Evaluation of Magnetic Flux Density of MR Fluid by Different Approaches

S. K. Mangal and Vivek Sharma

Abstract—**Magneto Rheological (MR) Fluids possess on-state rheological properties like yield strength and viscosity which are dependent on the strength of the applied magnetic field. This paper presents the comparison of on-state magnetic flux density of MRF122-EG fluid using different Techniques *i.e.* Experimental Technique, Carlson Equation and simulation by MAG-NET software of Infolytica Modeling Works Canada. An experimental set up comprising of an electromagnet capable of generating 2.0 Tesla for an air gap of 18 mm has been designed and fabricated to determine magnetic flux density values. The results show that the magnetic flux densities obtained by various approaches are matching quite well and are within the 5% percentage error. It, thus, validates the design of the fabricated electromagnet in this work which is proposed to be used for development of economical and effective MR fluid in the laboratory.**

Index Terms— **Magnetic flux density, Volume fraction, Magnetic flux intensity, Infolytica, electromagnet**

1. INTRODUCTION

THE MR fluids mainly consist of magnetically permeable micron-sized particles dispersed throughout a carrier medium (a non-magnetic fluid). These fluids can be termed as the materials which undergo substantial change in their rheological properties under the influence of some external (magnetic) fields. Most of the researchers have used carbonyl iron as particles scattered in a medium mainly oils, *e.g.* silicone oil, hydrocarbon oil, mineral oil or hydraulic oil. Iron powder is the next most popular particles because of its high saturation magnetization which is about 2.1 Tesla. Initially, in the absence of any magnetic field, the iron particles move unrestrained in the carrier fluid. With an application of magnetic field, the iron particles get arranged in an order to from strong chains or flux. A further increase in the magnitude of applied magnetic field leads in an increase in number of the chains formed by aggregation of iron particles along the lines of magnetic flux. These strong chains themselves combine together to form a thick column type microstructure [1] resulting in development of high yield stress [2]. The yield stress, τ_y, is the stress required to rupture chain like arrangement of the particles along the line of magnetic flux [3].

Shetty & Prasad [4] made and analyzed MR fluid with a non-edible vegetable oil. Three samples of such MR fluid containing different percentages of carbonyl iron powder were prepared for comparing their rheological properties. It was observed that the one of the samples containing 40% carbonyl iron powder exhibited maximum viscosity of 334 Pa-s and yield stress of 13.23 kPa.

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Mangal & Kataria [5] prepared four different MR fluid samples using different weight percentages of its constituents. These samples were analyzed and tested for sedimentation characteristics under an off state condition. It was found that increase in the percentage of lithium grease provides better stability of the fluid. Mangal & Ashwani Kumar [6] studied the rheological characteristics of MR Fluids and concluded that the apparent yield strength of these fluids can be changed significantly on the application of an external magnetic field. Varela-Jiménez *et al.* [7] developed a constitutive model to describe the behavior of the yield stress of the MRF-122EG fluid, MRF-132DG and MRF -140CG fluids as function of the applied magnetic field, material and volume fraction of particles in a shear mode. Sapiński & Horak [8] investigated the rheological properties of the three different MR fluids using the Herschel–Buckley model and concluded that these fluids exhibit nearly a same yield stress of 12 kPa for an applied magnetic field of less than 0.3 Tesla. Roupec *et al.* [9] performed experiments to determine yield stress and viscosity at varying temperatures from 50° C to 70° C for Lord MRF140CG fluid and reported an increase in yield stress from 1 to 4 kPa on raising the temperature. Plunkett *et al.* [10] calculated the yield stress of MR fluid under an applied magnetic field in the range of 0.1-0.25 Tesla and reported that the magnitude of the yield shear stress is approximately one sixth of the compressive stress value obtained by subjecting the MR fluid to a compression-state. Hoon Lee *et al.* [11] calculated the resisting torque of Lord MRF-140CG fluid by rotating it inside a rotational damper and reported a maximum torque of 475 Nm at a rotational speed of 10 rpm. Nakano *et al.* [12] investigated the transient shear stress variation and the flow patterns of a MR fluid under a constant shear rate using a parallel disk rotary rheometer comprising of two parallel plates fixed at a gap of 0.2 mm rotating under a weak magnetic field and reported that a maximum yield stress of 800 Pa. Premalatha *et al.* [13] have prepared three different MR fluids using iron powder, silicone oil and grease in varying proportion. They analyzed the flow behavior of MR fluids in terms of its internal structure, stability and magneto rheological properties. It was found that the sedimentation and storage modulus were improved by adding higher percentage of grease. Chaudhuri *et al.* [14] have prepared a nano particle cobalt based MR fluid and examined their rheological flow curves using Bingham-plastic (BP) and Herschel–Buckley (HB) models using a parallel disk rheometer. It was found that the dynamic yield stress varies from 10 Pa at 0.03 T to almost 1450 Pa at 0.30 T for the HB model, and from 50 to 1750 Pa for the BP model. Sarkar & Hirani [15] have developed MR fluid by mechanical mixing of carbonyl iron powder, silicon oil and tetra methyl ammonium hydroxide to improve the sedimentation stability of MR fluid. The synthesized MR fluid showed better chain strength, higher torque carrying capacity and less agglomeration as compared to commercially available MRF241-ES fluid. Kumbhar *et al.* [16] synthesized various electrolytic (EI) and carbonyl iron powder (CI) based MR fluids by mixing grease as a stabilizer, oleic acid as an antifriction additive and gaur gum powder as a surface coating to reduce agglomeration of the MR fluid. It was found that the samples with CI powder have higher yield stress than that of commercially available Lord MRF132–DG fluid. Sarkar & Hirani [17] developed MR fluid by mechanical mixing the carbonyl iron powder, silicon oil, oleic acid and copper powder. It was found that an increase in the weight percentage of copper powder only improves the cooling capabilities of the MR fluid devices and does not affect the shear stress of the MR fluid.

