Study of Traveling Conduction Wave Accelerator

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The Traveling Conduction Wave Accelerator is a repetitive impulse gas accelerator designed to achieve high-density, high-velocity gas flow with reduced heat transfer. Two limiting modes of operation can be distinguished for this accelerator, resulting in either pulsed or pseudo-continuous gas flows, and these are treated theoretically and their suitability for space propulsion and hypersonic wind-tunnel applications are discussed. Expected values are obtained for thrust, specific impulse, and efficiency for space propulsion applications with a pulsed gas outflow and values for stagnation pressure, stagnation enthalpy, and efficiency for operation with a pseudo-continuous gas outflow are also obtained. It is shown that the Traveling Conduction Wave Accelerator can be expected to operate as a high specific impulse—medium thrust space propulsion rocket with a significant reduction in the round trip times to the planets, compared with the round trip times expected to be achievable with other propulsion systems existing or proposed. It is also shown that, when operating as a hypersonic wind tunnel, the traveling conduction wave accelerator would be capable of simulation of a major portion of the manned re-entry corridor. Preliminary experimental results giving good agreement between theory and experiment are discussed and it is shown that the traveling conduction wave accelerator can be expected to operate successfully in the manner indicated by theoretical analysis.

Introduction

THE Traveling Conduction Wave Accelerator is a repetitive impulse device designed for space propulsion and hypersonic wind-tunnel applications which employs a traveling conduction wave to accelerate a gas flow to high velocities with reduced heat transfer. In a previous paper,[1] a theory of operation of the Traveling Conduction Wave Accelerator as a propulsion rocket was developed. Expressions were obtained for the thrust and specific impulse, for operation in a pulsed gas flow mode, and it was shown that successful operation as a medium thrust—high specific impulse propulsion rocket could be expected. In this paper a continuous output gas-flow mode is also considered, and experimental results which gave reasonable argument between the derived theories and measured values are discussed.

Method of Operation

The main accelerating section of the traveling conduction wave accelerator is a linear channel consisting of a pair of electrodes separated by insulating sidewalls, as shown in Fig. 1. The traveling conduction wave is presumed to have a square wave shape produced by introducing to the channel a series of ionized gas slugs with known constant repetition frequency. These slugs are separated by regions of cooler gas with negligible conductivity, thus completing the square wave shape. A constant voltage is applied across the electrodes and a constant magnetic field is maintained perpendicularly to the electric field, as in a conventional $j \times B$ configuration. As each ionized slug enters the linear channel an electric arc is struck and accelerated by the applied Lorentz force. Constant arc current is maintained by means of a series inductance. As seen from Fig. 1, a rotating arc vortex acclerator, similar to the one described in Ref. 2, and employing a separate power supply, is used to supply both the ionized gas slugs and the test gas to be accelerated.

Theoretical Analysis

It is presumed that, on entering the linear channel, each arc behaves as a solid body,[3,4] analogous to a solid piston that completely fills the channel cross section, and interaction between the arcs and the test gas takes the form of expansion waves, compression waves, and shock waves set up in the gas by the arc motion. If it is assumed further that the thermal energy transferred to the gas from joule heating in the arc column is a negligible fraction of the total input energy to the accelerator (i.e., the main gas driving mechanism is direct kinetic energy transfer from the arc column and thermal energy dissipation may be neglected for present purposes; this assumption is in agreement with experimental results) and that the gas flow is quasi-one-dimensional, then for a known applied accelerating force, the dependence of the piston velocity on time is specified and, provided the initial conditions are also known, the conditions existing in the gas in any region along the linear accelerating channel can be calculated by the method of characteristics. The conditions obtained will vary considerably, depending on the mode of arc acceleration adopted (the two extremes being 1) instantaneous arc acceleration, in which case the mass of the arc is assumed to be negligible compared with the mass of the gas being accelerated, or the accelerating forces are assumed to be very large and the arc is accelerated instantaneously to its final velocity, and 2) the case of constant arc acceleration, where the mass of each arc is assumed to be equal to the mass of the gas that it accelerates and the accelerating force is more gentle, with the arc reaching its final velocity more slowly over a longer accelerating channel length), and in general the solution will have to be obtained numerically. Under certain circumstances, however, useful analytical results may be obtained.

In Ref. 4 an analytical solution is obtained for the case of several arcs being accelerated uniformly in the linear channel at any time. This solution is used to indicate under what con-

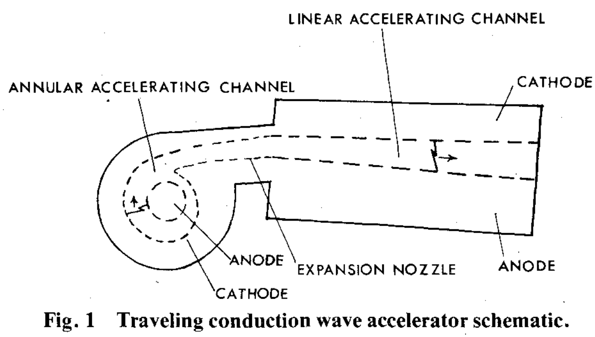

Fig. 1 Traveling conduction wave accelerator schematic.

