values to compute other parameters and these by an iterative procedure recomputing the assumed starting values. The iterative process can be carried out until a consistent set of values are obtained for all the desired parameters.

A suitable set of starting parameters comprise gas velocity, v_g, the Hall angle, ⊕, (between the electric field intensity relative to the gas and the operating field intensity), together with a trial assumption of electric field intensity, E_e, (relative to the electrons), and the average gas pressure $\bar{p}$.

Alternately, another suitable set of starting parameters is the magnetic field intensity, B, the gas velocity v_g, the average gas pressure, $\bar{p}$, and the electric field intensity, E_e, can be chosen. Whichever set of assumptions is made, the subsequent iterative process yields the same resultant set of derived parameters. If agreement between the assumed and the derived values is lacking, new starting values are taken for the assumed parameters and the calculations are repeated. In the following, assumed starting values are used which have been found to lead to self consistent results.

These are:

$B=3.75$ webers/m.²
$v_g=1000$ m./sec.
$E_e=500$ volts/m.
$p=10$ lbs./in.², absolute.

The value assumed for the gas velocity is made low enough for tolerable frictional pressure drop along the duct containing the gas.

The first step in the computations is based upon experimental data shown in Table V, relating electron mobility, μ_e, for helium, to the electric field intensity, E_e, relative to the electrons, with the gas pressure, p, as a parameter.

TABLE V.—HELIUM ELECTRON MOBILITY (μ_e)
[In m.²/V, s]

Gas Pressure p, in p.s.i.a.	Electric Field, with respect to the Electron, E_e, in V/m.							
	500	1,000	2,000	4,000	6,000	8,000	10,000	11,000
10	2.93	2.50	1.95	1.46	1.23	1.08	0.97	0.94
20	1.77	1.60	1.33	0.95	0.80	0.72	0.61	0.59
30	1.35	1.19	1.02	0.73	0.64	0.57	0.47	0.45

From Table VI there is selected the value of

$$\mu_e=2.935 \text{ m.}^2\text{/volt, second}$$

corresponding to a field intensity of 500 volts per meter, and a pressure of 10 pounds per square inch, absolute.

The Hall (effect) parameter is then:

$$\mu_e B=(w_c)_e t_e=l_e/r_1=(2.935)(3.75)=10.99$$

where l_e, t_e, r_i and $(w_c)_e$ denote the electron mean free path and time, Larmor radius and electron angular cyclatron frequency, respectively. As described in the text initially in connection with FIGS. 1A to 1D inclusive, values of the Hall effect parameter, greater than about 10 are sufficient to insure large power density and high efficiency in the type of MHD generator for which these approximate non-optimizing calculations are made, namely for longitudinal voltage and current or power extractions or coupling with segmented electrodes.

The value of the Hall effect parameter just found is used in connection with a relationship which is derived between the generator efficiency, loading factor, E/E_0, or ratio of operating to open circuit electric field intensity or terminal voltage, and Hall (effect) parameter $\mu_e B$. In essence this represents the ratio of power density delivered to the power of electro-magnetic $v_g B.J._T$, where J_T denotes the transverse current density, or

$$\eta=(1-E/E_0)(E/E_0)(\mu_e B)^2/[1+(E/E_0)(\mu_e B)^2]$$

In Table VI this relation is used to tabulate the maximum generator efficiency as a function of the Hall (effect) parameter, for a condition of optimum loading, taking into account only electrical losses. The data gives the value of 83% for the maximum generator efficiency. This compares fairly well with the value of 80% assumed above.

TABLE VI

Hall (Effect) Parameter (μ_eB)	Maximum MHD generator Efficiency ($\eta_{max.}$)
6	0.72
8	0.78
10	0.82
12	0.84

The electric field intensity, E_0, at open circuit, for the generator under consideration can be shown to be:

$$E_0=(\mu_e B)(V_g B)/[1+(\mu_e B)(\mu_i B)]$$

Here μ_i is the ion mobility, which under the conditions assumed in the generator under consideration is much less than the electron mobility, μ_e, so that an approximation is in order, such that

$$E_0=(\mu_e B)(V_g B)=41,150 \text{ volts/meter}$$

since in the present case $V_g B=3,740$ volts/meter.