From the literature review of the MR fluids, it is evident that yield stress or any other characteristics of MR fluid has been investigated by only one technique at a time while other techniques have not been unexplored simultaneously. Various researchers have characterized MR fluids on the basis of their rheological parameters like yield stress, viscosity *etc* using different techniques but none have focused to bring an insight into on-state magnetic field density of MRF122- EG fluid. The objective of the present study is to compare the on-state rheological characteristic *i.e.* magnetic flux density of the Lord MRF-122 EG fluid using three different techniques viz. experimental approach, modified Carlson equation and simulation using Infolytica Software approach under a high applied magnetic field (up to 2.0 Tesla). It has been found that the maximum value of magnetic flux density of Lord MRF-122 EG fluid using different approaches is 1.476 Tesla at an input current of 5.6 A. Further, for a varying current from 1.0 A to 5.0 A, the magnetic flux density values are nearly same with the percentage error of less than 5%. It, thus, validates the design of the fabricated electromagnet during this work which is proposed to be used for development of economical and effective MR fluid in the laboratory.

II PROPERTIES OF TESTED MR FLUID

In this work, commercially available MR fluid MRF-122EG (Lord Corporation) [18] is chosen to characterize its on-state magnetic flux density using different techniques. The MRF-122EG is a hydrocarbon-based MR fluid which can be used in energy-dissipating applications such as shock absorbers, dampers and brakes etc. This fluid can generate a high yield stress up to 40 kPa due to higher percentage of iron particles (72%) in its composition. Other typical physical properties of MR fluid (MR-122EG), as used in this work, are listed in Table I [18].

Table I Physical properties of tested MR fluid

Property	**Values / limits**
Base Fluid	Hydrocarbon Oil
Temperature Range	-40 to +130 °C
Density Range (g/cm^3)	2.28-2.48
Appearance	Dark Gray Liquid
Solids Percentage Weight (%)	72

III. TECHNIQUES USED FOR DETERMINATION OF ON-STATE MAGNETIC FLUX DENSITY

A. EXPERIMENTAL APPROACH

In this approach, an experimental set up of an electromagnet (Fig. 1) has been designed and fabricated to determine the on-state magnetic flux density of the MRF122–EG fluid. The electromagnet is capable of generating a magnetic field up-to 2.0 Tesla for an air gap (between the soft iron poles) of 18 mm. The pole diameter of the electromagnet is 75 mm. The electromagnet is made of two energizing coils with 1800 turns of copper wire (resistance of 8 ohm) wound around non magnetic formers. In order to find the magnetic field of the MR fluid, the fluid is put inside the vertically placed perspex tube constricted between the flat poles of the electromagnet. The length of perspex tube is 50 mm with its inner and outer diameters as 15 mm and 18 mm respectively. A DC current is supplied to electromagnet which induces a magnetic field between the poles of the electromagnet. The current is incremented using the DC regulated power supply. This varying current results in change in rheological characteristic and micro structure of the MR fluids. The on-state values of magnetic field corresponding to input current are then measured by placing the gauss probe vertically inside the perspex tube. This gauss probe measures the generated magnetic field which is displayed on the gauss meter screen. This magnetic field is termed as B_{on}. This on-state magnetic field as a rheological characteristic of the MR fluid is to be compared with the results of other techniques. Table II shows the magnetic flux density variation thus obtained with respect to input current.