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ditions a uniform or pulsed gas outflow might be expected. It is shown that an acceptable pseudo-continuous gas outflow should be obtainable if the arc acceleration is relatively gentle (i.e., if the accelerating channel is long), and if the inlet gas temperature is increased significantly beyond room temperature. (It is also shown that a further improvement can be expected if the acceleration decreases along the channel, rather than remaining constant, which is intermediate between the instantaneous and constant acceleration cases.)

Pulsed Gas Flow

For short accelerator channels, with a small number of arcs in the channel, and with high arc accelerations, the gas flow will be strongly pulsed, with shock wave formation distances very much less than the channel length, i.e., the arcs will influence very little of the gas in front of them. The limit to this type of operation is the case of instantaneous accleration and, hence, these are the operating conditions associated with that mode. In this case a shock wave is formed in front of and a rarefaction wave behind each arc, and it can be shown[4] that the maximum efficiency for pulsed operation will be obtained if the channel length is chosen such that the rarefaction wave head and the shock wave arrive at the channel exit at the same time. This ensures that all the gas which is not accelerated by the shock wave will be accelerated by the rarefaction wave. The condition of noninteraction between the shock and rarefaction waves allows an analytical solution to be obtained[1] and expressions for the thrust, specific impulse, and mean power required are obtained as functions of the arc velocity u_p, the inlet Mach number M, and the stagnation enthalpy h_{0_1}, as illustrated in Figs. 2 and 3. The linear channel inlet conditions chosen for the purpose of this calculation correspond to typical outlet conditions of the rotating arc vortex accelerator.[2]

In Fig. 4 the efficiency η is plotted as a function of the mean power requirement $\langle P \rangle$, for mass-flow rate of 6×10^{-3} kg/sec and a value of initial stagnation enthalpy h_{0_1} of 3×10^6 joules /kg, where η is defined by

$$\eta = \dot{m} u^2_{\text{eq}} / 2P$$

where $\dot{m}$ = gas mass-flow rate; $u_{\text{eq}} = u_e + (p_e - p_a / \dot{m}) A_e$ = equivalent gas exhaust velocity; p_e = exhaust gas pressure; P_a = ambient gas pressure, and A_e = cross-sectional area of accelerating channel exit.

It is seen that high efficiencies are obtained for megawatt operation. (In the discussion of experimental results that follows, it is shown that successful accelerator operation can be expected at megawatt power levels. Similar efficiencies would be obtainable at other power levels with an appropriate choice of arc velocity.) For a fixed value of arc velocity the efficiency increases as the specific impulse and thrust increase, as is observed with conventional $j \times B$ and Hall current accelerators. The efficiency also increases as the inlet Mach number increases, but decreases as the arc velocity increases. Therefore, the most efficient method of operation as a propulsion rocket is with the initial Mach number M as high as practicable and with the value of the arc velocity equal to the minimum necessary to achieve the required value of specific impulse.

The values of specific impulse and thrust shown in Figs. 2 and 3 indicate that the traveling conduction wave accelerator would operate as a medium thrust—high specific impulse propulsion device, and estimates of the interplanetary round trip times to both Mars and the deep space planets indicate that these times would be reduced significantly compared with those calculated to be obtainable with either high thrust-low specific impulse, or low thrust-high specific systems, either existing or proposed.[4,5] If a solid-core nuclear fission reactor is assumed as the electric power source for the rocket, a round trip time to Mars of 90 days is calculated for rocket with a 10^{-1} payload ratio and a specific impulse of 1.3×10^4 sec, reducing to 50 days and 6×10^3 sec specific impulse for a 10^{-4} payload ratio. For deep space missions, round trip times of three years would be possible to Uranus with a 10^{-1} payload ratio and a specific impulse ratio of 4×10^4 sec, and to Pluto with a payload ratio of 10^{-4} and a specific impulse of 1.7×10^4 sec. If the recently proposed space radiator cooled gas-core nuclear fission rocket[6] is assumed as the electric power source, round trip times to Mars could be reduced to 40 days for a 10^{-1} payload ratio and specific impulse of 5×10^4 sec, and to 30 days with a 10^{-2} payload ratio and specific impulse of 2×10^4 sec. A three-year round trip time to Pluto could also be achieved with a 10^{-1} payload ratio and specific impulse of 4.5×10^4 sec.

