

United States Patent [19]

Pollin

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[54] **CONTROL OF ELECTRON DENSITY
ENVELOPING HYPERSONIC VEHICLES**

[75] Inventor: **Irvin Pollin**, Bethesda, Md.

[73] Assignee: **The United States of America as
represented by the Secretary of the
Army, Washington, D.C.**

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[51] Int. Cl. **H01q 1/28**

[58] Field of Search..... **343/705, 708, 872**

[56] **References Cited**

UNITED STATES PATENTS

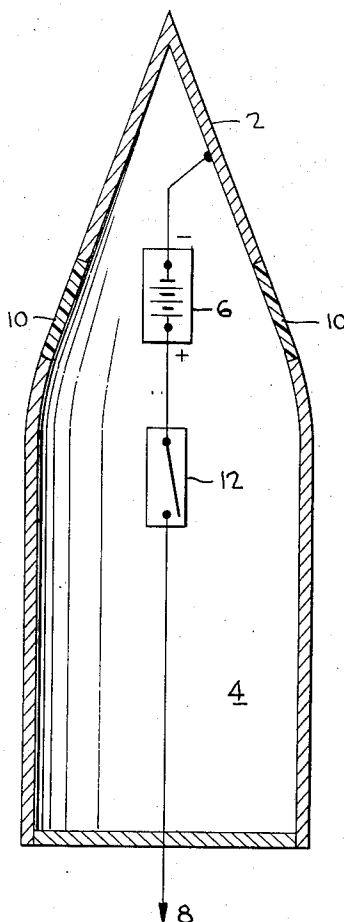
3,544,998 12/1970 Vandenplas et al. **343/705**

Primary Examiner—Eli Lieberman
Attorney—Harry M. Saragovitz et al.

[57] **ABSTRACT**

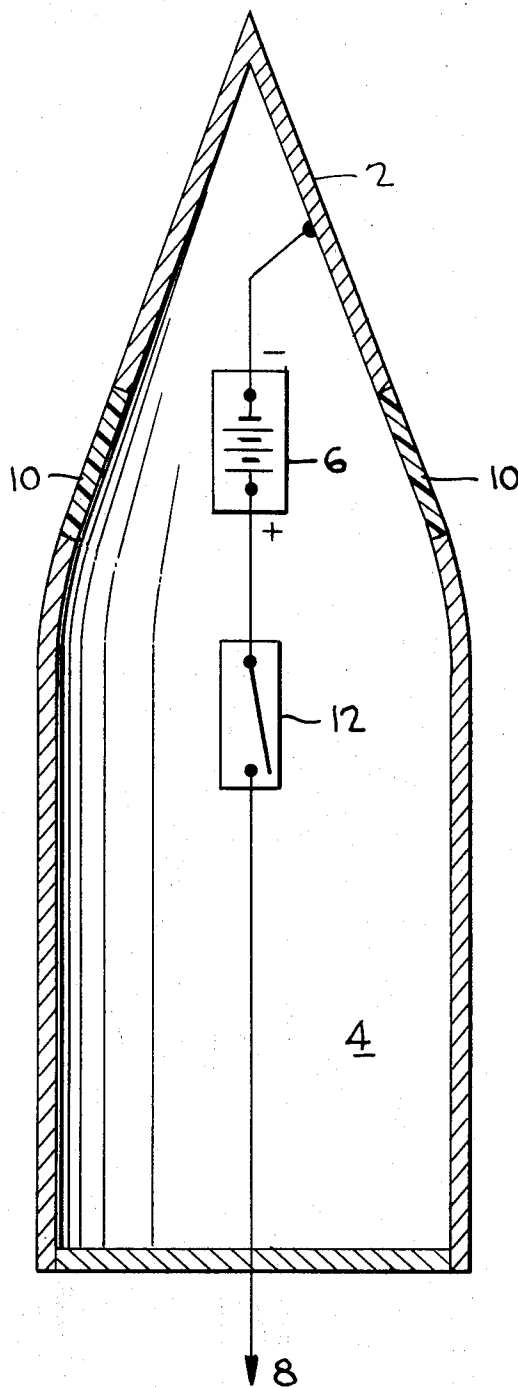
A device wherein a portion of an electrical conducting interface of a vehicle in hypersonic flight is electrically biased relative to the surrounding plasma to cause currents to pass thru the plasma. Proper selection of the bias causes a current to pass thru the plasma, thru a battery-type device and into the vehicle wake to thereby reduce the electron density and/or alter the electron distribution enveloping the vehicle. Reduction of the electron density and/or alteration of the electron distribution in the plasma increases the accuracy of communications to or from the vehicle to permit proper functioning of vehicle communications, guidance, arming and fuzing as well as other possible onboard equipment.

