On the Physical Properties of Oil-Based Ferrofluids

Cooper W. York '26 and Hugh O. Thurman III

Department of Physics and Astronomy, Hampden-Sydney College, Hampden-Sydney, VA 23943

Abstract

A topic of an abundance of recent scientific inquiry, ferrofluid has grown significantly in popularity and has a multitude of applications across various fields. In this paper, the density, viscosity, ultrasonic velocity, and magnetic permeability were experimentally measured and used to calculate several other physical properties of oil based ferrofluids. Although the trends found in this paper were in accordance with other literature on the subject, there are several notable differences between the observed values recorded through this paper's experimentation and those found in other literature. Most glaring of them all, the stiffness of water was experimentally found to be remarkably different than a listed literature value to the degree of eleven orders of magnitude. It was also found that temperature plays an inverse role in determining density, viscosity, and ultrasonic velocity, and there exists an inverse relationship between input frequency and magnetic permeability within an oil based ferrofluid. Further research needs to be done to inquire about the temperature variation that occurs in a ferrofluid returning to rest after being rotationally agitated, as well as in the determination of the ultrasonic velocity using various means of applying an external magnetic field.

Introduction

At its core, ferrofluids are simply magnetic materials suspended into a fluid; but in real world applications, ferrofluids are more complex than the above statement. Ferrofluids are created by combining a ferromagnetic solid where each particle is on the nanometer scale, a surfactant that prevents the magnetic particles from agglomerating, and some form of aqueous solution that acts as the carrier liquid for the materials to be suspended in [1]. Ferrofluids have been in existence since the mid-1960's, but it wasn't until the 2000's that ferrofluids were researched to the scale of thousands of research papers a decade [1,2]. The utility of ferrofluids is expansive, and currently has widespread uses in electronics, dynamic sealing, water/waste filtration, adaptive braking, dampening, cooling/heat-transfer systems, and bioengineering [2,3,4]. Although there is a plethora of measurable quantities within a ferrofluid, such as thermal conductivity, viscosity, impedance, etc.; it is highly dependent on the application of ferrofluid which determines the properties of importance. In heat transfer technology, the thermal conductivity of the ferrofluid beingused is of vital importance and is a direct result of the aqueous solution that the magnetic material is suspended in [3]. Similarly, in dampening applications the viscosity of a ferrofluid is of paramount importance, both at its base level and when exposed to a magnetic field. Although it is widely known that the viscosity increases with respect to the strength of the magnetic field it is exposed to, as well as the concentration of dissolved magnetic particles, it's also been found that despite experiencing a decrease in viscosity due to rising temperatures, the ferrofluid viscosity relative to the carrier fluid remained constant [3,4]. Lastly, the impedance of a ferrofluid has drastic impacts in the field of electronics, and along with viscosity, will be the primary focus of this paper.

Figure 1: Sample of the ferrofluid used in the experiments exposed to an external magnetic field

In this paper, the measurable quantities that will be gathered experimentally are: density, viscosity, ultrasonic velocity, and impedance. Using these values, the following physical properties can be derived: magnetic permeability, isentropic compressibility, acoustic impedance, stiffness, viscous relaxation time, ultrasonic attenuation, and intermolecular free length. Each property is vital to know to ensure that the ferrofluid is being properly utilized and safe for interaction with humanity. The following sections will enlighten the reader on the importance of each property and how it is found.

Viscosity is a measure of a fluid's internal resistance to movement. There are two major types of viscosity: Dynamic Viscosity, and Kinematic Viscosity. Dynamic Viscosity is a fluid's resistance to movement under an externally applied force/pressure. Kinematic Viscosity, however, is simply a fluid’s resistance to movement only under earth’s gravitational field. Although most common fluids, such as water, are categorized as Newtonian fluids and have a linear/constant viscosity, there also exist non-Newtonian fluids that have different degrees of resistance depending on the speed and magnitude of the force provided. The viscosity of fluids is incredibly important in applications such as dampening technologies, the transportation of fluids, manufacturing, etc.

Ultrasonic Velocity is the speed at which sound propagates through a liquid. Knowing this has many uses in sound transmission and is heavily utilized in technology like sonar. Using a time-of-flight calculation method, the ultrasonic velocity can be experimentally calculated by using the equation:

$$V = \frac{d}{t}$$

Where “d” is the distance traveled by the sound wave and “t” is the time it takes to cross that distance.