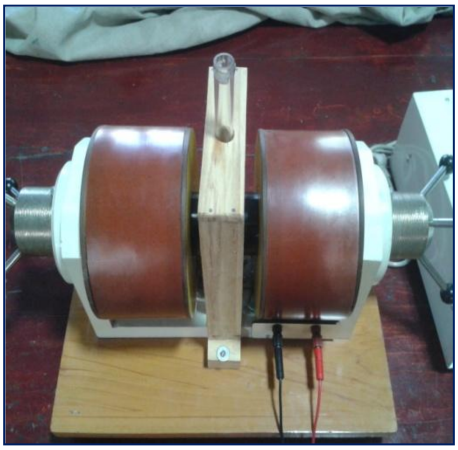

Fig. 1 Experimental set up

Table II Current and magnetic flux density values using experimental approach

Current (A)	**B_{on} Experimental (Tesla)**
0	0
0.2	0.227
0.4	0.314
0.6	0.394
0.8	0.483
1.0	0.543
1.2	0.606
1.4	0.664
1.6	0.715
1.8	0.766
2.0	0.81
2.2	0.855
2.4	0.902
2.6	0.949
2.8	0.993
3.0	1.031
3.2	1.072
3.4	1.114
3.6	1.149
3.8	1.192
4.0	1.226
4.2	1.259
4.4	1.291

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4.6	1.338
4.8	1.367
5.0	1.397
5.2	1.425
5.4	1.449
5.6	1.476

B. CARLSON APPROACH

Carlson performed series of experiments to study the MR fluids & its rheological characteristics. He has derived an empirical equation [1] describing the salient properties of the most of MR fluids. The relationship between magnetic flux density (B) and the applied magnetic field intensity (H) for any MR Fluid is given as

$$B = 1.91 C \phi^{1.133}\left(1 - e^{-10.97\mu_o H}\right) + \mu_o H \qquad [1]$$

where the B represents the magnetic flux density (Tesla), ϕ denotes the volume fraction of iron particles in the fluid, H is magnetic field intensity (A/m), μ_0 is the magnetic field constant in vacuum (which is equal to $4\pi\times10^{-7}$ Henry/m). The value of constant, C, depends on the type of carrier fluid used for preparation of the MR fluid and is equal to 1.0, 1.16, or 0.95 for hydrocarbon oil, water or silicone oil respectively. The value of constant C is taken as 1.0 as carrier fluid for a MRF 122–EG fluid. In this approach, the value of magnetic flux intensity is varied up to 925 kA/m in order to generate the different values of magnetic flux density (B). For a fixed ratio of number of turns of copper wire in electromagnet coils to length of air gap, the magnetic flux density is directly proportional to current. Thus, one can obtain different values of magnetic flux density with respect to varying current which is shown in Table III.

Table III Current and magnetic flux density values using Carlson approach

Current (A)	**B_{on} Carlson (Tesla)**
0	0
0.2	0.269
0.4	0.362
0.6	0.436
0.8	0.498
1.0	0.551
1.2	0.598
1.4	0.640
1.6	0.716
1.8	0.751
2.0	0.819
2.2	0.851
2.4	0.916
2.6	0.948
2.8	1.011
3.0	1.043
3.2	1.074
3.4	1.116
3.6	1.148
3.8	1.200
4.0	1.231
4.2	1.263
4.4	1.294
4.6	1.326
4.8	1.357
5.0	1.389
5.2	1.420
5.4	1.451
5.6	1.483

