ELECTROMAGNETIC EFFECT ON THE RHEOLOGY OF LIQUID SUSPENSION

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by
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ABSTRACT

Innovative methods to control the viscosity and turbulence in the flow of liquid suspension can be engineered by way of incorporating the concepts of electric and magnetic field into the rheology of complex fluids.

Rheology of liquid Chocolate is a very crucial factor in determining the cost of manufacturing process as well as formulating varieties of end consumer products, for example, containing less fat. We have invented a method to lower the viscosity of liquid chocolate flow with the application of electric field. In the lab, we have found that viscosity of chocolate samples is reduced by 40~50% with our method. Thus, fat content in those samples can be reduced by 10% or more. Therefore, we expect to see much healthier and tastier chocolate product in the market once this technology gets implemented in commercial manufacturing.

High viscosity and turbulence in blood flow greatly increase the risk of cardiac diseases. Hence, discovering new method to address turbulence suppression and viscosity reduction is critically important. In our study, we have found that in the in-vitro experiment, if blood is subjected to flow through a channel placed inside a strong magnetic field, its viscosity reduces by 10~20%. Based on these findings, a Megneto-Rheology (MR) therapeutic device has been developed to examine the effect on the blood pressure in human subjects. Preliminary clinical trials show that application of this MR therapy reduces blood pressure by 10% or more.

In this thesis, above mentioned inventions for the flow of Blood and liquid Chocolate will be thoroughly discussed.
Dedicated

to

The most precious element of harmony in my life,

My daughter

ZYENA
ACKNOWLEDGMENTS

First and foremost, thanks to the Almighty ALLAH for keeping me healthy and fortunate enough to see this day, and hopefully beyond to achieve my life goal. I would take this opportunity to express my appreciation to all the people in my life who are in one way or other have helped me to complete this journey.

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CHAPTER 1
INTRODUCTION

One of the most important modes of transporting material is fluid flow. In fact, life as we know it is practically impossible without fluid. Majority of the observable mass in the universe exists in a fluid state. Vast oceans, rivers covering this Earth is fluid. Thus, science of fluid flow has immense practical importance.

Rheology is the science of the flow and deformation of materials (liquid or soft-solid) because of an applied force. Understanding the traits of materials, especially the behaviors how they flow and break, is very important for a wide variety of applications. Rheology is very important to understand the fundamental nature of fluid system. Improvement of rheological properties of a system has many every day applications including chemical industries, pharmaceutics, oil drilling, etc.

1.1 Motivation

High viscosity and turbulence in blood flow greatly increase the risk of cardiac diseases, such as, heart attacks and strokes, which are the leading causes of death. Turbulent blood flow makes the vasculature vulnerable to development of atherosclerotic plaque. In consequence, heavier workload on the heart results in high blood pressure, reduced oxygen function, heart murmur etc., which eventually may lead to heart attacks or
ruptured blood vessels. Hence, studying the rheology of blood to discover new method for both turbulence suppression and viscosity reduction at once is critically important.

Rheology of liquid chocolate is a very crucial factor in determining the cost of manufacturing process as well as formulating varieties of end consumer product, for example, containing less fat. However, removing even a small amount of fat from product composition would make the chocolate so viscous that the flow pipeline gets jammed.

Both Blood and liquid chocolate fall under the broad definition of liquid suspension. Innovative methods to control the viscosity and turbulence in the flow of liquid suspension can be engineered by way of incorporating the concepts of electric and magnetic field into the rheology of complex fluids.

1.2 Research Objectives

We were motivated to explore the effects of electromagnetic field on Chocolate and Blood because of previous successful result for Crude Oil flow, invented by Rongjia Tao [3]. It was found that application of electric field parallel to the flow direction reduces the viscosity of crude oil by 20% or more [4]. That invention has already been commercialized into AOT, acronym for Applied Oil Technology, by QS Energy Inc.

Hence, we have designed and developed experiments to observe the effect of electric field on the flow of liquid chocolate. Application of electric field on the liquid chocolate along the flow direction forces cocoa particles to aggregate into prolate spheroids in micrometers. Such change in micro-structure breaks the rotational symmetry, reduces
the viscosity of chocolate along the flow direction, and increases its maximally random jammed density significantly. Hence the fat level in chocolate can be effectively reduced.

On the other hand, to manipulate blood flow we opted for magnetic field. Because, we hope to develop a therapeutic device for actual application on human out of our invention. High voltage may not be safe for such therapy. Moreover, our target component is red blood cell due to their magnetic property. Similar to crude oil and chocolate, when blood passes through magnetic field, the red blood cells would align along the applied field direction, resulting in streamlined less viscous flow.

1.3 Accomplishments

In the lab, we have found that viscosity of chocolate samples is reduced by 40~50% with this electrorheology method. Thus, fat content in those samples can be reduced by 10% or more. We have published these results in Proceedings of the National Academy of Sciences of the United States of America 113(27):7399–7402. The invention has already been patented. And currently in the process of commercialization.

On the other hand, the in-vitro experimental results show that after blood passes through a channel placed inside magnetic field, its viscosity reduces by 10~20%. Also imaging on the channel revealed suppressed turbulence. Based on these findings, a Megneto-Rheology (MR) therapeutic device has been developed to find the effect on the blood pressure in human. We are currently conducting clinical trials of this technology.
It is worthwhile to mention that, the underlying principles of physics established for electrorheology and magnetorheology technique is, in general, applicable to manipulate flow properties of appropriate type of liquid suspension, some will be affected by electric field, while others by magnetic field.

1.4 Thesis Outline

In the chapter 2, physics behind the electromagnetic effect on the flow of liquid suspension will be discussed. Also, a brief review on the experimental techniques and results for crude oil will be presented.

In chapter 3, the development of the device and experimental techniques to observe the effect of electric field on the liquid chocolate flow will be discussed. Preparation of the liquid chocolate, calculating viscosity will be thoroughly described.

Next in the chapter 4, a strikingly innovative way to manipulate rheological properties of blood by magnetic field will be discussed. How we have treated the blood samples inside the magnetic field, how we recorded viscosity, how we prepared the device for clinical trials will be described.

Finally, the conclusion will be given in chapter 5 describing the current status towards the future of our research.
CHAPTER 2
INTRODUCING ELECTRO-RHEOLOGY FOR LIQUID SUSPENSION

Let us first revisit few basics.

2.1 Basics of Rheology

Three basic ideas constitute rheological terms. These are stress, strain, and viscosity. Stress is the amount of force applied to a given area of the material. Strain is the degree to which the material deforms. Viscosity of fluid is the ratio of stress to rate of strain, which indicates the tendency of the fluid’s resistance to flow.

In a simplest illustration, Figure 2.1 [3], two plates, each of area $A$, is separated by a distance $H$. If the top plate is moved at velocity $V$ by a force $F$ relative to each other, Newton's law states that the shear stress, the force divided by the area parallel to the force, $F/A$, is proportional to the shear strain rate, ratio of relative velocity to the distance of top moving plate, $V/H$. The proportionality constant is denoted as the viscosity, $\mu$.

Newton’s law of viscosity,

$$\tau = \mu \cdot \dot{\gamma} \quad (2.1)$$

where, shear stress, $\tau = F/A$, shear rate, $\dot{\gamma} = V/H$, and $\mu$ is the viscosity.

Rheology has developed two classes of liquids. Depending on their viscosity behavior as a function of shear rate, stress and deformation, fluids are characterized as either Newtonian or non-Newtonian.
Figure 2.1: Displacement of a material caused by shear stress
Newtonian fluids are described by the flow behavior of fluids with a simple linear relation between shear stress and shear rate, as in Equation 2.1. With Newtonian fluids (include water, organic solvents, and honey) the viscosity is independent of shear rate.

However, most fluids are non-Newtonian, which means that their viscosity is dependent on shear rate (Shear Thinning or Thickening) or the deformation history (Thixotropic fluids). Unlike Newtonian fluids, non-Newtonian fluids display rather a non-linear relation between shear stress and shear rate, Figure 2.2(a). A fluid is “shear thickening” if the viscosity of the fluid increases as the shear rate increases. By contrast, a fluid is “shear thinning” if the viscosity decreases as the shear rate increases, Figure 2.2(b).