Impedance refers to the amount of resistance that’s applied in an AC circuit and can be experimentally measured using an RL circuit with known resistor and capacitance values. In theoretical applications, or when all presented values are known, the following equations can be used:

$$V = IZ$$

$$Z = R + i\omega L$$

$$L = \frac{\mu N^2 A}{l}$$

Where “μ” is the magnetic permeability of either the substance, or of free space; “N” is the number of turns in the inductor, “A” is the effective area of the inductor, and “l” is the length/height of the inductor. To measure the impedance experimentally, using an RL circuit as shown above, use the equations:

$$\theta = 2\pi t f$$

$$Z = \frac{V_{A2} R_{ref}}{\sqrt{V_{A1}^2 - 2V_{A1}V_{A2}\cos\theta + V_{A2}^2}}$$

$$\alpha = \theta - \tan^{-1}\left(\frac{-V_{A2}\sin\theta}{V_{A1} - V_{A2}\cos\theta}\right)$$

$$L = \frac{Z\sin\alpha}{2\pi f}$$

Where “t” is the peak-to-peak time, “f” is the input frequency, “V_A1” is the Voltage amplitude measured at resistor A1, “V_A2” is the Voltage amplitude measured at resistor A2, and “R_ref” is the resistance of the resistor with known resistance.

Isentropic Compressibility is how the relative volume of a substance, or in this case a fluid, changes when pressure is applied. In fluid mechanics and dynamic systems this is important and heavily impacts the speed of sound in the medium. The equation used to define Isentropic Compressibility is:

$$K_S = \frac{1}{pV^2}$$

Where “p” is the density of the material and “V” is the ultrasonic velocity.

Acoustic Impedance is defined as the resistance of a material to sound waves propagating through it. This value has a wide range of uses in multiple fields of engineering but one of its most prominent uses is in diagnostic equipment for testing structural integrity [5]. The Equation used to define Acoustic Impedance is:

$$Z = pV$$

Stiffness is a material’s or fluid's ability to resist external pressure and is extremely useful for material and structural engineering. Stiffness is the inverse of Isentropic Compressibility and can be calculated with the equation:

$$S = pV^2$$

Viscous Relaxation Time is the amount of time for a fluid to return to its rest state after being agitated. Although it is helpful in a range of applications, it’s especially so in dampening systems. The equation to calculate viscous relaxation time is:

$$\tau = \frac{4\eta}{3pV^2}$$

Where "η" is the fluid's viscosity.

Ultrasonic Attenuation is the loss of energy of an ultrasonic wave traveling through a medium. This is crucial property to understand and knowing it well is part of the basis of ultrasound imaging. The equation to calculate ultrasonic attenuation is given by:

$$a = \frac{\omega^2 \tau}{2V}$$

Where "ω" is the radian frequency of the ultrasonic wave.

Intermolecular Free Length is the distance between molecules in a liquid phase. It has an inverse relationship with the speed of sound in a fluid and is an important property in chemistry and chemical engineering. The equation used to define the Intermolecular Free Length is given by:

$$L_f = \frac{(93.875 + 0.375T) \cdot 10^{-8}}{V \cdot \sqrt{p}}$$

Where "T" is the temperature in kelvin.

Materials and Methods

The experimentally derived results for density, viscosity, ultrasonic velocity, and magnetic permeability were done using different experimental designs which will be outlined in this section.

The density measurement was the simplest and was made by using a 150ml beaker and an Ohanas Scout Pro scale with a systematic bias of +-0.005 grams. By first zeroing out the weight of the beaker, the ferrofluid was slowly poured into the beaker until it reached the 50ml height line. After which we performed the necessary calculation to determine its' density.