Continuous Gas Flow

The case of constant arc acceleration with long channels and a large number of arcs in the channel at any time has been treated numerically by the method of characteristics for the particular case of an assumed maximum arc velocity of 10^4

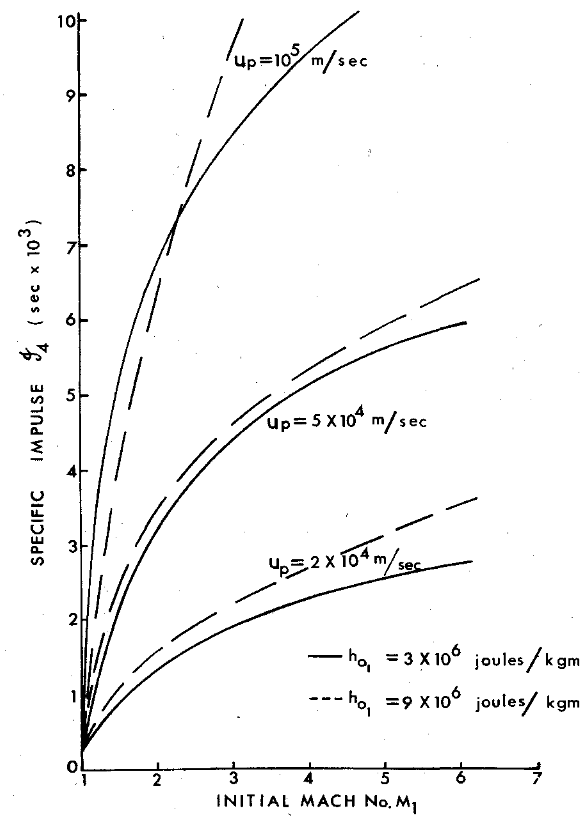


Fig. 2 Variation of specific impulse with initial Mach number.

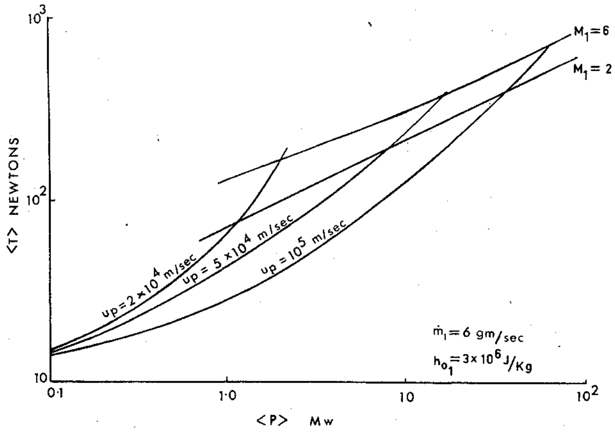


Fig. 3 Mean thrust—power performance curve.

m/sec[4] (where this value is chosen as a typical value that can be expected to be easily obtainable experimentally). It has been found that shock wave formation could be suppressed by increasing the sound speed a_I of the inlet gas (i.e., increasing the inlet temperature, T_I, in agreement with the previous prediction) and decreasing the ratio of specific heats γ. The ratio of the shock wave formation distance to the total accelerating channel length is denoted by ξ_s, and the dependence of ξ_s on γ is shown in Fig. 5 for the following range of inlet conditions: $\rho_I = 0.372$ kg/m^3, $775 \leq a_I \leq 1.79 \times 10^3$ m/sec, $1.3 \times 10^3 \leq u_I \leq 2 \times 10^3$ m/sec, $1.65 \leq p_I \leq 9.63$ atm, $1.1 \times 10^3 \leq T_I \leq 5.8 \times 10^3$ °K, $1.18 \leq \gamma \leq 1.33$, where u is the gas velocity, p pressure, and ρ density.

It is seen that the dependence of ξ_s on γ is quite marked, and the value of γ must be optimized for any particular case, with the upper limit being set by the minimum value necessary to prevent formation of shock waves or unnecessary large pressure gradients along the linear accelerating channel.

For the particular conditions: $\rho_I = 3.72 \times 10^{-2}$ kg/m^3 $a_I = 1.7 \times 10^3$ m/sec, $p_I = 0.9$ atm, $T_I = 6.1 \times 10^3$ K, $\gamma = 1.18$ (where again the inlet conditions have been chosen to conform to typical outlet conditions of the rotating arc vortex accelerator) and with 20 arcs in the channel, the variation in the gas outflow condition is small, as illustrated in Fig. 6 and 7. It is seen that the variation in enthalpy and stagnation enthalpy is of the order of 20% and the variation in pressure and stagnation pressure is of the order of a factor of 2. An indication of whether the gas outflow can be considered to be pseudo-continuous under these conditions is obtained by considering the term $\int_0^\tau \dot{q}_0 dt / [\dot{q}_0]^\tau_{\max}$, which indicates the extent of variation from an effective continuous output state, where $\dot{q}_0$ is the stagnation point heat transfer rate and τ the period of one oscillation. A value of 0.7 was obtained for this integral and the outflow conditions can be considered to be effectively continuous with a mean value of stagnation pressure $\langle p_{0_4} \rangle$ of 7.6 atm and a mean value of stagnation enthalpy $\langle h_{0_4} \rangle$ of 4.6×10^6 joules/kg. These values are of the same order as those obtained with conventional $j \times B$ accelerators.[4]

