# Final Lab Report

## Experiment:

# STEERING PARAMAGNETIC LEIDENFROST DROPS IN INHOMOGENEOUS MAGNETIC FIELD


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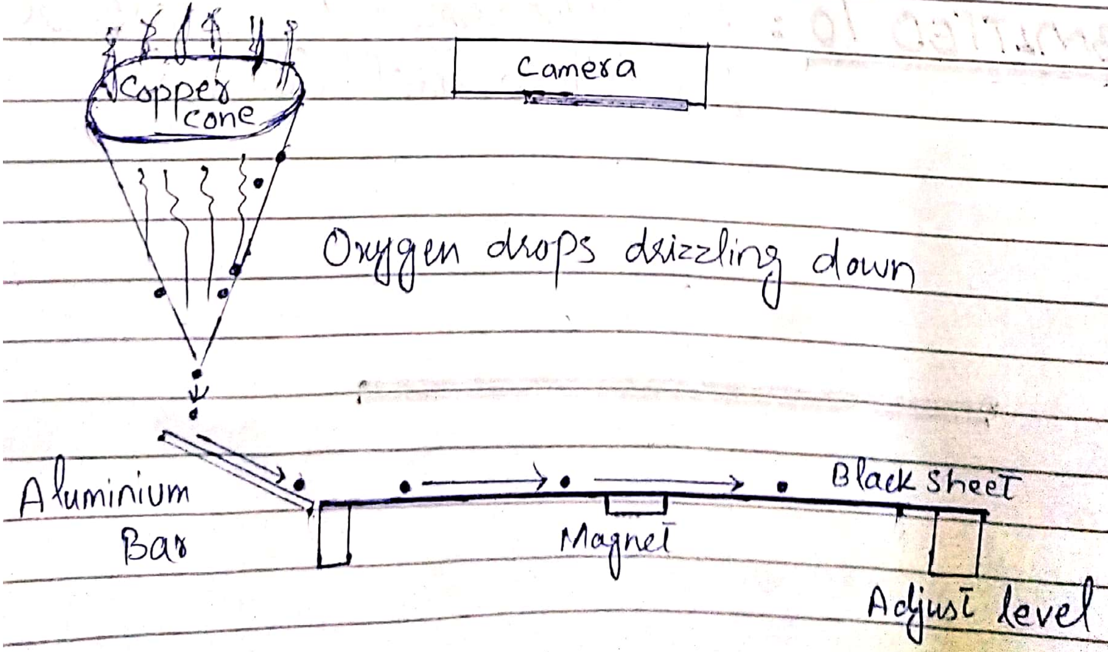
# ABSTRACT:

We observed the magnetic behaviour of paramagnetic oxygen drops in this experiment. According to Molecular theory oxygen is paramagnetic in nature. Liquid Nitrogen liquifies oxygen so thus it leads to formation of oxygen droplets. By video and computational analysis we traced trajectory of oxygen drops, in the presense of inhomogeneous magnetic field. We then calculated the peripheral radius i.e, the radius where radial velocity of drop becomes zero or minimum, and angle of deflection. Afterwards we compared it with theoretical values.

# EXPERIMENTAL OVERVIEW



Experimental setup consists of a black sheet which contains a magnet at its centre. A camera is used to record the top view of experiment. liquid nitrogen is poured into a copper cone and because of this, temperature decreases to a certain degree. Oxygen in contact with the cone gets liquified in the form of drops and started moving toward the sheet because of inclined plane, later on its trajectory was traced.

## THEORY

"The leidenfrost effect is a phenomenon in which a liquid drop levitates on a surface that is significantly hotter than a its boiling point."

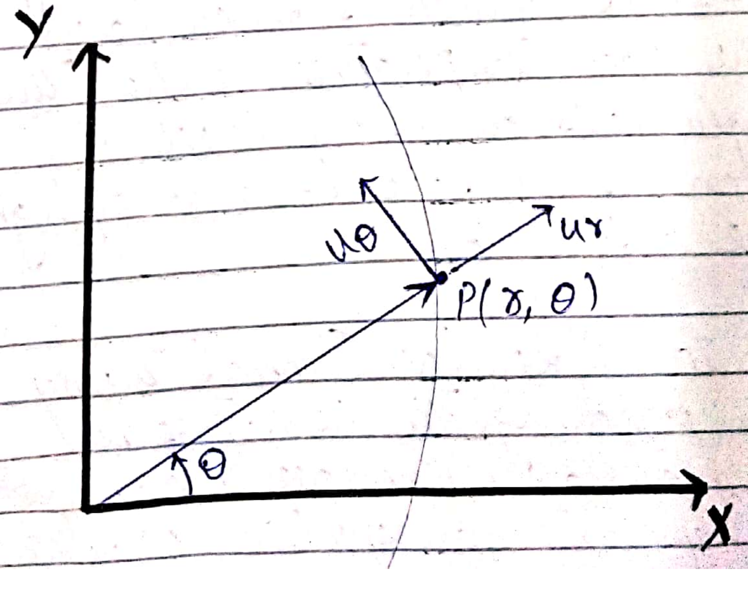
Oxygen a diatomic gas has a boiling point of -183°C which is much lower than the room temperature. When the liquid oxygen falls on black sheet it levitates on its surface because of high temperature difference.

