Sept. 30, 1969 W. F. HASSEL 3,469,401

MAGNETIC COLLOID PROPULSOR

Filed Nov. 8, 1967

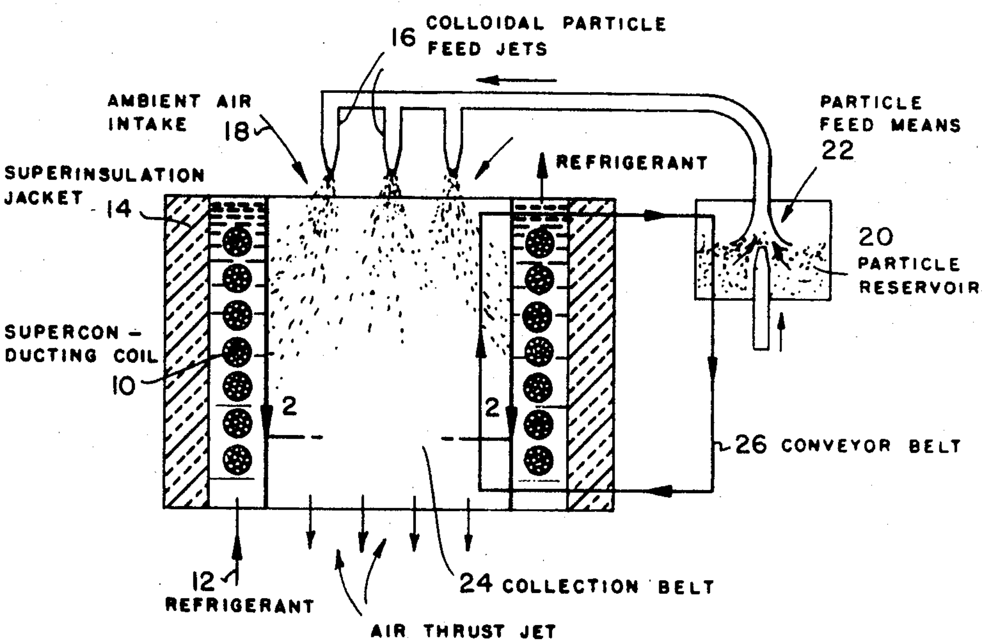

FIG. 1.

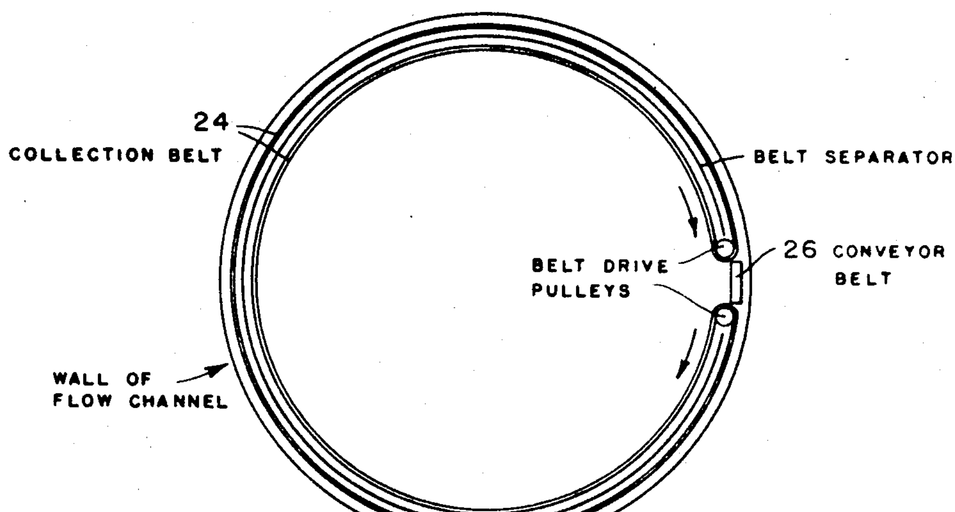

FIG. 2.

INVENTOR.
WILLIAM F. HASSEL
BY
V. C. MULLER
ROY MILLER
ATTORNEYS.

United States Patent Office

3,469,401
Patented Sept. 30, 1969

1

3,469,401

MAGNETIC COLLOID PROPULSOR

William F. Hassel, Woodland Hills, Calif., assignor, by mesne assignments, to the United States of America as represented by the Secretary of the Navy

Filed Nov. 8, 1967, Ser. No. 681,468
Int. Cl. F03h *5/00;* F04b *19/00*
U.S. Cl. 60—204 2 Claims

ABSTRACT OF THE DISCLOSURE

Method of producing an air thrust jet by introducing ferromagnetic particles into one end of the hollow core of an electromagnet, which accelerates the particles through the core, producing drag on induced ambient air, accelerating it through the core, and recovering the particles for recirculation, whereby only air is discharged from the other end of the core.