For an assumed increase in the value of the inlet density of a factor of 10 (i.e., an increase in the rotating arc vortex acceleration mass flow of approximately the same amount) a maximum value of 0.7 was obtained for $\int_0^\tau \dot{q}_0 dt / [\dot{q}_0]_{\max} \tau$ with the following inlet conditions: $\rho_I = 0.372$ kg/m^3, $a_I = 1.79 \times 10^3$ m/sec, $u_I = 1.8 \times 10^3$ m/sec, $\gamma = 1.22$, $p_I = 9.63$ atm, $T_I = 5.8 \times 10^3$ °K, and a min value of $\int_0^\tau \dot{q}_0 dt [\dot{q}_0]_{\max} \tau$ of 0.33 was obtained with a_I reduced to $1.27 \times {}^3$ m/sec; i.e., an acceptable pseudo-continuous outflow is obtained with the higher values of a_I, and with $a_I = 1.79 \times 10^3$ m/sec $\langle p_{0_4} \rangle$ equals 45 atm and $\langle h_{0_4} \rangle$ equals 4.8×10^6 joules/kg. This constitutes an improvement by a factor of 6 in comparison with operation at $\rho_I = 3.72 \times 10^{-2}$ kg/m^3, and an improvement by a factor of 10 in stagnation pressure, compared with results obtained with conventional $j \times B$ accelerators,[4,7] and this mode of operation would be particularly suitable for hypersonic wind-tunnel applications.

Expressions for the power required, efficiency of operation, and channel length necessary are obtained as follows. For constant arc acceleration with a constant current flow, a series inductance is necessary and the total voltage which must be supplied across the inductance-accelerating channel combination is

$$V_T \sim (u_p)_{\max} B\ell \tag{1}$$

where $(u_p)_{\max}$ = maximum value of u_p, ℓ = arc length, B = constant applied magnetic field. Also, the accelerating force on the arcs is $IB\ell$, therefore $I = [((u_p)_{\max} - u_I)/B\ell]\dot{m}$, where $\dot{m}$ is the gas mass-flow rate. Therefore, for N arcs in the channel the mean power requirement is

$$P = (u)_{\max} [(u_p)_{\max} - u_I] \dot{m} N \tag{2}$$

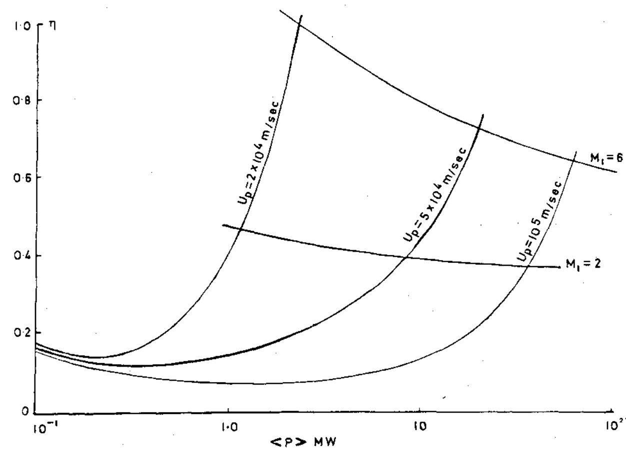
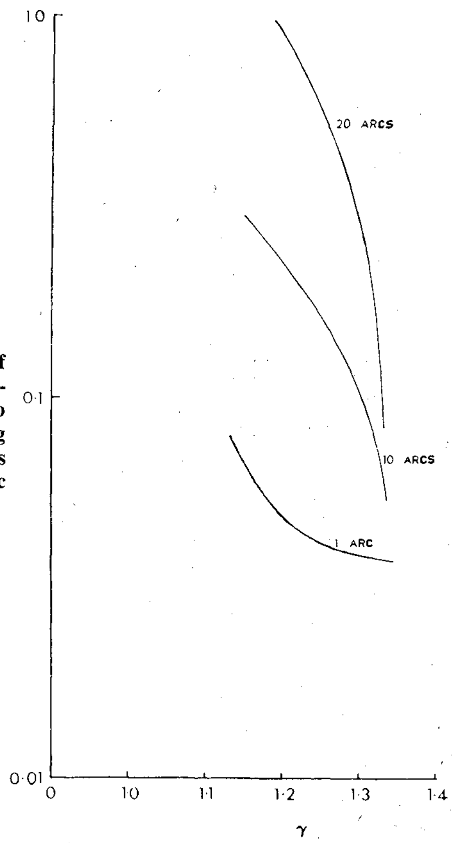


Fig. 4 Efficiency η vs mean power.