C. SIMULATION OF THE MAGNETIC FIELD USING INFOLYTICA SOFTWARE

The MAG-NET software from Infolytica Modeling Works, Canada [19] is used to simulate the magnetic field of MRF-122EG fluid. The initial design, as shown in Fig. 2(a), consists of development of geometrical wire frame model of the fabricated electromagnet. The subsequent parts of wire frame model are then selected using a materials options command in the material section tool-bar. It is also used to assign the specific material to various parts from software database. The material for the poles of electromagnet is selected as soft iron with a relative permeability of 100. The material for electromagnet coils is selected as copper wire with the relative permeability of one. The airs gap between the poles is substituted with MRF-122 EG fluid having the relative permeability of the order of six [20]. After these assignments, the model is transformed into a solid model and is shown in Fig. 2(b). The various parts of the solid model are selected for the mesh formation in a 2-D design. For this, different parts are selected and are assigned with various triangular nodes of 0.09 mm mesh size. The Initial 2-D mesh, thus, generated is shown in Fig. 2(c). This mesh model is converted into solid model for the purpose of specifying the number of turns of the copper wire wound around the pole of electromagnet, magnitude and type of current flowing through the primary and secondary coils of electromagnet. For this, one has to create a simple current driven coil option from the drop down menu of the software. In the present study, the number of turns of copper wire is set to 1800. The coil is driven by DC current and the maximum value of the current is set to 5.6 A. Further, the boundary condition of magnetic flux is set normal to the face of circular iron poles to prevent the magnetic flux leakage. Both coils are assumed to be connected in series and thus carry same input current. Table IV shows the different B_{on} values as obtained by the simulation for the varying current from 0.2 to 5.6 A. The 2-D magnetic and 3-D magnetic solver options are then clicked alternately to obtain a 2-D and 3-D magnetic flux density graphs.

Table IV Current and magnetic flux density values using simulation approach

Current (A)	**B_{on} Infolytica (Tesla)**
0	0
0.2	0.212
0.4	0.288
0.6	0.360
0.8	0.455
1.0	0.515
1.2	0.588
1.4	0.657
1.6	0.716
1.8	0.778
2.0	0.826
2.2	0.876
2.4	0.929
2.6	0.983
2.8	1.029
3.0	1.066
3.2	1.107
3.4	1.150
3.6	1.182
3.8	1.225
4.0	1.256
4.2	1.286
4.4	1.314
4.6	1.364
4.8	1.387
5.0	1.414
5.2	1.437
5.4	1.455
5.6	1.477

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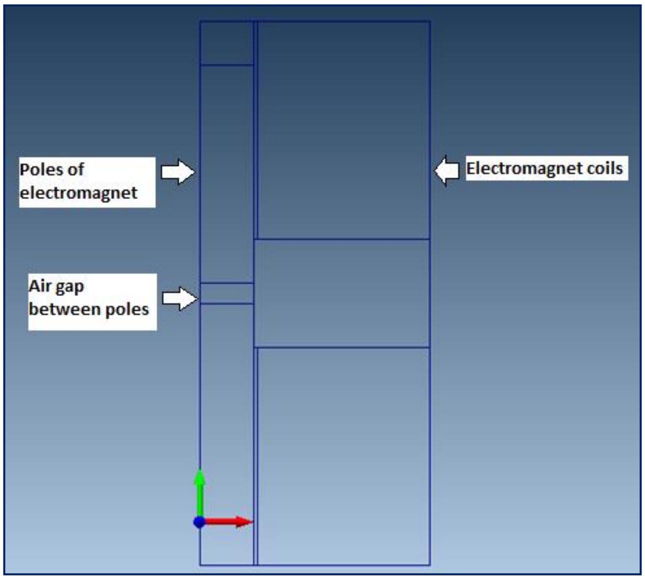