6 Claims, 1 Drawing Figure



PATENTED OCT 16 1973

3,766,562



CONTROL OF ELECTRON DENSITY ENVELOPING HYPERSONIC VEHICLES

DEDICATORY CLAUSE

The invention described herein may be manufactured, used and licensed by or for the United States Government for governmental purposes without the payment to me of any royalty thereon.

BACKGROUND OF THE INVENTION

This invention relates to hypersonic vehicles and in particular to the control of the electron density in the plasma enveloping the vehicle to prevent interference with vehicle tracking or communications. The accuracy with which a hypersonic vehicle receiving electromagnetic radiation through a dielectric window can track a target is affected by electrons produced by aerodynamic heating of the tracking vehicle.

Hypersonic vehicles flying through the atmosphere produce a region of high electron density enveloping the vehicle; this electron density increases with increased vehicle speed and reduced altitude. Conditions thus appear for which high electron densities occur; the high electron densities enveloping the vehicle inhibit the proper functioning of the vehicle communication, guidance, arming and fuzing equipment as well as possible other onboard equipment. The plasma distorts an incoming signal by changing its propagation velocity through the plasma, refracting it at the plasma radome interface, and causing additional changes in the passage of the signal within the radome itself. Accordingly, wherever the electron number density exceeds $10^8/\text{cm}^3$, the calculation of boresight error requires a description of the electron distribution.

There has long been a need for a means of effectively controlling a portion of the plasma to enable communication with the vehicle. U. S. Pat. No. 3,176,227 to Bender, No. 3,176,228 to Phillips et al., No. 3,208,068 to Hoffman and No. 3,296,531 to Seaton are indicative of efforts of others to elude the condition created by the enveloping plasma. Bender discloses magnetic and electrostatic means for propagation of the plasma electrons. Information is thus transmitted via the electromagnetic waves thus radiated and are received at a distant point.

Phillips provides a magnetic field from within the fuselage which causes the plasma electrons to describe a circular path about the lines of force. Signals transmitted from the vehicle are circularly polarized to pass through the magnetic field.

Seaton discloses electrodes placed within the plasma and intermittent reversal of polarities on the electrodes to provide periodic decreases in electron density wherein a signal from within the vehicle is transmitted. The signal received at a distant receiver is indicative of the encoded repetition of the reversal of polarity and may be decoded to reveal the information transmitted by the change in the plasma density.

The patent to Hoffman discloses a means for coupling a waveguide apparatus to the plasma sheath.

In addition, plasma quenchants in the form of electrophilic gases and transpiring coolants are known to reduce electron density; however, the reduction accomplished by any of the above methods is less than desirable and none provide the reduction necessary to provide accurate communication through the plasma medium.

Accordingly, it is an object of this invention to provide a means for reducing the plasma electron density and/or its distribution to provide for effective communication through the plasma.

It is a further object of this invention to provide a means for reducing the peak electron density below that provided by known devices by passing a current through the plasma.

Yet another object of this invention is to provide a means for reducing the electron density whereby the exact voltage and power required to reduce the electron density to a level which will permit effective communication may be predetermined, calculated, or programmed.

