Study on the Aggregation Performance of Nitrogen and Oxygen Gas Based on Permanent Magnet Gradient Magnetic

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Abstract. Oxygen and nitrogen in the air have different magnetic properties in a magnetic field. Oxygen and nitrogen are paramagnetic gases and diamagnetic gases, and the magnetizing force received in a gradient magnetic field is in opposite directions. Based on the magnetization theory and simulation experiment analysis, this paper uses the difference in the direction and magnitude of the magnetization force of oxygen and nitrogen in a gradient magnetic field to study the force state of oxygen and nitrogen molecules in the input air in a gradient magnetic field and the oxygen mass fraction of the output gas to explore effective ways to obtain oxygen-enriched gas. The results of this study can provide oxygen-enriched gas for operations such as oxygen-enriched combustion technology and sewage treatment engineering, and improve operational efficiency.

1. Introduction
High-gradient magnetization separation technology is widely used in ore screening, separation of magnetic immobilized enzymes, and separation of red blood cells. The use of high-gradient magnetization separation technology to enrich oxygen based on different magnetic properties of oxygen and nitrogen is the main direction of current research. With the advancement of science and technology, the application of oxygen-enriched gas is now more widely used, and oxygen-enriched combustion technology is becoming more and more mature. The installation of magnetized oxygen-enriching mechanisms on internal combustion engines of automobiles and ships has been applied abroad. In addition, oxygen-enriched gas is also widely used in sewage treatment, indoor oxygenation and refreshing [1].

2. Mechanism of the Magnetizing Force of Gas Molecules in a Gradient Magnetic Field
According to the Helmholtz free energy, combined with Landau's derivation [2], the magnetic field force experienced by a unit volume of gas molecules $F$ can be expressed as:

$$F = \frac{1}{2} \nabla \left( H^2 \rho \frac{\partial \mu}{\partial \rho} \right) - \frac{1}{2} H^2 \nabla \mu + \mu [j \times H]$$

(1)

In the formula, $H$ is the magnetic field strength, $\rho$ is the molecular density, $\mu$ is the magnetic permeability of the magnetic molecule, and $j$ is the current density.

According to the magnetization law and electromagnetic knowledge of magnetic media, the magnetic permeability $\mu$ and volume susceptibility $\chi$ can be expressed as:

$$\mu = \mu_0 \cdot \mu_r, \mu_r = 1 + \chi, \chi = \rho \chi_m$$

(2)
In the formula, $\mu_0$ is the vacuum permeability, $\mu_r$ is the relative permeability of the magnetic molecule, $\chi$ is the volume susceptibility of the magnetic molecule, and $\chi_m$ is the mass susceptibility.

The Lorentz force experienced by gas molecules per unit volume is zero. Substituting equation (2) into equation (1), the magnetic field force experienced by gas molecules per unit volume is:

$$F = \frac{1}{2} \mu_0 \rho \chi_m H \nabla H$$

The magnetic field intensity and the magnetic induction intensity have the following relationship: $B=\mu H$, where $B$ is the magnetic induction intensity generated by the magnetic field. Using the relationship between the two, the magnetizing force received by a single gas molecule can be obtained as formula (4):

$$f = \frac{1}{2\pi\mu_0} \rho \chi_m B \nabla B$$

In the formula, $\nabla B$ is the magnetic induction intensity gradient of the non-uniform magnetic field, $n$ is the number of molecules per unit volume.

3. Force Analysis of Gas Molecules in Gradient Magnetic Field

3.1. Performance Analysis of Gradient Magnetic Field Magnetic Induction Intensity between Permanent Magnets

In this paper, the gradient magnetic field generated by two permanent magnets is used to explore the gas magnetization performance. Two permanent magnets are magnetized in the same direction, with opposite poles facing each other. The arrangement of two permanent magnets is shown in figure 1. Where $L$ is the length of the permanent magnet, $W$ is the width of the permanent magnet, $h$ is the thickness of the permanent magnet, $\delta$ is the air gap between the two permanent magnets, $L=78\text{mm}$, $W=38\text{mm}$, $h=30\text{mm}$, $\delta=3\text{mm}$.

Using Maxwell software to simulate and simulate, the distribution of magnetic induction intensity (vector diagram) generated around the permanent magnet is shown in figure 2. It can be seen from figure 2 that the magnetic flux density in the gap between the two permanent magnets is changing. In order to understand its internal changes more clearly, the XZ plane magnetic induction intensity (scalar) cloud diagram is obtained by further simulation as shown in figure 3. It can be seen that the middle area is a uniform magnetic field. Due to the edge effect, the magnetic induction intensity of the peripheral area decreases, forming a gradient magnetic field.