Hence, in experimental rheometry the rheology, is described in terms of an apparent viscosity, \( \eta = \frac{\tau}{\dot{\gamma}} \), measured at a particular stress or strain rate. Obviously, for a Newtonian fluid, \( \eta \equiv \mu \), however, for a non-Newtonian fluid, apparent viscosity is a function of shear strain rate.

The fluids that will be discussed in this thesis are of liquid suspension type, which are very complex non-Newtonian. A suspension is a mixture between two substances, one of which is finely divided and dispersed in the other.

The rheology of a suspension is a complex function of its physical properties and of processes that occur at the scale of the suspended particles. The most important factors are particle volume fraction, particle shape, interactions between particles, the spatial arrangement of particles and the nature of the bulk flow [4]. Other factors which are important in certain suspensions, but have received less attention, are the size- and shape-distribution of the particles and inter-particle forces (e.g. electroviscous effects).
Figure 2.2: Difference in characteristic between Newtonian and non-Newtonian fluid
2.2 Properties of Fluid Flow

Flows through pipes and channels are the most common and important method of transportation of fluids. To enhance the flow output via pipeline requires reducing the fluid viscosity and suppressing turbulence. Fluid flow through a pipeline can be classified as laminar and turbulent. Laminar flow is characterized by smooth streamlines and highly ordered motion, whereas turbulent flow is characterized by velocity fluctuation and highly disordered motion, Figure 2.3. Laminar flow occurs when a fluid flows in parallel layers, with no disruption between the layers. There are no cross-currents perpendicular to the direction of flow, nor eddies or swirls of fluids. On the other hand, turbulent flow is a less orderly flow regime that is characterized by eddies or small packets of fluid particles.

The Reynolds number correlates different flow characteristics. The Reynolds number is a dimensionless quantity that measures the ratio of inertial forces to viscous forces and describes the degree of laminar or turbulent flow. By definition:

\[ N_R = \frac{\rho v D}{\eta} \]  

where \( D \) is the diameter of the pipeline, \( v \) is the average flow velocity, \( \rho \) is the density of fluid, and \( \eta \) is the viscosity of fluid. Typically, for a smooth pipeline when the Reynolds number \( N_R \leq 2300 \), the flow in the pipeline is laminar.
Figure 2.3: Velocity profile in laminar and turbulent flow
The friction factor for laminar flow is

\[ f = \frac{64}{N_R} \]  

(2.4)

The pressure drop is

\[ \frac{\Delta P}{L} = \frac{\rho v^2 f}{2D} = \frac{32v\eta}{D^2} \]  

(2.5)

where \( L \) is the length of the pipeline.

The flow rate is given by

\[ Q = \pi D^2 v/4 = \pi D^4/128\eta \left( \frac{\Delta P}{L} \right) \]  

(2.6)

A turbulent flow with \( 2300 < N_R < 100000 \), its friction factor can be estimated by Blasius relation [5],

\[ f = \frac{0.3164}{(N_R)^{0.25}} \]  

(2.7)

The flow rate of the turbulent flow is then takes the form:

\[ Q = 2.2526 \frac{D^{19/7}}{\rho^{3/7}\eta^{1/7}} \left( \frac{\Delta P}{L} \right)^{4/7} \]  

(2.8)

2.3 Electro-Rheology of Liquid Suspension

Most fluids in nature are liquid suspensions. They can either be a fluid having solid particles suspended in a base liquid or a fluid made of different molecules: The large molecules are regarded as particles suspended in the base liquid, consisting of small molecules. Examples include Crude oil, liquid Chocolate and Blood, which are the topics of our interest within the scope of this thesis.
The viscosity of most fluids is isotropic. The important exception is nematic liquid crystal. When its molecules are aligned by a magnetic field in the field direction, it has very low viscosity along the field direction. Meanwhile, its viscosity in the directions perpendicular to the magnetic field is very high [6].

Getting insight from the nematic liquid crystal behavior, Rongjia Tao has proposed [7,8] that electro-rheology (ER) provides an efficient solution to overcome the turbulence in crude oil flow in pipelines. According to his theory, if we apply a strong electric field along the flow direction in a small section of pipeline, the suspended particles inside the base liquid will polarize and aggregate into short chains along the flow direction. Such aggregation breaks the rotational symmetry and makes the fluid viscosity anisotropic. Along the flow direction, the viscosity is significantly reduced, but in the directions perpendicular to the flow, the viscosity is substantially increased. Therefore, all vortices and rotating motions are suppressed; hence the turbulence will be suppressed.

Aggregation into short chain, thus forming a prolate spheroid shape has been confirmed by the small-angle neutron scattering experiment done at the NIST Center for Neutron Research. This excellent work [9] was done our group colleague Dr. Enpeng Du.

Currently, many pipelines use a drag-reducing agent (DRA), an additive made of polymer chains, to suppress turbulence [10]. The ER treatment enforced short chains will play a similar function as polymer additives in DRA, without actual additives. Thus, ER technology is friendly to the refineries in the crude oil case. Moreover, the technology also significantly reduces the viscosity along the flow direction and enhances the flow output, while DRA cannot reduce the oil’s viscosity.
Figure 2.4: Device setup for Crude oil ER experiment
Figure 2.5: Environment control chamber
2.4 Experiments and Results

The device is shown in Figure 2.4, is kept in an environment chamber, Figure 2.5. Oil flows down from top reservoir via pipeline due to gravity. In the middle of the pipeline we put a custom designed capacitor, Figure 3.7, to build up the desired electric field along the flow. Oil passes through this capacitor, gets ER treatment. Then flows through a capillary tube, finally accumulates in a cup on microbalance. LabVIEW connected to this microbalance records mass of collected oil and elapsed time, thus gives mass flow rate data. The capillary tube serves as viscometer. Initially, we let the oil flow without electric field. Then we turn on the field, and oil gets ER treatment. We continuously record flow rate data.

One recent example result is shown in Figure 2.6. In this case, flow rate of a Cenovus sample was increased by 86.7% at 23°C. Further tests on that Cenovus sample revealed following data [11]:

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Pre-Treatment Viscosity (cp)</th>
<th>Post Treatment Viscosity (cp)</th>
<th>Electric Field Applied (V/mm)</th>
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<tr>
<td>23</td>
<td>715.8</td>
<td>383.4</td>
<td>1612</td>
</tr>
<tr>
<td>16</td>
<td>1,821.2</td>
<td>1,022.0</td>
<td>1704</td>
</tr>
<tr>
<td>12</td>
<td>2,750.5</td>
<td>1,559.2</td>
<td>1704</td>
</tr>
<tr>
<td>6</td>
<td>6,003.7</td>
<td>3,594.0</td>
<td>1612</td>
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</table>
Figure 2.6: Flow rate of the Cenovus crude oil sample was increased 86.7% [11].
2.5 Conclusion

Successful results for crude oil primarily inspired us to begin the project on other fluids. The ER physics is a general concept which applies on variety of liquid suspension. Incidentally, similar physics can be developed using Magnetic field for Blood flow, which will be described in chapter 4.

Detailed theoretical rigor for crude oil is already explained in R. Tao’s article [8]. In the next chapter, the rigorous development for Chocolate will be discussed.
CHAPTER 3
EFFECT OF ELECTRIC FIELD ON LIQUID CHOCOLATE

We see chocolate products in stores everywhere, mostly in solid or powder form. However, chocolate is liquid during the manufacturing processes into those end products. And that’s where physics of chocolate comes into action.

Liquid chocolate is a suspension of solid particles consisting of cocoa, sugar, milk solids etc. in a base liquid of melted fat and oil, mainly cocoa butter. Viscosity of liquid chocolate is a very critical quantity that determines manufacturing process and cost [12]. Whereas, viscosity depends on the fat content in chocolate. Reducing the fat level would make the chocolates much healthier, however, removing even a small amount of fat would make chocolate very thick and viscous, and would be very difficult to maneuver through pipelines. An innovative method to tackle this challenge will be discussed in this chapter.

