Feasibility of Increasing Oxygen Density through the Application of Electromagnetic Fields

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Overview

The success of this project lies in the investigation of physical models and real world analysis of the results. These models trace to the principles of electricity and magnetism when applied to paramagnetic gases learned at CNU PCSE. The project will move forward through careful, focused research of the oxygen (O_2) molecule, dipole moments, magnetic forces and the sorting of oxygen molecules through magnetic field gradients. By applying this research, the feasibility of supplying combustible engines with greater oxygen content will develop.

The majority of efforts on this project were spent on the research of paramagnetic gases and their properties. Through this study, algorithms and parameters necessary to further this system's model were explored. In particular, some principles necessary include molecular orbital theory, electron spins, physical properties of oxygen, magnetic dipoles, their associated torques and forces, and magnetic field gradients. With these physics principles in hand, models developed for the further exploration of increasing oxygen density.

The Oxygen Molecule

The most prevalent oxygen configuration found in Earth's atmosphere is the O_2 molecule. The significance of this configuration lies in the valence electrons found in the molecule. Two of these electrons are unpaired and are in the degenerate orbital, allowing them to have the same spin without violating the Pauli Exclusion Principle. This sort of configuration is known as a triplet because the molecule has three different ways to align with an external magnetic field. Because the two electrons have identical spins, the oxygen molecule has a net spin of one. Moreover, a non-zero spin marks the oxygen molecule as being paramagnetic, meaning that the molecules will attempt align to an externally applied magnetic field. These paramagnetic properties of oxygen allow for magnetic fields to interact with the oxygen molecules in Earth's atmosphere while other elements (nitrogen, argon, carbon dioxide) will remain unaffected. Using this property, this project hopes to filter out or concentrate oxygen for a multitude of purposes.

Magnetic Dipole Moments

The charge density of the oxygen (O_2) molecule concentrates mostly on one side of the molecule when applied to a magnetic field. This causes a magnetic dipole moment across the molecule. The magnitude of these magnetic moments is dependent on the distance between the opposing charges and their strengths. However, when looking the large number of oxygen (O_2) molecules present in this theoretical circumstance, looking at the magnetic moment per unit of volume, or magnetization, becomes easier than considering every individual magnetic dipole moment. Magnetization results from electrical currents created by the motion of electrons within atoms or, like in this case, from the spin of surrounding electrons. The magnitude of the magnetization depends entirely on the magnetic susceptibility constant of the substance and the strength of the applied magnetic field. Positive magnetic susceptibilities indicate a paramagnetic substance while negative values indicate diamagnetic ones. For oxygen, the magnetic susceptibility constants are positive and as follows:

$$\chi = 4.3 \times 10^{8}\ per\ mole$$
$$\chi = 1.34 \times 10^{-6}\ per\ mass$$
$$\chi = 3.73 \times 10^{-7}\ per\ volume$$
$$\chi = 2.78 \times 10^{-3}\ per\ density$$

(Lide 4-142) Considering magnetization to be a measurement of magnetic moment per volume, the optimal choice would be $\boldsymbol{\chi_{volume}}$. Knowing the magnetic susceptibility allows for the approximation of the magnetization, **M**, of oxygen with an applied magnetic field of strength in the medium, **H**, through the expression:

$$M = \chi_{\text{volume}} H$$

where the field **H** relates to the magnetic field by:

$$H = \frac{B}{\mu_0(1 + \chi_{vol})}$$

This magnetization points in the direction of the magnetic field **B** and creates a vector quantity. By means of this derivation of magnetization, the net magnetic dipole moment, **μ**, of a volume, **V**, of oxygen is expressed as:

$$\mu = MV$$

This vector quantity becomes instrumental for future measurements of force and torque about the molecule, ultimately leading to the extraction of oxygen for increased oxygen density.

Torque and Forces

These magnetic dipole moments are significant because in the presence of a magnetic field they attempt with a magnetic field due to a torque about the molecule. A torque is the tendency for a force to rotate an object about an axis. (Serway and Jewett 282) The molecules will not perfectly align however due to associated angular moment and will rather precess around the axis of alignment. More importantly, thermal energy will cause motion in the oxygen gas, causing oscillations rather than simply aligning with the field.

Using the approximated net magnetic dipole moment, the potential energy, **U**, can be described as the scalar product of the net magnetic dipole moment and the strength of the magnetic field:

$$U = -\mu \cdot B$$

The force, **F**, acting on the volume of oxygen gas falls out of this equation by taking the negative gradient of the potential energy. Therefore, the force results as:

$$F = -\nabla U$$

The importance of this quantity lies in the next stage of the project– the use of high gradient magnetic fields to separate oxygen molecules from the Earth's atmosphere to increase oxygen density.