The operating electric field intensity, E, is related to the open circuit electric field intensity, E_0, in terms of the internal resistance, R_i, of the generator and the load resistance, R_L, so that the loading factor

$$E/E_0=V_L/V_0=R_L/(R_L+R_i)$$

where V_L and V_0 denote the line and open circuit voltages, respectively, and L denotes the gas duct length. In terms of the loading factors, E/E_0, which maximized the generator efficiency and other parameters, the load conversion efficiency, η, of the generator as just given above is tabulated in Table VII, for a range of values of the Hall (effect) parameter, μ_eB, which indicates a maximum efficiency for a loading factor of $E/E_0=0.1$, for μ_eB–10.99 and $\eta=80\%$.

TABLE VII.—MAXIMUM MHD GENERATOR EFFICIENCY, $\eta_{max.}$

Hall (Effect) Parameter, μ_eB	Loading Factor, E/E_0			
	0.1	0.2	0.3	0.4
6	0.705	0.702	0.640	0.560
8	0.778	0.743	0.666	0.578
10	0.817	0.763	0.678	0.585
12	0.840	0.773	0.685	0.590

This loading factor should be kept to a minimum for the sake of minimum duct length.

The operating electric field intensity is thus found to be:

$$E=(E/E_0)E_0=4115 \text{ volts/meter}$$

The magnitude of the angle, ϕ, between the electric field intensity, E_g, relative to the positive ions of the gas, and the operating field intensity, E, is given by

$$\phi=\arctan|\overline{v}_g\times\overline{B}|/E=\arctan v_gB/E=42.3°$$

Since $\sin \phi=v_gB/E_g$, then $E_g=5560$ volts/meter.

The Hall phase angle, Ⓗ, between E_g and E_e is given by Ⓗ$=\arctan \mu_eB=84.8°$

Finally, $E_e=E_g \cos$ Ⓗ$=505$ volts/meter, which checks well with the assumed value of 500 volts/m.

Also, since

$$|\overline{v}_e\times\overline{B}|=v_eB=E_g \sin Ⓗ$$

the electron velocity, v_e, which is in the direction of the vector of the field E_e, can now be determined in two ways:

Either $V_e=v_eB/B=1485$ meters/second; or

$$v_e=\mu_eE_e=1475 \text{ meters/second}$$

and so gives a check upon the prior computations.

It can be shown that the power density associated with the MHD generator is

$$\rho_P=(\mu_eB)^2(v_gB)^2\sigma_e(E/E_0)[1-(E/E_0)]/[1+(\mu_eB)^2]$$

At this point it should be noted that for the sake of high power density, not only should the electron mobility, μ_e, and gas velocity, v_g, be high, but the magnetic field B, should be high also. Of course, considerations of frictional pressure drop apply to v_g and magnetomotive forces apply to B and so these set limits on their practical values. In compensation, the gas electrical conductivity, σ_e, should be a maximum on account of other considerations (e.g. size and duct length) as well. Strictly, the Hall effect causes the electrical conductivity to assume tensor properties and would normally be taken account of in a more sophisticated analysis. Except for the quantity σ_e, the factors of the above expression for the power density have already been determined.

Now

$$\sigma_e=\overline{\rho}_ie\mu_e$$

where $\overline{\rho}_i$ denotes the average ion charge density and e denotes the charge per electron.

The ion densities are sufficiently small to insure a very small fraction of the ratio of the power density required for ionization of the gas. $(\rho_P)_i$ to the total power density, ρ_P or

$$(\rho_P)_i/\rho_P=1.6\times10^{-19}\cdot\overline{\rho}_i\cdot\epsilon_i\cdot v_g/\rho_P\cdot L$$

under the conditions contemplated of the total generated energy in the whole interaction space for initial ionization of the gas at the inlet, aside from that of recombination. However, the fraction

$$(\rho_P)_i/\rho_P=1.6\times10^{-19}\cdot\overline{\rho}_i^2\cdot\epsilon_i\cdot\alpha/\rho_P$$

required for repetitive ionization on account of recombination, under the same conditions, can be expected to overshadow that of initial ionization, since the recombination/attachment coefficient, α, for the noble gas considered (HE) under normal ambient conditions is of the order of 10^{-14} m.^{3}/sec.