The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

In prior methods of providing vertical takeoff or hovering flight it has been the practice to utilize rotating impellers, as in helicopters and ducted fan aircraft, or high thrust turbojet or rocket engines. These methods of producing thrust are inherently noisy, making them undesirable for applications where noise is a disadvantage.

One of the objects of the present invention is to provide a method to accelerate ambient air to produce a thrust jet, without the use of mechanical impellers and the like.

Other objects are to obviate noise inherent to thrust jets produced by mechanical impellers and the like, together with their complicated mechanisms.

Still further objects, advantages and salient features will become apparent from the description to follow, the appended claims, and the accompanying drawing, in which:

FIG. 1 illustrates apparatus for performing the method, and

FIG. 2 is a section taken on line 2—2, FIG. 1.

Referring now to the drawing, superconducting coil **10**, composed of multi-strand super conducting wire, such as niobium-tin, is maintained at a temperature approaching absolute zero by a refrigerant **12**, such as liquid helium, and is energized by a suitable source of current (not shown). Superinsulation jacket **14** serves to minimize the refrigeration load. As is well known, when a superconducting coil is maintained near its transition temperature its resistance approaches zero and high currents may be conducted with small loss of energy. The coil thus produces a high magnetic field within its core, which is preferably a steady state field. Patent 3,267,306 to William F. Hassel and Hugh Powell Jenkins, Jr. discloses a coil and refrigeration system for producing a similar magnetic field.

Particle feed jets **16** are disposed adjacent ambient air intake **18**, which are supplied from a particle reservoir **20** by particle feed means **22**. The particles are iron powder of extremely small dimensions, such as several microns in diameter. Spherical carbonyl iron powder, which is available from Antara Chemicals, may be employed.

In the operation, as so far described, the iron particles are fed as a colloidal suspension to the magnetic field of the coil and are accelerated into the field, producing drag on the ambient air and inducing a flow of air into the intake and through the core.

To conserve the supply of iron particles they are recovered within the core so that only air is exhausted to

2

form the thrust jet. Illustrative of a method of recovery is a moving endless belt **24** surrounding the core on which the particles are collected, these being continuously delivered to a conveyor belt **26** which returns them to the reservoir. An alternative method of recovering the particles comprises heating them by an inductive heating process (not illustrated) to a temperature above the Curie point where they become nonmagnetic and then recovering the nonmagnetic particles. In such a process, the particle composition would preferably be one having a low Curie temperature.

The theory of operation is as follows. First, assume the ideal case of a conducting particle is one able to penetrate the surface of such a particle. Consequently, the particle can be considered diamagnetic. If a diamagnetic particle is subjected to a magnetic field, surface currents will be induced in the particle which will exactly cancel the magnetic field which would otherwise occupy the interior volume. In order to examine the interaction between a diamagnetic sphere and a magnetic field the following assumptions are made:

(1) the sphere is prefectly diamagnetic;

(2) the size of the sphere is sufficiently small in relation to some characteristic dimensoin of the magnetic field that the field can be considered uniform over the dimensions of the sphere.

A uniform magnetic field in the z direction can be achieved within a spherical volume of radius a by means of a surface current density for which the axial component J_z remains constant over the dimensions of the sphere.

The dipole moment M associated with such a current distribution is obtained directly from the definition of magnetic dipole moment-current I times area enclosed. Considering the origin of coordinates to be at the center of the sphere, the total dipole moment of the sphere becomes (in MKS units)

$$M=\int_{-a}^{a}\pi(a^2-z^2)dI$$
$$=\pi J_z\int_{-a}^{a}(a^2-z^2)dz \qquad (1)$$
$$M=\frac{4}{3}\pi a^3 J_z$$

The magnetic field B on the axis of a circular loop of radius d carrying current I is given by

$$B=\frac{\mu_0 I a^2}{2(a^2+z^2)^{3/2}} \qquad (2)$$

Therefore the field in the center of the sphere due to an infinitesimal current ring of radius $(a^2-z^2)^{1/2}$ located a distance z from the center is

$$dB=-\frac{\mu_0 dI(a^2-z^2)}{2a^3}$$

Integration over the surface of the sphere gives for the field at the center resulting from the contributions of all current rings

$$B=-\frac{2}{3}\mu_0 J_z \qquad (3)$$

Since the current distribution has been chosen to provide a uniform field throughout the sphere, that field is given by Equation 3. Substituting J_z from Equation 3 into Equation 1 gives the desired expression for the magnetic dipole moment of the sphere.