A modified version of the Couette Viscometer was used to take the viscosity of the liquid in response to a rotating drum submerged in the fluid, both under the effects of a magnetic field and without it [6]. The Rotational Viscometer used was a Bonvoisin NDJ-5S/8S Viscometer with the size 0 drum being used to take the measurements at 60 rpm. This was done to ensure the most accurate results due to the low viscosity of the ferrofluid, which was confirmed after the water calibration was found to be only 11.9% different from the currently accepted value. The experimental procedure was to ensure that the viscometer was level with the use of a leveler and ensure that the drum was positioned in the middle of a beaker with diameter 1.5mm greater than that of the drum. Once the equipment was positioned appropriately, the measurement was run for 2 minutes measured by a stopwatch and the viscosity was recorded. Once recorded, the rotating drum stopped, and the fluid temperature was tested with the apparatus probe both immediately after conclusion of the test and immediately before the start of the next test. An initial attempt to measure the viscosity using a solenoid proved unsuccessful due to the non-uniform magnetic field produced. The issue was resolved by utilizing two Helmholtz coils to create a uniform magnetic field. The Helmholtz coil setup was probed and confirmed to be uniform within the entire testing area. The small Helmholtz coils used had a diameter of 15cm, turn count of 320, and a maximum current rating of 2A. These coils were configured both in a horizontal orientation and in a vertical one with a +-0.5mm precision ruler being used to ensure proper distance. The large pair of Helmholtz coils used had a diameter of 68cm, turn count of 119, and maximum current rating of 5A. All experimental setups were probed to ensure a uniform magnetic field and were positioned correctly.

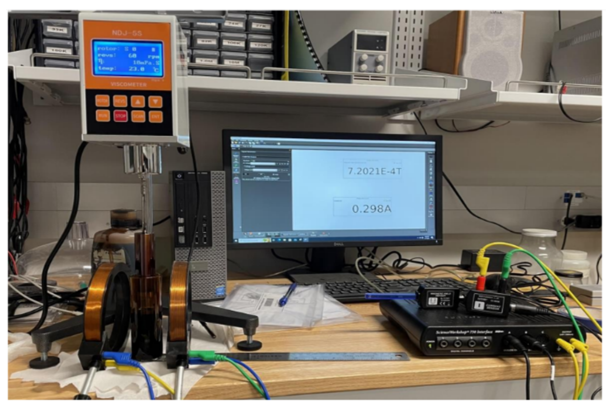


Figure 2: Experimental setup for the horizontal Helmholtz coil experiment.

The Ultrasonic velocity was found using a time-of-flight calculation by measuring the peak-to-peak gap between two ultrasonic pulses. As a means of calibration, the test was first performed with air and water to ensure the apparatus's accuracy, and the ferrofluid without external magnetic field influence. After calibration, the tests under an external magnetic field were made using a one solenoid setup and two solenoids in series setup to ensure a more uniform axial magnetic field.

The single solenoid was positioned directly in the middle of the testing apparatus to make the magnetic field as uniform as possible. Similarly, the two-solenoid setup was placed in the middle, with only a small amount of space between the edge of the solenoids and the transducers. The last experiment was conducted using neodymium magnets placed in alternate polarity held together by an acrylic sheet, which were then positioned with a separation of 0.061m and 0.071m away from one another with the ferrofluid in the middle to create a transverse magnetic field. The apparatus used was produced by Kanon Technologies and named *Speed of Sound in Fluids, An Acoustics Laboratory Experiment*, utilizing two transducers/receivers and an acrylic tube housing the liquid separating the transducers with a distance measured to be 41cm; the current supply used was Tenma 72-7660 with a systematic bias of +-0.005A; the pulse generator was a Kanon Technologies Tone Burst Generator, model TBG-100; and the oscilloscope used was a Tektronix TDS 2012B with a range of 100MHz and 1GS/s. The frequency used for the first trial was 300 kHz in which the current somewhat remained constant at 4.92V +-0.01for the one-solenoid setup and at 4.98V for the two -setup. The second trial used a 40 kHz frequency and was conducted in steps of 0.5A from 0.5A-5A for the one solenoid and two solenoid experimental configurations. The temperature was measured additionally and used VWR education thermometer with a systematic bias of +-0.05C and was placed on the apparatus itself.

Figure 3: Experimental setup for the two-solenoid ultrasonic velocity experiment.