3.1 Challenges to Manipulate the Rheology of Liquid Chocolate

For all liquid suspensions, two important quantities are Maximally Random Jammed (MRJ) density, \( \varphi_x \) [13], and particle’s intrinsic viscosity, \( \nu \), which depends on the particle shape. For example, a suspension of monodispersed spherical particles has \( \varphi_x \) about 64% and \( \nu = 2.5 \). The generalized form for viscosity of liquid suspensions with different particle shape and volume fractions is [14]:

\[
\eta = \eta_o \left(1 - \frac{\varphi}{\varphi_x}\right)^{-\nu \varphi_x} \quad (3.1)
\]
where, \( \eta_0 \) is the viscosity of base liquid; \( \phi \) and \( \nu \) are the particle’s volume fraction and intrinsic viscosity, respectively. Since cocoa solids are spherical in shape of diameter 2\( \mu \)m [15], the fat level cannot be lower than \( 1 - \phi_x = 36\% \). Otherwise, the liquid chocolate would jam in the pipeline. Even when \( \phi < \phi_x \), removing small amount of fat from base liquid, i.e., if \( \phi \) approaches \( \phi_x \), the viscosity increases sharply, as shown in Figure 3.2. Hence, we need a new technology that would achieve two key conditions simultaneously:

(i) Reducing the viscosity of liquid chocolate effectively at high volume fraction of solid particles

(ii) Increasing the \( \phi_x \), the MRJ density.

Previous attempts in reducing fat level in chocolate products via conventional methods [12,16] were unsuccessful in accomplishing both conditions.

### 3.2 New Physics Discovered for Treating Chocolate with Electric Field

Our unconventional ElectroRheology (ER) research addresses this critical issue. Application of an electric field in the flow direction of liquid chocolate can aggregate the solid particles into prolate spheroids along the flow direction. This microstructure change breaks the rotational symmetry, leading to increased \( \phi_x \), thus viscosity reduces substantially along the flow direction. This method is very much different than traditional ER fluids, where the applied electric field is perpendicular to the flow direction, leading to the increase of effective viscosity or even solidify the ER fluids [17-19]. In our method, applied electric field is along the flow direction to control the size of aggregated particles.
Figure 3.1: Liquid chocolate flows through a strong electric field; the solid particles aggregate along the field direction to form short chain, and hence viscosity along the flow direction is reduced significantly.
The method can be sketched as in Figure 3.1. Liquid chocolate flows from left to right through a pipe. In the middle of the pipe a strong electric field is set up with metal mesh electrodes along the flow direction.

The cocoa solid particles polarize when they pass the electric field, because the electric permittivity of cocoa solid, \( \epsilon_p \approx 2.5\epsilon_o \) is higher than that of melted cocoa butter \( \epsilon_f \approx 1.8\epsilon_o \) [19,20]. The polarization:

\[
\vec{p} = 4\pi\epsilon_f\vec{E}_{loc}a^3 \left( \frac{\epsilon_p - \epsilon_f}{\epsilon_p + 2\epsilon_f} \right)
\]

where, \( \epsilon_o \) is the vacuum permittivity and \( \vec{E}_{loc} \) is the local electric field acting on the particles, which is stronger than applied electric field. The interaction between two induced electric dipoles:

\[
U = \frac{p^2(1 - 3\cos^2\theta)}{4\pi\epsilon_f r^3}
\]

here \( r \) is the distance between the center of two particles, and \( \theta \) is the angle between the field and the line joining two dipoles. \( U \) reaches minima,

\[
U_{min} = \frac{-p^2}{(16\pi\epsilon_f a^3)}
\]

when two particles touch each other and align along the field direction, i.e., \( \theta = 0 \) and \( r = 2a \). Hence, the induced dipolar interaction would force the particles to aggregate into short chains. The aggregates are shaped like prolate spheroids with their long axis in the flow direction. Such change in microstructure results in two following situations.
(1) Since MRJ density, \( \varphi_x \), depends on particle shape, so for spheroids, \( \varphi_x \geq 0.72 \), minimum base liquid, fat, would be \( 1 - 0.72 = 28\% \); which is 22.2\% less than the minimum, 36\%, required for spheres [21,22]. Moreover, ER aggregation introduces polydispersity in particle size, which increases MRJ density even more.

(2) In addition, short chain formation along the flow direction would break the rotational symmetry. Thus, viscosity would be anisotropic. That is, viscosity is substantially reduced along the applied field direction. Since we impose the field along flow direction, the flow rate will enhance as well [7,8].

A prolate spheroid can be given by –

\[
\frac{x^2 + y^2}{b^2} + \frac{z^2}{a^2} = 1
\]  

where, \( a > b \) and the intrinsic viscosity along the rotational axis \( z \), \( \nu_\parallel \) is smaller than the intrinsic viscosity of spheres 2.5. In contrast, the intrinsic viscosity along the directions perpendicular to the \( z \) axis, \( \nu_\perp \), is higher than 2.5 [23]. For example, if \( b/a = 1/3 \), \( \nu_\parallel = 2.089 \) and \( \nu_\perp = 3.099 \).

To show the ER effect, in Figure 3.2, we plot viscosity of a fictional chocolate consisting 60\% cocoa solid and 40\% melted fat. Without ER treatment, the relative viscosity of chocolate is given by –

\[
\frac{\eta}{\eta_o} = (1 - 0.6/0.64)^{-2.5*0.64} = 84.45
\]  

After the ER treatment, if the particles are aggregated into the prolate spheroids of same size, the relative viscosity along the flow direction would be –

\[
\frac{\eta_\parallel}{\eta_o} = (1 - 0.6/0.72)^{-2.089*0.72} = 14.80
\]
which is 82.47% less than the original viscosity. Whereas the relative viscosity along the direction perpendicular to the flow would be –

\[
\eta_\perp / \eta_o = \left(1 - \frac{0.6}{0.72}\right)^{3.099+0.72} = 54.48
\]  \hspace{1cm} (3.8)

This higher viscosity along the perpendicular directions to the flow will not impede the flow, rather assists in suppressing vortex formation and turbulence [22].

This approach significantly differs from the conventional ER fluid applications, where the electric field is always perpendicular to the flow direction and the aggregated structures would be large enough to connect the two electrodes, which eventually increases viscosity. Here we propose a novel way to apply electric field along the flow direction. In the above example, viscosity along the flow direction, \(\eta_\parallel\), is significantly reduced. Equation 3.7 can be manipulated to give the same value as in Equation 3.6 as –

\[
\eta_\parallel / \eta_o = \left(1 - \frac{0.682294}{0.72}\right)^{-2.089+0.72} = 84.45
\]  \hspace{1cm} (3.7)

Note, the particle volume fraction can be 68.2%; which implies total fat can be 31.8% instead of 40% while keeping the viscosity of the ER treated liquid chocolate the same as the original non-treated one. The new composition would have 20.5% less fat. Such drastic reduction may change the taste of chocolate. Let’s consider instead that, we want a reduction of 10%, i.e., from 40% to 36%. Then we make the particle volume fraction 64%, which would translate the relative viscosity, Equation 3.7, into 27.24. Which is 67.7% lower compared to Equation 3.6; still much favorable for chocolate production.
Figure 3.2: Viscosity of original liquid chocolate and the viscosity of ER-treated liquid chocolate along the flow direction.

Point A represents the original state at $\varphi = 0.6$. Removing a small amount of fat increases viscosity sharply, point B. In contrast, the same viscosity, point C, can be achieved with 20% less fat if the chocolate passes through electric field.
3.3 Description of Experimental Setup

To establish the theoretical prediction, we need to measure the viscosity of liquid chocolate along the flow direction after treating with electric field. Then we can determine on the amount of fat to be reduce.

Traditionally the viscosity of chocolate is measured with rotational viscometer. However, we cannot use such to measure the anisotropic viscosity, which is our expected outcome from ER treatment. Hence, we designed an innovative device as in Figure 3.3.