$$\overline{M}=-\frac{2\pi a^3}{\mu_0}\overline{B} \qquad (4)$$

The force on a dipole of moment M due to the presence of a field B is [2]

$$\bar{F}=\nabla(\bar{M}\cdot\bar{B})$$
$$=\bar{M}\times(\nabla\times\bar{B})+(\bar{M}\cdot\nabla)\bar{B}+\bar{B}\times(\nabla\times\bar{M})+(\bar{B}\cdot\nabla)\bar{M} \quad (5)$$

For current free space in the absence of charge accumulation the appropriate Maxwell equation is

$$\nabla\times\bar{B}=O \quad (6)$$

Therefore Equation 5 is reduced to

$$\bar{F}=(\bar{M}\cdot\nabla)\bar{B}+(\bar{B}\cdot\nabla)\bar{M} \quad (7)$$

The substitution of $\bar{M}$ from Equation 4 into Equation 7 gives

$$\bar{F}=-\frac{4\pi a^3}{\mu_0}(\bar{B}\cdot\nabla)\bar{B} \quad (8)$$

which is the force on a perfectly conducting sphere of radius a placed in a magnetic field $\bar{B}$. The instantaneous acceleration for a sphere of density ρ_p becomes

$$\bar{a}_i=-\frac{3}{\mu_0\rho_p}(\bar{B}\cdot\nabla)\bar{B} \quad (9)$$

If the spherical particle were composed of a non-conducting ferromagnetic material, the acceleration would again depend upon the interaction of an induced magnetic moment with the applied field, as presented by Equation 7. In this instance the magnetic moment is a result of the magnetization of the particle.

The magnetic polarization $\bar{P}$ of a sphere having permeability μ is

$$\bar{P}=3\frac{\mu-\mu_0}{\mu+2\mu_0}\bar{H} \quad (10)$$

for a constant applied magnetic intensity $\bar{H}$. $\bar{H}$ is considered to be spacially invariant over the dimensions of the sphere. The magnetic moment of a particle of radius a and permeability μ is

$$\bar{M}=\bar{P}\cdot\frac{4}{3}\pi a^3$$
$$=4\pi a^3\frac{\mu-\mu_0}{\mu+2\mu_0}\bar{H} \quad (11)$$

But since $\bar{H}=\bar{B}/\mu_0$ in free space, $\bar{M}$ becomes

$$\bar{M}=\frac{4\pi a^3}{\mu_0}\frac{\mu-\mu_0}{\mu+2\mu_0}\bar{B} \quad (12)$$

where $\bar{B}$ is the applied magnetic field. Substituting for $\bar{M}$ in Equation 7 results in the expression

$$\bar{F}=\frac{8\pi a^3}{\mu_0}\frac{\mu-\mu_0}{\mu+2\mu_0}(\bar{B}\cdot\nabla)\bar{B} \quad (13)$$

The instantaneous acceleration achieved by the particle is therefore

$$\bar{a}_i=\frac{6}{\mu_0\rho_p}\frac{\mu-\mu_0}{\mu+2\mu_0}(\bar{B}\cdot\nabla)\bar{B} \quad (14)$$

As a ferromagnetic sphere composed of pure iron has an electrical conductivity which would permit eddy currents to be generated, the application of a high frequency magnetic field would cause the sphere to be subject to both of the opposing forces. A comparison of Equations 9 and 14 shows the ferromagnetic force to be predominant for spheres possessing moderate permeabilities.

The velocity of a particle of radius a as a function of time, when subjected to a known acceleration profile, will depend upon the drag characteristics of that particle. Consider the situation in which the Reynolds member is less than one, which requires that the velocities of a majority of the particles in an accelerating suspension are low, and the particles are small. In this case Stokes equation, given below, has been found to provide a reasonable approximation for the drag. Stokes equation for the drag, F_D of a particle of radius a is

$$F_D=6\pi\eta av \quad (15)$$

where η is the dynamic viscosity of the fluid and v is the velocity of the sphere.

