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On the Fabrication of Magnetorheological Brake with Optimum Design Factors

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Abstract: *In the recent trends, the automobile systems like transmission, suspension, brake, clutch are controlled through the wire systems called drive-by-wire concept, by replacing mechanical components, without affecting the functions. The advantages of the wire systems are the elimination of mechanical components and quick response when compared through conventional systems. In this work, we design and fabricate a Magnetorheological Brake (MRB) instead of a conventional brake like disk, grum and ABS brake which are currently used in automobile systems. The features of the MRB are no mechanical moving parts, less weight and quick response time. In this MRB, the Magnetorheological (MR) fluid is filled in the gap of outer casing unit and inner disk. The MR fluid has the change of rhological properties under magnetic fields. Commercially MR fluids are very costly. In this work we have prepare and charaterise the MR fluids. Next to the preparation, based on the fluid preparation, we optimize our design throught the COMSOL software. Based on the optimized design value we had design our MRB. Optimum design is found using Nelder Mead optomization technique combine with finite element simulations involving magnetostatic and heat transfer analysis finite element models are built to provide a means to analyze the performance of the MRB.*

Keywords: MR Brake, COMSOL Multiphysics®, Magnetorheological fluids, Optimization.

1. Introduction

MR fluids are smart fluids that change their rheological behavior when a magnetic field is applied. Typically and this change is manifested by the development of yield stress that increases with the applied field. When the magnetic field is absent, MR fluids behave like a Newtonian fluid. Jacob Rabinow at the US National Bureau of Standard discovers MR fluids in 1948 [1]. MR fluids consist of magnetically permeable micron-sized particles which are dispersed throughout the carrier medium. The carrier medium is either a polar or non-polar fluid, which influences the viscosity of the MR fluids. On the other hand, MR fluids are controllable fluids that exhibit dramatic reversible change in rheological properties (elasticity, plasticity or viscosity) either in solid-like state or free-flowing liquid state depending on the presence or absence of a magnetic field. When magnetic field is applied particles acquire dipole moment aligned with magnetic field to form linear chains parallel to field. The flow resistance (apparent viscosity) of the fluid is intensified by the particle chain. When the magnetic field is removed, the particles are returned to their original condition, which lowers the viscosity of the fluid [2].

Edward J. Park et al. (2006) developed an MRB in order to overcome the disadvantages of the Conventional Braking System. The proposed brake system consists of rotating disks immersed in MR fluid and is enclosed in an electromagnet. The yield stress of the fluid changes as a function of the applied magnetic field by the electromagnet. The controllable yield stress produces friction on the rotating

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disk surfaces and generates a retarding brake torque. The braking torque can be precisely controlled by changing the applied current to the electromagnet. An optimum MRB design with two rotating disks based on design optimization procedure using simulated annealing combined with FE simulations involving magneto static, fluid flow and heat transfer analysis are also carried out by them .The performance of the MRB in a vehicle is studied with the help of a quarter vehicle model. A sliding mode controller is also designed for an optimal wheel slip control. The simulation result shows the potential of their proposed MRB system to provide fast anti-lock braking [3]. J. Huang, J.Q. Zhang et al. (2002) investigated the geometric design method of the cylindrical MR fluid brake theoretically. The torque developed by the MRB under different magnetic field strength conditions has been analyzed. The equation for the torque transmitted by the MRB is derived to provide the theoretical foundation in the design of the MRB. Based on that equation, after analytical manipulation, the calculations of the thickness, volume and width of the annular MR fluid within the cylindrical MR fluids brake are yielded [4].

