QUALITATIVE ASSESSMENT OF FACTORS IMPACTING MAGNETOHYDRODYNAMIC FLOW

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Duration: Mar 2023 to Aug 2023

ABSTRACT

The magnetohydrodynamic flow of ink drops under the influence of a Lorentz force is studied using an experimental setup, which was developed at home. The experimental setup comprises the electrically conducting fluid between two parallel plates, which are connected to the positive and negative terminals of the DC source. The MHD flow is established under the effect of the magnetic field due to the neodymium magnets. The flow of the working fluid was traced using ink, recorded, and studied by varying the operating parameters such as current, electrode gap, magnetic field, and electrical conductivity of the fluid. Changes in these parameters led to an increase or decrease in the Lorentz force, resulting in an increase or decrease in the flow speed. The development of the fluid flow in the horizontal plane shows the pattern which is similar to the distribution of the magnetic field lines present in the perpendicular plane. The fully developed and under-developing MHD flow between the parallel plates was studied and is discussed in the report.

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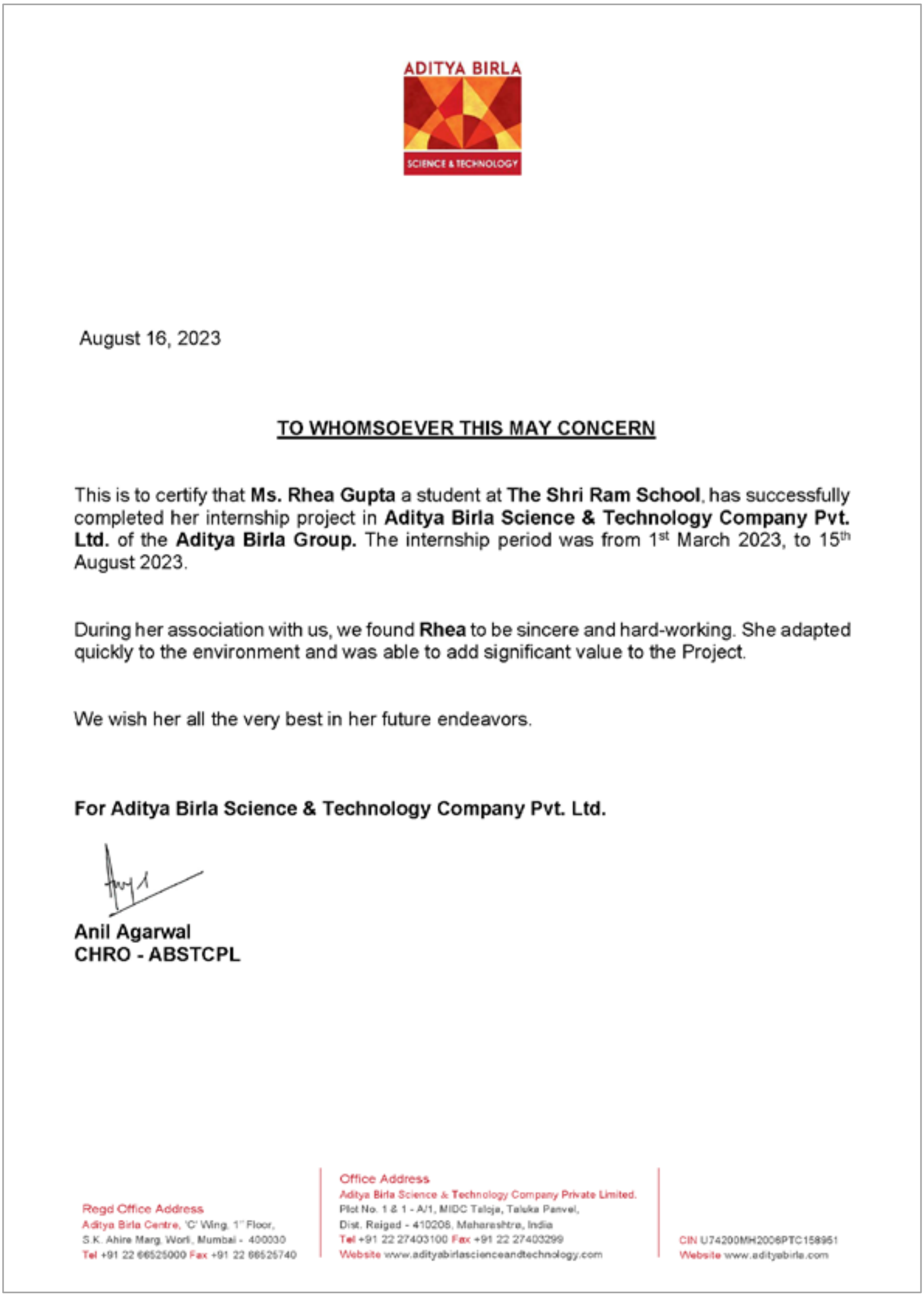

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August 16, 2023

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This is to certify that **Ms. Rhea Gupta** a student at **The Shri Ram School**, has successfully completed her internship project in **Aditya Birla Science & Technology Company Pvt. Ltd.** of the **Aditya Birla Group.** The internship period was from 1st March 2023, to 15th August 2023.

During her association with us, we found **Rhea** to be sincere and hard-working. She adapted quickly to the environment and was able to add significant value to the Project.

We wish her all the very best in her future endeavors.

For Aditya Birla Science & Technology Company Pvt. Ltd.

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1 INTRODUCTION

Magnetohydrodynamics (MHD) is the branch of science dealing with the interaction of magnetic field and fluid dynamics (Davidson). An electrically conducting fluid under the influence of a magnetic field deforms and moves due to Lorentz force. The fluid in motion under imposed magnetic field also experiences an induced magnetic field and induced current. This interacts together to produce force, which, in turn, inhibits the motion of the system (Tillack & Morley, 1998; Gangl & Schafelner, 2016). A simple illustration shown in Figure 1 describes the MHD flow of the conducting fluid between two parallel plates under the influence of electric current and magnetic field (Zhang Yang Z. H., 2019). MHD has a wide range of applications in astrophysical phenomena, electrolysis cells, levitation, electromagnetic stirring, nuclear fission reactors etc (Al-Habahbeh, Al-Saqqa, Safi, & Khater, 2016). In the report, we record and study the MHD flow of current-carrying brine solution in a simple home setup. The experimental studies of MHD flow reported earlier (Lenka, Mehrotra, & Shekhar, 2007; Pedchenko, 2009) inspire the authors to study the phenomenon through simplistic experiments. The main objectives of the present study are (1) the development of a homemade experimental setup to produce an MHD flow in a conducting fluid and (2) the qualitative study of change in various operating parameters of the experimental setup.