SUMMARY OF THE INVENTION

The present invention provides a means to reduce the electron density enveloping a hypersonic vehicle to effectuate better communication to or from the vehicle and otherwise improve the performance of equipment which can be influenced by a surrounding plasma. The improved performance of equipment includes not only onboard equipment but the performance of external equipment which can be used in connection with the hypersonic vehicle. The electron density signature, which includes the electron density distribution and especially the peak electron density, is useful in determining the identity, speed, and mission of a vehicle. Hence, the change in the electron density signature can be useful as a penetration aid for a military application. The electron reduction is accomplished by establishing an electric field at the body surface and extending the plasma to attract or repel electrons at the body surface and throughout the immediate region surrounding the vehicle. The electron reduction and change of electron distribution occurs over the surface at which the electric field is applied and for some distance behind this surface. Thus, significant reductions of electron density and changes of electron distribution are possible over metallic and/or non-metallic surfaces located downstream of an electrically biased metallic surface. By suitable selection of the electric field, the electron density distribution can be significantly altered and the peak electron density can be significantly reduced. The device itself requires that a part of the vehicle interface with the enveloping air be of an electrical conducting material. Many hypersonic vehicles normally meet this requirement. For other vehicles using a non-metallic covering, a high resistive metallic coating, e.g., ceramic, can be sprayed on, or otherwise applied to accomplish the same end. In addition, the electrically conducting surface need not be a continuous conducting surface, but can be in the form of a continuous or broken string-like net where the applied bias can vary from section-to-section of the total net.

The metallic covering of the vehicle is electrically connected to a battery or battery-type device, whose purpose is to provide this covering with an electrical bias relative to the surrounding plasma. In addition, because of the electrical bias, the electrical covering acts as a collector or emitter plate for electrons. Thus, electrons are transmitted to or from the electrical covering to one terminal of the battery type device. Thus, currents are passed to or from the surrounding plasma and to or from one terminal of the battery-type device. The other terminal can be electrically connected to the plasma in the wake or at any location on the vehicle.

In this manner, the current is passed through the plasma, through the vehicle covering, through the battery-type device and then back into the plasma at any other location of the vehicle, including possibly the vehicle wake.

The value of the bias needed in the battery-type device depends on the desired reduction in peak electron density and the location on the vehicle at which the reduction is to occur as well as on the vehicle and flight conditions. It should be noted that the required change of electron density can be accomplished within about one millisecond following the application of the electrical bias. The bias can be programmed with respect to the trajectory to meet the changing needs with changes of trajectory. In principle, there are an unlimited number of ways in which this bias can be acquired and programmed. The actual battery-type device and associated auxiliary equipment will depend on the vehicle, trajectory and communication specifications. For each application, calculations of the electron density distributions can be made and the design of the required electron reduction apparatus can be determined therefrom.

The battery-type device can be any device capable of storing or discharging electrical charge, such as a condenser or generator. In addition, any of a number of well-known electric field generating devices can be used in conjunction with an electric connection joining one part of the plasma (where the electron reduction occurs) to a second part of the plasma (where the removed electrons in the first part are dumped.)

BRIEF DESCRIPTION OF THE DRAWING

The single FIGURE drawing is a schematic diagram of an embodiment of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to the drawing, the metallic covering 2 of the vehicle 4 is electrically connected to a battery or battery-type device 6. Many hypersonic vehicle have metallic coverings; however, for others which use a non-metallic covering such as ceramic, as previously stated, a highly resistive metallic coating can be sprayed on or otherwise applied to accomplish the same end.

Positive ions, or electrons, or both are attracted to the metallic covering 2. Thus, currents are caused to pass from or to the surrounding plasma, to or from one terminal of the battery-type device 6, and back into the plasma at some other location on the vehicle, such as the vehicle wake via switch means 12 and terminal 8. In this manner, the current is passed from the plasma, through the vehicle covering, through the battery-type device and back again into the plasma in the vehicle wake. Electro-magnetic windows 10 composed of electrical insulative material is provided which allows communication signals to be transmitted through the surrounding plasma whose electron density has been reduced.