2. Design of the MRB

For MR brake, the analysis problem would simply consist of running the finite element models of a given brake configuration (i.e., with known dimensions and materials). Clearly, the solution to the design problem of finding the ideal configuration of the MR brake is not so direct. Without closed-form solutions of the equations describing its dynamics, no immediate approach exists. In such cases, the design problem generally consists of an iterative process involving a sequence of analysis problems. Based on the results of each analysis some changes are made to the design and the performance of the resulting configuration is compared with that of the previous one, continuing this process until no further improvements in the design are achieved. Hence, in order to design a suitable MR brake, two different tasks are necessary: a model capable of analyzing the performance of a given brake design and an optimization tool capable of using the results of such analyses to produce improved designs. Here the preliminary design, optimization, final design and analysis of the MRB are done in this paper.

In consideration of the dimensions of the various components of the MR brake, the first factor to take into account is the existence of physical limitations. For example, if the brake is to be placed within the wheel rim (where today's disk or drum brakes are located), the overall diameter must be such that it will fit within that area: it is recommended that a minimum clearance of 3 mm exists between the brake and wheel rim and spokes. The maximum acceptable diameter for the MR brake is then, for a 17" wheel, 16in x 25.4mm/in - 2 x 3mm = 425.8 mm i.e 42.58 cm, resulting in a maximum acceptable radius of 212.9 cm. Here we take the radius of the MR brake as 200 mm and set the disk radius to 17 cm and the width of the coil to 1 cm. In addition to these two quantities, the radius of the brake must also accommodate the fluid gap (0.1cm) adjacent to the edge of the disk, If the gap between disk and coil is chosen to have 4 mm, the maximum possible thickness for the end part of the casing is 20 - 18 - 0.1 - 1 - 0.4 = 1.5 cm. These are the values that had been used for the initial design. The 3D CAD model of the MRB was created using Unigraphics NX 8.0®. Fig.1 shows the 3D CAD model of the proposed MRB model and fig.2 shows the drawing view of the proposed model.

The major components of the MR Brake are Casing, Disc, MR fluid, Coil and Shaft. The material selection is a critical part of the MRB design process. Materials in the MRB have crucial influence on the magnetic circuit as well as the structural and thermal characteristics. Here, the material selection is discussed in terms of the (i) Magnetic properties and (ii) Structural and thermal properties.

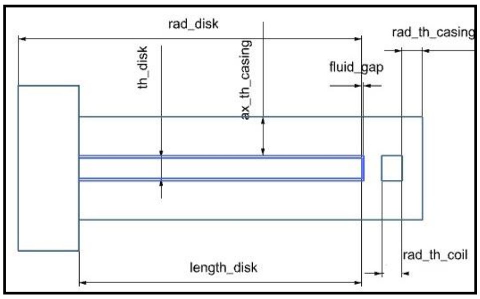

Figure 1. Drawing view of proposed MRB

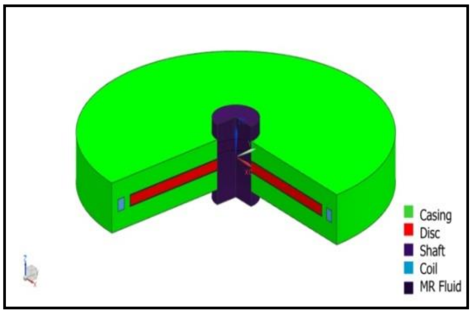

Figure 2. 3D CAD model of the proposed MRB

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Permeability (μ) is the property that defines a material's magnetic characteristics. It is the ratio between the applied magnetic field intensity (B) and magnetic flux density (H) due to B through the material .It is the ability of a material to transfer magnetic flux over itself. Relative permeability (μ_r) is the ratio between the material's permeability and vacuum's permeability (i.e. $\mu_o = 4\pi\times10^{-7}$H/m).

$$B = \mu H$$

$$B = \mu_r\mu_o H$$

In terms of structural considerations, there are two critical parts: the shaft and the shear disk. Thermal properties of the materials are another important factor. Since the permeability values of the ferromagnetic materials are temperature dependent and the MR fluid viscosity the heat generated in the brake should be quickly removed as soon as possible. In terms of material properties, in order to increase the heat flow from the brake, a material with high conductivity and high convection coefficient has to be selected as the material for the non-magnetic brake components. Aluminum is a good candidate material for the thermal considerations. AISI 1018, having a high yield stress is selected as the magnetic material in the magnetic circuit (i.e. the casing and disks) after considering the cost, permeability and availability. The B–H curve of steel 1018 with the saturation effect is shown in Fig.3.