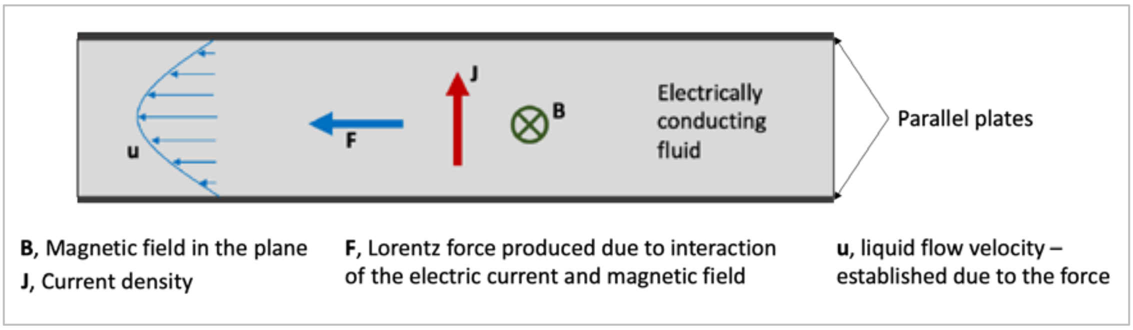

Figure 1: MHD flow of an electrically conducting fluid, driven by the Lorentz force.

2 DEVELOPMENT OF THE EXPERIMENTAL SETUP

The setup (Ingredients, 2017) comprises a transparent rectangular box containing the electrodes, magnet, and conducting fluid as shown in Figure 2. The rectangular tray was 12”x8”x1.5” and was made of plastic so that the tray itself would not conduct electricity. After a few experiments, the bottom at the centre of the tray curved upwards and became deformed, and had to be replaced with a new one.

The electric current is supplied through an external DC source. It has 3 memory settings – M1 (0.1 A), M2 (1.0 A), M3 (6.0 A). The current range (0-6.0 A) and voltage range (0-30.0 V) could be controlled to the 100th of the unit by double-clicking the respective knob and rotating it to the digit one needed to change.

Clip wires were used as conducting wires and one had to be careful about the positive and negative orientation of the wires as connected to the DC source. We used black to be connected to the positive terminal and red connected to the negative terminal.

We used aluminium electrodes of 12” in length (30 cm) and stuck them to the base of the tray using blu-tack with the default distance between them being two graph squares.

We used 250 ml of tap water as the default conducting source. We tried using distilled water but no amount of salt addition helped it to conduct electricity appreciably. We used common salt to add to water at a default ratio of 1 tsp (5mg) to every 50 ml of water. The salt solution was replaced frequently as the experiment would cause insoluble solid particles from the magnet coating to hinder the experiment.

Five ferrite silver magnets of 20x10x10 mm size were brought close to each other in the N-S-N-S-N-S-N-S-N-S configuration and stuck to the base of the tray again using blu tack. The magnets were placed on the surface of the tray and submerged below water. During the experiment, the silver magnets would turn black quite quickly but would not lose their magnetic property and hence were not replaced.

We used ink drops of red, blue and green colour and used a dropper to drop them on the surface of the water between the channel that the electrodes formed.

In order to capture the images and videos, we used an iphone 12 camera with 4K resolution, and 60 FPS (frame per second) speed of capture. We kept the phone steady by using a small tripod.

The detailed specification and dimensions are shown in Table 1.

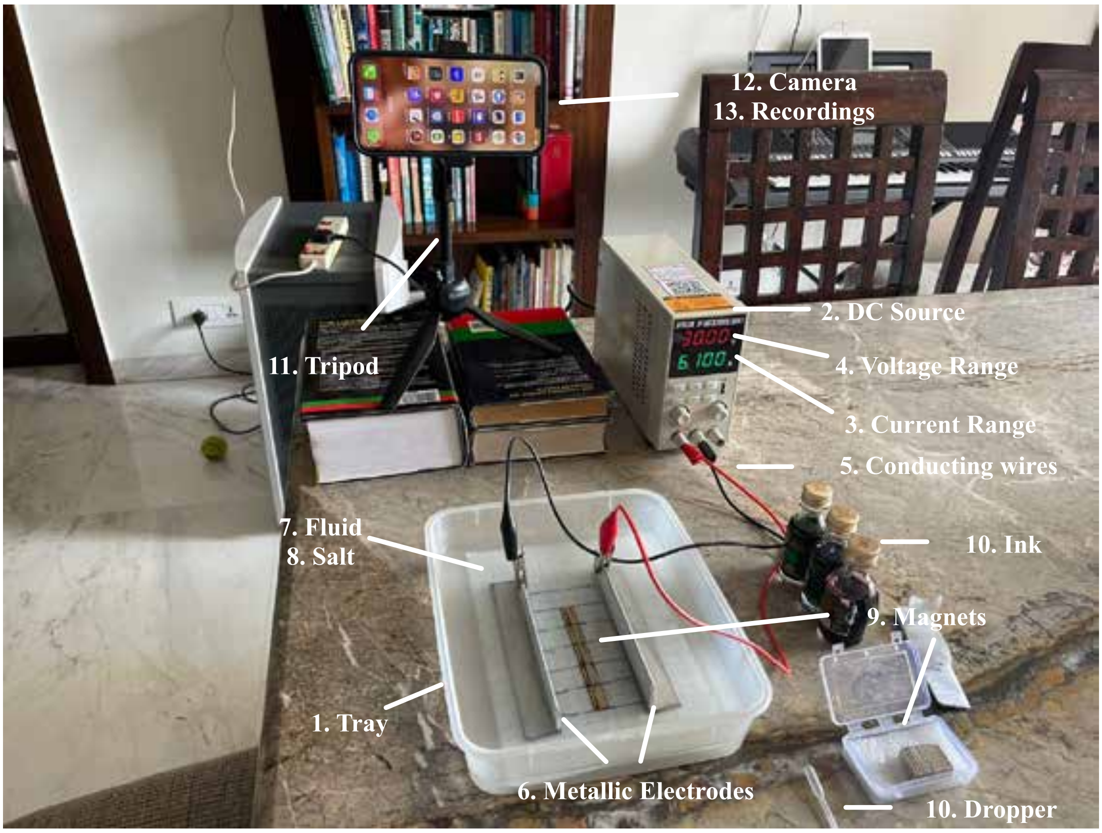

Figure 2: The experimental setup with two electrodes also acting as parallel walls of the channel through which the electrically conducting fluid flows.