The magnetic permeability was tested using an RL circuit with a beaker containing ferrofluid. As a calibration, trials were performed with nothing inside, to verify the permeability of free space given by the apparatus was correct, as well as with an empty beaker, and with water to ensure that the beaker wouldn't impact the measurement. After finishing the air trial, a measurement was conducted without the capacitor in series to determine the effective area. Once the calibration was concluded and the effective area determined, an oil that was similar to the carrier fluid utilized in the ferrofluid was chosen so the degree in which suspended ferromagnetic particles submerged in a fluid impacts magnetic permeability could accurately be compared. The RL circuit used a PASCO CI-6512 with a maximum working voltage of 10V and a listed inductance of 8.2 mH. The Function generator used was a BK Precision 4012A with a 5MHz maximum and a systematic bias of +- 0.05 Hz. The oscilloscope used was a Tektronix TDS 2012B with a range of 100MHz and 1GS/s and a systematic bias of +-100ns. The calibration and first trial measurements were all conducted in the range of 100Hz-500Hz in steps of 100Hz. In the second trial, the ferrofluid was measured from 100Hz-100kHz at discreet intervals outlined below. To ensure data accuracy, the room temperature was measured with the VWR education thermometer with a systematic bias of +-0.05C and was placed more than 25cm away from the testing apparatus.

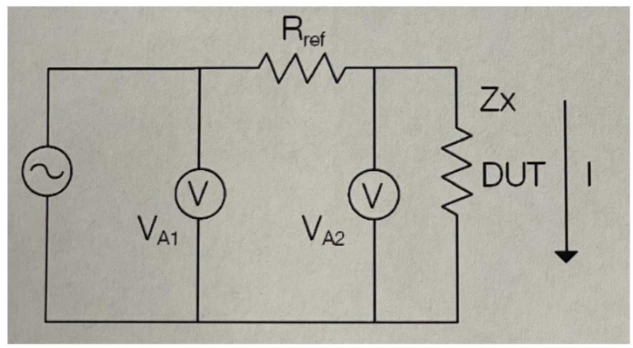


Figure 4: Circuit diagram of the RL circuit used to measure the fluids inductance.

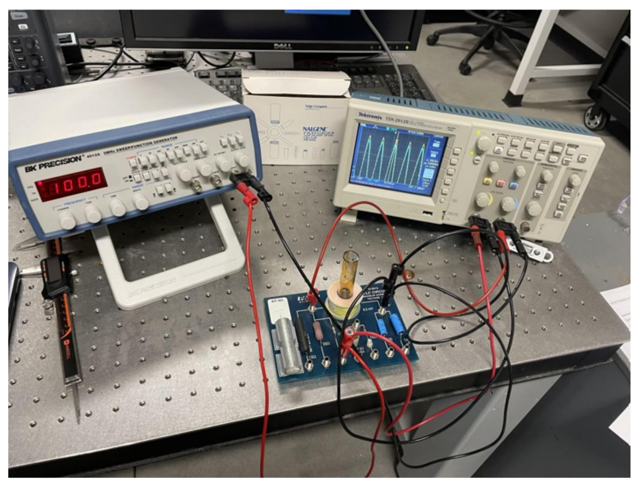
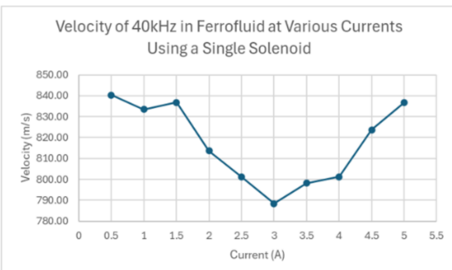


Figure 5: Experimental setup utilizing an RL circuit to measure the fluids inductance.