At first, we set the Queue Cell Culture Incubator to a prespecified temperature, and keep ample amount of solid chocolate sample, Figure 3.10-12, in a food grade jar inside the incubator, Figure 3.5. When the sample completely melts, Figure 3.13(A), we pour liquid chocolate in a big cylindrical container sitting atop a metal stand. The lid of the container is removable, connected to compressed Nitrogen gas supply. At the bottom of container, we attach a special custom-made electric field grid, Figure 3.7. Which is essentially a Capacitor containing 3 parallel plate electrodes made of metal meshes, Figure 3.8, separated by small hollow glass tubes of equal length. The sections are glued with epoxy, and wires are soldered with the mesh. High voltage power supply, Figure 3.6, builds up the Electric field between the meshes. Lastly, capillary tube, Figure 3.9, of desired length and diameter is inserted at the bottom of capacitor.

Naturally, liquid will flow down due to gravitational push from contents in the top container. In addition, Nitrogen gas maintains balanced pressure from above. Liquid chocolate will pass through the capacitor, thus gets ER treatment, flowing down the
capillary and finally accumulates in a cup on microbalance, Figure 3.14. The balance, in conjunction with LabVIEW, gathers the data as collected chocolate mass against time. Thus, enables us to compute mass flow rate, \( Q \). The capillary tube serves the purpose to calculate the viscosity along the flow direction based on the following formula –

\[
\eta = \frac{\pi \rho^2 g R^4}{8Q} \left( 1 + \frac{h}{L} + \frac{P}{L \rho g} - \frac{v^2}{2gL} \right)
\]

where, \( h \) is the height of chocolate inside glass cylinder, \( \rho \) is the density of liquid chocolate, \( g \) is the acceleration due to gravity, \( P \) is Nitrogen gas pressure, \( R \) and \( L \) is the radius and length of the capillary tube, respectively, and the average flow velocity is –

\[
v = \frac{Q}{\rho \pi R^2}
\]

We have used few variations of capacitor, having different separation between electrodes, Figure 3.7, or different mesh pattern, Figure 3.8. Also, we have used variety of capillary tubes, Figure 3.9, to control the flow parameters.

For the results discussed in next section, the experiments were conducted with capillary tube of radius, \( R = 0.284 \text{ cm} \), and length, \( L = 15 \text{ cm} \). Chocolate height was measured as \( h = 18 \text{ cm} \), at the beginning, which slowly decreases as chocolate flows out. We constantly monitor this height to account for proper gravitational push.

When the accumulated chocolate reaches the limit of microbalance, we transfer the treated chocolate to a large storage jar, Figure 3.14. We let the chocolate solidify overnight, Figure 3.15, so that short chain formation retains. Then we repeat the flow measurement few days later without electric field to verify whether it retained lower viscosity. Also, we taste both the ER treated and non-treated solid chocolate to distinguish any difference.
Figure 3.3: Schematic diagram of the ER device
Figure 3.4: Device setup for Chocolate ER experiment
Solid sample kept inside the incubator, so that it turns liquid before flow experiment.

Figure 3.5: Queue Incubator
Figure 3.6: High Voltage (Electric Field) power supply and control system
Figure 3.7: The capacitor design for applying electric field in the pipeline

Dimension markups are NOT TO SCALE, design representation only.
We have used few variations of this capacitor. The opening at the bottom of container is fixed at 4.65 cm. However, the plate distance varies from 1 cm to 2 cm, also, different mesh patterns as shown in following figures.
Figure 3.8: Pattern variation of metal mesh in the capacitor

(A) Hole size is 2 mm
(B) Hole size is 3 mm
Figure 3.9: Different capillary tubes used.
Figure 3.10: Blommer Chocolate Sample A.
Figure 3.11: Blommer Chocolate Sample B.
Figure 3.12: Blommer Chocolate Sample C
(Milk Chocolate Bar)
Figure 3.13: Chocolate sample liquified

(A) Non-treated before pouring in the device.

(B) Treated after collecting from device.
Figure 3.14: Treated chocolate collection procedure
Figure 3.15: Storing treated chocolate

Liquid chocolate solidifies overnight.
3.4 Measurement Process and Results

At the beginning electric field is not applied. The whole assembled setup, Figure 3.4, is kept inside the incubator, whose temperature is fixed to the manufacturer recommended value for the chocolate sample, for example, Mars Chocolate requires 40°C for their samples, whereas Blommer requires 43°C. We left the device loaded with sample untouched for a while to let it come to equilibrium with the ambient environment. Then we open the valve so that chocolate starts flowing downward. Adjusting the Nitrogen gas pressure, $P$, we can control the flow velocity, $v$, until it interprets the prespecified shear rate, $\dot{\gamma}$, for that particular sample. Flow velocity is related to shear rate as –

$$v = R\dot{\gamma}$$  \hspace{1cm} (3.10)

Combining with Equation 3.9, we have –

$$Q = \rho \pi R^2 v = \rho \pi R^3 \dot{\gamma}$$  \hspace{1cm} (3.11)

where, $R$ is the radius of the capillary tube, $\rho$ is the density of liquid chocolate.

LabVIEW software is continuously capturing the flow rate data. When the desired level is reached, we let pass out another 20~30 g of chocolate so that flow rate stabilizes. Then the Electric Field (EF) is switched on. We see that until the untreated chocolate inside the capillary tube passes out, flow rate remains somewhat same, however, begins to increase slowly. Soon after when the treated chocolate starts accumulating on the cup, flow increases substantially, which signifies that the viscosity is reduced along the flow direction. During the test, temperature and pressure remain unchanged, to keep the ambient conditions similar.
Table 3.1: Effect of electric field on the flow rate and viscosity of Mars chocolate

<table>
<thead>
<tr>
<th>Applied Voltage (V/cm)</th>
<th>Flow rate (g/s)</th>
<th>Viscosity (Poise)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.05327</td>
<td>1088.59</td>
</tr>
<tr>
<td>1600</td>
<td>0.09284</td>
<td>614.65</td>
</tr>
</tbody>
</table>

Figure 3.16: Flow rate of Mars chocolate
Figure 3.16 shows flow rate plot for one sample of Mars chocolate. This sample has density $\rho = 1.35 \text{ g/cm}^3$, and prespecified temperature is 40°C. During that test, applied pressure was 3 PSI. EF was applied when about 30 g chocolate had flown out. Here we mentioned EF strength as 1600 $V/cm$; which implies the distance between top and bottom electrode inside the capacitor is 3 $cm$, and the applied voltage was 4.8 $kV$. It is evident on the plot that, steady linear flow rate at the beginning without EF. Whereas, in presence of EF, the rate increases significantly.

Data in table 3.1 clearly supports our theoretical prediction. Flow rate was increased by 74.3%, whereas, viscosity along the flow direction was reduced by 43.5%. Moreover, the electric current during the process was very small; certainly, smaller than the sensitivity 0.1$\mu$A of the multimeter. That implies this process is very much energy-efficient.

The trend is quite similar for every other sample from major chocolate manufacturers, Figure 3.18-20. Depending on the density and temperature, strength of electric field varies. Viscosity of any kind of chocolate can be reduced by 40~50%. Therefore, fat level in such chocolate can be reduced by 10% or more, and with ER treatment viscosity would still be lower compared to the original viscosity.

We have also conducted tests to verify the chain formation of cocoa particles under the electric field. In figure 3.17(a), cocoa particles are spherical. On the other hand, in presence of electric field the particles shaped as prolate spheroid, Figure 3.17(b), evidencing our prediction that the particles formed short chains.
Figure 3.17: Verification of short chains of cocoa particles in electric field

(a) Without electric field, particles are spherical.