The value of the bias needed in the battery-type device or electric field generator depends on the electron density requirements, vehicle, and flight conditions. The electric field inserted into the plasma can be programmed with respect to the trajectory to meet changing needs with corresponding changes of trajectory. In principle, there are an unlimited number of ways in

which an external electric field can be applied and programmed. The actual electric field generator device and associated auxiliary equipment will depend on the vehicle, the trajectory, the communications, and other specifications. For each application, calculations of the electron density distributions can be made and the design of the required electron reduction apparatus can be determined therefrom. The time required for the electron reduction to take place corresponds to the time required for the vehicle to travel two vehicle lengths. This establishes the required "warm-up" time for the system. For the most efficient way of reducing electron density or altering electron distribution in terms of energy required to provide the above, the applied electric field is programmed as a function of time and position along the vehicle.

The ionization enthalpy is everywhere small in comparison with the free stream enthalpy, so that the ionization is decoupled from the neutral gas. See Pollin, *Ion and Electron Distributions in the Boundary Layer of Hypersonic Vehicles for Chemical Non-Equilibrium Flow, Part I, Aerodynamics and Numerical Results*, Harry Diamond Laboratories, HDL-TR-1565 (1971). The x-component of the neutral gas velocity for a turbulent boundary layer is given by

$$u = u_\delta \eta^{1/m}, \text{ with } m = 8.$$

(1)

A list of symbols used in this specification appears at the end of the specification.

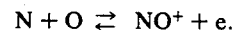
The Crocco relation, limited by the recovery factor of 0.90, is used to determine the local enthalpy. Since $p = \text{constant}$ in the boundary layer for conical flow, there results $\rho = \rho(\eta)$ and $h = h(\rho, T) = h(\eta)$. For ogival contours, $\rho = \rho(x, \eta)$ and $h = h(x, \eta)$ are known functions. The component of the neutral gas velocity normal to the vehicle surface, v , is determined from the mass conservation equation for axisymmetric flow. Everywhere $v \ll u$ and thereby v has no effect on h . However, v is included in the calculation of v_D and $\bar{n}$. Finally, the boundary layer thickness is given by

$$\delta = bx^a, \text{ with } a = 0.8 \text{ and } 0.02 \leq b \leq 0.002.$$

(2)

Values of b of 0.02 and 0.002 are chosen for Mach numbers 10 and 15 respectively.

The ion mass fraction nowhere exceeds 10^{-4} , and therefore all electrons are produced through the reaction



(3)

The neutral gas is in dissociated equilibrium for the N and O, and for conical flow these distributions are functions of η only. The charged particle distributions in the non-equilibrium turbulent boundary layer are determined from the exact non-linear conservation equations and the Poisson equation as follows:

$$J_\eta = (\delta n_e u_{sx}/P) - (We \delta n_e / \rho_e c_e) - n_e s(v/P) \eta \quad (4)$$

for either ions or electrons,

$$(5) \quad s_\eta = \frac{1}{D_T + D} \left[\frac{\pm J P \delta}{e n_e} + \frac{\pm s v \delta \pm K s \theta_\eta}{\pm} \right]$$

where the (-) and (+) signs preceding the electric mobility term are for ions and electrons, respectively, and

$$\phi_{\eta} = -(10^{14}/8.85) [(en_e \delta^2/P) (\bar{s}^+ - \bar{s})] \quad (6)$$

The $\bar{W} = \bar{W}(\eta)$ functions determined from equations (11) and (12) are

$$\bar{W}/\bar{M} = \bar{W}/\bar{M} = dn/dt = K_f \langle N \rangle \langle O \rangle - K_r n \bar{n}, \quad (7)$$

where the formation and recombination rate constants are

$$K_f = 5(10^{-11}) T^{-0.5} \exp(-32,500/T)$$

$$K_r = 3(10^{-3}) T^{-1.5} \text{ cm}^3/\text{ion-sec.}$$

Assuming $\bar{T} = \bar{T}$,

$$\bar{D} = (\bar{M}/\bar{M})^{1/2} = 234 \bar{D} \quad (8)$$

$$D_T = 0.02 u \delta \eta^{9/8} \text{ and} \quad (9)$$

$$K = 11,600 D/T \quad (10)$$

for both ions and electrons.