The recombination/attachment loss, $-d\overline{\rho}_e/dt$, is directly proportional to the square of the average electron density for given recombination coefficient. So, for the sake of tolerable recombination/attachment loss, the average ion density, ρ_i, must be made low. However, since the power output density is proportional to the ion density as well as the electron mobility, it is necessary to make the latter correspondingly high. Low ion density and high electron mobility imply a low pressure noble gas. Solving for ρ_i, in the appropriate foregoing relations, gives

$$\overline{\rho}_i=\frac{(\mu_eB)^2\cdot(v_gB)^2\cdot(\rho_P)_i/\rho_P)(E/E_0)[1-(E/E_0)]\mu_e}{\alpha\cdot\epsilon_i\cdot[1+(\mu_eB)^2]}$$

The power required for initial ionization of the gas molecules by electrons of the beam or the power delivered to the electron gun was stated to be relatively low, compared with the total electric power output of the generator. In these computations, based on the foregoing ratio of $(\rho_P)_i/\rho_P$, for initial ionization under the contemplated conditions (and low ion densities) a nominal value of one percent of the total power output will be alloted to the ionization process, meaning in effect that $\rho_i=0.01\rho_T$ or

$$\frac{(\rho_P)_i}{\rho_P}\simeq0.01$$

The factor ϵ_i, for the first ionization potential, for helium is approximately 25 electron volts. The remaining factor to be assigned a numerical value is α the recombination coefficient, which is taken to be 10^{-14} m.^{3}/s under normal ambient conditions.

Substituting these numbers, and the results previously obtained, into the expression for $\overline{\rho_i}$ gives

$$\overline{\rho_i}=1.48\times10^{17} \text{ ions/m.}^3$$

substituting this value of $\overline{\rho_i}$ into expression for σ_e gives for $e=1.6\times10^{-19}$, $\sigma_e=0.0695$ mho/m. Generally, the minimum acceptable electrical conductivity is about 0.1 mho/m. Although the illustrative calculations were made on the basis of this minimum acceptable value, it will be evident that higher values will be required in practice in order to keep the size and especially the length of the gas duct within reasonable limits.

Finally, substituting this value of σ_e into expression for ρ_P gives $\rho_P=87.4$ kw./m.^{3} for σ_e 0.0695 mho/m.

With this power density in the generator, the interaction volume required to generate the desired $P_G=15.3$ kw. is $v_i=P_G/\rho_P=0.175$ m.^{3}.

Now, the axial or longitudinal current density for $\mu_i\ll\mu_e$ and $\mu_iB\ll1$, for $\sigma_e\cong0.07$ mho/m. can be shown to be

$$J_A=(\mu_eB)(v_gB)[1-(E/E_0)]\sigma_e/[1+(\mu_eB)^2]=21.25 \text{ amperes/m.}^2$$

Whereas, the corresponding transverse current density, for the same conditions, is:

$$J_T=[1+(E/E_0)(\mu_eB)^2](v_gB)\sigma_e/[1+(\mu_eB)^2]=28.2 \text{ amperes/m.}^2$$

These current densities are reasonable for $\sigma_e=0.07$ mho/m. It will be noted that they increase with any increase of the electrical conductivity of the gas.

The gas pressure gradient along the duct length can be shown to be:

$$dp/dx=\sigma_ev_gB^2[1+(E/E_0)(\mu_eB)^2]/[1+(\mu_eB)^2]=J_TB=105 \text{ Newtons/m.}^3$$

The required length L, of the duct can be shown to be:

$$L=(\rho_1-\rho_2)(6.8947\times10^3)/\sigma_ev_gB^2\{[1+(E/E_0)(\mu_eB)^2]/[1+(\mu_eB^2)]\}=(\rho_1-\rho_2)(6.8947\times10^3)/(dp/dx)$$

The evaluation of this relation requires a determination of the inlet and outlet gas pressures, ρ_1 and ρ_2, respectively, in the generator. It should be noted that the pressure drop, $(\rho_1-\rho_2)$, and loading factor, E/E_0, should be kept to minima while the other factors are kept at maxima in order to minimize the duct length L.

Two relationships are now known between ρ_1 and ρ_2. One of these relates the pressures to the assumed average pressure $\overline{\rho}$, giving $(\rho_1+\rho_2)/2=\overline{\rho}$, and the other previously derived gives $\rho_1/\rho_2=2.1$.