According to Molecular Orbital theory. Oxygen is paramagnetic in nature i.e those materials which are weakly attracted by external applied Magnetic field.

due to presence of unpaired electron in their molecular orbitals.

As the oxygen drop moves over a region where external magnetic field is present, it gets attracted toward the magnet and follows a path that is somehow similar to a parabola. To derive the equation of motion of an oxygen drop passing through the magnetic field we deal velocity in polar co-ordinates.

Polar co-ordinate system is a system in which position, velocity and acceleration of particle are defined as system of $r$ and $\theta$ instead of $x$ and $y$ system. Here $\vec{u_r}$ and $\vec{u_\theta}$ are the unit vectors used in polar co-ordinates system. Instead of cartesian unit vectors $i, j$. $\vec{U_r}$ and $\vec{u_\theta}$ are in the direction of increasing $r$ and $\theta$. Respectfully.

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Transformation of cartesian unit vectors in polar unit vectors are given by following equation

$$\vec{u_r} = \cos\theta\hat{i} + \sin\theta\hat{j} \quad \text{--- (i)}$$

$$\vec{u_\theta} = -\sin\theta\hat{i} + \cos\theta\hat{j} \quad \text{--- (ii)}$$

Now differentiating equation (i) and (ii) with respect to '$\theta$'.

$$\frac{d\vec{u_r}}{d\theta} = -\sin\theta\hat{i} + \cos\theta\hat{j} = \vec{u_\theta} \quad \text{--- (iii)}$$

$$\frac{d\vec{u_\theta}}{d\theta} = -\cos\theta\hat{i} + (-)\sin\theta\hat{j} = -\vec{u_r} \quad \text{--- (iv)}$$

Now differentiating equation (i) and (ii) with respect to 't'.

$$\dot{u}_r = \frac{d\vec{u_r}}{d\theta}\cdot\dot{\theta} = \vec{u_\theta}\cdot\theta \quad \text{--- (v)}$$

$$\dot{u}_\theta = \frac{d\vec{u_\theta}}{d\theta}\cdot\dot{\theta} = -\vec{u_r}\cdot\dot{\theta} \quad \text{--- (vi)}$$

$$\dot{\vec{u_r}} = \dot{\theta}\vec{u_\theta}$$

$$\dot{\vec{u_\theta}} = -\theta\vec{u_r}$$

We know that velocity is derivative of position vector with respect to time.

$$\vec{V} = \frac{d\vec{r}}{dt}$$

As $\vec{r} = r\vec{u_r}$

$$\vec{v} = \frac{d(r\vec{u_r})}{dt}$$

$$\vec{v} = \dot{r}\vec{u_r} + r\dot{\vec{u_r}}$$

$$\vec{v} = \dot{r}\vec{u_r} + r\dot{\theta}\vec{u_\theta}$$

$$\boxed{\vec{V} = \dot{r}\vec{u_r} + r\dot{\theta}\vec{u_\theta}}$$

Following is the representation of velocity in polar co-ordinates system.
$\dot{r}$ is the radial component of velocity where $r\dot{\theta}$ is the angular component of velocity

The oxygen drop moves with initial velocity v. Initial kinetic energy per unit volume is

$$E_{initial} = \frac{1}{2}\rho\dot{r}^2$$

Radial and angular kinetic energy per unit volume

$$E_{radial} = \frac{1}{2}\rho\dot{r}^2$$

$$E_{angular} = \frac{1}{2}\rho(r\dot{\theta})^2$$

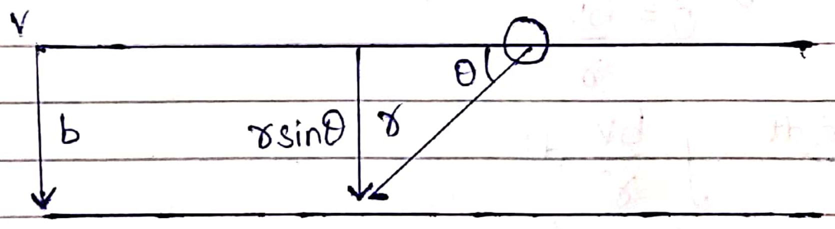
Magnetic energy per unit volume at each point in plane is

$$E_{magnetic} = \frac{-E_0}{9+\left(\frac{r}{r_0}\right)^6} = \frac{-1.256}{0.2949+\left(\frac{r}{0.1238}\right)^6}$$

