Levitation by Electromagnetic Ion Confinement

Risto-Antti Paju, Queens' College

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Except where specific reference is made to the work of others, this work is original and has not been already submitted either wholly or in part to satisfy any degree requirement at this or any other University.

Risto A Paju

Abstract

While almost ignored in the mainstream scientific research, there remains an interest in a kind of magnetic levitation technology that could replace conventional hovercraft. This would have a number of advantages over current technologies, mostly arising from the lack of moving parts.

Contrary to the current “maglev” technologies, a hovercraft must be able to operate on top of different kinds of surface. Therefore the methods involve the manipulation of air molecules, possibly in ionized form, to generate lift forces.

Loosely based on a document by the HoverTech company, I have examined three different propositions for this type of levitation. The aim is to use simple physical principles, to analyze the practical viability of each. For the application I have assumed a single-person vehicle about 0.5 m across, which needs a lift force of the order 10^3 N.

Two of the methods have been found potentially useful. Both of them have certain practical problems, and it will be a case of further simulation and/or experimentation to clarify these remaining issues.

The first method exploits the paramagnetic nature of oxygen molecules. The gas of O_2 could be contained by a static magnetic dipole field $\mathbf{B}$ at a low temperature T, provided that $B/T \gg 1\ \mathrm{T/K}$. This principle is likely to fail in normal atmospheric conditions, but should work in near-vacuum, as on the surface of Moon. As an advantage the power consumption would be fairly low.

The second method is analogous to the “magnetic bottle” already employed in plasma physics. A single dipole field $\mathbf{B}$ would act like a “magnetic fan” propelling ionized air downwards. The conditions for levitation at room temperature are

$$\begin{aligned} B &\gg 2 \times 10^{-4}\ \mathrm{T} \\ n_{\mathrm{ion}} &> 10^{24}\ \mathrm{m}^{-3} \end{aligned}$$

where n_{ion} is the ion density (cf. the molecular density of air, $n_{\mathrm{air}} = 2.4 \times 10^{25}\ \mathrm{m}^{-3}$). The necessary ionization rate is an issue of further research because of the complexities involved, and it may be a major difficulty in the practical application of this method.

Of the second method I have also found that it might be more suitable to vacuum environments, given the necessary ion source. Since the advantages of EM levitation are mainly in increased durability and reliability, it could be with extraterrestrial missions that these technologies will have an edge over the mechanical ones.

Contents

1 Introduction

1.1 The concept of electromagnetic hovercraft

The topic of this paper is a technology that could replace conventional hovercraft systems and greatly extend their usability. Instead of using fan blowers to maintain air pressure under a rubber skirt, there may be another possibility: if the air is ionized, electromagnetic (EM) effects could be used to provide the necessary pressure gradient. Then one could eliminate the moving parts and the rubber flaps, resulting in the following advantages:

1. Ground clearance would be significantly increased. This would widen the range of accessible terrain, as well as increase the general agility of the vehicle.
2. The vehicle would be virtually noiseless. The ionization system, with its high-voltage generator, might produce some low-level noise, but nothing in the magnitudes of mechanical hovercraft.
3. The lack of moving parts would mean a high level of durability and reliability.
4. Possibly lower energy consumption. This is not a virtue of EM confinement *per se*, but it might be expected on the basis of overall simplicity.

There is more to hovercraft than merely levitation; propulsion is equally important in a transportation device. This may be one aspect where mechanical fans cannot be eliminated. But it may turn out that some of the ideas from levitation could be applied for propulsion as well. In fact, ionic propulsion of spacecraft has undergone serious development, albeit designed for near-vacuum environment.

The general idea of transportation using some form of EM levitation is not a recent one. Pioneers of electromagnetism such as Nikola Tesla are known to have worked on EM levitation technologies [1]. Therefore it is interesting to note that EM levitation is now more likely to appear in the realm of science fiction, rather than serious scientific publications. There could be a number of reasons why research on the topic has faded, and some of these may become apparent throughout this project.

At the moment there is at least one commercial venture dedicated to the development of EM levitation, namely HoverTech based in Florida, USA. In the spirit of open research, they have published the booklet “Hoverboard design notes” [2], enabling anyone to participate in the development. The document describes a number of different methods for achieving EM levitation. Some of those methods are chosen as the starting points of this project.

1.2 Research goals

The intent of this paper is a critical analysis of several distinct methods of EM levitation, as loosely described in the HoverTech document [2]. The goal is to determine the physical feasibility of each method.