Fig. 2 (a) Wire frame model of design

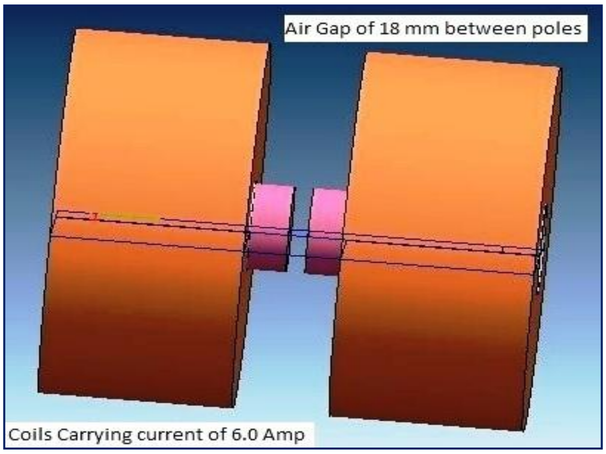

Fig. 2(b) MAG-NET model for simulating Magnetic field

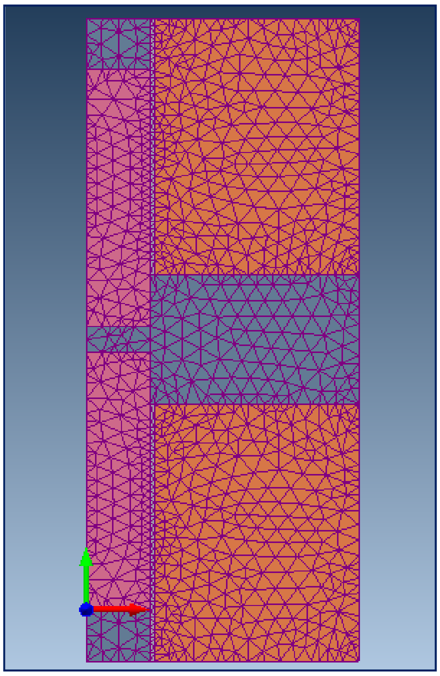

Fig. 2(c) 2-D triangular meshing of the electromagnet

IV. RESULTS AND DISCUSSION

The modeled value for 2-D magnetic density as obtained by MAG-NET software is shown by in Fig. 3(a). It can be seen that a uniform magnetic field up to 1.9 Tesla penetrates through a MR fluid placed in the air gap. The Fig. 3(b) shows that the maximum number of magnetic flux lines is penetrating through the MR fluid placed between the poles of electromagnet. This results in uniform magnetization of MR fluid which leads to a uniform value of yield stress all over the fluid.

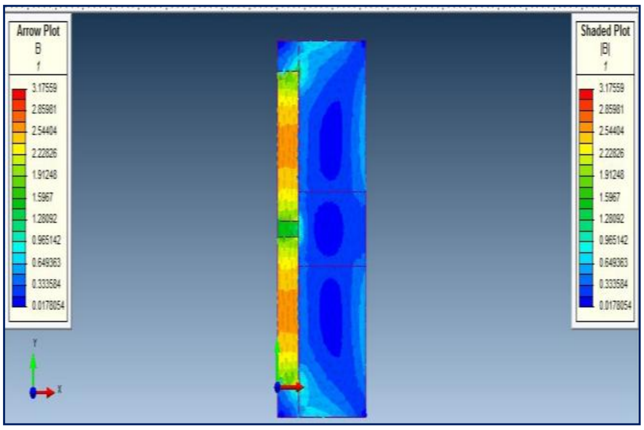

Fig. 3(a) 2-Dimensional shaded view of Magnetic field density

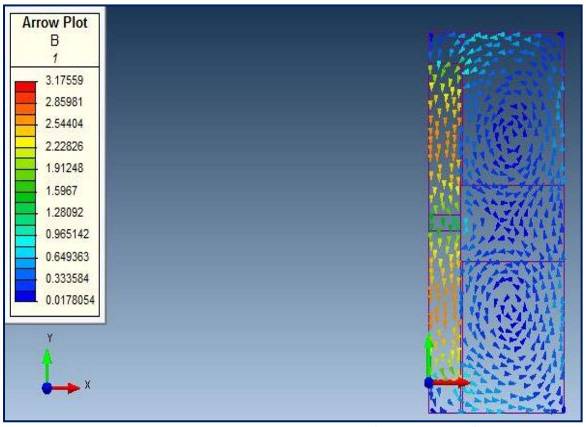

Fig. 3(b) 2-Dimensional shaded view of Magnetic flux lines

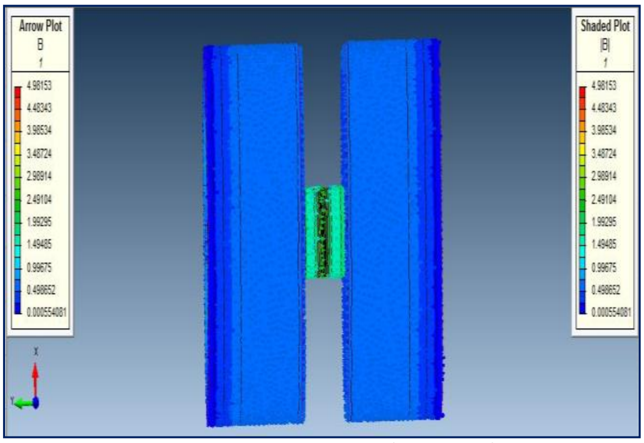

Fig. 4(a) 3- Dimensional shaded view of Magnetic field density

The 3D solution of the simulation in the form of magnetic flux is shown in Fig. 4. Figure 4(a) shows a 3-dimensional shaded view of magnetic field density while Fig. 4(b) shows 3-dimensional shaded view of the magnetic flux lines. These figures show the maximum magnetic field is concentrated around the air gap. The maximum magnetic field concentration is due to the retention of the magnetic field between the poles of an electromagnet which has high relative permeability of the order of 100 than the copper