Solving for ρ_1 and ρ_2 and substituting the value of $\bar{\rho}$ gives $\rho_2=2\bar{\rho}/3.105=6.44$ p.s.i.a.;

Since $\bar{\rho}=10$ p.s.i.a., $\rho_1=2.1\rho_2=13.52$ p.s.i.a.;

So, the pressure drop in the MHD generator is 7.08 p.s.i.a.

Relative to the segmented electrode pitch the following comments are appropriate. The ratio R of electrode pitch p_e (i.e., center to center distance of two side by side electrodes including insulator spacer) to the electrode pair spacing 1_T (i.e., normal distance between electrodes facing each other) should be small (i.e., $R=p_e/1_T=E_T/E_L=\tan(E_T,E_L)\rightarrow 0$). Normally (i.e., for low Hall parameter) such segmentation not only prevents flow of axial electrode currents but is made small so as to minimize the distortion of the electric field on this account. However due to the actual tensor conductivity involved, substantial distortion in the field does occur. In effect the current lines concentrate at the trailing flow edges of the electrodes as the Hall parameter increases. Hence, precautions in electrode design and materials at these edges are necessary to minimize erosion of the electrodes at these trailing edges.

The duct length may now be calculated as

$$L=462 \text{ meters}$$

for $\sigma_e=0.07$ mho/m. For higher electrical gas conductivities sought via appropriately increased average ion charge density $\bar{\rho_i}$ (i.e., >10 mho/m.) this duct length markedly decreases as illustrated in Table VIII.

TABLE VIII

Electrical Gas Conductivity, σ_e, mho/m.	Length of Duct, L meters
0.07	463
0.1	320
0.5	65
1.0	32
5.0	6.5
10.0	3.2

The corresponding interaction cross section is then $A=V_1/L=0.000379$ m.^{2}, for $\sigma_e=0.07$ mho/m. For higher electrical conductivity anticipated via appropriately increased average ion charge density $\bar{\rho_i}$ (i.e. >10 mho/m.) the cross section increases as illustrated by Table IX.

TABLE IX

Electrical Gas Conductivity σ_e, mho/m.	Cross Section of Duct, A m.^{2}
0.07	0.000378
0.1	0.00054
0.5	0.0027
1.0	0.0054
5.0	0.027
10.0	0.054

From this the line voltage of the generator is calculated as: $V_L=EL=1900$ kilovolts for $\sigma_e=0.07$ mho/m. For higher electrical gas conductivity anticipated via appropriately increased average ion charge density $\bar{\rho_i}$, (i.e., >10 mho/m.) the line voltage markedly decreases as illustrated by Table X.

TABLE X

Electrical Gas Conductivity, σ_e mho/m.:	Line Voltage at Generator, V_L, K.V.
0.07	1,900
0.1	1,350
0.5	270
1.0	135
5.0	27
10.0	13.5

The operating line current is $I_L=J_A=0.008$ ampere, for $\sigma_e=0.07$ mho/m. For higher electrical gas conductivity anticipated via appropriately increased average ion charge density, $\bar{\rho_i}$ (i.e., >10 mho/m.) the currents and current densities increase, as illustrated by Table XI.

TABLE XI

Electrical Gas Conductivity, σ_e, mho/m.	Line Current, I_E, amp.	Current Density, Axial, J_A, amp./m.^{2}	Current Density, Transverse, J_T, amp./m.^{2}
0.07	0.008	21.25	28.2
0.1	0.017	30	40
0.5	0.4	115	200
1.0	1.6	300	400
5.0	40.0	1,500	2,000
10.0	160.0	3,000	4,000

As another check upon the calculations the power output is found to be:

$$P_0=P_G=V_LI_L=15.2 \text{ kilowatts}$$

which agrees well with a power output of 15.3 kilowatts made initially.

It is instructive to recall here that relatively small momentum transfer between the charges and gas atoms, in the manner previously described, can account for this output power since a small fraction (i.e., >1%) of the total gas energy is utilized for producing charges due to the relatively high ionization potential of gases and since the ionization process is not ideally efficient. At the gas temperature and speed considered this corresponds to a total energy equivalent of a small fraction of an electron volt. In fact, gas ionization as low as 0.01% are utilized in MHD generation. Such low degree of gas ionization corresponds to gas atom, positive ion and electron populations in the ratio of the order of 10,000:1:1 yet, it is this minority population of charges on which the transverse magnetic field impresses its retardation force. Since, the charges are associated with such small fraction of the total gas energy, equal to its fractional ionization, power interaction between charges and gas atoms, especially at about 0.01% ionization, must prevail to effectively retard of the order of 10,000 gas atoms per charge in the interaction region to account for the observed MHD efficiencies.