Fig. 5 Ratio of shock wave formation distance to total accelerating channel length ξ_s vs ratio of specific heats.



The efficiency can now be defined as

$$\eta = [(d/dt)(mH_4) - (d/dt)(mH_I)]/\langle P \rangle \tag{3}$$

where mH_4 = total output energy of gas and mH_I = total input energy of gas.

or assuming

$$H_4 \gg H_I$$

and writing

$$H_4 \equiv \langle H_4 \rangle = \int_0^\tau H_4 dt \Big/ \int_0^\tau dt$$

(where the variation in H_4 is small)

$$\langle \eta \rangle \approx \dot{m} \langle H \rangle / \langle P \rangle$$

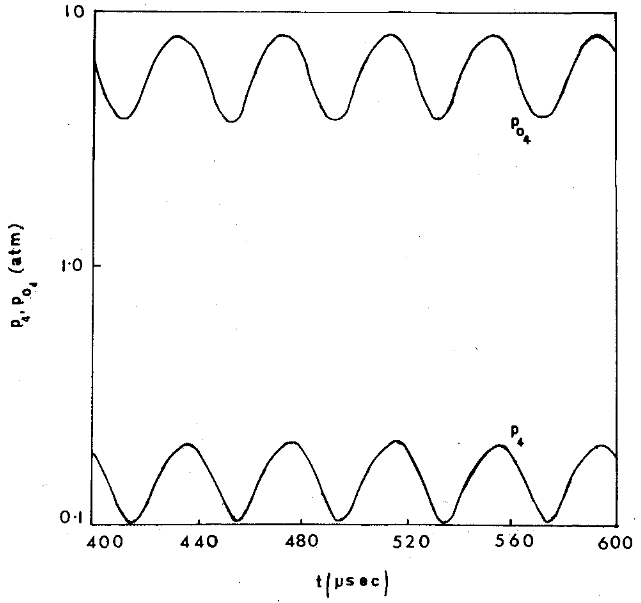


Fig. 6 Channel exit pressure p_4 and channel exit stagnation pressure p_{0_4} vs time t.

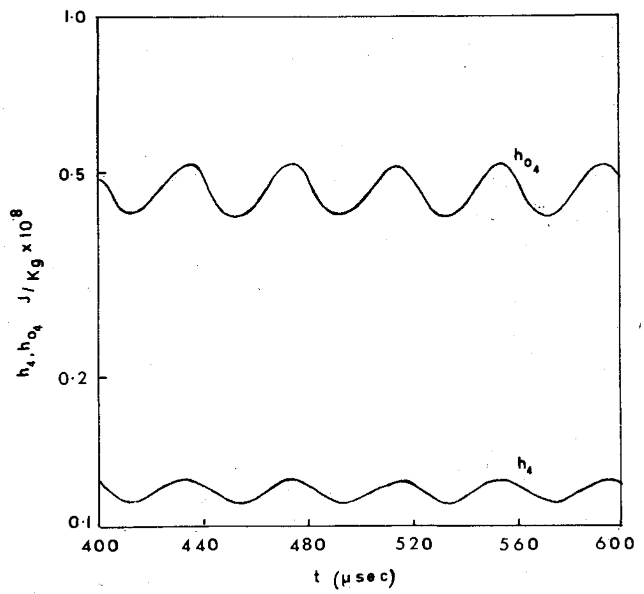


Fig. 7 Channel exit enthalpy h_4 and channel exit stagnation enthalpy h_{0_4} vs time t.

or putting $H_4 \approx \frac{1}{2}u_4^2$ and substituting for $\langle P \rangle$ from Eq. (2)

$$\langle \eta \rangle \approx (1/2N)\left[\frac{\langle u_4^2 \rangle}{(u_p)_{\max}((u_p)_{\max}-u_l)}\right] \tag{4}$$

or since $u_4 \approx (u_p)_{\max}$ and $[((u_p)_{\max} - u_l) \approx (u_p)_{\max}$

$$\langle \eta \rangle \approx \tfrac{1}{2}N \tag{5}$$

i.e., to first order, the efficiency is a function only of the number of arcs in the channel; i.e., the efficiency decreases as the outlet conditions become more continuous. For $N=20$, therefore, the efficiency is $\eta \approx 2.5\%$. This value can be compared with the values obtained for $\langle \eta \rangle$ and $\langle P \rangle$, using calculated outflow conditions and Eqs. (2) and (3), which are shown in Table 1 for $N=20$.

