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Temperature and Velocity Modulated M.H.D. Systems

V. J. Ibberson and D. Harris

Phil. Trans. R. Soc. Lond. A 1967 **261**, 429-439
doi: 10.1098/rsta.1967.0011

B. M.H.D. PLANT, COMBUSTION TECHNIQUES AND SEEDING

VII. Temperature and velocity modulated m.h.d. systems

By V. J. Ibberson* and D. Harris†

* *Department of Mechanical Engineering, Queen Mary College, London University*
† *Department of Fuel Technology and Chemical Engineering, University of Sheffield*

A study is made of the means by which plasmas used for generating m.h.d. power may be modulated in order to provide higher power densities. Temperature and/or velocity modulation may be obtained in a quasi-steady flow combustion system, e.g. by introducing striations of high temperature fluid, or in a non-steady system by exciting pulsations or oscillations.

Studies on striations are outlined and the relevant work on non-steady modulation is discussed. A description is given of the joint work at Sheffield University on an oscillatory vortex m.h.d. generator (Sheffield) and a proposed linear m.h.d. system (Queen Mary College, London).

Introduction

The power output per unit volume from an m.h.d. generator increases with plasma velocity (v') and electrical conductivity (σ_e, which is a function of temperature), i.e.

$$P_E = \sigma_e v'^2 B^2 K (1-K),$$

where B is the magnetic field strength and K is the loading factor (Coombe 1964). In the classical m.h.d. cycle the two requirements of velocity and temperature are conflicting in that the velocity is obtained by expansion through a nozzle and a reduction of temperature is incurred. Either or both parameters may be increased by suitable modulation in either a quasi-steady or a non-steady flow system.

Steady flow modulation may involve two fluids; the working fluid at a suitable velocity plus striations of a highly conducting fluid as first proposed by Thring (1962). Temperature modulation increases the electrical conductivity. Non-steady operation by pulsating or oscillatory combustion leads to periodic modulation of temperature and velocity with consequent improvement of the power density within the m.h.d. interaction length.

In general for modulated systems a higher mean conductivity is obtainable at a lower mean operating temperature, compared with steady flow conditions.

As the production of the required ionization level is of major importance (particularly in open cycle m.h.d. where non-equilibrium ionization is difficult) modulation merits careful consideration.

Further possible advantages of modulated systems are:

(i) The output may be available directly as alternating current.

(ii) Improvements in the thermodynamic cycle, using, for example, constant volume combustion, which gives an increase in total pressure and is appropriate to non-steady systems. Thus the sevenfold increase in temperature of hydrocarbon–air flames can give a sevenfold increase in pressure. This increase in pressure can be used to additional cycle work as compared with constant pressure combustion.

(iii) Oscillatory systems may be driven to high pressure amplitudes and ultimately to detonation waves. The high temperature behind a detonation wave causes a high ionization level which gives a correspondingly high power density for m.h.d. purposes.

Steady flow modulation

With steady flow simple temperature modulation is required to enhance the conductivity at the stream velocity. At similar mean temperatures to those in the conventional m.h.d. duct, higher mean conductivities are possible. Two ways of modulating the temperature are by chemical heating (Thring 1962) and by electrical heating (Ricateau & Zettwoog 1963). In the latter method, high temperature striations in the plasma flow may be produced by an a.c. electrical discharge across two electrodes forming opposite walls of the duct. The conductivity is thus increased by the effect of joule heating. Devime, Lecroart & Zettwoog (1964) have continued this work, and Devime, Lecroart, Porte & Yerouchalmi have recently reported on types of electrodes and structures suitable for such a temperature modulated generator. In the chemical method highly ionized striations may be formed by the separate, intermittent injection of a secondary fuel-oxidant mixture. Karr (1964) obtains the chemical striations by pre-modulation of the fluid composition using a rotating disc modulator. The subject of striations has been treated theoretically by Fraidenraich, McGrath, Medin & Thring (1964).

At Sheffield University the rig constructed to investigate chemical striations consists of a 9 in. $\times 4\frac{1}{2}$ in. diameter gas turbine combustor with a convergent water cooled nozzle (exit diameter 1 in.) and a fused quartz duct 2 ft. 6 in. long (Komninos 1965). The generator operates on Avtag aviation fuel and air and the hot zones are formed by injecting short bursts of Avtag (seeded with 1 % by weight of potassium) and pure oxygen at a position 2 in. upstream of the nozzle exit. This secondary injection system consists of solenoid valves operated by microswitches and an electric motor.