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wire. This magnetic field travels from one pole to another attaining maximum value at 5.6 A. At this input current value, the fluid reaches to its saturation-state.

The values of the magnetic flux density as obtained by various approaches (Tables II- IV) with respect to input current are graphically shown in Fig. 5. This shows that the magnetic flux densities obtained by various approaches are matching quite well. It, thus, validated the design of the fabricated electromagnet during this work which is proposed to be used for development of economical and effective MR fluid in the laboratory.

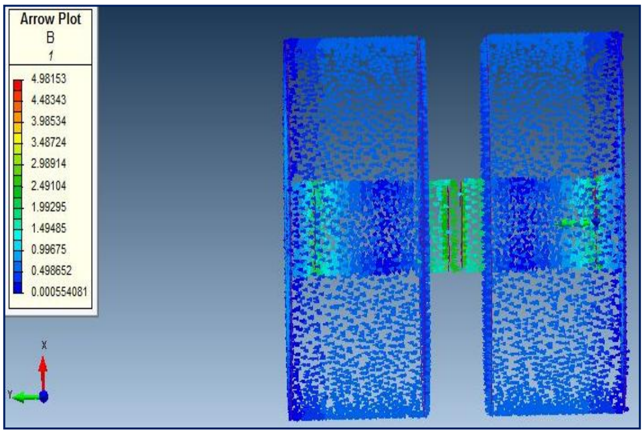

Fig. 4(b) 3-Dimensional shaded view of Magnetic flux lines

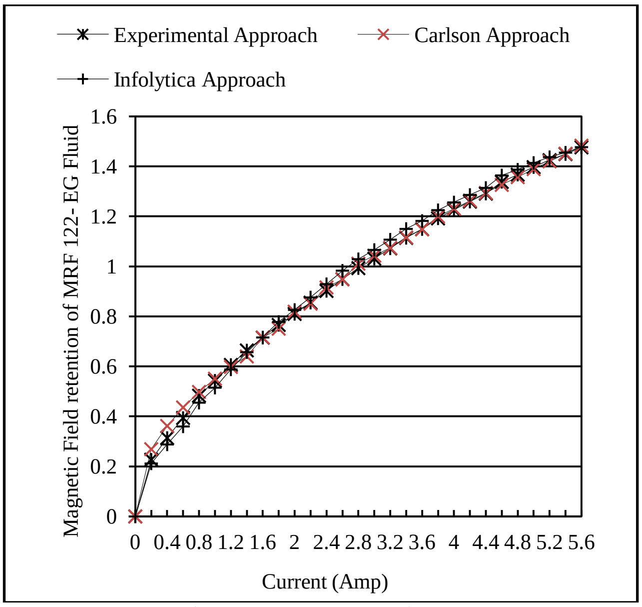

Fig. 5 Comparison of Magnetic Flux Density from Various Approaches

V. CONCLUSIONS

This work is primarily carried out to compare magnetic flux density for a Lord MRF-122 EG fluid using various approaches. The magnetic flux density values are investigated experimentally using the in-house designed and fabricated experimental set up consisting of an electromagnet capable of generating a magnetic field up to 2.0 Tesla. These values are also determined analytically using the Carlson equation and by simulation approach using the Infolytica Software. The maximum value of magnetic flux density of a MR fluid using different approaches is found to be 1.476 Tesla. The qualitative results as shown in Fig. 5 has illustrated that the magnetic flux densities obtained by various approaches are matching quite well with a percentage error of less than 5%. It, thus, has validated the design of the fabricated electromagnet during this work which is proposed to be used for development of an economical and effective MR fluid in the laboratory. From this research work, it can be concluded that one can find the value of magnetic flux density of any MR fluid directly either from simulation of magnetic field using MAG-Net software rather than going for experimental approach or Carlson approach which is a cost effective approach.

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