On the XZ plane, $X = 0\text{mm}$, $16\text{mm}$, $17\text{mm}$, $18\text{mm}$, respectively, and the change curve of the magnetic induction intensity corresponding to the change in the $Z$ direction is shown in figure 4. In the interval of $8\text{mm}<Z<70\text{mm}$, the magnetic induction intensity $B$ is almost unchanged; in the interval of $Z\leq8\text{mm}$ and $Z\geq70\text{mm}$, the magnetic induction intensity $B$ shows a gradient change. On the XZ plane, when $X$ takes different values, the magnetic induction intensity change curve corresponding to the
change in the Z direction has similar changes. Therefore, a gradient magnetic field is formed in this area [X=-19mm~19mm, Y=0mm, Z=0mm~8mm]. In the same way, the other three areas around the area of figure 3 are also gradient magnetic fields. Due to the different directions of the magnetic induction intensity gradient of the gradient magnetic field in the four regions, in order to facilitate the distinction, we named the four regions as gradient magnetic fields 1, 2, 3, and 4, as shown in figure 3.

3.2. Analysis of the Magnetizing Force of Oxygen and Nitrogen Molecules in a Gradient Magnetic Field

Oxygen molecules and nitrogen molecules have different magnetic properties: oxygen molecules are paramagnetic, and their mass magnetic susceptibility $\chi_m > 0$, the direction of the magnetizing force received by oxygen molecules is the direction of increased magnetic induction; nitrogen molecules are diamagnetic, and their mass magnetic susceptibility $\chi_m < 0$, the direction of the magnetizing force received by the nitrogen molecules is the direction in which the magnetic induction intensity decreases.

When air is input from the position shown in figure 5, the force of oxygen molecules and nitrogen molecules in the gradient magnetic field in the edge area is shown in figure 5.

Usually a gradient magnetic field formed by two permanent magnets is used, the magnetic induction intensity is usually between 0.1-2T, and the magnetic induction intensity gradient is 0-200T/m. Select the magnetic induction intensity as 1T and the magnetic induction intensity gradient as 100T/m as the prerequisites for the calculation. The mass magnetic susceptibility of oxygen and nitrogen are $+43.43 \times 10^{-6} \text{m}^3/\text{kg}$, $-15.08 \times 10^{-8} \text{m}^3/\text{kg}$ respectively [3], combined with formula
4. Oxygen and Nitrogen Molecules Pass Performance Analysis in a Gradient Magnetic Field

4.1. Analysis on the Movement Characteristics of Oxygen and Nitrogen Molecules in Gradient Magnetic Field

In solving the magnetization movement of oxygen and nitrogen molecules, the micro-element method is used for processing. In a short time, the product of the magnetic induction intensity and the magnetic induction intensity gradient can seem to be constant.

The magnetic induction intensity gradient around the permanent magnet is not uniformly distributed, but it can be approximately regarded as a uniform gradient magnetic field in the instantaneous region of each micro-element, and the trajectory of the gas molecule movement can be obtained as follows [5]:

\[
\begin{align*}
\Delta x &= u_x \cdot \Delta t + \frac{1}{2} a_x \cdot \Delta t^2, u_x, a_x, \Delta t \\
\Delta y &= v_y \cdot \Delta t + \frac{1}{2} a_y \cdot \Delta t^2, v_y, a_y, \Delta t \\
\Delta z &= w_z \cdot \Delta t + \frac{1}{2} a_z \cdot \Delta t^2, w_z, a_z, \Delta t
\end{align*}
\]

Since the influence of gas buoyancy and gravity are ignored, only the magnetizing force is considered, and the influencing factors of the molecular motion only need to consider the magnitude of the magnetizing force in different directions. Through simulation and theoretical analysis, as shown in figure 1, the magnetizing force in the Y direction is very small and can be ignored, that is, the magnetizing force has no effect on the movement of the molecules in the Y direction, and the magnetizing force is mainly reflected in the Z and X directions. When the air is input from the position shown in figure 5, it is mainly affected by the gradient magnetic field 1, that is, it is mainly affected by the magnetizing force in the Z direction. For the convenience of research, we set the initial velocity of the out flowing molecules to be along the Z direction, that is, the gas molecules in the gradient magnetic field 1 region can be seen as the superimposed effect of uniformly accelerating linear motions in multiple micro-element intervals. In the region of gradient magnetic field 1, the magnetizing force of nitrogen molecules is opposite to the speed of nitrogen molecules in the Z direction. The nitrogen molecules will decelerate, and the speed of some molecules will drop to zero, and then the speed will be discharged in the reverse direction, making it along the Z axis. The content of oxygen in the output gas increases to form an oxygen-rich gas.

It can be seen from figure 4 that at different positions of the magnetic field, the magnetic induction intensity is different. Figure 5 shows the B×B change curve of the magnetic induction intensity and the magnetic induction intensity gradient product B×B corresponding to changes in the Z direction with Y=0mm and X being 0mm, 16mm, 17mm, and 18mm. It can be seen from figure 9 that when X takes different values, the product B×B of the magnetic induction intensity and the magnetic induction intensity gradient changes differently. X=0mm, the value of B×B is larger. When nitrogen molecules are input from positions with different X values on the left side of the permanent magnet, the
magnetizing force they receive is different. When entering from the position of X=0mm, the magnetizing force of nitrogen molecules is greater.