Upstream injection was found to be more efficient than downstream injection and uneven hot layers of about 0·2 mho/m. conductivity were obtained compared with 'cold' layer values of the order of 0·04 mho/m. The frequency of formation of the hot zones was 2·2/s and the ratio of hot to cold layer length was about 1:3. Current work is directed to obtaining a higher frequency of better defined striations with a higher conductivity. The main difficulty is in producing a striated flow free from the Rayleigh–Taylor instability of the hot–cold gas interface (Fraidenraich *et al.* 1964).

Modulation by non-steady flow

The principle of pulsating combustion as advocated by Reynst (1961) and exemplified in the VI pulse jet was suggested by M. W. Thring as another means of improving the classical m.h.d. cycle. At Sheffield University, Taylor (1964) investigated the application of pulsating combustion to coal burning. The purpose was to intensify the combustion by means of the scrubbing action of pulsations on the coal particles. Thus a larger particle surface area is exposed to the action of the air. This demonstrates the feasibility of using non-steady flow as a means of velocity modulation.

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Marchal & Servanty (1964) have reported on a two-stage pulsating combustor designed to produce a temperature modulation suitable to m.h.d. power generation. The first stage is an accoustic resonance burner to obtain the required frequency of 400 c/s. The second stage is required to amplify the pressure pulsations. Fonda-Bonardi & Thornton (1964) studied the feasibility of a static type a.c. m.h.d. system in which standing waves are established in a resonance cavity in the presence of an external magnetic field. Acoustically this acts as a tube closed at both ends and the fundamental standing wave produces maximum velocity variation at the centre of the cavity to give an a.c. output.

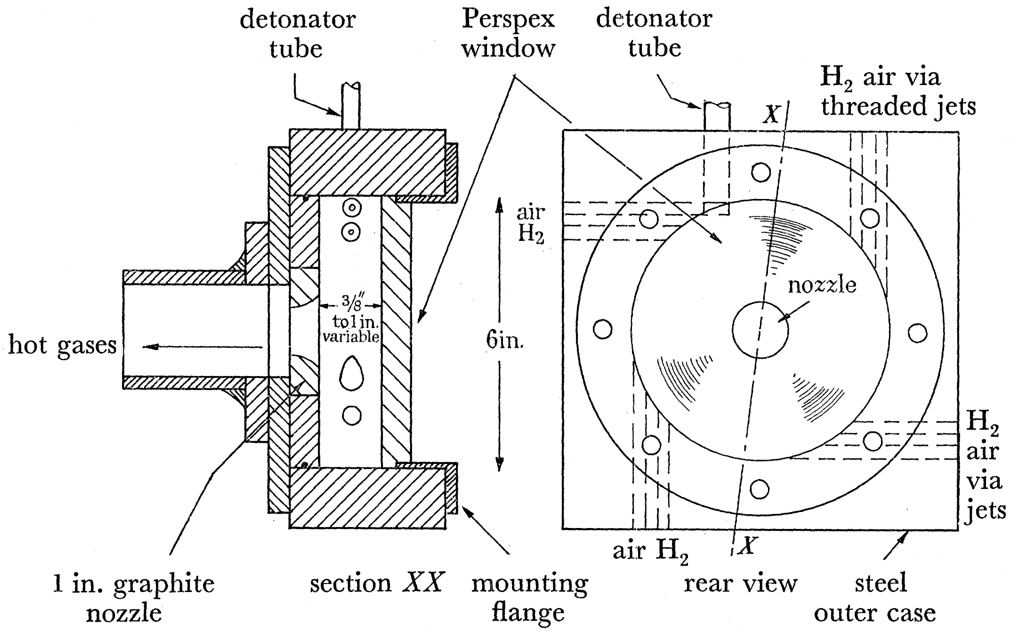

FIGURE 1. Short cylinder vortex generator.