Table 1. Details of the setup with specifications and dimensions of various components.

Ref	Component	Dimensions	Comments
1	Tray	12 inches long; 8 inches wide; 1.5 inches high	A plastic tray was used to avoid the tray material conducting electricity. The tray had to be replaced after a set of experiments as the bottom at the centre of the tray curved upwards through the experiments
2	DC Source		An external DC source was used which had 3 memory setups – M1 (least 0.1 A), M2 (moderate 1.0 A), M3 (highest 6.0 A)
3	Current Range	0-6.0 A	Could be controlled to the 100th of the unit
4	Voltage Range	0-30.0 V	Could be controlled to the 100th of the unit

Ref	Component	Dimensions	Comments
5	Conducting wires		Clip wires were used; was critical to check the positive and negative points
6	Metallic Electrodes	Length: 30 cm Distance between them: 4 cm (default)	
7	Fluid	250 ml of tap water (default)	Tried distilled water as well but results were poor; used tap water instead and bucket to keep pouring off the tap water after a couple of test runs each (Banerjee & Evans, 1990)
8	Salt	Common salt (1 tsp per 50 ml of water)	When using some of the recommended salt quantities, we found that there was significant sedimentation
9	Magnets	5 magnets (20x10x2 mm ceramic ferrite silver magnets)	Magnets were submerged under water on the surface of the tray. Magnets turned black quite soon but did not lose their magnetic strength.
10	Ink drop	Red, blue, green	Were dropped using a dropper on the surface of the water at different points between the electrodes and along the electrodes
11	Tripod		
12	Camera	iPhone 12 camera and 4K at 60 FPS (Pedchenko, 2009)	
13	Recordings	Google drive to store recordings	https://drive.google.com/drive/folders/1FiYySbEgyc4x7VttUWqmEQCSlf3h43mh

3 DESIGN OF THE EXPERIMENT

The set of experiments was designed considering the main parameters such as the magnitude of the electric current, electrode gap, concentration of the brine solution, location of the magnet, polarity of the signals, amperage and voltage settings and timing of the ink drop (David Cebron, 2017).

While we used a default of 250 ml of water, we also experimented with increasing (333 ml) and decreasing (200 ml) the quantity of water in the tray. We also changed the concentration of the salt solution by increasing it by 25% and 50%. Reducing the salt concentration is also a test that we tried (Dolezel, Kotlan, Ulrych, & Valenta, 2009).

Electrode distance was a default of two graph squares (4 cm), but we tried increasing it to three squares (6 cm) and reducing it to one square (2 cm). Between the electrode channel, we placed five magnets stuck to the bottom of the tray with opposite polarities facing each other, so that the magnetic fields of attraction would cause them to stick to each other. The magnets were latitudinal to the electrodes; we briefly tried placing them longitudinally, but it yielded no results. While we placed the magnets on the surface of the tray, however, placing them below the tray did not yield any flow and hence we did not experiment much with that.

The electrical signal polarity was set with the black (positive) clip wire closer to the camera. We tried switching it around as well and have recorded the findings. We changed the amperage settings between 6.0 A, 1.0 A and 0.1 A. The voltage reading was then captured.

We experimented with the timing of the ink drop. Once we chose an amperage setting and switched on the D-C power supply, it would take a few seconds for the voltameter to stabilize. We tried placing the ink drop (i) before switching on the current (ii) at the same time and (iii) after stabilization and all these three settings yielded interesting results. We also experimented with the position of the ink drop – at the center of the channel over the magnets, or closer to either of the electrodes.

The experiments performed are shown in Table 2.

Table 2. Design of the experiment.

Ref	Component	# of test values	Default values	Other Test Values	Comments
1	Quantity of water	3	250 ml	333 ml; 200 ml	33% higher; 20% lower
2	Salt	3	5 tsp (20 g)	6.25 tsp (25 g), 7.5 tsp (30 g)	25% and 50% higher; lower than 20 g induced no flow
3	Electrode distance	3	4 cm	6 cm, 2 cm	50% higher; 50% lower
4	Number of magnets	1	5 magnets	None	
5	Magnetic polarity	1	Opposite polarities facing each other	None	Similar polarity induced no flow
6	Magnet direction	2	Latitudinal (to electrodes)	Longitudinal (to electrodes)	
7	Magnet location	1	On surface of tray, submerged under water	One – on surface of tray, submerged under water	When water volume was 200 ml, magnets were not fully submerged; magnets when below the surface of tray induced no flow
8	Electrical signal polarity	2	+ve (black closer to image)	-ve (red closer to image)	
9	Ampere settings	3	M3	M2, M1	
10	Voltage settings	Multiple	Based on ampere settings		

Ref	Component	# of test values	Default values	Other Test Values	Comments
11	Timing of ink drop	3	When voltage stabilised	As soon as current starts to flow; Before current starts to flow	
12	Position of ink drop (latitudinally)	3	Between two electrodes	Close to +ve (black); close to -ve (red)	
13	Position of ink drop (longitudinally)	3	Closest to wires	Close to exit of electrodes; close to centre	

4 OBSERVATIONS FROM THE EXPERIMENT

4.1 Initial Setup

The MHD flow of the conducting liquid was monitored with respect to time by changing one variable at a time. We started with the following parameters:

- Concentration of salt water: Base case (5 tsp or 20 g of common salt in 250 ml of water).
- Electrode distance: 4 cm.
- Number of magnets: 5.
- Magnetic polarity: Opposites facing each other (N-S-N-S-N-S-N-S-N-S).
- Location of magnets: On the surface of the tray, immersed below water.
- The polarity of the electric signal: +ve (black) closer to observation; -ve (red) further away.
- Position of ink drop (P): Centre
- Timing of ink drop (T): Once voltage had stabilised

4.2 Change in amperage (and resulting change in voltage)

Once we set this up, we switched on the DC power supply and changed:

- Amperage Settings (A): M3, M2, M1 (6.0 A, 1.0 A, 0.1 A respectively)
- Voltage Settings (V): the voltage would start at a higher value and then dip rapidly and finally stabilise at a voltage value that changed in different trials and is noted in the readings below

Table 3: Readings with change in amperage (and resultant change in voltage)

Recording	A	V	Timing	Position	Direction	Time
8022	M3 (6.0 A)	21.0 V	Stabilisation	Centre	Flow of current	1.8 s
8027	M2 (1.0 A)	4.8 V	Stabilisation	Centre	Flow of current	5.8 s
8031	M1 (0.08 A)	1.0 V	Stabilisation	Centre	Flow of current	No movement

8022 (Figure 3) was the first of all the observations and **once the voltage had stabilised**, we placed an ink drop which, very quickly (1.8 s) moved in the direction of the electric flow and exited the channel. The voltage reading was 21.0 V. Changing the amperage setting to M2 (1.0 A, 4.8 V, recorded in 8027) also worked predictably and took longer (5.8 s) to move in the direction of electric flow and exit the channel. Reducing it further to M1 (0.08 A, 1.0 V recorded in 8031) did not have any impact on the ink drop and there was no movement whatsoever.