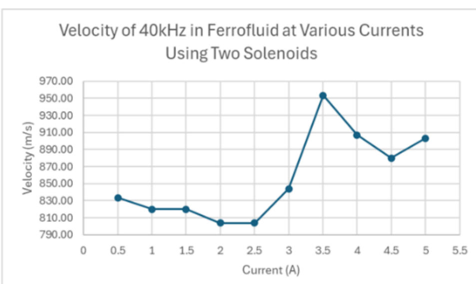
Results

Acoustic Parameters	Variable	Units	Specification	Specfication 2	Average Magnetic Field Strength (T)	Average Temperature Range (C)	Water Value	Ferrofluid Value
Density	P	kg/m^3	-	-	0	23.3	1000	1027.8
Viscosity	n	Pa*s	Using Rotational Viscometer	Horizontal	0	23.1	1000.6	3740
				Helmhotlz coil	0.0094	23.42	1000.6	3960
				Small Vertical	0	22	1000.6	4260
				Helmhotlz coil	0.0035	22.18	1000.6	4325
				Large Vertical	0	22.82	1000.6	4300
				Helmhotlz coil	0.0011	23.88	1000.6	3980
Ultrasonic Velocity	V	m/s	Trasducers at 300 kHz	No Solenoid	0	23.9	1561.9	3420
				One Solenoid	0.0264	23.94	1561.9	1730
				Two Solenoids	0.0535	24.08	1561.9	1560
			Trasducers at 40 kHz	One Solenoid	0.0148	23.92	1561.9	817.4
				Two Solenoids	0.0148	24.83	1561.9	856.9
Isentropic Compressibility	K_s	m^2/N	Calculation	Using Measured Values	0.0163	24.32	0.000409915	0.001250646
Accoustic Impedance (Under No Magnetic Field)	Z	kg/((m^2)*s)	Calculation	Using Measured Values	0.0163	24.32	1561900	3515076
Stiffness	S	N/m^2	Calculation	Using Measured Values	0.0163	24.32	2439.53	1393.08
Viscous Relaxation Time	T	s	Calculation	Using Measured Values	0.0127	23.96	5.46881E-07	7.558036818
Ultrasonic Attenuation	a	-	Calculation	Using Measured Values	0.0127	23.96	398.1	8162352595
Intermolecular Free Length	L_f	m	Calculation	Using Measured Values	0.0127	23.96	1.901E-11	3.765E-08

Table 1: Table showing the recorded values of Density, Viscosity, and Ultrasonic velocity of the tested ferrofluid in comparison to water.



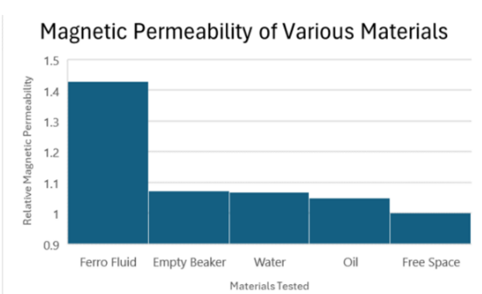
Graph 1: This graph shows the relationship between how different current intervals impact the Ultrasonic velocity. Utilizing only one solenoid made the magnetic field not as strong across the entire apparatus.



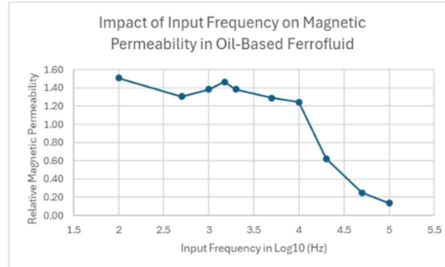
Graph 2: The two-solenoid configuration of Graph 1. By utilizing two solenoids, it is believed that the magnetic field was much more uniform across the testing apparatus.

Ultrasonic Velocity Under a Transverse Magnetic Field				
Input Frequency	Distance (m)	Average Magnetic Field Strength (T)	Average Temperature Range (C)	Average Velocity (m/s)
40kHz	0.061	0.0696	24.68	767.85
	0.071	0.0474	24.68	803.92

Table 2. Table showing the velocity recorded under a uniform transverse magnetic field at separate distances.



Graph 3: This graph shows the Magnetic Permeability of the various materials tested relative to the Magnetic Permeability of Free Space (μ/μ_0).



Graph 4: This graph shows the relationship between the input frequency, beginning at 100Hz and ending at 100kHz, and the substances Magnetic Permeability relative to the Magnetic Permeability of Free Space (μ/μ_0).

In Summary, it appears that there is evidence for a strong correlation between the presence of a magnetic field and its impact on the physical properties of an oil based ferrofluid. Additionally, the presence of ferromagnetic material when in contact with an external magnetic field is shown to be the cause of the variation in physical properties, as opposed to being due to the carrier fluids properties themselves.

Despite meticulous efforts to ensure the findings are observed to the highest degree of accuracy attainable from the methods utilized, there are three major points of uncertainty that arose upon further analysis.