Dyott (1965) has proposed velocity modulation of a supersonic gas stream by means of the Acoustiklystron. This applies the Klystron principle to acoustic waves. An energy source in a tube would propagate waves along the tube in both directions. In a supersonic stream both waves would travel downstream and the fast and slow waves would form a 'beat' pattern of high temperature bunches of gas with elevated electrical conductivity.

These non-steady systems are acoustic in nature and therefore should not be subject to the Rayleigh–Taylor instability previously mentioned. Interference with these systems such as m.h.d. braking may alter the amplitude or frequency, but the acoustic wave character will persist (Swithenbank & Harris 1964). A further advantage is the possibility of constant volume combustion in that the pressure wave tends to contain the combustion and convert it to a pressure rise which can reduce the need for initial air compression.

The main practical difficulties inherent in oscillatory systems will be:

(*a*) The mechanical construction of generator walls with such high fluctuating thermal loadings. On the other hand, the mean temperature can be lower than the corresponding steady flow system.

(*b*) Structural design to withstand pressure loads oscillating between 0 and 200 Lb./in.^{2} (abs.).

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(*c*) If constant volume combustion is used to eliminate the need for a mechanical compressor (i.e. the system works like a pulse jet) then difficulties will arise with the design of suitable inlet valves.

Pressure oscillations in a given system may be inherent as occurs widely in rocket instabilities or may be imposed mechanically or otherwise. For pressure amplitudes less than unity the oscillatory combustion m.h.d. generator may be considered in terms of the following acoustic modes of a cylindrical cavity, namely longitudinal and transverse tangential.

The two generators to be considered are the short cylinder vortex generator and the long cylinder linear type. In the former a tangential oscillation rotates in a disc-shaped combustion chamber which contains a vortex through flow from periphery to axial outlet. This is shown diagrammatically in figure 1. The linear generator is essentially a long cylinder with one closed end and the other open, consisting of combined combustion chamber and m.h.d. channel. A longitudinal pressure wave is propagated in the same direction as the gas flow. Each of these may have a standing or travelling waveform and all systems provide a temperature and velocity modulation capable of improving the power density of the plasma.

Theory

Symbols

a	speed of sound
B	magnetic flux density
i	seed concentration
J_1	Bessel function of first kind of order 1
J_1'	derivative of J_1 with respect to α
K	generator coefficient or loading factor
k	Boltzmann's constant
P	non-dimensional pressure P'/P_0'
P'	pressure
P_E	power density
q	charge on electron
R	maximum radius of chamber containing oscillations
r	radius of chamber at which oscillation is considered
T	non-dimensional temperature T'/T_0'
T'	temperature
t	non-dimensional time $\omega t'$
t'	time
V_i	ionization potential
v'	longitudinal velocity
w	non-dimensional tangential velocity w'/a_0
w'	tangential velocity
α	wr/a_0
β	wR/a_0
γ	ratio of specific heats
Δ	difference
ϵ	amplitude parameter (equations (i) to (vi))
θ	angle in cylindrical coordinates
ξ	amplitude parameter (equation (x))
ρ	density
σ_e	electrical conductivity of gas
ϕ	$(t+\theta)$
ω	frequency
ω_1	fundamental frequency
Ω	electron–atom collision cross-section

superscripts

(1)	order of solution

subscripts

0	in absence of wave
max.	cosine function = 1
w	$r = R$

The analysis presented here is for the first order spinning tangential oscillation in the vortex generator. It is assumed that enough combustion energy is supplied to sustain the oscillation and the order of the increase in power density due simply to the pressure variation is estimated. The equations may also be adapted to suit the longitudinal wave system (Maslen & Moore 1956). When viscous terms are included the oscillation is accompanied by acoustic streaming. In the present case, with through flow of gas of about Mach 0·8, the acoustic streaming effects are small enough to be neglected.

(a) *Pressure oscillation*

Expressions for pressure and velocity variation in an 'acoustic' oscillation can be obtained from a consideration of the equations of motion of a viscous compressible fluid. Following Maslen & Moore we assume that the relevant properties can be expanded in powers of an amplitude parameter, thus:

$$P \simeq 1+\epsilon P^{(1)}, \tag{i}$$

$$W \simeq \epsilon W^{(1)}, \tag{ii}$$

$$T \simeq 1+\epsilon T^{(1)}, \tag{iii}$$

from which the solutions of the appropriate inhomogeneous Bessel equations for the first order travelling tangential mode of oscillation are:

$$P^{(1)} = -\gamma \cos(t+\theta) J_1(\alpha), \tag{iv}$$

$$W^{(1)} = \cos(t+\theta) J_1(\alpha)/\alpha. \tag{v}$$

Thus particle velocity and pressure are in phase and able to contribute simultaneously to the power density.