The y-component of the ion or electron current density is defined by

$$J = v_{pen}, \quad (12)$$

($J > 0$ is in the direction toward the body surface), where the y-component of the average drift velocity is

$$v_D = -v + (\bar{D} s_y/s) + (D_T s_y/s) \pm \bar{K} \phi_y, \text{ and} \quad (13)$$

where (+) is for ions and (-) is for electrons.

The solution of equations (4), (5) and (6) requires the specification of five boundary conditions in addition to initial conditions at $x = 0$.

For sharp nose cones,

$$\bar{s}^+ = 0 \text{ at } x = 0. \quad (14)$$

At the body surface and at the edge of the boundary layer, assume

$$\bar{s}^+ = 0 \text{ at } \eta = 0 \text{ and} \quad (15)$$

$$\bar{s}^+ = 0 \text{ at } \eta = 1. \quad (16)$$

An electric field acts to drive the electrons away from the vehicle surface when $\phi_{\eta} > 0$ and toward the vehicle surface when $\phi_{\eta} < 0$. For the purpose of numerical integration, either $\phi_{\eta}(0)$ or $\phi_{\eta}(1)$ can be specified. In the calculations, assume

$$\phi_{\eta} \approx 0 \text{ at } \eta = 1 \quad (17)$$

5 An electric field has a much smaller spreading effect on $\bar{s}^+$ than on $\bar{s}$, since $\bar{K} = \bar{K}/234$. Accordingly, when ϕ_{η} is not near zero, $\bar{s} < \bar{s}^+$ at every point in the boundary layer, and the integration of (6) gives $\phi_{\eta}(0) > \phi_{\eta}(1)$. The magnitude of ϕ_{η} must be sufficiently large to prevent ambipolar diffusion in the region of $\bar{s}_{max}$, which occurs in the neighborhood of $\eta = 0$. Consequently, $\phi_{\eta} < 0$ over the entire boundary layer. Further reductions of $\bar{s}_{max}$ require increased $|\phi_{\eta} < 0|$. The $|\phi_{\eta}(1)|$ is chosen sufficiently large to accomplish the required reduction of $\bar{n}_{max}$, but will be limited by the electric power that can be applied at the vehicle surface.

Finally, in the evaluation of ϕ , assume

$$\phi = 0 \text{ at } \eta = 1. \quad (18)$$

A means is described for the control of the electron density produced by aerodynamic heating of clean air in the turbulent boundary layer of a non-equilibrium ionized flow about sharply pointed hypersonic vehicles. The control is accomplished by the application of an electric field acting through the plasma surrounding the vehicle. One way of providing this electric field is by applying an electric potential at the surface of the vehicle. Significant reductions of maximum electron density can be obtained at the site and for some distance downstream of the site of the applied electric field. This indicates that significant reductions of electron density are possible over non-metallic surfaces (where an electric potential cannot be applied) located downstream of an electrically biased metallic surface. This fact is highly significant in view of the signal (e.g., optical) sensitivity of electromagnetic windows to electromagnetic radiation - plasma interference.

Steady state non-equilibrium ionization occurs within the time required for a vehicle to travel approximately 2 vehicle lengths. The time required for precision line-of-sight accuracy is usually very small. Consequently, only a small energy may be required to be applied at the vehicle surface to reduce the maximum electron density over electromagnetic windows to values which nullify the electromagnetic radiation - plasma interference. It should be understood that the invention is not limited to the exact details of construction shown and described herein, for obvious modifications will occur to persons skilled in the art.

LIST OF SYMBOLS

- 55 c_j mass fraction of component j
- D binary diffusion coefficient, cm^2/sec
- D_T turbulent eddy diffusion coefficient, cm^2/sec
- 60 e electron charge = $1.60(10^{-19})$ coulomb = $4.80(10^{-10})$ esu
- h enthalpy per unit mass of mixture
- H total enthalpy per unit mass of mixture = $h + V^2$
- J_y y component of ion current density, Amp/cm^2
- K electric field mobility coefficient, $\text{cm}^2/\text{V-sec}$
- 65 K_f rate constant for ion-electron formation, $\text{cm}^3/\text{ion-sec}$
- K_r rate constant for ion-electron recombination, $\text{cm}^3/\text{ion-sec}$