Perhaps most odd of the three, when conducting the viscosity measurements, it was observed that the temperature of the ferrofluid was on average 0.27C higher after one minute of rest following the conclusion of each trial. On one occasion, using a current that was on average 1.876A in the small vertical Helmholtz coil experiment, produced an average temperature difference of 3.16C. This temperature variation wasn't observed in any of the other experiments conducted, only those involving the rotational viscometer when an external magnetic field was applied to an oil-based ferrofluid.

The oil based ferrofluid used in these experiments is called a EFH Series Ferrofluid and was produced by Ferrotec in 2015, which was also the date of purchase of the sample used in this experiment. Upon review of the listed physical properties found by the producer, it was determined that our sample has altered over time. The listed viscosity at 27C was 0.006 Pa.S, the listed density at 25C was 1210 kg/m^3, and the initial magnetic susceptibility is listed at 2.64. Although the fluids ultrasonic velocity and magnetic permeability were not measured by the company, it's safe to assume that these values were similarly impacted. There was found to be a difference in viscosity and density between the listed value and the experimental value of 37.67% and 15.06% respectively. It's also important to note that these values were derived from the closest temperatures to the ones used in the listed values. This causes even more cause for concern due to the fact that it's known that viscosity decreases with an increase in temperature, which means that the listed viscosity would be even greater if it were measured at a temperature similar to those observed in these experiments.

The thrust of the research was focused on measuring the same set of physical parameters for ferrofluids as in Ultrasonic Study of Ferrofluids by S.C. Bhatt. It was discovered that many of the measured values were not similar to the oil based ferrofluid used in the paper by Bhatt [6]. Because the only values that can be compared are the water values, that will be this section's topic. In their results section, the table showing the recorded values listed the viscosity of water at “1.0087 in [Pa s] x 10^2,” a value one tenth of the value observed in this paper [6]. Similarly, the value listed for Isentropic Compressibility was found to be “.183 in [m^2/N] x 10^-8,” which is a difference in scale of 5 orders of magnitude different than what was observed in this paper [6]. Additionally, the inverse of Isentropic Compressibility, Stiffness, was listed to be “5.476 in [N/m^2] x 10^-8,” which creates a difference in order of eleven orders of magnitude [6]. Interestingly, apart from the density of water and Ultrasonic velocity, the only value within a single order of magnitude of the experimentally found values in this paper was the intermolecular free length, which they listed at “0.854 in [m] x 10^-10” [6]. The cause of these discrepancies between the two papers is unclear, but worthy of mention.

Discussion

Although much of the data found in this paper is only useful in specialized applications, it is still useful to know the behavior and physical properties of the fluid. It was found that the most effective way to increase the viscosity of a ferrofluid was to position the external magnetic field in a transverse configuration, as well as confirming the importance of fluid temperature in relation to the viscosity of a ferrofluid. The Magnetic Permeability of an oil based ferrofluid was found to be heavily dependent upon the magnitude of the input frequency; at which it is 143% greater than the Magnetic Permeability of Free Space at 100Hz but only 13% of the Magnetic Permeability of Free Space at 100kHz. The two most odd findings perhaps are the difference in Ultrasonic velocity when using a single solenoid or two solenoids in series, and the temperature variance between the initial temperature measurement after a rotational viscosity trial, and the one immediately prior to the next trial. The Ultrasonic velocity trial at 40kHz was conducted with less than 1C of difference between the average temperatures, with both solenoids being placed in the middle of the testing apparatus; yet, they had almost inverse velocity trends. After measuring the ultrasonic velocity as a function of applied external magnetic field both longitudinally and transversely, an anisotropic behavior was observed. Future research into the physical properties of oil based ferrofluids will need to be done to examine the cause of these effects because it is a mystery at the time of writing. Most glaring of which are the impacts on the degradation of a ferrofluid sample on its physical properties so that engineers utilizing ferrofluid in its respective applications can know what to expect at discrete time or usage thresholds. With the abundance of information present within this paper, the physical properties of oil-based ferrofluids can be utilized by other researchers to both learn more about the phenomena previously stated and find applications in various engineering fields to improve human understanding of the universe.

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