Referring further to Maslen & Moore, we evaluate the non-dimensional radial coordinate α $(= \omega r/a_0)$. For the case in question the frequency variation with amplitude will be small enough to be neglected; therefore $\omega = \omega_1$ where ω_1 is such that $J_1(\beta) = 0$ (β being 1·841). Hence

$$\omega = \frac{\omega a_0}{R} = \frac{1{\cdot}841 a_0}{R}, \quad \text{and} \quad \alpha = \frac{1{\cdot}841 r}{R}.$$

If the wave is now considered at its maximum amplitude, i.e. when $\cos(t+\theta) = 1$, equations (iv) and (v) become

$$P^{(1)}_{\text{max.}} \simeq -\gamma J_1(1{\cdot}841 r/R),$$

$$W^{(1)}_{\text{max,}} \simeq \frac{J_1(1{\cdot}841 r/R) R}{1{\cdot}841 r}.$$

Thus the pressure amplitude is found from equations (i) and (iv):

$$\frac{\Delta P'_{\text{max.}}}{P'_0} \simeq \epsilon\{-\gamma J_1(1{\cdot}841 r/R)\} \tag{vi}$$

where $\Delta P'_{\text{max.}} = P'_{\text{max.}} - P'_0$, and on substitution of equations (v) and (vi) into equation (ii) we have

$$-W^{(1)}_{\text{max.}} \simeq \frac{\Delta P'_{\text{max.}}}{P'_0 \gamma} \frac{R}{1{\cdot}841 r}. \tag{vii}$$

This expression gives the variation of particle velocity with pressure amplitude over any radius range of the m.h.d. generator and is useful for calculating the power density available.

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(b) *Conductivity modulation*

Considering equation (vi) when $r = R$, we have

$$\Delta P'_W/P'_0 = \xi \cos(t+\theta) \equiv \xi \sin\phi, \tag{x}$$

where ξ the amplitude paratameter $= \epsilon\gamma J_1(1\cdot 84)$, and $\Delta P'_W$ is the pressure increase at radius $r = R$.

For adiabatic pressure variations and neglecting entropy variations $P/\rho^\gamma =$ constant, from which the temperature variation can be obtained by

$$\left\{\frac{\Delta P'}{P'_0}+1\right\}^{(\gamma-1)/\gamma} = \left\{\frac{\Delta T'}{T'_0}+1\right\}, \tag{xi}$$

and substituting the latter expression in equation (x) gives the temperature modulation as

$$\frac{\Delta T'_W}{T'_0} = \{\xi \sin\phi + 1\}^{(\gamma-1)/\gamma} - 1. \tag{xii}$$

The modified Saha equation for a seeded gas defines electron conductivity (Coombe 1964) as

$$\sigma_e = \frac{7\cdot 05 \times 10^{-13}\, T'^{\frac{3}{4}}}{P'^{\frac{1}{2}} \exp(qV_i/2kT')} \frac{(i)^{\frac{1}{2}}}{\Omega} \quad \text{in m.k.s. units.} \tag{xiii}$$

Therefore if the increase in conductivity due to modulation is defined as

$$\Delta\sigma_e = \sigma_e - \sigma_{e0},$$

then the 'conductivity amplitude' is given in the form

$$\frac{\Delta\sigma_e}{\sigma_{e0}} = \left\{\left[\left(\frac{(1+\xi\sin\phi)^{\frac{3}{4}}}{(1+\xi\sin\phi)^{\frac{1}{2}}}\right)^{(\gamma-1)/\gamma} \exp\left(\frac{qV_i}{2kT'_0}\right)\left(1-\left(\frac{1}{1+\xi\sin\phi}\right)^{(\gamma-1)/\gamma}\right)\right]-1\right\}, \tag{xiv}$$

which for $\gamma = 1\cdot 4$ simplifies to

$$\frac{\Delta\sigma_e}{\sigma_{e0}} = \left\{\left[\frac{1}{(1+\xi\sin\phi)^{(\gamma-1)/\gamma}} \exp\left(\frac{qV_i}{2kT'_0}\right)\left(1-\frac{1}{(1+\xi\sin\phi)^{(\gamma-1)/\gamma}}\right)\right]-1\right\}.$$

In figure 2 this conductivity modulation has been plotted for pressure amplitudes in the range 0 to 1 and at $T'_0 = 2200$ °C.