(b) Particles aggregated in short chains, apparently similar to prolate spheroids.
Figure 3.18: Flow rate of various types of chocolates
Figure 3.19: Effect of Electric Field on chocolate flow rate
Figure 3.20: Effect of Electric Field on viscosity along flow direction
3.5 Discussion

As our results suggest, this ER method is universally applicable for all kinds of chocolate. It is worthwhile to mention that; viscosity reduction is achieved by the effect of electric field only. For liquid chocolate, the relationship between the shear stress and shear rate can be approximated by the Casson model [12]. Hence there is a shear-thinning effect, which was used to reduce its viscosity for a short period [16]. However, in our method, we don’t apply any additional shear force or pressure. Moreover, the viscosity reduction by this ER effect exceeds the reduction from the shear-thinning effect [15].

One critical concern about this viscosity reduction method would be: “how long this reduced viscosity state last?” Since our hypothesis is, cocoa particles aggregated into short chains along flow direction due to electric field. So, the chain would break without the field, and viscosity would return to normal.

We conducted follow up tests to investigate this issue. We store the chocolate in jar undisturbed right after the ER treatment to let it solidify. After few days, when that solid chocolate is melted again for flow test, it will eventually show a low viscosity after the short chains are tilted along the flow direction. So, it retains short chains as long as the chocolate is in the solid state. On the other hand, if the treated chocolate was kept in the liquid state after the treatment, we have found that the sample showed reduced viscosity even after 48 hours. The reasoning behind would be that, the aggregated short chains make the suspension a viscoelastic fluid. Dissembling such viscoelastic chains by thermal motion is very slow [8]. However, if the chocolate is shaken violently, the chains will break and the viscosity will return to the original value quickly.
3.5 Conclusive Remarks on Future Direction

The experimental results totally evidenced our hypothesis. However, there are certainly scopes for improvement. ER treatment depends on two important parameters – the electric field strength, and the duration of its effect the chocolate particles. So, there should be a balance between the flow velocity, applied voltage, dimension of the capacitor etc. For each unique sample, a unique combination of these parameters would give the optimum situation for viscosity reduction. Henceforth more tests are needed to be done.

In addition, flavor tests need to be conducted as well. To us, ER-treated chocolate tasted as good as regular ones. Though we cannot demand that definitively, without scientific blind taste experiments.

Therefore, ER treatment will match (or even lower) the viscosity of chocolate with less fat compared to the viscosity of regular chocolate. Eventually similar consumer products can be manufactured with less fat. We are thus expecting a new class of healthier and tastier chocolate products soon.

The physics of ElectroRheology is general, applicable to many other liquid suspensions to reduce the viscosity, improve the flow, or increase the volume fractions. For some fluids, magnetic field instead of electric field can be used [24]. We have explored one such fluid in our lab, which will be presented in next chapter.
CHAPTER 4

EFFECT OF MAGNETIC FIELD ON BLOOD

We have discussed the effect of Electric Field on liquid suspension (Chocolate) in previous chapter. At the end of the chapter, I mentioned that for some cases we can use Magnetic Field instead. One such liquid suspension is blood. We want to manipulate the properties of blood flow. However, the primary goal is to implement the invented technology to improve blood flow in Human.

As we have seen for chocolate, a capacitor would need to be installed in the pipeline, and applied voltage is relatively very high. Implanting such device inside the blood flow pipelines, i.e., arteries, veins is nearly impossible. Moreover, it may not be safe to apply such high voltage in human. So, the first alternative we may think of is magnetic field. Because, already established ubiquitous diagnostic technology Magnetic Resonance Imaging (MRI) uses relatively high magnetic field without any significant side effects. In this chapter I will describe one such application of magnetic field on blood flow.

4.1 Brief Overview of Blood and Its Components

Blood is a specialized body fluid, primarily composed of Red Blood Cells (RBCs or erythrocytes), White Blood Cells (WBCs or leukocytes) and Platelets (thrombocytes) suspended in base liquid Plasma, Figure 4.1. Such composition of any fluid is effectively a liquid suspension.
Figure 4.1: Illustration of blood and its components.

Image reproduced from Encyclopedia Britannica, Inc.
Plasma is a complex solution of water, salts, proteins, carbohydrates, and lipids. Its main function is to carry all other cells throughout the body as well as to transport nutrients, waste products, antibodies, clotting proteins, hormones, and proteins.

WBCs fight infections and aid in the immune process. They are only about 1% of total blood volume. Major types of WBCs are: Lymphocytes, Monocytes, Eosinophils, Basophils, Neutrophils, each has distinct properties.

Platelets are not actually cells but rather small fragments of cells. Platelets help the blood clotting process (or coagulation) by gathering at the site of an injury, sticking to the lining of the injured blood vessel, and forming a platform on which blood can clot.

RBCs are the most abundant cells in blood, about 40~45% of total blood volume. The shape of a RBC is a biconcave disk with a flattened center (like a solid donut); about 7.7 \( \mu m \) in diameter and 2.6 \( \mu m \) in thickness, Figure 4.2. RBC has no nucleus and can easily change shape, thus fits through the various blood vessels in the body. However, while the lack of a nucleus makes a RBC more flexible, it also limits the life of the cell as it travels through the smallest blood vessels, damaging the cell's membranes and depleting its energy supplies. RBC survives on average only 120 days.

Red color of blood comes from a special iron-containing oxygen-transport metalloprotein, Hemoglobin (Hb). It carries oxygen from the lungs to the rest of the body and then returns carbon dioxide from the body to the lungs, so it can be exhaled. Each RBC in human contains approximately 270 millions of these Hb biomolecules. Structurally the Hb molecule is an assembly of four globular protein subunits. Each subunit is composed of a protein chain tightly associated with a non-protein Heme group.
RBC can be approximated by an oblate ellipsoid of revolution
\[
\frac{x^2 + y^2}{a^2} + \frac{z^2}{c^2} = 1,
\]
with \(a = 3.85 \mu m\) and \(c = 1.3 \mu m\).

Figure 4.2: Illustration of Red Blood Cell.
Each Heme group consists of an Iron ion ($Fe^{3+}$ or $Fe^{2+}$) held in a heterocyclic ring, known as a porphyrin. This porphyrin ring consists of four pyrrole molecules cyclically linked together (by methine bridges) with the iron ion bound in the center. RBCs of an average adult human male store collectively about 2.5 grams of iron, representing about 65% of the total iron contained in the body.

4.2 Why Is It Vital to Improve Blood Flow?

The answer to this question is as trivial as it could be. An animal is alive only because of blood circulation. Let’s look in detail; what do we refer by “improve”. In the context of our research. We are referring low viscosity and less turbulence in blood flow inside vascular system in human body.

According to CDC, cardiovascular diseases, specially heart attacks and strokes are the leading causes of death, despite all the recent advances in interventions and treatments. Researches [25-40] indicate that high blood viscosity and turbulent blood flow are one of the major factors for all vascular diseases. In addition to causing ejection murmurs [34], turbulent blood flow puts heavier workload on the heart and higher pressure on blood vessels, consequently increasing the risk of heart attacks or ruptured blood vessels.

Moreover, biomechanical forces generated by blood flow play an important role in the pathogenesis of vascular disease [28]. Also, blood flow hemodynamic characteristics contribute to the pathogenesis of atherosclerosis [29,30]. Atherosclerotic lesions occur in a site-specific plaque. In vivo and in vitro studies have shown that disturbed flow is pro-
atherogenic by promoting inflammatory states in the artery wall, while steady laminar blood flow is athero-protective by actively reducing inflammatory genes such as cytokines and adhesion molecules in the vessel wall [29].

Vascular Endothelial Cells (VEC) are in direct contact with the flowing blood, thus they sustain most of the mechanical wall shear stress. One unique character of EC is that they act as mechanosensors. VEC respond to laminar or disturbed blood flow by activating signal transduction pathways. In the case of disturbed flow, these pathways result in maladaptive gene expression. Gene expression profiling has revealed that cultured VEC respond to fluid mechanical forces by modulating the mRNA level of many genes [31]. Studies indicate that the transcriptional response of cultured EC to disturbed flow conditions is similar to those at atherosclerosis-prone areas of the vasculature [32]. This gene expression profile is distinct from that elicited by athero-protective laminar flow [33]. Pro-inflammatory and thrombogenic gene expression initiate and propagate the changes in EC and underlying vascular smooth muscle cells, which eventually begin the plaque development in the areas of disturbed flow. A modality which can reduce disturbed blood flow hemodynamics would be potentially valuable as an anti-atherogenic therapy.