The analysis will follow an order-of-magnitude principle instead of exact calculations. There are several reasons for this choice:

1. Any given method has a vast number of variations in the details. We cannot predict how the details of future designs would evolve, so it is better to keep the analysis fairly open.

2. The systems under study are immensely complex, spanning several branches of physics. However, as pointed out above, we are not interested in the detailed operation of any system. It appears likely that simple physical principles (e.g. conservation laws) can be used to weed out the obviously impossible methods as early as possible. Further consideration will be reserved for the more promising ones.

From the above points it should be apparent that this analysis will not provide any definite answers. The utility is rather in providing useful guidelines for future research on the topic. By eliminating the *physically infeasible* systems, future engineers may have a better focus on the more fruitful technologies.

Of the methods in the booklet, three have been chosen for this analysis. The ones that were discarded fall into two categories: one of these are systems too complicated for the kind of analysis used here. The other kind is based on unipolar ionization, i.e. the gas and/or the vehicle would have net electric charges of high magnitude; the lift would arise from pure Coulomb forces. This was considered impractical on several grounds, notably the dangers of electric shock.

1.3 Practical requirements

The kind of vehicle that might use EM levitation is chosen to be a single-person system, perhaps not unlike the Segway Human Transporter [3]. The reason for this choice is a matter of scale; for a spatial dimension D, the lift generated from air pressure scales as D^2 but the total mass as D^3. Therefore a smaller value of D is regarded as an easier option.

Such a vehicle would require a lift force of order 1000 Newton. Its size would probably be around 0.5 m across. Hence we shall use the following order-of-magnitude figures in the subsequent analysis:

- Lift force $F_{\text{lift}} = 10^3$ N.
- Spatial dimension $D = 0.5\ \text{m}$ (diameter of system).

Naturally, a system with any smaller D will fit in the vehicle. However, it is expected that D should be as large as possible: for instance, it will allow lower pressure gradients. In some cases we may use the pressure requirement as $\Delta P = F_{\text{lift}}/D^2$.

2 Analysis and results

2.1 General notes

In the analysis that follows, we shall approximate the magnetic field as an ideal dipole field. The magnet shall be placed at the bottom of the vehicle with its symmetry axis vertical. Naturally, the field of any real magnet will be noticeably different, especially near the origin. However, this should be a reasonable guideline on the strength and variation of the field, particularly with regard to the r^{-3} dependence.

Using spherical polar coordinates, the dipole field has the vector potential

$$A_\phi = \frac{\mu_0 \mu}{4\pi} \frac{\sin\theta}{r^2}$$

where μ is the magnetic moment of the dipole, and the associated magnetic flux density has the components

$$\begin{aligned} B_\theta &= \frac{\mu_0 \mu}{4\pi} \frac{\sin\theta}{r^3} \\ B_r &= \frac{\mu_0 \mu}{2\pi} \frac{\cos\theta}{r^3}. \end{aligned}$$

In addition to the practical limitations D and F_{lift} defined above (section 1.3), we shall use the following constants throughout the analysis:

- Mean molecular mass of air $m = 29\ \mathrm{m_u} = 4.8 \times 10^{-26}\ \mathrm{kg}$
- Number density of molecules in air $n_{\mathrm{air}} = 2.4 \times 10^{25}\ \mathrm{m}^{-3}$
- Ambient temperature $T = 300$ K, unless otherwise defined
- We assume that the ions are singly charged with the magnitude $e = 1.6 \times 10^{-19}$ C

2.2 Paramagnetic levitation

The fact that the molecules of certain gases possess a magnetic dipole moment, has given rise to this simple proposition [2]. A sufficiently strong static magnetic field could, in principle, form a potential well for concentrating the molecules of these gases. In the atmosphere the obvious candidate is oxygen O_2 with its abundance of circa 21% and the magnetic moment $\mu \approx 2\mu_B$, where $\mu_B = e\hbar/2m_e$ is the Bohr magneton.

The dipole in the magnetic field experiences a torque $\mu \times \mathbf{B}$ tending to align the dipoles parallel to the magnetic field. In addition there is the force $\mu \cdot \nabla\mathbf{B}$, which can concentrate the molecules towards the stronger $\mathbf{B}$ field once they are sufficiently aligned. These are compactly described by the potential $-\mu \cdot \mathbf{B}$.