The hypothesis is that, higher the current (and hence, voltage), greater is the Lorentz force exerted on the ink drop. The force leads to greater acceleration, higher velocity and therefore reduced timing for the ink drop to flow when we have (i) settings that are higher (M3, 6.0 A, 21.0 V) versus (ii) moderate (M2, 1.0 A, 4.8 V) and the (iii) force was not sufficient to create movement in the lowest setting (M1, 0.08 A, 1.0 V).

For most of the trials going forward, we dispensed with the M1 setting as a feasible amperage (and voltage) setting, and continued predominantly with M2 and M3 settings only.

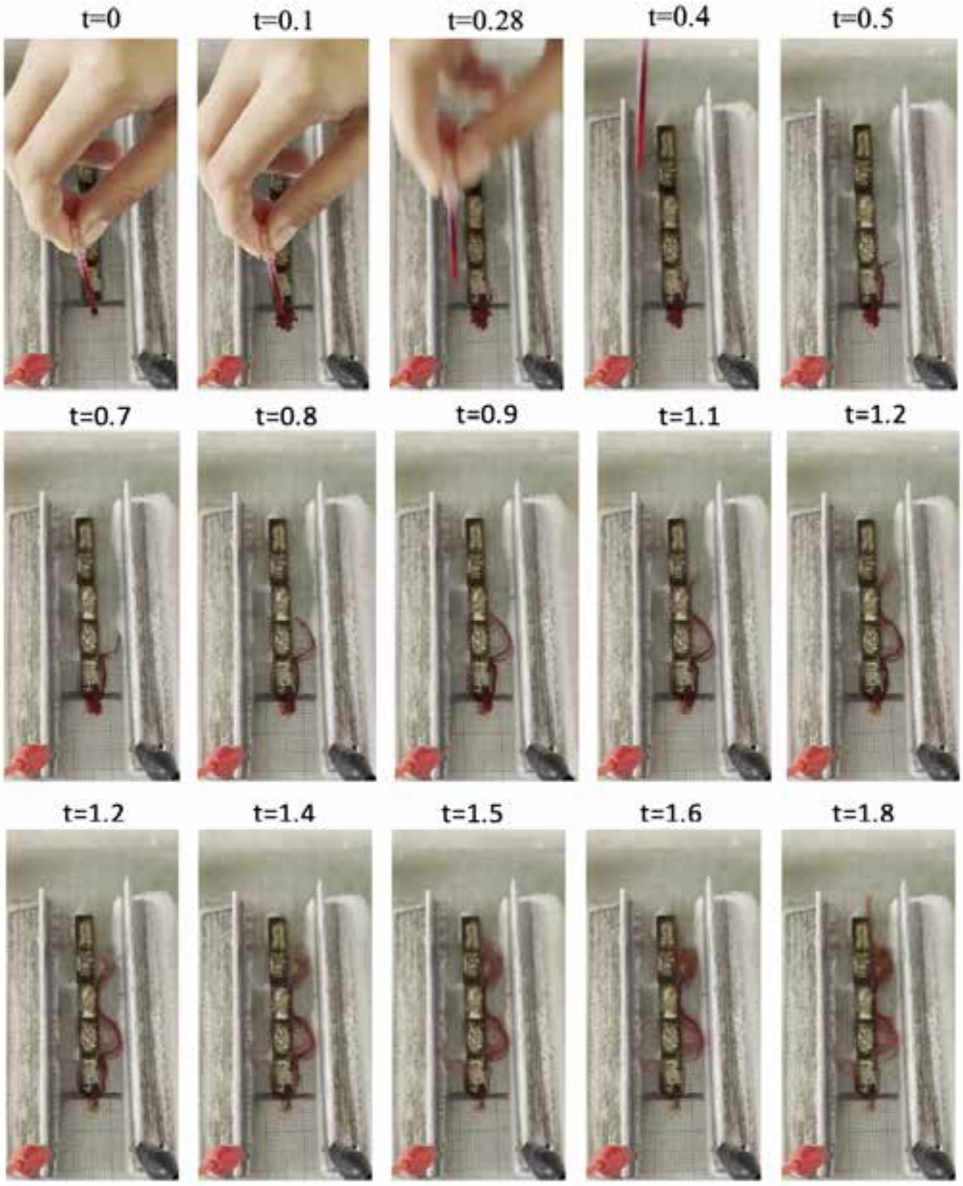

Figure 3: Established flow of the brine solution with time traced using red ink between t=0 to 1.8 seconds.

4.3 Change in timing of ink drop

The next variable we changed was the timing of the ink drop. There were three scenarios we considered: (i) once the voltage had **stabilised**, we inserted the ink drop at the centre between the electrodes (ii) **as soon as** we started the DC power supply which meant the ink drop was inserted while the voltage started at a higher value, and reduced and stabilised over time and (iii) even **before** starting the DC power supply.

We kept the amperage setting constant at M3 (6.0 A, 21.0 V), for this set of trials.

Table 4. Change in timing of ink drop (M3 setting for amperage)

Recording	A	V	Timing	Position	Direction	Time
8022	M3 (6.0 A)	21.0 V	Stabilisation	Centre	Flow of current	1.8 s
8023	M3 (6.0 A)	21.0 V	Start	Centre	Flow of current	4.9 s
8025	M3 (6.0 A)	21.0 V	Before	Centre	Flow of current	7.0 s

Recording 8022 (Figure 3) was already covered in Table 3 above and we have included it here for purposes of comparison. However, in 8023 (Figure 4), when we started the current **as soon as** we had placed the ink drop, the ink seemed to swirl for almost 1.0 second (see images from 0.9 sec to 1.8 sec) and had barely crossed the second magnet in the same time (1.8 s) that it had taken for 8022 to exit the channel. It seemed as if there was a latency in the reaction time for the ink drop to move in the direction of the electric flow.

In recording 8025, when we started the current **after** placing the ink drop, it seemed to behave similarly to 8023. Till the current started, the ink drop dispersed marginally. Once the current flow started, the ink drop seemed to swirl around the first two magnets for almost 2.0 seconds before moving in the direction of the current flow and exiting the channel.