Shaft should be non-ferromagnetic in order to keep, the flux far away from the seals that enclose the MR fluid, to avoid from MR fluid being solidified. 304 stainless steel is a suitable material for the shaft due to its high yield stress and availability. Thicker wires are capable of conducting greater currents but take more space and hence a smaller number of turns can be wound in the same area. The change in current carrying ability is inversely proportional to the number of turns per unit area. Magnetic flux produced by the coil is proportional to NI, the choice of a given wire dimension will not influence it. After referring American Wire Gauge (AWG) Cable / Conductor Sizes and Properties, AWG 21 is chosen The selection of MR fluid is important in the design of the MR brake. No-field viscosity of the MR fluid, operating temperature range and shear stress gradient are some of the key properties that have to be considered when making a selection. The density of the MR fluid chosen is 450 kg/m^3 and viscosity is 6 Ns/m^2. The flow curve and the BH curve for the selected MR fluid are shown in fig.4 and fig.5 respectively. The relationship between the magnetic field intensity and the generated shear stress of the MR fluid brake is shown in fig.6.

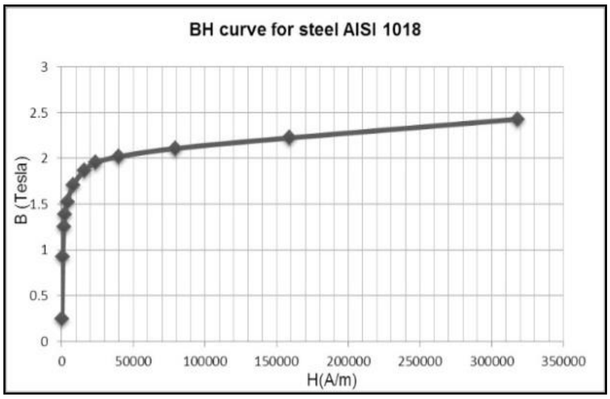

Figure 3. BH curve of steel AISI 1018

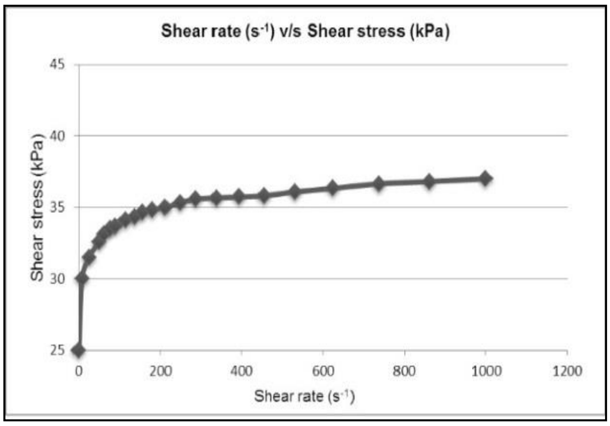

Figure 4. Flow curve of the MR fluid

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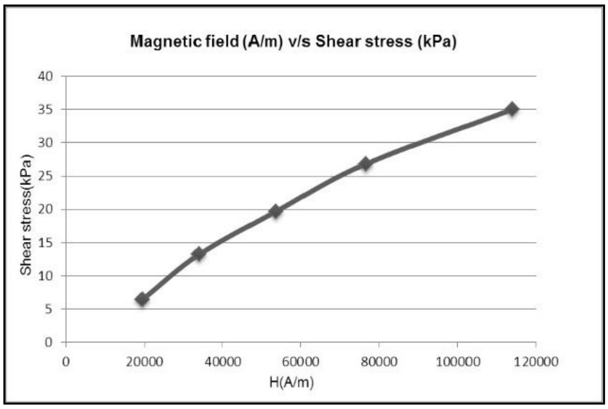

Figure 6. Magnetic field v/s shear stress curve

Figure 7. Viscosity v/s Time curve for MR fluid

3. Preparation of MR fluids

To prepare a low viscosity and high yield point MR fluids are prepared, which contains micron size of 1 – 2 μm iron particles, Silicone oil as career medium and additives as Triton X100.

