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Power Addition and Extraction From Gas Flow By Means of Electric Wind

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ABSTRACT

Progress on a theoretical study of the feasibility of adding or extracting power to or from a flowing gas is reported. The gas carries an excess positive charge and interacts with a strong electric field due to the space charge and/or an applied voltage.

I. INTRODUCTION

A theoretical study has been undertaken to determine the feasibility of using the *electric wind* concept as a means of adding or extracting power from a gas flow. *Electric wind* as described in the old literature (Ref. 1) refers to the induced motion in a gas caused by ions forced to move through the gas under the action of an electric field.

More recently, Harney has made an aerodynamic study of the *electric wind* using a corona discharge (Ref. 2). His experiments show that there is a measurable mutual interaction between the corona discharge and the flow. However, his problem is difficult to analyze because of the complexity of the corona discharge and the unfortunate geometry. An attempt has been made to define a problem which contains all the physical phenomena of interest yet lends itself to mathematical analysis.

A careful analysis of the effects of an ion current on the thermodynamic state and motion of the gas reveals many unexpected and perhaps useful aspects. When power is added to a high-density, lightly ionized gas (type A flow), the gas tends to become sonic (approaches Mach 1). On the other hand, if the gas is of low density and is highly ionized (type B flow), adding power causes the gas to go away from Mach 1.

Calculations show that it is possible to reverse these principles and extract power. When a gas containing ions flows against an opposing electric field, it must do work against the field. In this way, some of the energy of the flow is extracted and converted into useful electrical energy. Such a device is called an *electric wind* power generator.

II. POWER ADDITION TO A STEADY ONE-DIMENSIONAL FLOW

Consider a monatomic gas flowing in a straight channel (Fig. 1). Suppose that by some process, electrons are extracted from the flow of the anode, leaving an excess positive charge. (A method of doing this is described in Ref. 3.) The extracted electrons pass through the outer circuit and go to the cathode where they neutralize impinging ions. The gas downstream of the cathode can be assumed neutral. The problem is to determine how much power-per-unit-area JV can be added to the flow, and how this power addition affects the state of the gas.

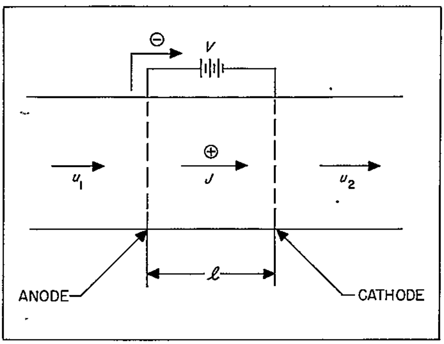

Figure 1. Electrogasdynamic channel flow

In order to answer these questions, it is necessary to make one basic assumption: there are no electrons between anode and cathode. This is true if the ions are not energetic enough to ionize by collision, and if the cathode does not emit electrons.

Equations describing this problem include those for mass flow; momentum flow; enthalpy flow; equation of state; one of Maxwell's laws, $dE(x)/dx = (e/\epsilon_0)\ n_+(x)$; conservation of change, $J = en_+(x)\ [u + V_+(x)]$; drift velocity, $V_+(x) = c_n\ [E(x)/\rho(x)]^{\frac{1}{2}}$; lightly ionized gas (Ref. 4), $V_+ = 0$; and heavily ionized gas. The expressions for drift velocity V_+ are simple only in these two extreme cases.

This system is solved in Ref. 3. Some results for type A flows are summarized in Fig. 2 and 3. The solutions are given in dimensionless form. The flow variables are non-dimensionalized with respect to sonic values (denoted by an asterisk). The electric variables and the length are non-dimensionalized with respect to the following characteristic quantities: $E_c \equiv (2P^*/\epsilon_0)^{\frac{1}{2}}$, $\phi_c \equiv mH^*/J$, $n_c \equiv 2P^*/e\phi_c$, $L_c \equiv \phi_c/E_c$. There are two dimensionless parameters: ω^* is the characteristic ratio of ion drift velocity to sonic velocity, and E^* is the dimensionless field at the cathode, where the gas is sonic; the value of $\omega^* = 8$ is reasonable for argon at standard temperature and pressure.