Besides the crossed field electron beam means of gas ionization there is herein considered also the periodic pulsed ionizing electric field gas ionization means impressed between the accelerator or anodes and cathodes of the MHD generator (and MHD motor). It was pointed out previously that while the electron beam means is limited with respect to the number of electrons produced or rather injected into the gas, the periodic pulsed ionizing electric field operates on all the electrons with a mean electron energy corresponding to gas ionization so that each collision corresponds to ionization. This gas ionization means is inherent in the crossed field electron guns' function in a gas medium. The degree of gas ionization can be varied from negligible to the sparking limit, by varying the pulse duration from the order of decinanoseconds to the order of microseconds. For the gas atom density, electron-ion collision cross section and electron thermal velocity considered, the cited degree of gas ionization and consequently gas electrical conductivity, extremely short pulse durations of the order of decimicroseconds are involved. Fortunately, prevailing switching transistor technology cites order of centimicroseconds, relatively flat top rectangular pulse durations with associated rise times of the order of a few dimimicroseconds as relatively common place. In fact, consideration is allotted to drivers operating at dimisecond pulse durations of the order of 1,000 volts and 100 c.p.s. repetition rate, into a minimum impedance of 50 ohms. Hence, the prospects of operating at such short pulse durations required for optimum gas electrical conductivity of the order of 10 mhos/m. and more are promising. On account of the gas ionization decay rate, previously cited, and for the sake of operating at maximum duty (approaching 100%) the repetition rate has to be appropriately controlled. Unfortunately, the required extremely short pulse durations cited also makes the correspondingly high repetition rate as serious a problem, but fortunately not practically insurmountable at the present state of art.

While the periodic pulsed ionizing electric fields, impressed between the accelerator and anodes and cathodes in the crossed field electron gun and interaction space, the applied pulsed duration on the grid and Wehnelt electrodes, when alternating current power output component is desired, must be much shorter so as to produce a negligible degree of gas ionization. For the desired conditions previously cited this corresponds to the order of a nanosecond or less and is, as previously cited, within bounds of present switching (transistor) driver technology, but with the high repetition rate desired presenting a more serious problem than in the case of the pulse duration associated with the ionizing electric field impressed between accelerator and anodes and cathodes.

Furthermore, the electron beam for gas ionization is derived from crossed field electron gun cathode and soles. Such electron emitters need not depend solely upon thermionic (or primary) emission, which is current density limited and entails relatively long starting time. The total electron emission under crossed field or MHD operation results from thermionic and non-thermionic means and in particular secondary type. The latter means results from electron backbombardment of the emitter, due to crossed field orbital motion of the electrons.

In contrast to thermionic electron emission, the secondary type is associated with relatively high D.C. and pulsed current density and efficiency. However, it is dissipation limited, possesses large energy spread and is subject to charging phenomena. In any event, the secondary emission ratio is made as high as is practicable with respect to stability in the operational environment. With such ("cold") emitters for the cathode and soles, thermionic emission may play a secondary role. Hence, no heater is required since the temperature of the gas with which the cathode and soles are in thermal contact may be virtually such as to ignore cathode and sole requirements, if any. However, since the hot gas is at adequate gas temperature for copious thermionic emission from most emitters to at least start and even maintain moderate MHD operation, the secondary electron emission provides a bonus to meet requirements for more beam current than that which can be derived thermionically. As a consequence, the finite electron emission capacity of emitters is increased by many orders of magnitude over that capable with thermionic emission alone.

Hence, ample gas ionization and electric conductivity of the high electron mobility gas (like He, A, etc.) is achieved for efficient MHD operation.

To operate the crossed field guns and soles in a gas atmosphere requires that the applied electric accelerating voltages be pulsed at sufficiently short durations so that excess gas ionization and hence sparking and arcing does not ensue. (Here we are concerned with the order of deka-to-hecto-nanoseconds.) To realize virtually D.C. power output, the pulse repetition rate is made sufficiently high to maintain relatively continuous uniform gas ionization.

With low drive sinusoidal voltage modulation of the non-interception electron crossed field gun and applied pulsed electric ionizing or non-ionizing voltages, alternating current power output results DC or AC power output is had at commercial load impedances.