We, then, changed the amperage setting to M2 (1.0 A) and ran the set of trials again by changing the timing of the ink drop. Recording 8027 was already covered in Section 4.2, Table 3 and is included here for purposes of comparison.

Table 5: Description of the cases performed by a change in amperage.

Recording	A	V	Position	Timing	Direction	Time
8027	M2 (1.0 A)	4.8 V	Centre	Stabilisation	Flow of current	5.8 s
8029	M2 (1.0 A)	4.8 V	Centre	Start		4.0 s
8030	M2 (1.0 A)	4.9 V	Centre	Before		7.0 s

The M2 (1.0 A, 4.8-4.9 V) setting had some interesting observations. When we placed the ink drop at the same time as the start of the current flow (recording 8029), in the M2 setting the flow was the fastest (4.0 seconds versus the 5.8 seconds when placed at stabilisation); this was different from the M3 setting, where the ink drop almost seemed to swirl for a while before moving quickly in the direction of the electric flow. When we placed the ink drop before the start of the electric flow (recording 8030), the ink drop moved slower (7.0 seconds) than the other two settings. Also, the movement of the ink drop was far more rhythmic and formed a nice pattern along the magnets, compared to the M3 setting (Figure 5).

The hypothesis is that when the amperage setting was high (M3, 6.0 A, 21.0 V) in recording 8023 (and 8024), the voltage is still changing and this induces eddy currents that are stronger than the Lorentz force. These eddy currents make the ink drop swirl, and only once the voltage stabilises that it leads to the Lorentz force taking effect and moving the ink drop move in the direction of the flow of current and exit the channel. This is consistent with the M2 setting and recording 8030 when it was 1.0 A and 4.9 V. However, recording 8029 seems to be an aberration to these recordings and more trials would be needed to confirm the readings. At this point, the hypothesis is that the voltage stabilisation happened quickly enough and/ or the effect of eddy currents was minimal in this trial.

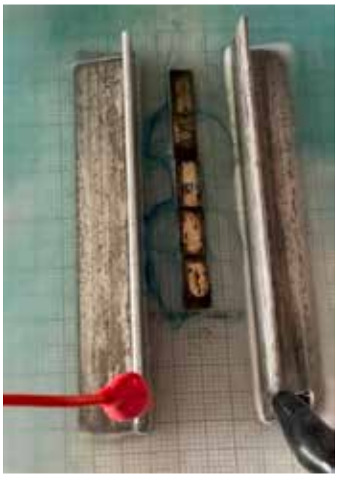

Figure 4: M2 setting.

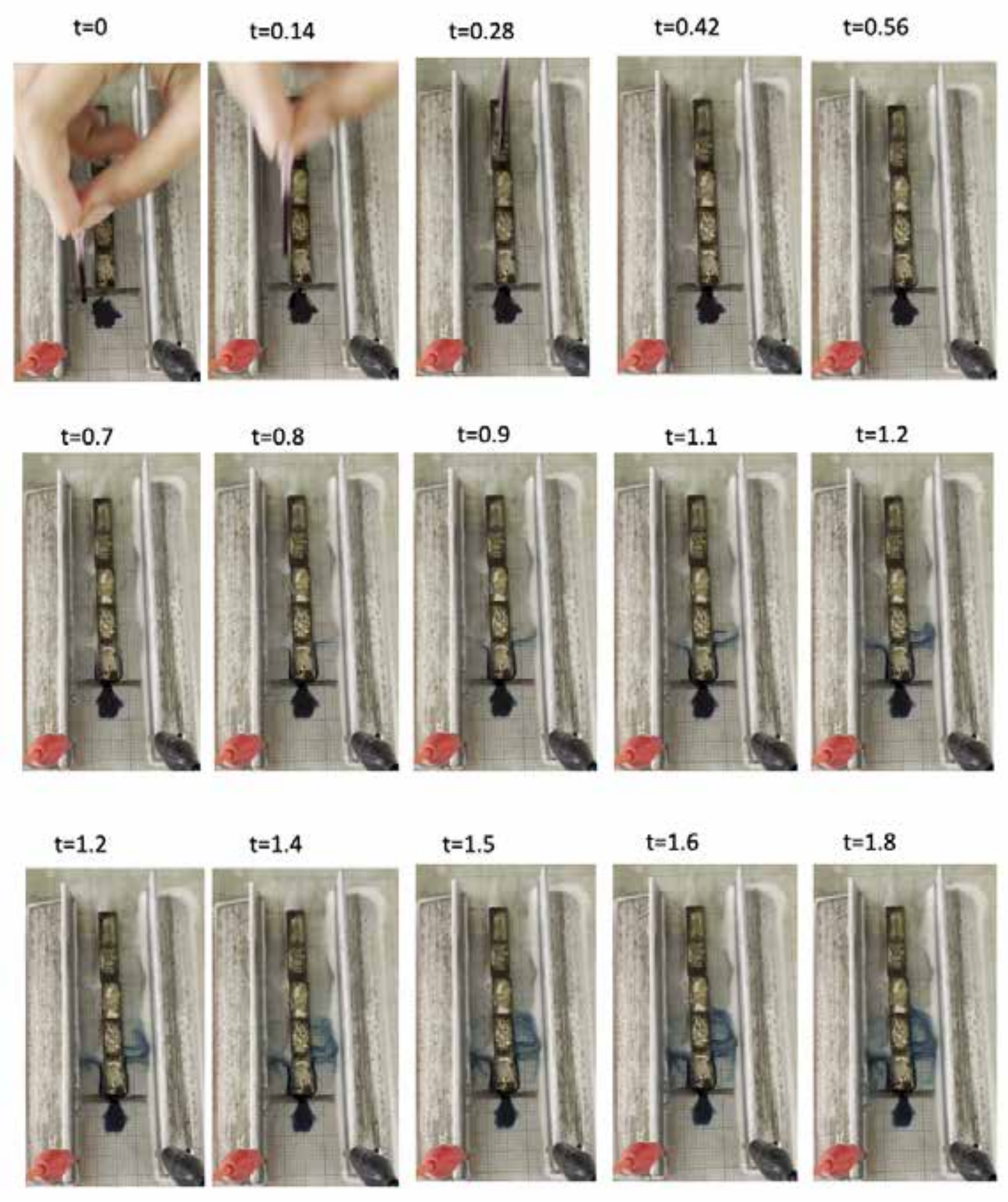

Figure 5: Development of the flow of the brine solution with time traced using red ink between t=0 to 1.8 seconds.