Despite the grave importance, no current medicine neither any therapy is available to suppress turbulence in blood flow. Aspirin or similar medicine works as blood thinner, thus reduces viscosity. However, such methods effect turbulence negatively. Because the Reynolds number goes up as the viscosity lowers.

Therefore, a safe and reliable method to reduce blood viscosity and suppress turbulence in blood flow will be critically beneficial in preventing heart attacks and strokes.
4.3 The Physics of MR (Magneto-Rheology) Technology for Blood Flow

As mentioned in previous chapters that viscosity of liquid suspension can be reduced by three mechanisms [7] –

(1) increasing the average size of suspended particles
(2) aggregating the particles into clusters with a streamlined shape
(3) increasing the suspension polydispersity

Our hypothesis is, the second mechanism may be achieved for blood if the RBCs can be organized in streamlined shape based on the idea, Magneto-Rheology (MR) [8,24,42].

The basic principle is, when we apply a strong magnetic field to blood along the blood flow direction, RBCs are polarized by the magnetic field and aggregated into short chains along the flow direction, hence, viscosity is significantly reduced along the flow direction. On the other hand, viscosity is increased in the directions perpendicular to the flow. Thus, blood viscosity will become anisotropic. Since the motions deviate from the flow direction are suppressed, turbulence in blood flow is suppressed as well. The blood flow becomes laminar. With the reduced viscosity along the flow direction, the blood flow is greatly improved and the workload on heart is reduced. While these effects are not permanent, they last for about 24 hours after one treatment, can be repeated.

In the blood, the base liquid, Plasma has viscosity $\eta_0 \approx 1.0 \text{ cp}$ at $37^\circ\text{C}$. The overall viscosity of whole blood, $\eta$, increases as the percentage of cells in the plasma increases, mainly due to the RBCs [14,43]. The volume fraction of RBCs, i.e. the hematocrit, is the main factor affecting the viscosity of blood. If the hematocrit is about 40% and RBCs are
randomly distributed in plasma, the relative viscosity of whole blood to the plasma’s viscosity, $\eta/\eta_o$, is slightly above 4. When the hematocrit rises to 60%, which often happens in patients with polycythemia, or abnormally high RBC counts, $\eta/\eta_o > 8$. In addition to high hematocrit, there are many other causes which lead to high blood viscosity. For example, many studies have linked cholesterol with blood viscosity; low-density lipoprotein (LDL) is consistently associated with higher blood viscosity [35]. Smoking has been shown to cause blood viscosity to surge by as much as 20%. Different from the effect of red blood cells on the viscosity $\eta$, the other effects raise the viscosity $\eta$ by increasing the viscosity of base liquid, $\eta_o$.

As discussed earlier, Hemoglobin (Hb) contains iron, and hence, RBC has magnetic behavior due to these irons. When the Hb is not carrying oxygen, it is more paramagnetic than oxygenated blood. In the last fifteen years this difference in magnetic property is used in Magnetic Resonance Imaging (MRI) research to examine the BOLD (blood oxygenation level dependent) signal for brain and other research [36-40]. It has been generally accepted that deoxygenated red cells have a magnetic susceptibility

$$\chi_r \approx 2.2 \times 10^{-5}$$

Since plasma mainly contains water, it is diamagnetic with

$$\chi_w = -5.4 \times 10^{-6}$$

Let the magnetic permeability of red cell be

$$\mu_r = \mu_0(1 + \chi_r)$$

and the magnetic permeability of the plasma be

$$\mu_f \approx \mu_0(1 + \chi_w)$$
In a magnetic field, the red cell is polarized with an induced dipole moment along its diameter direction parallel to the applied magnetic field in \( x \) direction,

\[
\vec{m} = \beta^{(x)} H_o \hat{e}_x
\]

where

\[
\beta^{(x)} = \frac{\Omega}{4\pi \left( \frac{\mu_f}{\mu_r - \mu_f} + n^{(x)} \right)}
\]

and

\[
n^{(x)} = \frac{1 - n}{2} = 0.1839
\]

\( \Omega \) is the volume of each red blood cell. For an oblate ellipsoid, as in Figure 4.3, eccentricity \( e = \sqrt{(a/c)^2 - 1} \), thus the constant

\[
n = (1 + e^2)(e - \tan^{-1} e)/e^3 = 0.63214
\]

The interaction energy between the magnetic field and the RBC can be given by [15] –

\[
U = \frac{a^2 c (\mu_f - \mu_r) H_o^2 [2(\mu_f - n(\mu_f - \mu_r)) \sin^2 \theta + \{\mu_r + \mu_f + n(\mu_f - \mu_r)\} \cos^2 \theta]}{6[\mu_r + \mu_f + n(\mu_f - \mu_r)][\mu_f - n(\mu_f - \mu_r)]}
\]

where \( \theta \) is the angle between the magnetic field and the red cell symmetry axis (z axis), which is perpendicular to the plane of disk face. Corresponding torque on RBC is

\[
N = -\frac{\partial U}{\partial \theta} = \frac{a^2 c (\mu_f - \mu_r)^2 H_o^2 (3n - 1) \sin 2\theta}{6[\mu_r + \mu_f + (\mu_f - \mu_r)n][\mu_f + (\mu_r - \mu_f)n]}
\]

This torque will rotate the cells. Since \( 3n - 1 > 0 \), the stable position will be \( \theta = \pi/2 \).

So, RBC disc face becomes parallel to magnetic field. If the applied magnetic field is one Tesla or above, the induced interaction energy between two dipole moments is stronger than the thermal motion, \( k_B T \). Hence, the cells will form short chains along flow direction.
Figure 4.3: Schematic representation – effect of magnetic field on blood flow.
Schematically, the MR effect can be illustrated in Figure 4.3. Blood is flowing from left to right. When the RBCs pass through strong external magnetic field $\vec{B}$, they become polarized. The strongest polarization occurs along the diameter acquiring a dipole moment $\vec{m}$. The corresponding torque forces RBC to rotate and make their symmetric axis perpendicular to the field. Force $f$ between the magnetic dipoles parallel to each other is repulsive. However, magnetic dipoles will feel attraction force $f'$ to each other along the diameter. Hence, they will form short chains along the direction of applied magnetic field. Consequently, the viscosity will be reduced along the flow direction. On the other hand, chains have very high intrinsic viscosity in the directions perpendicular to the flow. Thus, the treated blood has high viscosity in the directions perpendicular to the flow, making turbulence in blood flow suppressed as any disturbed flow requires motions in the directions perpendicular to the flow [8,24,42].

Recall Equation 3.1, the generalized form for viscosity of liquid suspensions:

$$\eta = \eta_o \left(1 - \frac{\varphi}{\varphi_x}\right)^{-\nu\varphi_x}$$

Let’s assume for a blood sample with relatively higher RBC volume fraction, hematocrit $\varphi = 50\%$. Then the ratio of blood viscosity, $\eta$, to the plasma viscosity, $\eta_o$, is

$$\frac{\eta}{\eta_o} = \left(1 - \frac{0.5}{0.72}\right)^{-2.38 \times 0.72} = 7.63$$

If the RBCs aggregate in short chains after passing through magnetic field, then they will have intrinsic viscosity along its axis direction $\nu_{\parallel} = 2.01$, while the intrinsic viscosity in the directions perpendicular to its axis $\nu_{\perp} = 3.17$ [23].

Therefore, the blood viscosity along the flow direction is given by
\[ \frac{\eta_{\parallel}}{\eta_o} = \left(1 - \frac{0.5}{0.72}\right)^{-2.01+0.72} = 5.66 \]

which is reduced by 25.6\% from the original high blood viscosity. Meanwhile, the blood viscosity in the directions perpendicular to the flow is given by

\[ \frac{\eta_{\perp}}{\eta_o} = \left(1 - \frac{0.5}{0.72}\right)^{-3.17+0.72} = 14.97 \]

which is increased by 96.2\%.