By law of conservation of Energy

$$E_{initial} = \frac{1}{2}\rho\dot{r}^2 + \frac{1}{2}\rho(r\dot{\theta})^2 - \frac{E}{9+\left(\frac{r}{r_0}\right)^6}$$

The angular momentum along the trajectory is




$$L = mr \times V = mr\sin\theta\, v = mbv$$

$$L = mr^2\dot{\theta}$$

$$\dot{\theta} = \frac{bv}{r^2}$$

Now

$$mr^2\dot{\theta} = mbv$$

Eliminating $\dot{\theta}$

$$\frac{1}{2}\rho v^2 = \frac{1}{2}\rho\dot{r}^2 + \frac{1}{2}r^2\frac{b^2v^2}{r^4} - \frac{E_0}{9+\left(\frac{r}{r_0}\right)^6}$$

$$E_{eff}(r) = \frac{1}{2}\rho\frac{b^2v^2}{r^2} - \frac{E_0}{a+\left(\frac{r}{r_0}\right)^6}$$

At end we get

$$\frac{1}{2}\rho v^2 = \frac{1}{2}\rho\dot{r}^2 + E_{eff}(r)$$

Where $r_p$ is the Peripheral radius i.e, distance from centre of magnet to the point where radial velocity becomes zero

Radial distance $r_p$ can be calculated by using above equation. Solution of this equation gives peripheral radius.

Now the angle of deflection $\alpha$ can be calculated by integrating $\dot{\theta}$ with respect to $t$

$$\dot{\theta} = \frac{bv}{r^2}$$

$$\int \dot{\theta}\,dt = \int \frac{bv}{r^2}\,dt$$

$$= \int \frac{bv}{r^2}\frac{dr}{\dot{r}}$$

where

$$\dot{r} = \sqrt{v^2 - \frac{2}{\rho}E_{eff}(r)}$$

Applying limits of integration

$$\int_{\pi}^{\alpha} \dot{\theta}\,dt = 2b\int_{r_p}^{\infty} \frac{dr}{r^2\sqrt{1 - \frac{2}{\rho v^2}E_{eff}(r)}}$$

$$\alpha = 2b\int_{r_p}^{\infty} \frac{dr}{r^2\sqrt{1 - \frac{2}{\rho v^2}E_{eff}(r)}} - \pi$$

# Graph Analysis:

By using tracker, we get the $x$ and $y$ with respective values of the drop with respect to time also we get the distance of drop from origin

We plotted graph of $y$ vs $x$ to get exact trajectory of drop. Then by using $r$ values we get $E_{eff}(r)$ at each respective $r$. Thus we plotted another graph between $E_{eff}(r)$ and $r$. On this graph we plotted a line of $\frac{1}{2}\rho v^2$.

The Intersection of these two graph give us the value of peripheral ($r_p$). These two graphs and calculation obtained by tracker are hereby attached.

# Results & Discussion:

We measured the angle of deflection $\alpha$ and the radial difference from the pericenter of magnet ($r_p$). Theoretically we measure $r_p$ by the required equation and the angle of deflection by integrating $\dot{\theta}$ using Matlab.

Then we compare this result with our experimental results.

Theoretical value of $r_p = 0.0052m$
Experimental value of $r_p = 0.0072m$
Theoretical value of $\angle$ of deflection $= 18°$
Experimental value of $\angle$ of deflection = is found by slope method formula given as

We select two values of $x$ and $y$ and evaluated them as;

$$= \frac{-7.84 + 0.562}{-0.351 + 0.435}$$

$$= 20.72°$$

**% deviation in $r_p$** $= \frac{\text{Theoretical} - \text{Experimental}}{\text{theoretical}}$

$$= \frac{0.0052 - 0.0072}{0.0052} \times 100$$

$$= 38.4\%$$

**% deviation in $\alpha$** $= \frac{18 - 20.72}{18} \times 100$

$$= 15\%$$

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# ERROR & DISCUSSION:

We observe the leidenfrost effect using liquid to almost approximate precision. However improvements can be made to change the accuracy of results in +ve way. During video motion analysis, we observed that drops were deformed when came near the centre of magnet, dissipation of magnetic energy. This effect needs to be in account in equation of motion to get desired result

Experimental apparatus also needs improvements. During experiment Aluminium bar is controlled by hand causing deviation and also cause human error.

Also the topology surface of blacksheet on drop levitates was not smooth causing quantitative error.