In determining the accelerating force upon the particle in a high frequency field the diamagnetic effect, which opposes the acceleration of particles into the coil, must be considered. It appears reasonable to propose that the net acceleration of the particle is the sum of the ferromagnetic component given by Equation 14 and the diamagnetic component given by Equation 9, so that the peak acceleration becomes

$$a_0=\frac{3}{\mu_0\rho_p}\left(2\frac{\mu-\mu_0}{\mu+2\mu_0}-1\right)(\bar{B}\cdot\nabla\bar{B})_0 \quad (16)$$

The equation can be simplified to

$$a_0=\frac{3}{\mu_0\rho_p}(\bar{B}\cdot\nabla\bar{B}) \quad (17)$$

under the assumption that the iron particle is perfectly conducting and that its permeability remains high throughout the acceleration process. In reality, each of the opposing forces will be reduced somewhat from its calculated value because the particle is not ideally diamagnetic, nor does its permeability remain high when saturation magnetization is approached. Since, however, these two deviations from the ideal case tend to cancel in Equation 17, the equation is considered to offer a suitable basis for the determination of the expected velocities of the particles.

The acceleration of a ferromagnetic particle by magnetic means is independent of the size of the particle, providing drag deceleration effects are excluded. The acceleration force-time integral represents the impulse imparted to the particle by the action of the field forces. This impulse is subsequently transferred to the air through drag as the particle reaches its maximum velocity during the period of the application of the magnetic field, and then continues to decelerate after the current flow in the coil ceases. The determination of the impulse imparted to single particles can be used as a basis for the calculation of the efficiency of conversion of the drag of a colloidal suspension of particles into translational momentum of the air.

Assume that the colloid density ρ_c, defined as mass of solids per unit volume, is uniform throughout the accelerator section of the flow channel through the coil. Knowing the Q, or oscillatory figure of merit, of the circuit, its period T, and the number of half cycles k comprising the discharge, the total impulse generated throughout the channel is given by

$$I_t=\frac{Q^3}{\pi(1+4Q^2)}(e^{\pi/Q}-1)T\rho_c\sum_{n=1}^{k}e^{-(n\pi)/Q}\int_0^{z_{max.}}a_0(z)A(z)dz \quad (18)$$

where the area $A(z)$ corresponds to that area intersecting the axis at z which describes a surface of constant B within the flow channel, or a surface of constant acceleration.

The effectiveness of the interchange of momentum of unidirectional motion between the magnetically accelerated particle suspension and the air was determined. This effectiveness can be considered as the ratio of the measured impulse imparted to the ballistic pendulum by the air to the total impulse imparted magnetically to the particles during the period of application of the magnetic field. This latter impulse, given by Equation 18, was evaluated and found to be

$$I_t=80.0\times10^{-6}\rho_c \quad (19)$$

In the actual case the effectiveness of momentum transfer does not reach 100 percent because a portion of the drag on any body moving through the atmosphere consists of a viscous drag force on the internal surfaces of the flow channel which retards the flow.

For the configuration shown in the figure the field at the geometric center B_o is

$$B_o=0.86\ B_M \quad (20)$$

where B_M is the maximum field which exists at the inner surface of the coil. For the superconducting cable under consideration, B_M is made equal to 11.0 wb./sq. m. For a coil diameter D, a number of turns N and a current I the central field is given by

$$B_0=\frac{\mu_0 NI}{D} \quad (21)$$

Substitution of the appropriate values of field and current for the cable results in the following expression for the number of turns:

$$N=4.26\times 10^4 D \quad (22)$$

The total weight of the superconductor W_{sc} in a given coil then becomes

$$W_{sc}=245.0D^2 \quad (23)$$

The magnetic pressure produced by a field of 11.0 wb./sq. m. is 4.9×10^6 kg./sq. m.

The thrust output of the coil of the accelerator is obtained as follows

$$F=\rho_c\left(\frac{\pi}{4}D_c^2\right)\int^{\infty}{}_0 a_0(z)dz \quad (24)$$

Integration and modification for the arbitrary diameter gives

$$\int^{\infty}{}_0 a_0(z)dz=\frac{2.733\cdot 10^4}{D} \quad (25)$$

Previous analysis has shown that the velocity of the particles v_p relative to the air stream is only of the order of meters per second. Therefore the absolute particle velocity can be assumed to be equal to the flow velocity of the air in the channel v_2 with little error for thrust levels of interest. As the colloid density in a flowing system is not readily determinable, ρ_c can be replaced by

$$\rho_c=\frac{\dot{m}_p}{\left(\frac{\pi}{4}D_c^2\right)v_p}=\frac{\dot{m}_p}{\left(\frac{\pi}{4}D_c^2\right)v_a} \quad (26)$$