The above calculation also clearly distinguishes the key difference between blood thinner medicine and our MR approach. Aspirin and other blood thinner medicine change the blood composition to reduce \( \eta_o \), the viscosity of base liquid. Our MR method does not change the blood composition; therefore, it does not affect \( \eta_o \). The viscosity reduction along the flow direction is the result of formation of short chains of red blood cells along the flow direction.

We should also note that, the red cells are aggregated along their diameter direction Figure 4.3, the strongest polarization direction, so the surfaces of the red cells are fully exposed to perform their normal oxygen carrying function.

### 4.4 Description of The Equipment and Experimental Processes

The experimental setup is shown in Figure 4.4(a). Due to gravity, the blood sample flows down (direction shown by red arrow) from the funnel (positioned at the upper right corner), passing through a custom-made glass channel, Figure 4.4(b), placed inside an electromagnet, flowing further down through the capillary tube to a container on a microbalance.
Figure 4.4: Experimental setup to observe the effect of magnetic field on blood flow.
Figure 4.5: (a) Power supply for electromagnet, (b) Magnetometer
The electromagnet coil is powered by a current control power supply, Figure 4.5(a). And the strength of generated magnetic field is measured by a DC Magnetometer, Figure 4.5(b).

Few notable modifications were done on the H frame. We made a hole on the pole plate so that the channel can be placed right at the middle of magnetic field, Figure 4.4(b). Also, a bar is attached on the frame to hold the microscope right above the channel, Figure 4.4(c), so that the turbulence in the flow can be imaged with the camera. The microbalance connected to the computer via LabVIEW records the mass of collected blood as a function of time. Different types of channel designed for the experiment are shown in Figure 4.6.

We have also designed an alternative flow pipeline, as shown in Figure 4.7. Key difference is that instead of flowing one direction inside the magnetic field, the tube makes a u-loop, and the flow comes from reverse direction. This way the liquid will be affected by the magnetic field twice, and the total duration of exposure to field will be much longer since the liquid has to travel relatively longer capillary pipeline.

We utilize a Nikon upright microscope, Figure 4.8, to observe cells on slide. With the Omax camera we can record image directly to PC software, Figure 4.9(a). Viscosity of blood is measured with the VISCOLab 3000 oscillating piston viscometer, Figure 4.9(b).

We keep the blood samples in tubes, Figure 4.10(a), in temperature-controlled storage. Just before the experiment, we took the desired tube out, let it adjust to ambient temperature ~37°C. Then we pour the sample in the top funnel. Initially, we record flow rate and image the flow without magnetic field. Next, record the same with desired magnetic field strength. Varying the height of funnel, we can control flow rate. We have conducted many trials with different channels, varying duration and field strength.
Figure 4.6: Types of microfluidic channel
Figure 4.7: Alternative pipeline setup for Blood flow inside magnetic field
Figure 4.8: Nikon Microscope with Omax camera
Figure 4.9: Viscometer and Imaging software interface
Figure 4.10: Blood sample in test tube
Figure 4.11: Preparing the microscope slide
Typically, a small drop of sample is placed on microscope slide with a cover slip on top for imaging, as in Figure 4.11(a). However, such method posed an inconvenience for our purpose. The pressure on the cover slip is uncontrollable. Also, the blood drop dries up much quicker since the drop is effectively open to air from 4 sides. To remedy this issue, we designed an alternative method: make a rectangle with very thin layer of tape, and put a very small drop at the middle, then place the cover slip on top, Figure 4.11(b). The process is shown sequentially in Figure 4.11(c-e).

We image the condition of cells in blood before using the sample for flow measurements. Next, when ample of blood accumulates after passing through magnetic field, we repeat the imaging of cells in treated blood to examine the RBC aggregation.

However, we face another difficulty when we take blood drop from evenly composed sample, as in Figure 4.10(a), then there are multiple layers of cells on the slide. The workaround we found is that if the tube is left undisturbed for a long time, the cells precipitate at the bottom, Figure 4.10(b). Then we suck up plasma and cells in a ratio of about 10:1 with a syringe into another test tube, Figure 4.10(c), to make a customized low-density composition. With such method we were able to see single layer of cells, which are freely moving in plasma.

In addition, we also image the condition of cell distribution after holding the slide or the test tube inside the magnetic field, as in Figure 4.12. We repeat the process for different duration and field strength. This way we can focus on a specific region on slide and compare whether the RBCs formed the predicted short chain alignment.

The findings will be presented in next section.
Figure 4.12: Holding the blood sample on slide inside the magnetic field
4.5 Results Obtained in Bench Research

In our experiment the capillary end tube in the flow pipeline, as in Figure 4.4(a), has radius 0.4mm. In one of many trials, we had a very viscous blood composition. At the beginning, without the magnetic field blood flows very slowly. Figure 4.13-14 shows the flow rate is 0.00202g/s, corresponding to viscosity 28.86cp, which is well above the normal range. After a magnetic field of 1.33T is turned on, the blood flows much faster at 0.0147g/s, corresponding to a viscosity of 3.97cp, which is the typical range for normal human blood. This clearly illustrates the effectiveness of this MR technology.

The purpose of placing a microfluidic channel as in Figure 4.4(b) is to deliberately introduce turbulence in flow. Because of sudden change in the cross section along the flow path, the flow becomes turbulent, as shown in Figure 4.15. This mimics the mechanism to develop turbulence in blood flow at the aorta or when the blood vessel has atherosclerotic plaque. The images recorded by the camera clearly distinguishes that, without the magnetic field the blood flow was slow and turbulent, Figure 4.16(a). Whereas, after applying a 1.3T field about 4 minutes made the flow much faster and laminar, Figure 4.16(b). We specifically focused on an air bubble in the blood flow path to mimic the presence of a plaque. Without magnetic field applied this bubble triggers additional disturbance. When the magnetic field is active, the blood flow remains laminar even around the bubble.

All these observations – viscosity reduction, flow rate increase, and turbulence suppression are the outcome of RBC aggregation in short chains as theoretically predicted. Figure 4.17 depicts such evidence from flow process through magnetic field.
Figure 4.13: Blood flow rate increases sharply through an *In-Vitro* channel after turning on the magnetic field.
Figure 4.14: Effect of magnetic field on the blood viscosity and flow rate.
Figure 4.15: Illustrating the modification in the flow pipeline to introduce turbulence
Figure 4.16: Effect of magnetic field on the turbulence in blood flow

(a) Turbulent slower flow without Magnetic Field

(b) Laminar faster flow in presence of 1.3T field for about 4 minutes
Figure 4.17: Red blood cells aggregate in the blood after passing through magnetic field.
Figure 4.18: Red blood cells form short chain in the slide when placed inside magnetic field.
In Figure 4.17(a), blood drop was collected from regular composition. So, multiple layers of cells make this image pretty much useless as explained earlier. However, if the drop is collected from low concentration method as written earlier, then we see images similar to Figure 4.17(b). This image was taken from a non-treated sample. Figure 4.17(c) was from the same sample after treated by 1.7T field.

The stark difference between these two images suggests that without magnetic field RBCs are roaming freely, whereas after passing through magnetic field there are short chains of 2~4 RBCs. Similar images were observed for the method pictured in Figure 4.12 as well. In Figure 4.18(a), RBCs were mostly free on the microscope slide, whereas after holding the slide inside 1.3T field for 5 minutes we see that many short chains of 2~6 cells.