Typical results for an extreme type B flow (fully ionized gas, $\omega^* = 0$) are shown in Fig. 4. The solution shown

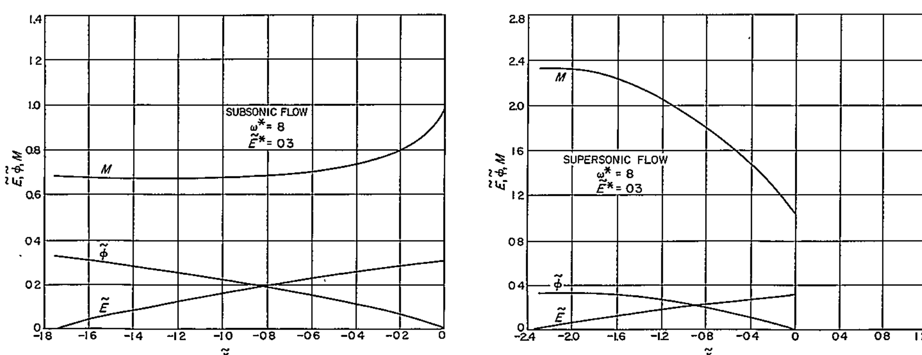

Figure 2. Electric field, potential and Mach number vs distance for type A flows

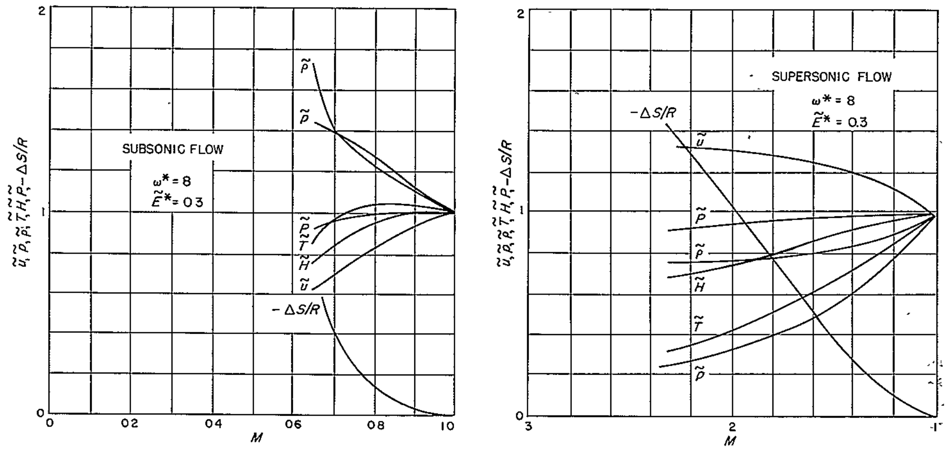

Figure 3. Flow variables vs Mach number for type A flows

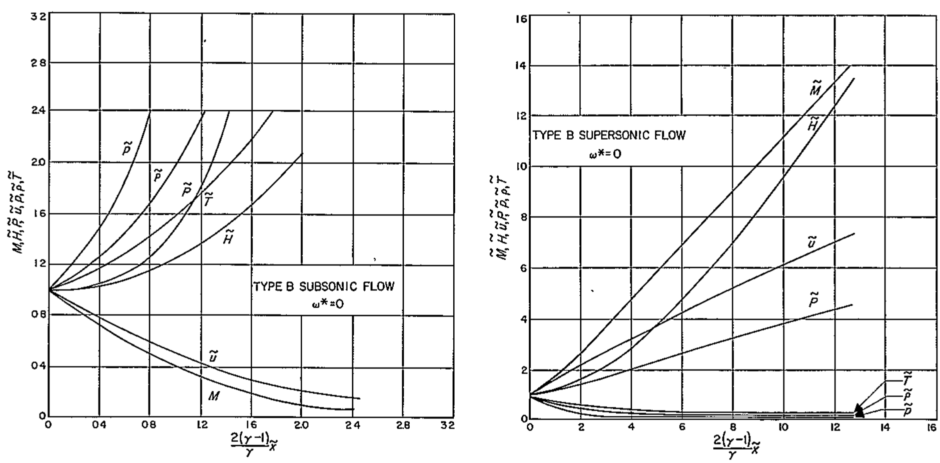

Figure 4. Flow variables vs distance for two type B flows

in Fig. 5 agrees with approximate solutions obtained for pure ion beams, as it should. The solution for $\omega^* = 1$ is compared with the solution for $\omega^* = 0$ in Fig. 6. The strong dependence of the solution on ω^* should be noted. It has been shown that if $\omega^* \geqq 1/(\gamma - 1) = 1.5$, the flow will tend to become sonic (type A flow) (Ref. 3). Since most gases have $\omega^* > 4$, the high-density laboratory flows are expected to be of type A. Perhaps at lower densities and higher ionization levels the flow will become type B. This will be studied experimentally.