4.4 Change in position of ink drop

The next variable we changed was the position of the ink drop. The default was placing the ink drop in the centre, between the two electrodes. We, then, changed the position of the ink drop from being at the centre, to closer to either the +ve (black) or -ve (red) electrode. We kept the amperage constant at M3 (5A, 20.6V-21.0V).

Table 6: Description of the scenarios with change in ink drop position.

Recording	A	V	Position	Timing	Direction	Time
8021a	M3 (6.0 A)	21.0 V	Red	Stabilisation	Flow of current	2.2 s
8021b	M3 (6.0 A)	20.6 V	Black	Stabilisation		2.4s

Changing the position of the ink drop had some interesting observations. When we placed the ink drop close to the -ve electrode (red) after allowing the voltage to stabilise, the ink drop behaved similar to 8022 although slower. It moved quickly through the channel (2.2 s) in the direction of the electric flow. Similar findings were observed when we placed the ink drop close to the +ve electrode (black) as well.

The hypothesis is that the behaviour of the ink drop is similar whether it is placed at the centre between the electrodes, or closer to the electrodes. However the Lorentz force is strongest at the centre and hence it leads to least time; Lorentz force reduces as we get closer to the electrodes.

Keeping M3 constant, we decided to change the timing of the ink drop and place the ink drop closer to an electrode.

Table 7: Description of the scenarios with change in ink drop position (and change of timing as well)

Recording	A	V	Position	Timing	Direction	Time
8024	M3 (6.0 A)	19.6V	Red	Start	Flow of current	Swirled, but did not exit
8026	M3 (6.0 A)	21.0V	Black	Before		Swirled, but did not exit

However, when we placed the ink drop at the start of the electric flow or before, either close to the -ve or the +ve electrode, the ink drop swirled close to the first magnet and barely swirled forward to the second magnet but did not exit the channel at all.

This has probably happened because of the combination of eddy currents (which are highest at the start of the current flow, while voltage is still stabilising) and Lorentz force (which is highest at the centre, and weakest close to the electrodes). As a result, the eddy currents overpower the Lorentz force as a result of which, the ink drop does not move initially. And by the time the eddy currents subside (voltage stabilises), the ink drop has had a physical affinity to the electrodes and does not react to the Lorentz force on it.

4.5 Change in polarity of the electrical signal

The next variable we changed was the polarity of the electrical signal (reversed the positive and negative electrodes).

As expected, change in polarity of the electrical signal had a direct impact on the direction of the flow of the ink drop. In simple terms, the ink drop flowed in the direction opposite to the direction of all the trials above. As a result, we had been placing the ink drop at one end of the channel and it was flowing (where relevant) down the 30 cms of electrode channel and taking some time (as recorded) to do so.

In our first trial (recording 8032), when we placed the ink drop at the same position as all the other trials, we could not measure any timing as the ink drop moved in the opposite direction. This effectively meant that there was virtually no distance for the ink drop to travel, and hence no time could be recorded.

We, then, changed the setup for this set of trials and started placing the ink drop at the farthest end of the channel to observe the flow of the ink drop in a direction opposite to all the trials thus far (Figure 6). We performed a set of trials with three different amperage settings (M3 at 6.0 A, M2 at 1.0 A, M1 at 0.1 A).

Table 8: Description of the cases performed by change in polarity of electric signal

Recording	Ampere	Volts	Position	Timing	Direction	Time
8032	M3 (6.0 A)	19.7 V	Close to electrodes	Stabilisation	Opposite to magnets	Immediate
8033	M3 (6.0 A)	17.4 V	Furthest	Stabilisation	Towards electrodes	3.0 s
8038	M2 (1.0 A)	4.6 V	Furthest	Stabilisation	Towards electrodes	14.1 s
8040	M1 (0.08 A)	1.0 V	Furthest; centre	Stabilisation	No movement	

Figure 6: MHD flow after change in electrical polarity

In all the recordings, like-for-like, we found that the velocity of flow was slower when we changed the polarity of the electrodes and placed the ink drop at the furthest end of the channel. For instance, in the default electrical polarity situation, with the M3 setting (6.0 A), the timing was 1.8s (recording 8022). All other things remaining constant, when we changed the polarity, the timing was 3.0 s (recording 8033). Similarly, when we did the same for M2 setting (1.0 A), the timing was 4.9 s (recording 8023) versus 14.0 s (recording 8038). In the M1 setting, the Lorentz force was very weak in both settings to record any timings.

We then changed the placement of the ink drop as well and with the M3 (6.0 A) setting, we placed the ink drop close to the electrodes (recording 8034). This behaved similarly to when the polarity was in the default position (recording 8021) but slower (9.1 s versus 2.2 s).

We further changed the timing of the ink drop to be before the start of the current flow for the M3 setting (recording 8036) and for the M2 setting (recording 8039). Once again, the readings were similar to the default polarity.

Table 9: Description of the cases performed by a change in polarity of DC.

Recording	Ampere	Volts	Position	Timing	Direction	Time
8034	M3 (6.0 A)	16.9 V	Close to electrodes	Stabilisation	Towards electrodes	9.1 s
8036	M3 (6.0 A)	16.7 V	Furthest; centre	Before	Swirled; did not exit	
8039	M2 (1.0 A)	4.6 V	Furthest; centre	Before	Swirled; did not exit	

The hypothesis is that when the polarity changed, the magnetic field is highest closest to the source of electricity (electrodes) and weakens along the channel. Hence the time the ink drop takes to travel the channel in the opposite direction is longer for when the polarity changes.

4.6 Change in quantity of the conducting liquid

The next variable to change is to increase the water quantity to 333 ml (instead of 250 ml; a 33% increase), without changing the salt quantity (5tsp of salt; 20g).

The first set of trials were performed with the three amperage settings (M3 6.0 A, M2 1.0 A, M1 0.1A).

Table 10: Description of the cases performed by increasing the quantity of the conducting liquid.

Recording	A	V	Position	Timing	Direction	Time
8043	M3 (6.0 A)	16.1 V	Centre	Stabilisation	Flow of current	2.9 s
8051	M2 (1.0 A)	3.9 V	Centre	Stabilisation	Flow of current	7.2 s
8052	M1 (0.1 A)	1.0 V	Centre	Stabilisation	Flow of current	36.0 s

With increasing the water quantity by 33%, and keeping all variables constant, we found that the flow of the ink drop worked predictably although slower compared to the default water quantity. For instance, in the M3 setting (recording 8043, 6.0 A, 16.1 V), the timing taken (2.9 s) was slower than the default setting (1.8 s); for the M2 setting (recording 8051, 1.0 A, 3.9 V), there was a similar observation where the new timing (7.2 s) was also slower than the default setting (5.8 s). However, the most interesting observation was with the M1 setting (0.1 A, 1.0 V). If we recall, then at a higher salt concentration (with 250 ml of water), we saw no movement at all. But with more quantity of water (333 ml) and hence a reduced salt concentration, we observed a slow but definite movement of the ink drop in the direction of the current flow which exited the channel in 36.0 s. This was the first time that, at M1 setting, we saw the flow of the ink drop.