(c) *M.h.d. power generation comparison*

One advantage of an oscillatory combustion m.h.d. generator can now be seen by considering the power density available and comparing it with that obtainable from a conventional generator. From equation (i) the power density ratio is given by

$$\frac{K(1-K)\,\sigma_e w'^2 B^2 \quad \text{(wave)}}{K(1-K)\,\sigma_{e0} w_0'^2 B^2 \quad \text{(conventional)}}.$$

Assuming a constant loading factor K (not quite true for a wave system) and for a given magnetic flux density B, the ratio reduces to $\sigma_e w'^2/\sigma_{e0} w_0'^2$.

For high oscillation amplitudes (ξ) (see figure 2), the peak value of conductivity is about five times that of a comparable steady flow generator. Also as the velocity and

conductivity variations are in phase a further advantage comes from the wave particle velocity, therefore
$$\sigma_e w'^2/\sigma_{e0} w_0'^2 > 5.$$

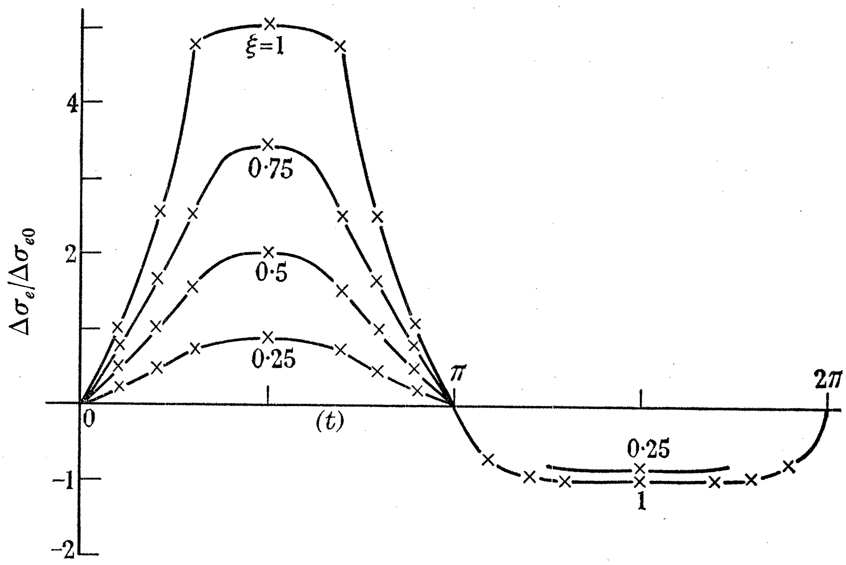

FIGURE 2. Conductivity modulation plotted, for pressure amplitudes in the range 0 to 1, and at $T_0 = 2200$ °C. $r = R$; $\gamma = 1{\cdot}4$.

We can estimate the order of the peak power density in the oscillatory vortex generator from equation (i) using the following assumptions and neglecting eddy current losses:

pressure amplitude parameter, $\xi = 1$;
loading factor (K) $= 0{\cdot}5$ (for maximum specific power);
$B = 30$ kG $= 3$ Wb/m^2;
$\sigma_{e0} = 10$ mho/m at 2500 °K and 0·02 atm potassium seeding (Coombe 1964);
therefore $\sigma_e \simeq 50$ mho/m.
maximum wave particle velocity $w' = a_0/2{\cdot}5 = 950$ ft./s;
tangential stream velocity $= 720$ ft./s.