Because of the microscopic origin of the potential, thermal fluctuations may play an important role. Specifically, the thermal kinetic energy of colliding molecules may flip the dipoles away from their energy minima. In other words, containment can only be achieved if the depth of the potential well significantly exceeds the typical thermal energy:

$$\begin{aligned} 2\mu_B B &\gg \frac{3}{2} k_B T \\ \Rightarrow B/T &\gg \frac{3k_B}{4\mu_B} \approx 1\mathrm{T/K} \end{aligned}$$

This is a demanding condition from a practical point of view. Even with the current state-of-the-art superconducting magnets grazing the 10 Tesla mark, the molecules would have to be cooled to liquid-helium temperatures.

However, the above does not strictly mean that a vehicle utilizing this principle could only operate in cryogenic environments. Possibly the vehicle could be “charged up” with suitably cooled oxygen gas, which would be contained within the loose bounds of the magnetic field [2]. In the terrestrial atmosphere, however, the surrounding air would not be restricted by the $\mathbf{B}$ field, and would soon bring the load of oxygen into thermal equilibrium with itself.

On the other hand, that problem would not exist in near-vacuum conditions which could arise, for instance, on the surface of Moon. The criterion $B/T \gg 1\mathrm{T/K}$ would nevertheless impose severe limitations on the practicality of this method.

There is a further problem arising from the low temperature requirement. Because the method relies on concentrating the gas, rather than propelling it in one direction (the usual hovercraft approach), the lift force can only be generated from the bulk pressure in the gas. In a temperature of only few Kelvin, the ideal gas approximation $P = nk_B T$ tells that the number density n must be fairly high, namely

$$\begin{aligned} n &= \frac{\Delta P}{k_B T} = \frac{F_{\mathrm{lift}}}{D^2 k_B T} \\ &= 2.9 \times 10^{26}\ \mathrm{m}^{-3} \approx 10 n_{\mathrm{air}} \end{aligned}$$

where we used $T = 1$ K and assume that no atmosphere is present. However, if we consider lunar vehicles, the required lift force would only be $1/6$ of its terrestrial value, bringing the density down by the same factor.

Nevertheless for simple Earthbound vehicles, we must conclude the method of paramagnetic levitation to be quite impractical. The mere possibility of having strong magnetic fields, with air molecules speeding at hundreds of metres per second, one may recall the Lorentz force and the possibilities it could open if the molecules were charged.

2.3 Magnetic ion containment

The concept of a magnetic bottle is a familiar one in modern physics, most notably in the context of nuclear fusion experiments. The pressures required for the hoverboard would be close to the atmospheric, orders of magnitude below those already achieved experimentally. In this view, the magnetic bottle would seem like a very plausible candidate for the method of levitation.

Even if the magnetic field is simplified to the dipole approximation, it is a complex task to evaluate its effect on the ion trajectories. To simplify this, there is a convenient approximative method described by Chen[4] which I will briefly outline below:

In a uniform magnetic field $\mathbf{B}$, the ions would follow helical paths around the field lines. In the plane perpendicular to $\mathbf{B}$, the trajectories are circles with the radii $r = mv_\perp/eB$, where $v_\perp$ is the velocity component in that plane. Here the key assumption is that, if $\mathbf{B}$ is sufficiently strong, r will be small enough that the ion will remain in a rather constant $\mathbf{B}$ over several gyrations. As a consequence, each ion will act as a simple magnetic dipole, directed antiparallel to $\mathbf{B}$. The force on each ion is then given by the previously used formula, $\mathbf{F} = \mu \cdot \nabla\mathbf{B}$.

The corresponding dipole moment of the ion is computed using the angular frequency $\omega = v_\perp/r$:

$$\begin{aligned}
\mu &= IA = \left(e\frac{\omega}{2\pi}\right)\pi r^2 \\
\text{where } \omega r^2 &= rv_\perp = \left(\frac{mv_\perp}{eB}\right)v_\perp \\
\Rightarrow \mu &= \frac{mv_\perp^2}{2B}
\end{aligned}$$

The above equation for the force on a dipole can now be applied. If we make some further approximations, concerning the direction of change of $\mathbf{B}$, we may conclude that

$$\begin{aligned}
F &= |\mu \cdot \nabla\mathbf{B}| \\
&= -\frac{mv_\perp^2}{2B}\frac{\partial B}{\partial s}
\end{aligned}$$

where s is a direction coordinate away from the origin. For our purposes it is a reasonable approximation to equate s with the r coordinate, away from the vehicle.