Table 1 Linear accelerating channel operating efficiencies and mean power requirements

ρ_l (kg/m^3)	u_l[(m/sec) $\times 10^3$	a_l[(m/sec) $\times 10^3$	$\langle \rho \rangle$ (Mw)	$\langle \eta \rangle$
3.72×10^{-2}	2	1.7	9.6	0.028
3.72×10^{-1}	1.8	1.79	97	0.029
3.72×10^{-1}	2	1.27	96	0.024
3.72×10^{-1}	1.3	1.27	104	0.023

Good agreement is obtained between these results and Eq. (5), and to the first order the operating efficiency is *not* a function of the thermodynamic state of the inlet gas. This means that, in particular, η is not a function of either the gas conductivity σ or the applied magnetic field B, as is the case for a conventional $j\times B$ accelerator, and therefore a traveling conduction wave accelerator will not be subject to the same excessive limitation of requiring high magnetic field values, nor is it necessary for the inlet gas to be seeded to increase the conductivity.

For example, for the operating conditions of $\rho_l=0.372$ kg/m^3, $u_l=1.8\times 10^3$ m/sec, and $a_l=1.79\times 10^3$ m/sec, the required vortex accelerator current $I_v \approx 5600$ amp, and the corresponding required magnetic field value $B\approx 2.5$ w/m^2. For this magnetic field value the current to each arc in the linear channel $I_L \approx 6400$ amp (for $\ell=3$ cm).

Shaw[8] estimates that for arcs rotating on water-cooled electrodes, the maximum current $I_{\max}$ for which electrode erosion does not occur is $250\sqrt{u_p}$, where u_p is in fps, i.e., $I_{\max}=1.4\times 10^4$ amp for $u_p=2\times 10^3$ m/sec, and therefore electrode burnout should not be a problem for $B\sim 2.5$ w/m^2. This value of B is a factor of 10 less than that estimated[9,4] as being necessary for conventional $j\times B$ accelerator operation.

The efficiency and power required for operation at $\rho=3.7\times 10^{-2}$ kg/m^3 can be compared with the results for a 20 Mw $j\times B$ accelerator, which has an efficiency of 8.4%, an outflow stagnation pressure of 5 atm, and stagnation enthalpy of 9.2×10^7 joules/kg; i.e., the efficiency of the $j\times B$ accelerator is three times that of the traveling conduction wave accelerator. The $j\times B$ accelerator is, however, operating at higher enthalpy and lower stagnation pressure and, moreover, is operating close to its optimum value. This means that little increase can be expected in the obtainable stagnation pressure at high density, whereas the expected outflow stagnation pressure of the traveling conduction wave accelerator can be increased by an order of magnitude without approaching an operating limit and with no decrease in the operating efficiency. Therefore, although the operating efficiency of the traveling conduction wave accelerator is less than that of the $j\times B$ accelerator for the particular case considered, it is still of the same order of magnitude, and can be expected to remain constant over an operating range which is very much greater than that of a conventional $j\times B$ accelerator.

The length of the accelerating channel is calculated simply by $L=b/2\tau^2+u_l$, where $b=(v_f-u_l)/\tau$ and $\tau=N/f$. N is the number of arcs in the channel and f is the arc frequency. Therefore, $v_f=10^4$ m/sec, $u_l=2\times 10^3$ m/sec, $1/f=40$ sec. $L=4.8$ m for $N=20$ and 2.4 m for $N=10$. For $\ell=3$ cm, $L/\ell=160$ for $N=20$ and 80 for $N=10$.

These values of L/ℓ are higher than the value of 40 suggested by Leonard and Rose[9] as a desirable value for a conventional $j\times B$ accelerator. This estimate is based on boundary-layer effects about which little is known, however, and larger values might not be unacceptable. If it is found necessary to reduce the value of L/ℓ, then ℓ can easily be increased, and such an increase has the added advantage of reducing the required value of IB. Alternatively, a divergent channel might be useful as a means of compensating for boundary-layer effects.

Conclusions

Based on the assumption that electric arcs can behave as solid conducting pistons, it has been shown that a traveling conduction wave accelerator can be expected to operate satisfactorily as both a high specific impulse-medium thrust propulsion device and as a high-density hypersonic wind tunnel. For propulsion applications, short channel lengths can be used, whilst for wind-tunnel applications, longer channel lengths with a number of arcs present in the channel at any time will be necessary. Also for wind-tunnel operation, high inlet gas temperatures (~6000 K) are necessary. These temperatures are not excessive, however, as vortex accelerator operation has already been achieved under these conditions. Further, the required inlet temperature does not increase with increasing outlet stagnation pressure, as it does for thermal arcjets, and therefore the required inlet temperatures are not expected to impose an operating limit as has previously been the case.

It was also shown that the high magnetic field values necessary for conventional $j \times B$ accelerator operation are not necessary for traveling conduction wave accelerator operation and that an applied magnetic field value of $B \sim 2.5$ w/m^2 should be more than adequate to provide the necessary arc acceleration and to prevent electrode erosion. Further, as the gas temperature falls through the accelerator and inlet temperatures are within present operating limits, it is expected that erosion of neither the walls nor the electrodes should be a problem.