Figure 6. Y=0mm, X takes different values, the $B\nabla B$ change curve corresponding to changes in the Z direction.

4.2. Using MATLAB Software to Analyze the Oxygen Mass Fraction of Oxygen-Enriched Gas

In order to analyze the passing rate of nitrogen and oxygen gas molecules in the gradient magnetic field, set the gas input position to $[X=-19mm~+19mm$ (interval 0.1, 381 analysis points in total), $Y=0mm$, $Z=0mm$], initial velocity $v_0=8m/s$ (the direction is along the positive Z axis) as shown in figure 5. Based on the ratio of velocity to magnetic field value change $\lambda = \frac{v}{B\nabla B}$, the unit of $\lambda$ is $m^2\cdot s/T^2$). Using MATLAB software to calculate the oxygen mass fraction of the output oxygen-enriched gas in figure 5 (oxygen mass fraction: the percentage of the oxygen mass to the total mass of the gas).

The analysis shows that the nitrogen molecules at different positions along the edge of the gas introduced into the magnetic block show different states due to the difference in the product of the magnetic induction intensity and the magnetic induction intensity gradient of the gradient magnetic field. In the area of $[X=15.8mm~19mm \text{ and } X=-15.8mm~-19mm$, $Y=0mm$, $Z=0mm~8mm]$, although the gradient magnetic field hinders the effect, the nitrogen molecules all pass through this area; and in $[X=-15.8mm~15.8mm$, $y=0mm$, $Z=0mm~8mm]$, the nitrogen molecules are discharged out of the permanent magnet because the magnetizing force it receives is greater than its inertial force, without entering the gap between the magnet blocks. The result of calculation and analysis is that the nitrogen molecules that have not entered the gap between the magnetic blocks account for 81.1% of the total nitrogen molecules introduced into the gas.

When oxygen molecules pass through the gradient magnetic field formed by the permanent magnet, they accelerate first, then at a constant speed, and then decelerate. Due to the symmetry of the magnetic induction intensity, the gradient magnetic field does not promote or hinder the passage of oxygen molecules. The gradient magnetic field has an obstructive effect on nitrogen molecules, and has a propelling effect on oxygen molecules, so that the nitrogen content in the output gas is reduced, the oxygen content is increased, and oxygen-enriched air is formed. Based on the above-mentioned velocity and magnetic field change ratio $\lambda$ value, it is calculated that the mass fraction of oxygen in the oxygen-enriched gas output after the gradient magnetic field is increased to 59.02%.

Using the same principle to obtain the value of $v_0=5m/s~9.5m/s$ with an interval of 0.5$m/s$, the results of the mass fraction of oxygen in the output gas are shown in table 1.
Table 1. Statistics table of oxygen mass fraction of output gas at different initial speeds.

| Round | V₀ (m/s) | B∙∇B(T²/m) | λ(10⁻² m² s/T²) | Oxygen mass fraction (%) |
|-------|----------|-------------|----------------|------------------------|
| 1     | 4.58     | 150         | 3.05           | 100                    |
| 2     | 5.0      | 150         | 3.33           | 88.81                  |
| 3     | 5.5      | 150         | 3.67           | 83.03                  |
| 4     | 6.0      | 150         | 4.0            | 77.95                  |
| 5     | 6.5      | 150         | 4.33           | 73.46                  |
| 6     | 7.0      | 150         | 4.67           | 69.46                  |
| 7     | 7.5      | 150         | 5.0            | 64.22                  |
| 8     | 8.0      | 150         | 5.33           | 59.02                  |
| 9     | 8.5      | 150         | 5.67           | 53.45                  |
| 10    | 9.0      | 150         | 6.0            | 46.67                  |
| 11    | 9.5      | 150         | 6.33           | 37.11                  |
| 12    | 9.84     | 150         | 6.56           | 21                     |

Figure 10 is a schematic diagram of the oxygen mass fraction in the output gas changing with λ.

Figure 7. Schematic diagram of the oxygen mass fraction in the output gas changing with λ.

5. Conclusion

(1) When $\lambda \leq 3.05$, the oxygen mass fraction in the output oxygen-rich gas after the gradient magnetic field magnetization is 100%; when $\lambda \geq 6.56$, the output gas the oxygen mass fraction is 21%. When $3.05 < \lambda < 6.56$, as $\lambda$ increases, the oxygen mass fraction of the output oxygen-rich gas after being magnetized by the gradient magnetic field will decrease.

(2) In order to increase the mass fraction of oxygen in the output gas, the goal can be achieved by increasing $B \cdot \nabla B$ or reducing the initial velocity $v₀$ of gas molecules.

References

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