Magnetic Field Gradients

The significance of magnetic field gradients to the project comes from the equation of the force derived from the potential. Moving terms about and solving for a magnetic dipole, the force on a magnetic dipole, $\boldsymbol{\mu}$, from a magnetic field gradient, $\nabla\mathbf{B}$, results in the following expression:

$$F = (\mu \cdot \nabla)B$$

This shows the force on a magnetic dipole not only depends on the magnitude of the magnetic dipole but also the orientation of the magnetic field gradient. The magnetic dipole will gravitates toward higher magnetic fields, or the state of lowest energy as expressed by the magnetic potential on a dipole:

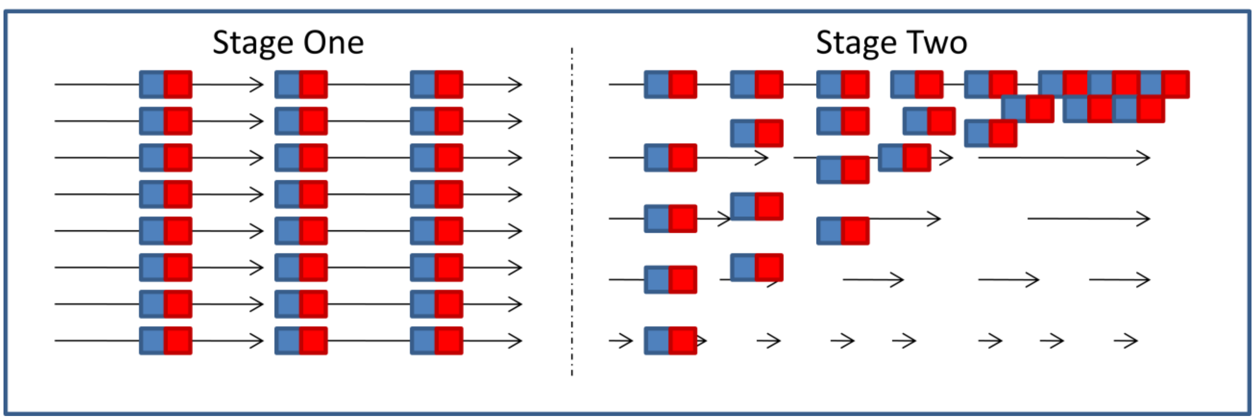
$$U = -\mu \cdot B$$

Noting the negative sign, one can see that the state of lowest energy results when the magnetic dipole and field align. Moreover, the magnitude of both the magnetic dipole moment and magnetic field affect the energy level of the magnetic dipole moment. This demonstrates the reasoning for why a magnetic dipole will pull towards the gradient of a magnetic field. With these fundamentals in place, modeling for such a system can begin.

Models and Assumptions

In order to reasonably model the complex system presented by this problem, assumptions must be made. First we assumed an ideal model divided into two stages. Stage one consists of a uniform magnetic field to align a volume of oxygen entirely in one direction. This sets up the oxygen so that when placed in a magnetic field gradient, the entirety of the oxygen molecules will deflect toward the region of highest magnetic field strength parallel to their own magnetic dipole moment. The magnetic field gradient comes about in the second stage of our model.

The second portion of the model assumes a linear magnetic field gradient in perpendicular to the direction of the net magnetic dipole moment generated by stage one. This creates a simple model where calculations can begin under an ideal situation. The figure below depicts this model as well as a list of assumptions:



List of Assumptions:

- Uniform Fields
- Linear Magnetic Field Gradient
- Room Temperature (20˚C)
- Magnetic Dipole Strength Constant Following Stage One
- Magnetic Field Gradient Only in One Dimension

The assumption that the magnetic dipole strength remains constant after stage one places importance on the time dependency of this model because the assumption that thermal forces will not affect the alignment of the magnetized air is unrealistic. However, for very short periods of time following stage one, the air should remain magnetized before chaotic thermal forces throw the system into disarray.

Calculations and Analysis

The basis for the calculations done for increasing oxygen density lie in the foundations laid by the equations for magnetic dipole potential and force mentioned in previous sections. First, one must normalize everything in terms of force and dipole moment per volume. This circumvents the pains of analyzing each individual magnetic dipole moment in the fluid. The equation for force per volume goes as:

$$\frac{F}{V} = \rho_{O_2} a$$

where **F** is the force, **V** is the volume, $\boldsymbol{\rho_{02}}$ is density of oxygen per volume of air at sea level at 20 degrees Celsius and **a** is constant acceleration of this volume created by the linear magnetic field gradient.

Next, the integration of the magnetic field gradient dependent force equation could be introduced:

$$F = (\mu \cdot \nabla) B$$

Placing the H field dependent expression for the magnetic moment then yields:

$$\frac{F}{V} = \chi_{vol} \left(\frac{B_i}{\mu_0 (1 + \chi_{vol})}\right) \cdot \nabla B_f$$

where the uniform, aligning magnetic field from stage one $\mathbf{B_i}$, magnetic susceptibility per volume $\boldsymbol{\chi_{vol}}$, magnetic constant $\boldsymbol{\mu_0}$, and linear magnetic field gradient $\boldsymbol{\nabla}\mathbf{B_f}$ come into the equation. After rearranging terms and noting that all vector components point toward the z direction, the resulting equation goes as:

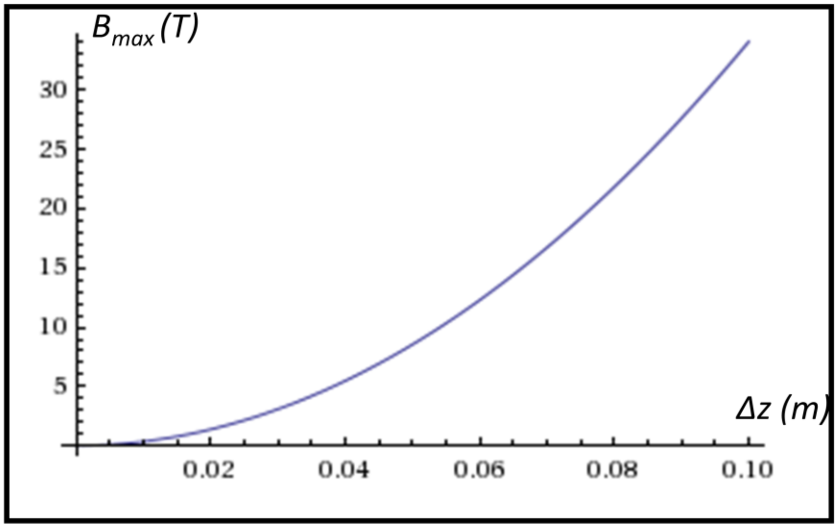
$$\frac{\partial B}{\partial z} = \frac{\mu_0(1+\chi_{vol})\rho_{02}\ddot{z}}{\chi_{vol}|\mathrm{B_i}|}$$

Finally solving for this first order differential equation and expressing the acceleration in z by its Δz and t dependencies results in:

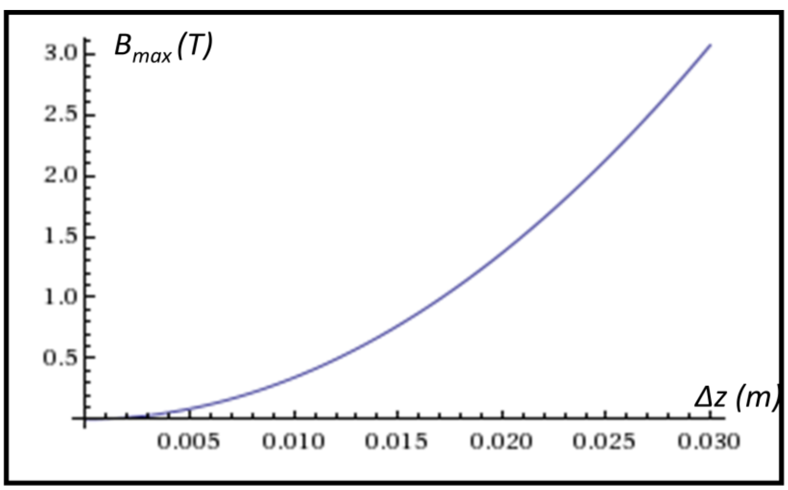
$$\int_0^{B_{max}} dB = \int_0^{\Delta z} \frac{\mu_0(1+\chi_{vol})\rho_{02}\ddot{z}dz}{\chi_{vol}|\mathrm{B_i}|}$$

$$B_{max} = \frac{\mu_0(1+\chi_{vol})\rho_{02}\Delta z^2}{\chi_{vol}|\mathrm{B_i}|\mathrm{t}^2}$$

And at last, the equation yields a result for the maximum magnetic field necessary to deflect oxygen a distance $\boldsymbol{\Delta z}$, over a period **t**, seconds. This equation's dependence on B_i also shows the importance of the initial aligning field. The importance of balancing the two fields becomes important under this model. Below depicts maximum magnetic fields required under specific parameters. Note that the time interval is kept short such that thermal forces on the magnetic moment following stage one remain minimal.



Parameters
t =.1 seconds
B_i = 5 T



Parameters
t =.1 seconds
B_i = 5 T

Analysis of the plots yields reasonable magnetic fields for deflections on the order of one to three centimeters but less reasonable for larger volumes of air requiring up to ten centimeters of deflection. While the time of deflection can appear rather arbitrary, smaller time intervals proved to require unreasonably high magnetic fields. So ultimately the accuracy of this model lies on the level of chaotic rearranging of the oxygen molecules following stage one. This leads to the conclusion that this model fits most with lower temperature systems over short periods of time and become less accurate with high temperatures and longer periods of time.

Results

The model developed by this research proves that oxygen deflection, collection and enrichment can happen but with restrictions. Large volumes of air, such as those needed by rocket engines for example, cannot collect large volumes of oxygen due to the limitations of present day technology. Under the heat of the rocket engines, magnetic fields would need to reach upwards of fifty teslas to sufficiently magnetize air to the point where it could deflect. Smaller scale collection at lower temperatures remains plausible however, for magnetic fields required for small deflections for less oxygen collection can happen. Magnetic fields for these orders of collection range around a quarter to a half a tesla– a much more practical level than compared to those required for combustion.

Ultimately, increasing oxygen density through the application of high gradient magnetic fields can happen. Whether or not this method applies to more practical means of oxygen extraction lies in the requirements set out by the user.

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