We, then, changed the timing of the immersion of the ink drop as well, and placed it at the start or before the flow of current.

Table 11: Description of the cases performed by increasing the quantity of the conducting liquid as well as timing of the ink drop.

Recording	A	V	Position	Timing	Direction	Time
8044	M3 (6.0 A)	16.1 V	Centre	At start	Flow of current	3.4 s
8045	M3 (6.0 A)	16.2 V	Centre	Before	Flow of current	4.3 s

In these set of trials, the flow of the ink drop behaved quite predictably and was consistent although slower by 3-4 seconds regardless of whether it was placed after stabilisation (8043), at the start of the current flow (8044) or before (8045).

Finally, we changed the position of the ink drop and placed it close to the electrodes.

Table 12: Description of the cases performed by increasing the quantity of the conducting liquid as well as position of the ink drop.

Recording	A	V	Position	Timing	Direction	Time
8046a	M3 (6.0 A)	15.8 V	Close to -ve	Stabilisation	Flow of current; very slow and did not exit	
8046b	M3 (6.0 A)	15.8 V	Close to +ve	Stabilisation	Flow of current	2.1 s

When we placed the ink drop close to either of the electrodes (recording 8046a), then when placed close to red (-ve), the ink drop swirled near the first magnet and seemed stuck due to some bubbles created there. However, when placed close to the black (+ve) electrode (recording 8046b), it moved quickly through the channel in 2.1 s.

Finally we reduced the quantity of water to 200ml, with no other change in the variable from the default situation.

Table 13: Description of the cases performed by reducing the quantity of the conducting liquid

Recording	A	V	Position	Timing	Direction	Time
8047	M3 (4.2 A)	30.0 V	Centre	Stabilisation	No flow	

Reducing the water quantity to 200 ml (8047) meant that the magnets were not even fully submerged, and we could see salt sedimentation (Nita, 2010). This led to some very inconsistent results. The ink drop moved in the opposite direction or stayed stuck to the unsubmerged magnets. With such reduced water quantity, the amperage also did not touch 6 A but stayed at 4.3 A with unusually high voltage (30.0 V) and one could sense smoke coming out of the apparatus.

Overall, increasing the water quantity seemed to work more predictably, especially in reduced amperage settings (M1 or M2). The hypothesis is that the brine solution has the salt that is fully dissolved (and hence no salt particles impeding the flow of the ink drops). The speed reduces potentially due to change in resistance of the electrolyte.

4.7 Change in concentration of the salt in conducting liquid

We next kept the water quantity constant (250 ml) but changed the salt quantity, and hence, concentration from 5 tsp (20 g) to 6.25 tsp (25 g). We checked the flow of the ink drop with the three different amperage settings.

Table 14. Description of the cases performed by changing the salt concentration.

Recording	A	V	Position	Timing	Direction	Time
8048	M3 (6.0 A)	16.9 V	Centre	Stabilisation	Flow of current	2.1 s
8049	M2 (1.0 A)	4.5 V	Centre	Stabilisation	Flow of current	5.3 s
8050	M1 (0.1 A)	0.08 V	Centre	Stabilisation	No movement	

Increasing the salt concentration to 6.25 tsp did not result in any substantive new observations. At M3 (8048), the ink drop flowed in the direction of current and exited the channel in 2.1 s; at M2 (8049), it did the same in 5.3 s; and at M1 (8050) it did not move.

We further increased the salt concentration, keeping the water quantity constant (250 ml) and added 7.5 tsp (30 g) of salt at the M3 (6.0 A) setting.

Table 15. Description of the cases performed by changing the salt concentration.

Recording	A	V	Position	Timing	Direction	Time
8042	M3 (6A)	15.6V	Centre	Stabilisation	Erratic	

Increasing the salt concentration to 7.5 tsp (8042) resulted in an interesting observation. The ink drop moved in both directions in the channel and moved randomly between the magnets.

The hypothesis is that increasing the quantity of salt in the brine solution increases resistance, and therefore decreases the speed of the ink drop flow. Further increasing the quantity of salt probably leads to salt sedimentation (Figure 7) thereby impeding the ink flow and making the readings erratic.

Figure 7: 8042 - Erratic movement with salt sedimentation.

4.8 Change in electrode gap

We next changed the distance between the electrodes from the default of 4 cm to 2 cm (Zhang Yang Z. H., 2019)

Table 16: Description of the experiments performed by reducing the electrode gap.

Recording	A	V	Position	Timing	Direction	Time
8054	M3 (6.0 A)	6.8 V	Centre	Stabilisation	Erratic	
8055	M3 (6.0 A)	13.4 V	Centre	Stabilisation	Erratic	

The change in distance between the electrodes had some significant impact on the flow of the ink drop. The default distance where the flow velocity was closest to what was expected was 4 cm. When we brought the electrodes closer to 2 cm (50% reduction in distance), the experiment (8054, 8055) yielded very erratic results. We found little repeatability as we performed the same experiment multiple times. Sometimes the ink drop moved towards one of the electrodes and just stayed there; sometimes it darted outwards and sometimes it moved in the opposite direction (Figure 8).

Figure 8: 8054 - Erratic movement when electrode distance is quite small.

We next increased the electrode distance to 6 cm and noted the reading for different amperage settings of M3 (6.0 A), M2 (1.0 A) and M1 (0.1 A).

Table 17: Description of the experiments performed by increasing the electrode gap.

Recording	**A**	**V**	**Position**	**Timing**	**Direction**	**Time**
8057	M3 (6.0 A)	13.4V	Before 1st magnet	Stabilisation	Erratic	
8058	M3 (6.0 A)	13.4 V	Above 1st magnet	Stabilisation	Erratic	
8059	M3 (6.0 A)	13.5 V	Above 3rd magnet	Stabilisation	Flow of current	2.2 s
8061, 8062	M2 (1.0 A)	3.3 V	Centre	Stabilisation	Swirled	
8063	M1 (0.1 A)	0.9 V	Centre	Stabilisation	Minor movement	

When we increased the distance between the electrodes, we had some interesting observations. When we placed the ink drop between the two electrodes and before the first magnet (8057), the drop seemed to swirl but did not move in the direction of the current. We repeated the experiment with the drop placed in the centre but above the first magnet (8058) and it did the same. However, when we moved the ink drop further down the channel and placed it over the third magnet (8059), then the flow happened as expected and the ink drop exited the channel in 2s.