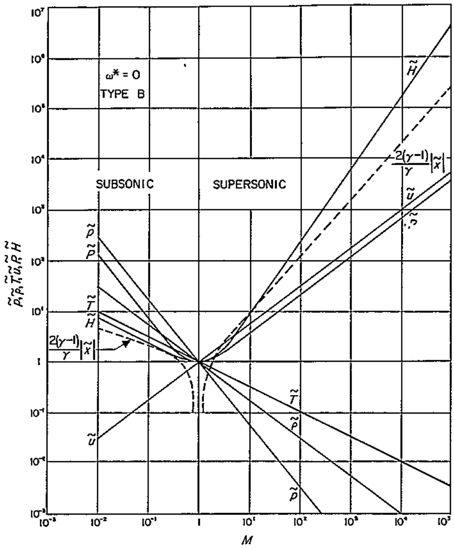

Figure 5. Flow variables and distance vs Mach number for type B flows

In a laboratory experiment, the following magnitudes might be expected for argon at STP: $V = 80$ kv; $J = 37$ amp/m^2, $n = 10^{17}$ ions/m^3, $L = 2$ mm, $E^* = 8 \times 10^7$ v/m, and the percentage ionization $\alpha = 10^{-8}$. A 30% change in the energy of the flow and a 4% change in momentum can be expected.

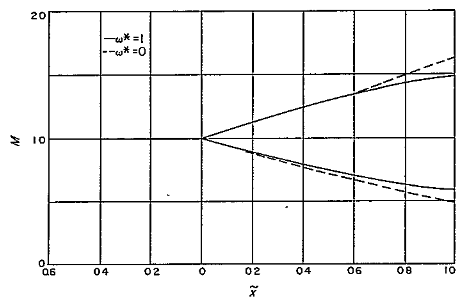

Figure 6. Mach number vs distance for two type B flows

III. POWER EXTRACTION FROM A STEADY ONE-DIMENSIONAL FLOW

Suppose the battery in Fig. 1 is replaced by a resistance and that electrons are still extracted from the flow at the anode (Ref. 5). The ions in the gas are then convected downstream to the cathode. The electrons in the outer circuit must flow through the resistance to reach the cathode where they neutralize the impinging ions. In this case, the gas is sweeping the ions downstream against an opposing electric field set up by the ion space charge. The gas does work against the field and loses momentum and energy. The rate at which the gas loses energy equals the electrical power dissipated in the load resistance.

The analysis for this problem assumes that only a small fraction of the total energy of the flow is extracted, so the state of the gas is essentially unchanged. However, the flow velocity plays a major role in determining the ion concentration and electric field distribution between the anode and cathode. We also assume that the ion drift velocity is given by $V_+(x) = k_+E(x)$, where k_+ is the ion mobility. The problem is determined by the following equations:

Maxwell's equations:

$$\frac{dE(x)}{dx} = \frac{e}{\epsilon_0} n_+(x) \quad (1)$$

$$\phi(x) = -\int_0^x E(x')dx' \quad (2)$$

Conservation of charge:

$$J = en_+(x)\,[u + k_+E(x)] = \text{constant} \quad (3)$$

The boundary conditions are: (1) the electric field vanishes at the cathode, and (2) the voltage drop across $\mathcal{R}$ equals the voltage drop between anode and cathode,

$$JA\mathcal{R} \equiv V = -\int_0^1 E(x')dx' \quad (4)$$

Finding the solution is straightforward because u and k_+ are constants. The solution in dimensionless notation is:

$$E(x) = -1 + [1 - J(1-x)]^{\frac{1}{2}} \quad (5)$$

$$\phi(x) = x - \frac{2}{3} J^{-1}\{[1-J(1-x)]^{3/2} - (1-J)^{3/2}\} \quad (6)$$

$$n(x) = \frac{J}{2}[1 - J(1-x)]^{-\frac{1}{2}} \quad (7)$$

The dimensionless quantities are defined as follows: $\tilde{E} \equiv E/E_c \equiv E(u/k_+)^{-1}$; $\tilde{\phi} \equiv \phi/\phi_c \equiv \phi\,(ul/k_+)^{-1}$; $\tilde{n} \equiv n/n_c \equiv n(\epsilon_0 u/elk_+)^{-1}$; $\tilde{x} \equiv x/x_c \equiv x/l$; $\tilde{J} \equiv J/J_c \equiv J(\epsilon_0 u^2/2k_+l)^{-1}$, where $\tilde{J}$ is actually a dimensionless parameter and is related to $\mathcal{R}$ through the boundary condition (4), and Eq. (6). The relation is

$$K = \frac{1}{\tilde{J}} - \frac{2}{3}\frac{1}{\tilde{J}^2}[1 - (1 - J)^{3/2}]$$

with

$$K \equiv \frac{A\mathcal{R}\epsilon_0 u}{2l^2}$$

Both $\tilde{J}$ and K are restricted to a finite range of values: $0 \leqq J \leqq 1$; $0.25 \leqq K \leqq 0.33$. The maximum amount of power that can be extracted occurs when $\tilde{J} = 1$, and $K = 0.33$. The dimensionless variables for $\tilde{J} = 1$ are plotted in Fig. 7 as a function of dimensionless distance.

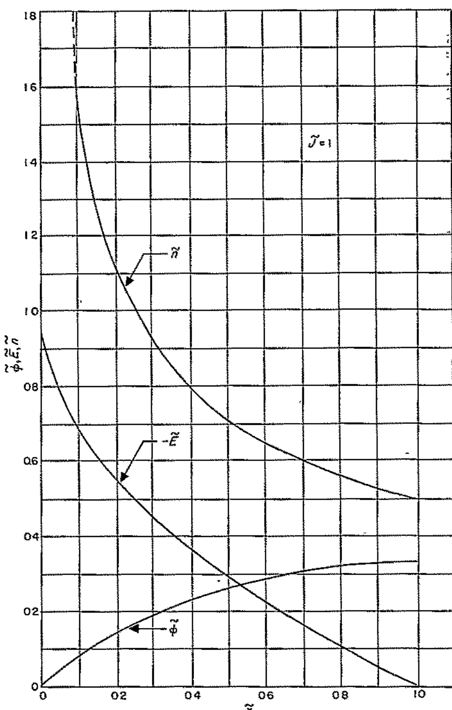

Figure 7. Ion concentration, electric field and potential vs distance

As a typical numerical example, consider the sonic flow of argon at STP: $u = 480$ m/s, $k_+ = 1.2 \times 10^{-4}$ m²/volt-s, $E_c = 4 \times 10^6$ v/m, $J_c V_c = (\epsilon_0 E_c^2)/2 \cdot u = 3.4 \times 10^4$ watts/m². The energy flux of the gas is 4.5×10^7 watts/m²; only 0.1% of the energy flux is extracted, and the state of the gas is unchanged. Varying the spacing between anode and cathode is a convenient way of varying the voltage and current output, because for fixed u, A, $\mathcal{R}$, one gets $J_c \alpha l^{-1}$ and $V_c \alpha l$. For $l = 10^{-2}$ m; $V_c = 4 \times 10^4$ volts, $J_c = 0.85$ amp/m², $n_c = 2.21 \times 10^{16}$ ions/m³; $\mathcal{R} = 1.57 \times 10^8$ ohms. This is clearly a high-voltage low-current generator.

A crude experiment has been performed that demonstrates in a qualitative way the correctness of these ideas (Ref. 5). Further experimentation will be performed in the future.

NOMENCLATURE

- A area
- c_p heat capacity at constant pressure
- c_v heat capacity at constant volume
- e charge on an electron
- E electric field strength
- E^* field at cathode where gas is sonic
- H total enthalpy per unit mass
- J current density
- k_+ ion mobility
- K $AR\epsilon_0 u/2l^2$
- l distance from anode to cathode
- L_c characteristic length
- m mass flux
- M Mach number
- n_+ ion concentration
- p pressure
- P total momentum flux
- R gas constant
- $\mathcal{R}$ resistance
- S specific entropy
- T temperature
- u velocity
- V_+ ion drift velocity
- V voltage
- x distance from anode
- α percentage ionization
- γ c_p/c_v
- ϵ_0 permittivity of free space
- ρ density
- ϕ electric potential
- ω^* characteristic ratio of ion drift velocity to sonic velocity

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