The conclusions so far drawn about wind-tunnel operation are based on the assumption of constant arc acceleration. However, further improvement in operation could be expected if the arc acceleration decreased with time, and such a decrease with time is the most likely practical situation. Joule heating effects were also neglected. However, joule heating can be expected to produce improved operation by reducing the decrease in sound speed along the channel, thus further delaying shock wave development and resulting in a more continuous gas outflow. A similar effect will result if the arcs are not completely impervious to the gas flow, as leakage of the gas from the hotter region directly in front of the arc to the cooler region behind it will again increase the sound speed in that region, resulting in a more rapid interaction between the expansion waves and the oncoming compression waves, as before. Hence, real effects that are likely to be encountered in the experimental situation and, which were neglected for the purposes of the analyses, can be expected to have an advantageous rather than detrimental effect and satisfactory pseudo-continuous operation can be expected.

Experimental Results

To test the predictions discussed, a simple experiment was conducted that would allow constant current operation without requiring segmented electrodes. This means that only one arc can be in the channel at any time and the channel length and arc frequency were chosen such that a new arc entered the linear accelerating channel as the previous one left.

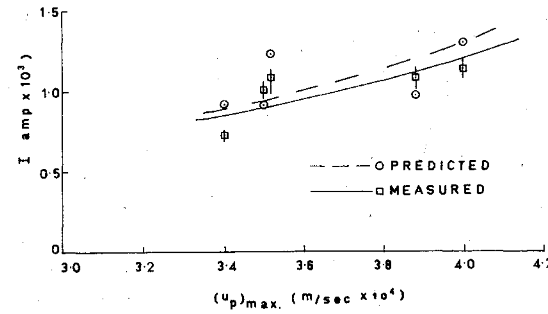


Fig. 8 Current I vs maximum gas velocity $(u_p)_{max}$.

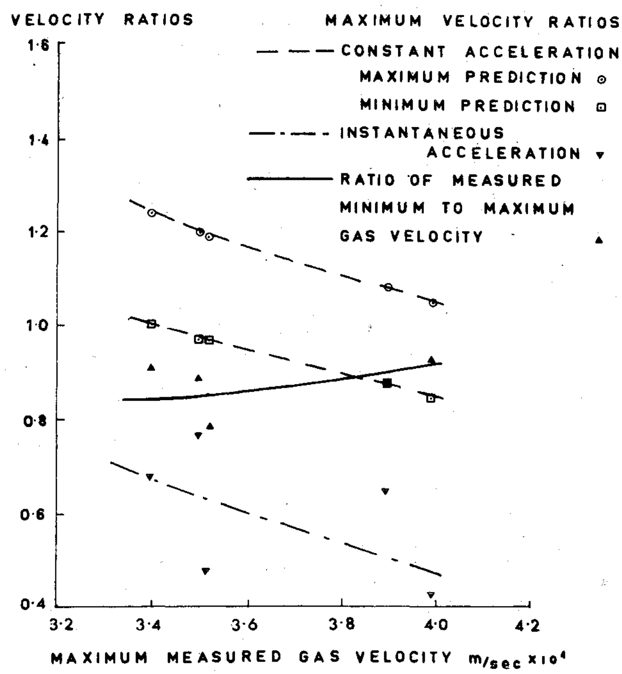


Fig. 9 Ratio of predicted to measured maximum gas velocity and ratio of measured minimum to maximum gas velocity vs maximum gas velocity.

A constant magnetic field value of 1 w/m^2 was used and power was supplied by a 31.5 mF capacitor bank, with run times of the order of 5 msec, allowing the use of an uncooled accelerator. The test gas was air and gas outflow velocities were measured by means of induction velometry. Heat flux to the accelerator components, total gas enthalpy, and accelerator efficiency were measured by the energy balance method.

As previously stated, the gas flow behavior is expected to be intermediate between that predicted by assuming either instantaneous or constant acceleration and the measured values

Table 2 Summary of results for operation at capacitance bank open circuit voltage of 850 v

Run no.	Applied v	Current (amp) Measured	Current (amp) Predicted (instantaneous acceleration model)	Measured velocity (10^4 m/sec) max.	Measured velocity (10^4 m/sec) min.	u_{min}/u_{max}	μ[a]	ψ[b]
1	560	1080±70	970	3.88	3.42	0.88	2.5	0.65
2a	420	1130±60	1300	3.99	3.7	0.93	1.7	0.43
2b	400	1070±60	1230	3.52	2.78	0.79	1.7	0.48
3	510	720±30	930	3.4	3.1	0.91	2.3	0.68
4	540	10^3±50	910	3.5	3.1	0.89	2.7	0.77
Mean	486	10^3	1070	3.66	3.22	0.88	2.2	0.6

[a] μ = predicted u_{max} (m/sec × 10^4) (instantaneous acceleration model).
[b] ψ = ratio of predicted maximum velocity (instantaneous acceleration model) to measured maximum velocity.