Hence, net particle velocity (for a wave in the direction of stream flow) $= 950+720 = 1670$ ft./s, and maximum power density $P_{E(\text{max.})} = 0{\cdot}25 \times 50 \times 1670^2 \times 0{\cdot}093 \times 3^2$
$$\simeq 29 \text{ MW/m}^3.$$

For a shock or detonation wave system the peak power density is still higher because of the high local value of conductivity, e.g. from Basu (1960) $\sigma_e \simeq 200$ mho/m. However, the gas behind the wave is essentially non-conducting so that only about 25 % of the generator length is active at any one time. The Mach number of the products with respect to the walls is taken as $0{\cdot}8 \simeq 800$ m/s. In this case therefore the quantities are approximately as follows:

$$\text{comparative local power density} = \frac{P_E\,(\text{wave})}{P_E\,(\text{conventional})} \simeq 20;$$

$$P_E\,(\text{detonation}) \simeq 0{\cdot}25 \times 200 \times 800^2 \times 3^2$$
$$= 288 \text{ MW/m}^2.$$

The practical difficulty is in extracting a significant proportion of the energy in the very short time taken for the products to move through the conducting region.

M.H.D. POWER EXTRACTION

The previous paragraphs show how the simple initiation of combustion oscillations leads to a higher power density in the generator. Maximum power extraction will depend to a large extent on the mode of oscillation employed and the more important modes of a circular cylindrical cavity are discussed below.

(i) *Standing waves*

Both the longitudinal and transverse tangential modes can exist in the standing wave form, but this means of modulation is not so convenient as the travelling oscillation for the following reasons:

(*a*) Combustion chamber and generator geometry will be more critical in design to give the required standing wave.

(*b*) The vibrational particle velocity in the flow direction is 90° out of phase with pressure, temperature and conductivity. Therefore only if there is a sufficiently high 'd.c.' value of conductivity can power be extracted at the velocity antinode as well as at the pressure antinode. For a travelling wave velocity and pressure are in phase and can both be used effectively.

(*c*) For standing waves the active electrode area is reduced to the interaction length corresponding to the pressure antinode hence the power extracted per unit length is reduced, i.e. temperature modulation is only effective at pressure antinodes.

(ii) *Travelling waves*

Two systems are considered in which travelling waves may modulate a plasma.

(*a*) *Linear generator*

In this case longitudinal pressure oscillations provide the required modulation. However, this mode tends to steepen into a shock pattern at relatively moderate amplitudes which may be disadvantageous for the reasons given previously. On the other hand, the high local ionization in a shock system is attractive. The amplitude at which the waves become steep-fronted depends on the driving mechanism, but both isentropic and shock waves are obtainable over a range of amplitudes.

The oscillating particle velocity is superimposed on the steady d.c. velocity of the through flow of combustion products. For suitable m.h.d. flow rates ($\simeq$ Mach 0·8) the particle velocity is always less therefore the power output is in the form of a steady level plus a superimposed periodic (but non-sinusoidal) output.

This type of generator therefore is attractive in that with a simple geometry full advantage can be taken of velocity and temperature modulation and rocket type technology can be used for its development.

(*b*) *Vortex generator*

The travelling tangential mode of oscillation can be readily initiated by introducing a swirling motion into the cylindrical combustion generator. The mechanism by which the oscillation is sustained is given by Heidmann (1965) thus, in this case a vortex flow of combustion products is caused which will be velocity and temperature modulated by a spinning tangential oscillation.

The wave form in this system is made up of multiple reflexions of pressure pulses from the containing wall (Maslen & Moore 1956), thus it appears that the steepening process, which limits the amplitude of 'acoustic' oscillation in the linear generator does not manifest itself. It is therefore possible to form large amplitude waves, provided the energy is available from the combustion process. Amplitudes of up to 300% have been observed and although the wave form is spiky, good conductivity modulation should result.

With regard to the velocity parameter in this system, any through flow of gas must be in the form of a radial flow component which as regards the extraction of m.h.d. power, is lost. Fortunately the tangential velocity and mass flow rate may be varied independently by varying the degree of swirl (Swithenbank & Harris 1964), therefore the gas can be made to travel many times round the chamber before its exit and the loss due to the radial flow is relatively small.

The possible advantage due to particle vibrational velocity is appreciable because of the large oscillation amplitudes attainable with the vortex geometry (Maslen & Moore 1956). The wave should therefore be initiated in the same direction as the vortex thus increasing the velocity parameter in the power density equation (Swithenbank & Harris 1964).