m velocity profile power law coefficient = 8
 M mass, g
 n ion or electron number density cm^{-3}
 $\langle N \rangle$ nitrogen number density, atom/cm^3
 $\langle O \rangle$ oxygen number density, atom/cm^3
 p pressure kg/m^2 or atmosphere
 P density ratio = ρ_e/ρ
 r radial distance of vehicle surface from axis of symmetry, cm
 R gas constant for air = $1.987 \text{ cal}/\text{mole}^\circ\text{K}$
 s mass fraction for ions or electrons = c/c_e
 t time, sec
 T absolute temperature, $^\circ\text{K}$
 u x component of neutral gas mixture velocity, cm/sec
 v y component of neutral gas mixture velocity, cm/sec
 V speed of neutral gas mixture velocity = $\sqrt{u^2 + v^2}$, cm/sec
 W mass rate of formation of ions or electrons, $\text{g}/\text{sec}\cdot\text{cm}^3$
 x distance along meridian profile, cm
 y distance normal to the surface, cm
 Z compressibility factor = $p/\rho RT$ ($Z = 1$ at STP)
 δ boundary layer thickness, cm
 η dimensionless boundary layer thickness = y/δ
 k Boltzmann constant = $1.38 (10^{-23}) \text{ joule}/^\circ\text{K}$
 ρ mass density, kg/m^3
 ϕ electric potential, V

SUBSCRIPTS

b vehicle surface
 D y component of total ion or electron velocity, cm/sec
 e recovery temperature condition ($\eta \leq 10^{-4}$)
 x partial differentiation along meridian profile
 y partial differentiation along surface normal
 δ edge of boundary layer
 η partial differentiation along dimensionless surface normal

SUPERSCRIPTS

— electron
 + ion
 I claim:

1. Means for reducing the electron density and altering the electron distribution in the plasma enveloping a vehicle in hypersonic flight to enable communications to and from said vehicle comprising means for impressing an electric field across said plasma to cause a predetermined current to pass from one location of the plasma to said vehicle and back into said plasma at an-

other location, said applied electric field and power requirements being determined by the procedure:

$$J_\eta = \frac{\delta n_e u s_x}{P} - \frac{W e \delta n_e}{\rho_e c_e} - c n_e s (v/P)_\eta$$

$$\pm s = \frac{1}{D_T + D} \left[\frac{\pm J P \delta}{c n_e} + s v \delta \pm K s \phi_\eta \right]$$

$$\phi_\eta = -\frac{10^{14}}{8.85} \left[\frac{e n_e \delta^2}{P} \left(\frac{\pm}{s} - \frac{-}{s} \right) \right]$$

10 and

where J_η is the partial derivative of the component of the current normal to the surface with respect to the distance normal to the surface; where Q_η is the second partial derivative of the electric potential with respect to the distance normal to the surface; and where $\pm$ is the mass fraction for ions (+) or electrons (-).

2. Means for reducing the electron density in plasma as set forth in claim 1 wherein said means for impressing said voltage comprises a switch means and an electric field generating device, said electric field generating device having a first terminal thereof connected to a conductive portion of the vehicle interface in the enveloping air and a second terminal connected through said switching means into a second location in the plasma, such as the wake of said vehicle.

3. Means for reducing the electron density in plasma as set forth in claim 2 wherein said vehicle has an electrically insulated window disposed rearwardly of said conductive portion of said vehicle interface to provide a communication channel through said window.

4. Means for altering the electron distribution in plasma as set forth in claim 2 wherein said vehicle has an electro-magnetic window disposed rearwardly of said conductive portion of said vehicle interface to provide a communication channel through said electro-magnetic window.

5. Means for reducing the electron density in plasma as set forth in claim 3 wherein said electric field is programmed and applied as a function of time and position along said vehicle in accordance with the required communication to or from said vehicle.

6. Means for altering the electron distribution in plasma as set forth in claim 4 wherein said electric field is programmed and applied as a function of time and position along the vehicle in accordance with the required communication to or from said vehicle.

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