Reducing the amperage to M2 (8061, 8062) resulted in the drop swirling but not moving forward. Reducing the amperage further to M1 (8063) saw a minor movement but nothing substantive.

We believe the distance between the electrode distances is an important variable to observe the MHD flow. When the electrodes are too close to each other, the magnetic field is probably not well defined and impedes flow of the ink drop. When the electrodes are quite distant from each other, the magnetic field and the resultant Lorentz force probably weakens and makes the flow of the ink drop quite sluggish. Only when the ink drop is placed at points where the Lorentz force is the strongest, does it move in the desired direction.

4.9 Other changes in the experiment

We placed the magnets as N-S-N-S-N-S. If we used similar polarities facing each other, there would be, as expected, no Lorentz force and no movement of the ink drop. If we placed two magnets with opposing polarity and two with same polarity (e.g. N-S-S-N-S-N), then there was some movement but a visibly slower and reluctant flow. We also tried placing the magnets longitudinally to the electrodes, rather than latitudinally, but this created no Lorentz force and no movement of the ink drop.

The best set up was three to five magnets, placed parallel to the electrodes with opposite polarities facing each other. During setup, it was important to firmly place one magnet at a time, with blu-tack to the surface of the tray. Else the magnets would attract each other and form a “pile” on top of each other rather than a “train” that we sought.

The magnets were placed on the surface of the tray and submerged below water. We tried placing the magnets on the underneath of the tray but, potentially due to the relatively weak strength of the magnets, we found no ink flow to happen and so we did not pursue that much further.

5 CHALLENGES FACED DURING EXPERIMENTS

5.1 Use of a fluid (ink drop) instead a solid (pellet)

Initially we tried using a solid pellet to measure the velocity under the influence of the Lorentz force. However, in our home experiment setup, the magnets used were not of industrial strength and therefore, the Lorentz force exerted was quite weak which did not move the solid pellets as desired. Hence we had to use an ink drop (which is similar to the experimental set up we had replicated) (Ingredients, Magnetohydrodynamics - Propelling Liquid Metal with Magnets). While the use of ink drop worked well from a fluid movement standpoint, however it was difficult to accurately measure the time it would take the ink drop to exit the channel as different particles of the ink would move at different speeds. Despite using a 60 fps camera, our measurement of time was relatively visual and accurate only to 1/10th of a second. This meant that this report could record only qualitative observations and hypotheses, and we were unable to perform quantitative calculations on our observations.

5.2 Deformation of the tray

The use of the tray itself had some implications on observing the flow of the ink drop. We used a plastic tray and because plastic is malleable, over the course of the experiments, the centre of the tray (which is where the maximum fluid flow was happening and hence, the highest Lorentz force was being applied) became somewhat deformed. This caused the ink flow to happen regardless of the Lorentz force and just because of the curvature of the bottom of the tray. We had to change the tray a few times during the experimental setup just to ensure that the surface is as flat as possible.

5.3 Consistency of voltage

We tried using 9V batteries in series with electrical wires to create the electrical flow. But we were not able to make the experiment work, probably because of the low electrical voltage and the consequent magnetic field induced. Also over a series of experiments, the electrical strength of the batteries would deplete and we were not able to measure the actual V-A to compare it to the theoretical values. Hence, we purchased a DC source of current so that we could accurately measure the V-A and so that there is no depletion in the flow of current.

5.4 Electrical polarity

Getting the setup with the electrical wires right was important. Initially we were not careful with where the +ve clip wire connect and where the -ve clip wire connect. We had to remain consistent with the use of colours (black for positive and red for negative) and note the position of the wires on the electrodes as that, in a binary manner, determined if the ink drop would flow along the channel created by the electrodes or in the opposite direction.

5.5 Working fluid

We used a long metallic rod as our electrode and used a saw to cut it into 12-inch stacks. We used water to fill the tray and salt to form a conducting liquid. Staying measured with the quantity of water and ratio of salt to water was important. Initially, we used distilled water, but we found it yielded very poor results despite the high usage of salt. Low quantities of salt would yield no movement of the ink drop. Higher quantities of salt, instead, would form a sedimentation despite significant stirring and waiting and this would, in turn, provide inconsistent results with the ink drop. Hence, we ended up using tap water for consistent results. We found that 1 tsp (4 g) of salt for every 50 ml of water is ideal for forming a perfectly dissolved and highly saturated solution. As default, we used 250 ml of water in the tray with 5 tsp of salt. This formed a highly saturated solution, as we desired, and also submerged the magnets well.

5.6 Other challenges

With the DC source of current, we struggled initially with controlling the specific current or voltage and we had to resort to youtube videos to understand the functioning of the apparatus itself and realised that double clicking the voltage knob or the amperage knob makes it flash. Then shifting it to the left or the right moves the unit of measure (from hundredths to tenths to units to tens).

6 SUMMARY AND CONCLUSION

A homemade experimental setup was made to study the MHD flow of an electrically conducting fluid between two parallel plates under the influence of electric current (DC) and magnetic field (constant with time). The current is passed using a DC source between the plates which also acts as the positive and negative electrode. A set of neodymium magnets was used to generate the magnetic field. The brine solution was used as the working fluid in the setup. The setup was used to study the MHD flow by modifying the parameters such as quantity of the brine solution, salt concentration, gap between the parallel plates, number of magnets, polarity of the magnetic field and current, and magnitude of the current. The flow of the solution was tracked by using ink which was dropped in the solution during experiments. It was observed that flow is dominant at the locations where the magnitude of the Lorentz force is significant. Additionally, the dominant flow makes a pattern similar to the magnetic field lines along the perpendicular plane (parallel to the plates). The pattern is the result of the Lorentz force distribution in the liquid. The timing of the ink drop was varied to study and compare the already established flow and development of the flow. The speed of the flow increases with an increase in the magnitude of the current and the flow is reversed with a change in polarity. The increased salt concentration results in increased current due to the lowering of the electrical resistivity.

In our study, since a homemade setup is used, the lack of flow measurement devices limits the applicability to some extent. Although qualitative observations were made, there is further scope for continuing the study by measuring the flow using advanced techniques and comparing the same with the theoretical results.

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