The r^{-3} dependence of B on distance gives the result

$$\frac{1}{B}\frac{\partial B}{\partial r} = -\frac{3}{r}$$

and, moreover, we can identify $mv_\perp^2$ as $k_B T$ on the average, since $v_\perp$ is effectively a two-dimensional velocity. As a result, the force is of the order

$$F \approx \frac{3k_B T}{r}$$

per ion. From our derivation using dipoles, it is not very surprising that this is independent of the actual B-field strength. Of course there is a minimum B required for the dipole approximation to hold; for our overall system dimensions of order D, we have

$$\begin{aligned} r &= \frac{mv_\perp}{eB} \ll D \\ \Rightarrow B &\gg \frac{\sqrt{2mk_BT}}{eD} \end{aligned}$$

where the RHS is about 2×10^{-4} T for air at 300 K. Such fields are easily achievable without special equipment or cooling.

Continuing with the crude approximations, we now switch to the z-direction exclusively. By symmetry, the total force on the ionized gas will be in the z-direction. From the above we can roughly state, that the average force per particle is k_BT/z when reasonably close to the z-axis; this could be the area $A \approx D^2$. With the ion number density n_{ion} the total force integrates to

$$\begin{aligned} F_{\text{tot}} &= \int_{z_1}^{z_2} \frac{k_BT}{z} n_{\text{ion}} A dz \\ &= n_{\text{ion}} A k_B T \ln \frac{z_1}{z_2} \end{aligned}$$

The lower limit of integration should not be very small, because the effective area A there would be negligible. Therefore, we can estimate that the logarithm is of the order unity. We should regard it as a geometric factor, whose true value can only be found via more accurate calculations.

Alternatively, and perhaps more appropriately, we could integrate from $z = 0$ to D and use a variable area $A(z) = O(z^2)$. This would have the same effective result: the force is of the order $n_{\text{ion}} D^2 k_B T$. From here it is simple to derive the ion density required to create a sufficient lift of order $F_{\text{lift}} = 10^3$ N.

$$\begin{aligned} F_{\text{lift}} &= n_{\text{ion}} D^2 k_B T \\ \Rightarrow n_{\text{ion}} &= \frac{F_{\text{lift}}}{D^2 k_B T} \approx 10^{24}\ \text{m}^{-3} \end{aligned}$$

This is a significant fraction of n_{air}, about 4%, but probably not an impossibly high level of ionization.

It should be recalled that the force on the particles is magnetic, and cannot alter their kinetic energy. Acceleration parallel to $\mathbf{B}$, i.e. changing $v_{||}$, takes place at the expense of $v_\perp$. Chen [4] has derived some interesting results from this – for example that the dipole moment μ is a constant of motion for a given particle.

The situation is further complicated, since the collisions between molecules (whether ionized or not) tend to randomize the motion to some extent. This does not alter the general expression of force on the ions, which only depends on the instantaneous $v_\perp$.

On the other hand, if most of the air is in ionized form, the randomization effect is less significant.

For our purposes it is useful to note the average velocity parallel to $\mathbf{B}$. From the previous usage of $v_\perp$ we have

$$\begin{aligned} v_\perp^2 + v_{||}^2 &= v^2 = \frac{3k_BT}{m} \\ v_{||}^2 &= \frac{k_BT}{m}. \end{aligned}$$

Most particles are "brought to rest" (i.e. $\left|v_{||}\right| \to 0$) by the magnetic force, and their motion is reflected backwards. The system acts as a magnetic mirror. Particles already traveling away from origin, are similarly affected by the force. We can estimate an average drift velocity by which particles travel away from origin as follows:

$$\begin{aligned} F &= \frac{k_BT}{z} = m\ddot{z} \\ \Rightarrow k_BT\frac{\dot{z}}{z} &= m\ddot{z}\dot{z} = \frac{m}{2}\frac{\partial\left(\dot{z}^2\right)}{\partial t} \\ \int \Rightarrow k_BT\ln\frac{z_2}{z_1} &= \frac{m}{2}\Delta\left(\dot{z}^2\right) \ \text{(where } \dot{z} \approx v_{||}\text{)} \end{aligned}$$

As we previously argued, the logarithmic factor is (mostly) of the order unity across the system. Therefore the drift velocity is of the order

$$v_{\text{drift}} \approx \sqrt{\frac{k_BT}{m}}.$$

Now we can estimate the required rate of ion production. The average ion will be driven away in the time $\tau = D/v_{\text{drift}}$. There are of the order $N = n_{\text{ion}}D^3$ ions in the system. Thus the rate of ionization required is approximately

$$\dot{N} = \frac{n_{\text{ion}}D^3}{\tau} = n_{\text{ion}}D^2\sqrt{\frac{k_BT}{m}}$$

or about $70\text{m}^3\text{s}^{-1}$ times the ion density.