If a sufficiently strong vortex is introduced into the chamber and a detonation wave system initiated, it is theoretically possible to produce a trapped detonation system, i.e. the detonation wave travels round the disk-shaped chamber-generator being contained by the vortex flow. As in the case of the linear generator there is a high-power density, although power extraction is more difficult because of the short interaction length.

Electrode sizes

For a travelling wave system equation (vii) shows that the maximum tangential or longitudinal particle velocity can be appreciable for large pressure amplitudes, namely

$$v' = w' = a_0/2{\cdot}5 = 400 \text{ m/s}.$$

This oscillatory particle velocity can be best utilized if the electrode length is of the same order of magnitude as the particle displacement, which limits the electrode size.

A further limitation is apparent from figure 2. The electrodes must be segmented to prevent the e.m.f. generated by the high pressure part of the cycle being short circuited by the lower conductivity region and optimum power will be generated when the electrode length coincides with the high conductivity peak on the graph.

For the vortex generator the above condition is met when the electrodes subtend an angle of $0{\cdot}6\pi - 0{\cdot}4\pi = 0{\cdot}2\pi$ radians at the centre of the chamber. The figure of $0{\cdot}2\pi$ radians represents the maximum angle which an electrode can subtend and for small radii represents the limiting size. When the radius of the chamber is increased the electrode length is then only limited by the particle displacement. For the longitudinal mode the particle displacement will determine the size of the electrodes.

Experimental programme

(i) *Vortex generator*

From the foregoing considerations a two-dimensional rocket motor was designed at Sheffield University in order to determine the following:

(*a*) The extent to which the amplitude of oscillation modulates temperature, hence electrical conductivity of the gas.

(*b*) The range of amplitudes and frequencies which can be obtained for different fuel/air ratios and combustion chamber lengths.

(*c*) The possibility of obtaining a trapped detonation wave system with its correspondingly high power density.

The motor is a 6 in. diameter gas fired 'pancake' shaped chamber with length variable from $\frac{3}{8}$ to 1 in. The gases are injected tangentially at four peripheral points and expanded through a 1 in. graphite nozzle on the axis.

A travelling tangential oscillation has been obtained as shown by high speed cine photographs ($\simeq$ 3000 frames/s) taken through a Perspex window. With a combustion chamber pressure of about 50 Lb./in.^{2}(a) and a stoichiometric air–hydrogen mixture, the pressure amplitude is 30 % at a frequency of about 600 c/s. The periodic variation of conductivity has been demonstrated using the r.f. coil method developed by Olson & Lary (1962).

(ii) *Linear generator*

Experiments are being carried out by Queen Mary College (University of London) on a small rocket type combustion chamber (9 in. $\times$ 2 in. diameter) with a view to obtaining a travelling longitudinal combustion oscillation.

As high frequency pressure oscillations (500 to 1000 c/s) appear to be most likely to occur with high reaction rates, injector performance is important. Therefore different injector heads will be tried for the most efficient initiation and maintenance of instability. If found desirable a jet driven resonance tube (Thompson 1964) will be used to assist the oscillations. This is to be situated near the main injection point or constitute a secondary fuel–oxidant injector at the nozzle.

Conclusion

The prospect for m.h.d. power generation using combustion oscillations to modulate the velocity and temperature of the plasma appears to be good. Substantially higher local power densities have been shown to be theoretically possible. The effect of m.h.d. braking has yet to be considered.

The travelling wave system is most suitable for modulation and two possible modes of oscillation, namely longitudinal and tangential, give rise to generators of different characteristics each of interest for different applications. With the linear generator all the through flow of gas reacts with the magnetic field but the pressure amplitude is somewhat restricted by the steepening process which leads to shock waves. The vortex generator is less liable to this restriction but there is a radial component of flow which is lost as regards m.h.d. power extraction. This loss, however, can be minimized as tangential velocity and the mass flow radial component can be varied independently. This type of generator should be suitable for light-weight generators for mobile power stations and space vehicles.

The authors wish to thank Mr J. Swithenbank for all his help concerning this research programme.

Part of the research reported in this document has been sponsored by the Office of Scientific Research under grant no. AF. EOAR 65-23 with the European Office of Aerospace Research (OAR), United States Air Force. The Science Research Council provided the remaining support.

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