It should be also mentioned that the pulsed electric fields can be adjusted with respect to pulse duration to supplement the primary gas ionization afforded by the crossed field electron beam. This is done by adjusting the

pulse duration so as to step by step increase the electron temperature in the gas to the required degree. So, together the pulsed electric ionizing field and electron beam can provide any degree of gas conductivity desired.

This dual non-equilibrium gas ionizing system not only reduces the tolerance on gas purity but permits use of gas and (easily ionizable) vapor or (easily ionizable) vapor alone, for those applications desiring a condensable working medium for the sake of heat radiator weight and hence rankine cycle, in spite of the problems encountered with condensible working medium, like cesium. Although, these extra features make for more flexibility, normally preference is in favor of a single (high electron mobility) noble gas, such as helium (because of its better heat conductivity over that of argon). With respect to gas ionization means, the electron beam means is considered the primary source, with the pulsed electric field operated at a pulse duration which does not create significant gas ionization or at most sufficient additional uniform gas ionization to supplement that afforded by the electron beam. However, under no circumstances is the pulse duration such as to cause excess, non-uniform gas ionization and hence sparking and arcing.

Obviously many modifications and variations of the present invention are possible in the light of the above teachings. It is, therefore, to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed is:

1. In a plasma energy converter, apparatus for generating ions comprising means for guiding plasma along a predetermined path, said conduit means including a gas input means and a gas output means, a source of heated neutral gas, means for connecting said source of heated gas to said gas input means so that the heated gas flows through said conduit means, means for injecting an electron beam into a given region within said conduit means, means for applying a magnetic field to at least said region within said conduit means, said magnetic field having a direction substantially perpendicular to said predetermined path, means for applying a pulsed electric field to said region, said pulsed electric field having a direction substantially perpendicular to both the direction of said magnetic field and said predetermined path, said pulsed electric field having a pulse duration of less than ten nanoseconds to field ionize said neutral gas without breakdown whereby the neutral gas is ionized partly by the injected electron beam and partly by the field ionization resulting from the pulsed electric field.

2. Apparatus according to claim **1**, in which said noble gas is maintained at a pressure materially below atmospheric pressure.

3. Apparatus according to claim **1**, in which said noble gas is helium at a pressure materially below atmospheric pressure.

4. Apparatus according to claim **1**, in which the said noble gas is helium at a pressure substantially in the range between 10 and 30 pounds per square inch absolute.

5. The apparatus of claim **1** wherein said electron beam injection means includes an electron emitter electrode and an accelerator electrode disposed in opposed relation in said conduit means and straddling said predetermined path.

6. The apparatus of claim **5** wherein said pulsed electric field applying means includes a voltage pulse generator including output terminals connected to said electron emitter electrode and said accelerator electrode, respectively.

7. The apparatus of claim **6** wherein said electron beam injection means further comprises a control electrode interposed between said electron emitter electrode and said accelerator electrode and a bias voltage source connected between said control electrode and said electron emitter electrode for modulating the injected electron beam.

8. The apparatus of claim **7** wherein said bias voltage source includes a pulse voltage source, the duration of the pulses being of the order of a nanosecond.

9. The apparatus of claim **8** wherein said bias voltage source further includes an alternating voltage source connected in series with said pulse voltage source.

10. The apparatus of claim **7** wherein said bias voltage source includes an alternating voltage source.

11. The appartus of claim **1** wherein said heated gas is a noble gas.

12. Apparatus according to claim **11**, in which the said noble gas is argon at a pressure materially below atmospheric pressure.

13. Apparatus according to claim **11**, in which the said noble gas is argon at a pressure substantially in the range between 10 and 30 pounds per square inch absolute.

14. Apparatus according to claim **11**, in which the noble gas is a mixture of helium and cesium.

15. Apparatus according to claim **11**, in which the noble gas is a mixture of argon and cesium.

16. Apparatus according to claim **14**, in which the combined pressure of said gases is below atmospheric pressure.

17. Apparatus according to claim **14**, in which the combined pressure of said gases is substantially in the range between 10 and 30 pounds per square inch absolute.

18. The apparatus of claim **11** wherein said noble gas is ionized helium gas at a temperature not materially above 2,500 degrees Fahrenheit and at a pressure materially below atmospheric pressure.

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