However, considering the collisions which tend to randomize the motion, the average drift velocity is probably much smaller. Moreover, as the device propels the ions away from the magnet, a slight underpressure is created. This will naturally be balanced by air currents from the sides. Therefore it is expected that a certain fraction of expelled ions will return to the system, and the necessary rate of ionization is further diminished.

2.4 Oscillating fields

There is a rather well known method for creating levitative forces between an electromagnet and a conductor. It has its roots in the skin effect, which occurs in conductors subject to oscillating EM fields. Because partially ionized gases are also conductors, it might be possible to utilize this effect for our ionic hovercraft.

The skin effect comes about from currents induced in the conductor due to the changing $\mathbf{B}$ field. By Lenz's law these currents in turn generate magnetic fields that oppose the changes in the original field. Thereby the field is expelled from the conductor. The electric and magnetic fields decrease as $e^{-z/\delta}$ with the depth z from the surface; δ is the characteristic length or "skin depth", given by

$$\delta = \sqrt{\frac{2}{\sigma\mu_0\omega}}$$

where σ is the conductivity and ω is the angular frequency of the oscillating fields [5].

The magnitude of the repulsive force is indicated by the energy density U of the electromagnetic field:

$$\begin{aligned} U &= \frac{\langle B^2\rangle}{2\mu_0} + \frac{\langle E^2\rangle}{2\mu_0} \\ &= \frac{\langle B^2\rangle}{\mu_0} \end{aligned}$$

As the region beyond depth δ is essentially free from EM fields, there is effectively a pressure of magnitude U driving the conductor away from the external field. To estimate the strength of the fields, we use the expression involving $\mathbf{B}$ only. For the desired overpressure of $\Delta P = F_{\text{lift}}/D^2 \approx 4 \times 10^3$ Pa we would thus need

$$B_{\text{rms}} = \sqrt{\mu_0 \Delta P} \approx 0.1\text{T}$$

A field this strong is not uncommon to produce, but its oscillatory nature poses other hurdles to the practicality of this method. It will probably become more demanding as the frequency is increased. The minimum frequency is determined from the required skin depth: it should be smaller than the dimension D of the apparatus.

We can estimate the conductivity using a formula from solid state physics; the gas is only partially ionized so the plasma analysis would not hold. For the conductivity we have

$$\sigma = \frac{n_{\text{ion}} e^2 \tau_{\text{coll}}}{m}$$

where τ_{coll} is the average time between the subsequent collisions of one particle [6]. This can be estimated from the mean free path ℓ which for air in NTP equals about 3×10^{-7} m [7].

$$\begin{aligned} \tau_{\text{coll}} &= \frac{\ell}{\langle v\rangle} = \ell\sqrt{\frac{m}{3k_BT}} \\ \Rightarrow \sigma &= \frac{\ell n_{\text{ion}} e^2}{\sqrt{3mk_BT}} \end{aligned}$$

Then our expression for the skin depth δ becomes

$$\delta^2 = \frac{2\sqrt{3mk_BT}}{\mu_0\omega\ell n_{\text{ion}}e^2}$$

and the condition $\delta < D$ translates into

$$\omega > \frac{2\sqrt{3mk_BT}}{D^2\mu_0\ell n_{\text{ion}}e^2} \approx \frac{1}{n_{\text{ion}}} \times 2 \times 10^{28}\text{m}^{-3}\ \text{rad/s}$$

The total number density of molecules in air is $n_{\text{air}} = 2.4 \times 10^{25}$, and n_{ion} is necessarily a small fraction of this. So $\omega > 10^3$ rad/s depending on the degree of ionization.