where $\dot{m}_p$ is the mass flow rate of particles through the accelerator. For a system at rest the thrust attributable to momentum of the *e* exhaust is

$$F=\rho_a\left(\frac{\pi}{4}D_c^2\right)v_a^2 \quad (27)$$

By substituting ρ_c from Equation 26 into Equation 24, and then solving for v_a in Equation 27 and substituting into Equation 24, the resulting solution for F becomes

$$F=896\left(\dot{m}_p\frac{D_c}{D}\right)^{2/3}\text{ (newtons)} \quad (28)$$

$$=91.4\left(\dot{m}_p\frac{D_c}{D}\right)^{2/3}\text{ (kg.)} \quad (29)$$

The same energy must be expended in removing the iron particles from the region of high field as was provided to the particles and air upon entering the field. If the particles are removed at the rate that they enter the accelerator coils, the power required to accomplish their removal by means of a conveyor device is

$$P_c=\frac{27.33\cdot 10^3\dot{m}_p}{D} \quad (30)$$

The weight of the power system is a function of its assumed specific power γ, defined as

$$\gamma=\frac{\text{Power Output (kw.)}}{\text{Power System Weight (kg.)}} \quad (31)$$

γ is assumed to range from 1.0 to 8.0, which is one to two orders of magnitude greater than is anticipated in nuclear space power systems. For a propulsor intended to operate in the lower atmosphere a chemically fueled power plant would be satisfactory. Present gas turbine technology would permit the development of turbine engines having a γ greater than 5.0.

Therefore, the electric power system weight is

$$W_e=\frac{P_c\text{(kw.)}}{\gamma} \quad (32)$$

Optimization of the propulsor consists of determining the power input which will provide the maximum thrust to weight ratio for a given coil size. This is accomplished as follows:

The total weight of the propulsor is

$$W_t=W_{st}+P_c\text{(kw.)}/\gamma \quad (33)$$

where W_{st} is the structural weight, including the coils and refrigerator. $\dot{m}_p$ from Equation 30 can be substituted into Equation 29 to give

$$F=10.06(P_cD_c)^{2/3}(P_c\text{ in kw.}) \quad (34)$$

The ratio of weight to thrust becomes

$$\frac{W_t}{F}=\frac{W_{st}+P_c/\gamma}{10.06(P_cD_c)^{2/3}}\ (P_c\text{ in kw.}) \quad (35)$$

Differentiation of W_t/F with respect to P_c gives a minimum at

$$P_c=2\gamma W_{st}\text{ (kw.)} \quad (36)$$

The power system weight should therefore be twice the remaining weight of the propulsor.

Converting Equation 36 to watts and equating it to Equation 30 results in

$$\dot{m}_p=0.0732\gamma W_{st}D \quad (37)$$

The ratio of thrust to mass flow rate is readily obtained from the use of Equations 34, 36, and 37 and is seen to be

$$\frac{F}{\dot{m}}=218\left(\frac{D_c^2}{\gamma W_{st}D^3}\right)^{1/3}\left(\frac{\text{kgf}}{\text{kgm/sec}}\right) \quad (38)$$

The most important parameter, of course, is the thrust to weight ratio. Eliminating P_c between Equations 35 and 36 results in the following expression for the ratio.

$$\frac{F}{W_t}=5.32\left(\frac{\gamma^2 D_c^2}{W_{st}}\right)^{1/3} \quad (39)$$

What is claimed is:

1. The method of producing an air thrust jet comprising the steps of:

(a) supplying electric current to an annular coil of an electromagnet composed of super conducting material maintained substantially at its transition temperature,

(b) delivering a colloidal suspension of ferromagnetic particles to one end of the coil for acceleration thereinto, the particles producing drag on ambient air and accelerating same through the coil,

(c) separating the particles from the accelerated air prior to its discharge from the other end of the coil, producing thrust by the discharged air, and

(d) collecting the separated particles and recirculating same for redelivery as a colloidal suspension to said one end of the coil.

2. A method in accordance with claim 1, wherein the particles are separated from the accelerated air by attrac-

tion to the inner wall of the annular coil and continuously removed therefrom for recirculation.

References Cited

UNITED STATES PATENTS

3,071,705	1/1963	Coleman et al.	230—69 XR
3,210,915	10/1965	Kraus	230—69 XR
3,267,306	8/1966	Hassel et al.	307—149
3,399,534	9/1968	Hunter et al.	60—203

CARLTON R. CROYLE, Primary Examiner

U.S. Cl. X.R.

103—1; 230—69