To further evidence the viscosity reduction, we pour 1 ml amount of blood in the viscometer to directly measure the viscosity at 37°C, mimicking body temperature. First, we measured for fresh unmodified sample. Next, we let that sample flow through magnetic field, and immediately after collecting the treated blood, we check its viscosity. We repeat the measurement on same treated sample after few hours. Figure 4.19 shows the example data for such measurements. In this sample, original viscosity was 3.65 cp. The treatment immediately reduced it to 3.2 cp, down by 13%. After 24 hours, it is 3.4 cp, still 7% lower than original. This data clearly evidenced the reduction of viscosity due to magnetic field. Also answered one very important question regarding the duration of low viscosity state in blood. Not all the short chains of RBC broke apart. Certainly, the chains will disappear due to thermal motion, but very slowly. It is well known that to dissemble such viscoelastic chains by thermal motion is very slow.
Figure 4.19: Viscosity of blood before and after the MR treatment.
This MR treatment process is also repeatable. Once the short chains are dissembled, re-application of strong magnetic field to the blood will make the blood viscosity anisotropic again. Therefore, with application of strong magnetic field, we can successfully reduce blood viscosity along the flow direction and suppress turbulences, making the blood flow laminar. One of the primary motivations of studying health related, i.e., blood research is to eventually apply the invention to improve health condition. In our case, we theorize that improving blood flow will result in preventing cardiac diseases. We found that exposure to magnetic field will impede the disturbances in blood flow. So, how can we verify whether this MR technology would affect health condition?

4.6 Translating the Research Towards Bedside Implementation

Since blood flow will become laminar due to MR treatment, eventually the Heart, which pumps the blood would have to work much smoother. Thus, if any person undergoes this MR therapy, his blood pressure will reduce. However, the key concept of our theory is that the direction of external magnetic field should be parallel to the blood flow direction. It is documented that major arteries and veins in the upper arm area of hand are linear towards fingers, Figure 4.20(a) [44]. So, if we can apply unidirectional field along the upper arm as in Figure 4.20(b), we may see some effect.
(b) Major arteries and veins in upper arm

(a) External magnetic field lines parallel to the blood flow direction in arteries and veins

Figure 4.20: Sketch of MR application on upper arm of human.
Figure 4.21: Modified electromagnet device to conduct clinical trials of MR therapy.
Figure 4.22: Blood pressure monitor Omron 786N.
To this end, we modified the electromagnet device as shown in Figure 4.21(a). A bore of 10cm diameter was made to go through the frame and poles. The modified electromagnet has a magnetic field close to 1T inside the bore, which is along the axial direction. Target audience for this study would be exclusively subjects with hypertension.

Blood pressure is recorded by a FDA approved BP monitor, Figure 4.22, from the left arm as it is typically done with such cuff band in clinics. First, we measure the subject’s blood pressure, heart rate, and heart murmur (if any) without any application of magnetic field. Next, the subject will place his/her right arm into the bore of the electromagnet to have MR therapy as shown in Figure 4.21(b), while we keep monitoring his/her blood pressure, heart rate and heart murmur. The MR therapy will last about 15 minutes.

We expect that this MR therapy will have the following benefits:

(i) Blood pressure will be lowered by 10~20%.

(ii) The turbulence in blood circulation will be suppressed by the treatment. Hence, heart murmur, if ejected by the turbulence, will be diminished for a while. Since, after the treatment, the blood flow will be laminar.

(iii) The blood oxygen function will be improved by the treatment. Especially, if the subject has rouleaux in his/her blood, the effect will be significant.

These effects will last for about 24 hours after one treatment and slowly decay. However, re-treatment will bring back the effects. Also, since steady laminar blood flow is athero-protective by active reduction of inflammatory genes, this MR therapy, reducing disturbed blood flow hemodynamics, would have long term effect as an anti-atherogenic therapy if the treatment is repeated for a while.
Table 4.1: Reduction in blood pressure during a 6-minute application of Magnetic Field.

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<th>Timestamp</th>
<th>Blood Pressure (Systolic/Diastolic mm Hg)</th>
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</thead>
<tbody>
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</table>

*Magnetic Field turned on*

<table>
<thead>
<tr>
<th>Timestamp</th>
<th>Blood Pressure (Systolic/Diastolic mm Hg)</th>
</tr>
</thead>
<tbody>
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<td>125/87</td>
</tr>
<tr>
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<td>120/81</td>
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<tr>
<td>05:00 pm</td>
<td>118/79</td>
</tr>
</tbody>
</table>

Effect of magnetic field on blood pressure

Figure 4.23: Sample data from clinical trials.
The preliminary results appear to be very promising. One sample data in Figure 4.23 and Table 4.1, shows this subject had untreated BP 134/90 mmHg. Over the duration of 6 minutes of exposure to 1T field, BP reduced by 12 %, the Systolic down to 118 mmHg and Diastolic down to 79, which is considered very good condition for heart functioning.

4.5 Discussion

In summary, we have discovered that blood flow can be manipulated with a strong magnetic field. However, there are some definite areas that we need to verify.

Due to the limitation of our instrument, we could not see the RBC chains in blood flow inside the magnetic field. With different setup we may be able to see RBC aggregation along the applied field. Also, we are inferring that chain formation retain even after 24 hours based on the measurement of viscosity. However, we need to image RBC then apply magnetic field right on the microscope to see any movement of RBC, and following up in intervals we can find out the exact duration of RBC chain retention.
CHAPTER 5
FUTURE WORK AND CONCLUSION

5.1 Studies Using Mouse Model

To further verify our claim that magnetorheology would impede development of plaque in arteries, we have collaborated with research group at Cardio Vascular Research Center to conduct in-vivo study on mouse model. Our plan is: a group of mice will be prepared with a very small Magnet surgically implanted next to jugular vein as in Figure 5.1; another control group with similarly shaped non-magnet metal. Both groups will be fed same high fat diet for 12 weeks. Then blood will be collected from the sacked mice. Viscosity and plaque development in aortic arch will be analyzed.

Until now we conducted this procedure on a very small set of mice. The results suggest a potential evidence of our hypothesis. In Figure 5.2, viscosity of blood from a magnet inserted mouse is lower compare to that of non-magnet metal inserted mice. Also, en-face of aortic arch revealed that less plaque in magnet treated mice.

This data is very preliminary. Currently, we are nurturing second batch of mice. Once they mature, then we will conduct trials. With a bigger dataset we can establish statistically justifiable conclusion.
Figure 5.1: Surgically implanting metal/magnet in mouse
Figure 5.2: Preliminary result from Mouse model
5.2 Continuing Clinical Trials

Our planned clinical trial is non-invasive. There is no medicine or surgery involved. It is well documented that magnetic resonance imaging (MRI) is safe to apply a magnetic field of 2-3T to human head for 1 hour. Our device has magnetic field about 1T, weaker than the magnetic field of MRI, and only applies it to human arm for 10-15 minutes. Therefore, our MR technology should be safe.

This MR therapeutic technology has been already approved by FDA for clinical trials. We have observed that significant reduction in blood pressure occurs when the subject has preexisting hypertension. So currently we are recruiting volunteers, exclusively hypertensive. Initial data suggests that the field strength and exposure duration may vary depending on subject. We expect to establish a standard operating procedure upon successful completion of clinical trials. We believe this MR therapy will help to reduce the risks of heart attacks and strokes.

Our patent application of this technology is still pending the approval.

We also hope that; MR technology can be applied to sickle cell anemia disease. Magnetic field may reorient the RBC. Such that even with elongated shape, cells can flow through the veins. So risky blood transfusion procedure can be avoided.
Figure 5.3: Design variation of ring electrodes in the capacitor
5.3 Improving ER Technique for Chocolate and Crude oil

As shown in Figure 5.3, we developed various capacitor designs. Instead of full mesh, we use ring shaped electrodes, so that particles can pass through after aggregation. Also, different radius to apply electric field at different layers inside the flow. Either very close to tube inner surface, or about 3mm away from the tube, or 1cm away from the tube.

5.4 Summary

Therefore, our hypothesis for Chocolate and Blood based on the success for crude oil have been evidenced in experiments. Chocolate flow rate can be affected by electric field, and Blood flow rate can be affected by Magnetic field.

For practical application, a major chocolate manufacturer is developing the ER device. Once completed, low fat chocolate will be flowed to test its feasibility for mass production. We hope that soon we will see new varieties of low fat chocolate in the stores.

On the other hand, clinical trials of MR therapy to reduce blood pressure is going on. Hopefully we will be able to develop this into reality.

At the same time, we continue experiments on new types of crude oil samples.
REFERENCES CITED