In fact the exact details of gas-to-field interaction are not crucial. For example, if the gas is highly ionized we can treat it as plasma with freely moving charges. A plasma has the relative permittivity ϵ_r given by [5]

$$\begin{aligned}\epsilon_r &= 1 - \frac{\omega_p^2}{\omega^2} \\ \omega_p^2 &\equiv \frac{n_{\text{ion}}e^2}{m\epsilon_0}\ \text{(plasma frequency)}\end{aligned}$$

When $\omega < \omega_p$ the refractive index $\sqrt{\epsilon_r}$ is imaginary, and the EM waves will be totally reflected[1]. The radiation pressure on the plasma is therefore $2U$, the same order of magnitude as we had before for the repulsive force.

The high amplitude required for the EM field means a significant energy expenditure. Keeping with the dimension D, we can estimate this from the energy flux density Uc, giving the power requirement of the order $UcD^2 = 3 \times 10^{11}$ W which is simply too large to be practical.

3 Discussion

The method of oscillating fields (section 2.4) turns out a failure. It is interesting to note that radiation pressure does have certain practical, macroscopic uses in the form of solar sails. But the forces involved are minuscule, and it is the long-term accumulation of momentum at the minimal energy cost, that makes solar sails a realistic alternative for certain interplanetary missions. The personal vehicle using EM levitation would need an enormous intensity of radiation to achieve the desired lift.

Perhaps the most promising alternative is the confinement with static magnetic fields (section 2.3), which is a direct analogy of a "magnetic bottle" apparatus. The

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[1] With an imaginary refractive index, there will be evanescent waves in the plasma. The EM field amplitude decreases as exp $\left(-\omega\sqrt{|\epsilon_r|}z/c\right)$ with the depth z into the plasma. Therefore, for plasma sheaths of thickness around $c/\omega\sqrt{|\epsilon_r|}$ and below, a significant fraction of the radiation is tunneled through. In our simple analysis, however, we ignore this detail.

magnetic field strength is in a very practical range. In fact, to minimize the effects of external stray fields, it might have to be stronger than what the method itself requires. Even then, the field strength could be achieved without any special equipment, and pose no significant disturbance to its environment.

However, this method may have real practical problems arising from the high degree, and rate, of ionization involved. This is not a straightforward question, as there are several complex factors affecting the ion trajectories. For example, a fraction of ions will probably return to the system from the sides, thereby reducing the overall need for ionization. This problem will certainly need further analysis, in the form of either simulations or experiments.

In some sense, the most surprising of the methods turned out to be paramagnetic levitation, discussed in section 2.2. While it would require very low temperatures and strong magnetic fields (as summarized by the condition $B/T \gg 1\ \mathrm{T/K}$), it posed the new possibility of using EM levitation in near-vacuum conditions such as lunar expeditions. In those conditions the low temperature of the oxygen would be maintained, although the presently difficult B/T condition would persist.

Naturally, one could ask if extraterrestrial conditions would provide a fruitful ground for the other method as well. Ions would have to be injected into the system, as there would be no neutral molecules around to ionize. The problems arising from the random motion of neutral molecules might be diminished, although not completely eliminated as there would be a degree of recombination of the ions.

4 Conclusions

I have found two methods for electromagnetic levitation, which could potentially rival the conventional hovercraft technology. They have been analyzed in the context of a single-person vehicle requiring a lift of the order 10^3 N and measuring about 0.5 m across. Both of these methods have certain practical problems, and it will be a case of further simulation and/or experimentation to clarify these remaining issues.

The first method exploits the paramagnetic nature of oxygen molecules. The gas of O_2 could be contained by a static magnetic dipole field $\mathbf{B}$ at a low temperature T, provided that $B/T \gg 1\ \mathrm{T/K}$. This principle is likely to fail in normal atmospheric conditions, but should work in near-vacuum, as on the surface of Moon. As an advantage the power consumption would be fairly low.

The second method is analogous to the “magnetic bottle” already employed in plasma physics. A single dipole field $\mathbf{B}$ would act like a “magnetic fan” propelling ionized air downwards. The conditions for levitation at room temperature are

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where n_{ion} is the ion density (cf. the molecular density of air, $n_{\mathrm{air}} = 2.4 \times 10^{25}\ \mathrm{m}^{-3}$).

The necessary ionization rate is an issue of further research because of the complexities involved, and it may be a major difficulty in the practical application of this method.

The second method also appears to work better in near-vacuum environments. Incidentally, extraterrestrial missions demand a high level of reliability and durability, which is why EM levitation might be considered for them, instead of mechanical technologies.

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