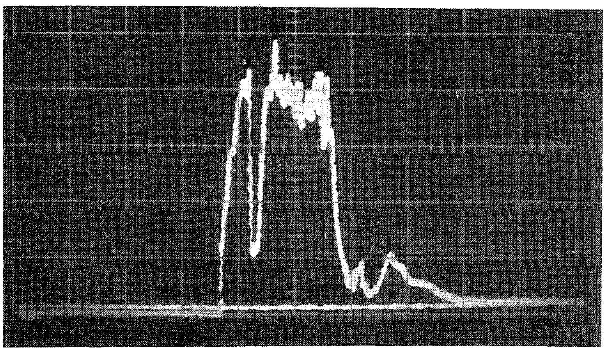


Fig. 10 Induced emf. Vertical scale 200 v/division, time scale 1 msec/division.

are compared with values calculated using both these models in Table 2 and Figs. 8 and 9. (For the instantaneous acceleration case a partial interaction will result between the shock and rarefaction waves, leading to a modification of the pulsed effect.) The mean value of the measured gas velocities is 3.4×10^4 m/sec, which corresponds to an outlet to inlet gas velocity ratio of approximately 10, and the mean ratio of minimum to maximum gas velocity was 0.88, compared with values of 0.65 predicted by the instantaneous acceleration model and 1.0 predicted by the constant acceleration model. A typical induced voltage signal obtained with the induction velometry probes is shown in Fig. 10. Reasonable agreement is also obtained between predicted and measured current values and, in general, good agreement has been obtained between the experimental results and the two theoretical models, with the measured values falling between the limits prescribed by theory.

The heat losses to the accelerator components were measured with thermo-couples located in the accelerator electrodies and side walls and the total heat loss subtracted from the known input power to give the total energy transfer to the gas. The measured heat flux values, power losses, and total efficiency are indicated in Table 3. The heat flux values obtained are more than an order of magnitude less than the maximum value of 6.15 kw/cm^2 for such successful cooling was achieved with forced-convection water flows by Gambill and Greene in 1958,[10] and this result, combined with the high efficiency range of 70-88%, indicates that the input powers could be increased by two orders of magnitude without causing burnout of a water-cooled linear accelerator, and therefore successful operation at long run times can be expected at the megawatt power levels predicted to be necessary for the hypersonic wind-tunnel and propulsion applications.

The test gas mass-flow rate was estimated to lie within the range of 6×10^{-4}-3×10^{-3} kg/sec, and corresponding to this range the values obtained for stagnation pressure p_o, thrust T, and specific impulse I_{sp} are 4 atm $\leq \langle p_0 \rangle \leq 20$ atm, $2 \times 10^2 N \leq \langle T \rangle \leq 10^3 N$, $\langle I_{sp} \rangle = 3.8 \times 10^3$ sec. While these values are far from the expected maximum operating values, they are of the same order as, or better than, the output results obtained with other existing accelerators[4] and further very substantial improvements can be expected, as predicted by the theoretical analysis for operation at higher powers, with the eventual limit being set by the conditions under which the arc can no longer maintain its identity. Similar improvements cannot be expected for other accelerators, mainly because of their lower efficiencies or higher heat-transfer rates.

Table 3 Linear accelerating channel heat flux, power losses, and total efficiency

Heat flux Kw/cm^2				
Anode	Cathode	Side walls		
0.2 ± 0.03 to 0.05 ± 0.07	0.03 ± 0.02 to 0.74 ± 0.06	0.19 ± 0.03 to 0.47 ± 0.08		
Power loss fraction of total power supplied				Total efficiency (%)
Anode	Cathode	Side walls	Total	
0.03 $\pm 27\%$	0.07 $\pm 26\%$	0.06 $\pm 60\%$	0.21 $\pm 44\%$	79 ± 9

Recommendations for Future Work

Agreement obtained between theory and experiment indicates that the traveling conduction wave accelerator can be expected to operate successfully as a medium thrust-high specific impulse propulsion rocket and as a hypersonic wind tunnel, and future work should be aimed initially at further confirmation of these predictions by increasing the regime of experimental operation to include higher mass flow and higher input powers. For simplicity, these experiments could be performed with uncooled accelerators over short-duration run times, if suitable power supplies are available; further heat-transfer data could be collected at the same time.

The experiments carried out so far have been aimed at confirming assumptions made about arc behavior and demonstrating that the general principles of operation are sound. With these aims achieved, special purpose accelerators can now be built, aimed at optimum performance for particular applications. Optimum thrust and thrust efficiency can be expected with a traveling conduction wave accelerator employing a short linear accelerating section, such that the shock wave and rarefaction head arrive at the outlet at the same time.

For hypersonic wind-tunnel operation with continuous gas outflow, it will be necessary for a number of arcs to be in the channel at any particular time. Once satisfactory operation in the required regimes has been obtained, further experiments could be carried out with water-cooled accelerators.

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