These particles and oil are varied with a volume fraction method as per our requirements. As per the method, the required amount of iron powder, Silicone oil and additives are taken. First the Silicone oil and additives are mixed with a magnetic stirrer for more than 8 hrs for getting a homogeneous mixture. After obtaining the homogeneous mixture of oil and additives, the iron powder is poured and stirrered with mechanical stirrer. This procedure is followed to avoid sudden sedimentation ratio [5]. The viscosity of the above prepared fluid was then tested using the Brookfield Viscometer® and the results obtained is given in fig.7.

The volume fraction of iron particles is varied between 20% to 40% for improving the yield strength. For 20% volume fraction, the required volume of Silicone oil and iron powder is calculated as:-

Total volume of MR fluid = 100 cc

20% volume fraction of Iron powder = 0.35×100 = 20 cc

Mass density of Iron powder = 7.8 g/cc

Mass of Iron Powder = $7.8 \times 20 = 156$ g

80% volume fraction of Silicone oil = 0.8×100 = 80 cc

Table 1

MR Fluid Constituents for 20% Volume Fraction

Total Volume of MR fluid = 50 cc Density of Iron powder = 7.8 g/cc		
Vol. Fraction [%]	Mass of Iron powder [g]	Volume of Silicone oil [cc]
20	78	40

Table 2

Properties of MR Fluid Prepared

Carrier fluid	Silicone Oil
Solid particles	Carbonyl Iron
Volume fraction of Solid phase	20 %

Mass density of Iron Powder	7.8 g/cc
Mass density of Silicone Oil	1.25 g/cc
Color	Dark grey

4. Analytical Modeling and FEA of MRB

We can describe devices and behaviors in many ways. Analytical modeling is the way of describing devices or behaviors using the language of mathematics. For the MRB, the braking torque produced by the MRB is to be derived in terms of applied magnetic field.

Braking force (F_b) is the tangential force acting between the disc and the stator Braking torque (T_b) is the moment of braking force about the center of rotation.

Braking torque,

$T_b = F_b r$ (1)

r = Effective radius

Shear stress, $\tau = \frac{F_b}{dA}$ (2) $F_b = \tau dA$

$T_b = \tau r dA$ (3)

Equation for τ can be derived from fitting the curve using the table values of the flow curve (τ v/s$\ddot{Y}$) with and without magnetic field.

4.1 Without magnetic field

$\tau = \mu\ddot{Y}$ (4)

μ = Viscosity of the fluid without magnetic field

$\ddot{Y}$= Shear rate

4.2 With magnetic field

Experimental values of the flow curve (τ v/s $\ddot{Y}$) is used to derive the relationship between τ and $\ddot{Y}$. According to Bingham plastic model, the equation for shear stress of the MR fluid is given by

$\tau = \tau_y(H) + \mu\ddot{Y}$ (5)

By applying the above equation in the torque equation we get

$T_b = (\tau_y(H) + \mu\ddot{Y})\, r dA$ (6)

From the above curve a linear curve is fitted using the linear regression technique [6]. The equation for the above curve is found and is given as

$\tau = 32442 + 6.496\ddot{Y}$ (7)

Correlating the above equation with Bingham plastic model

$\tau_y = 32442\ N/m^2$ & $\mu = 6.496\ Ns/m^2$

Considering an elemental section of disc the area of contact between disc and fluid

$A = \pi r^2 \quad \rightarrow \frac{dA}{dr} = 2\pi r \quad \rightarrow dA = 2\pi r dr$

$T_b = 2\pi r^2(\tau_y(H) + \mu\ddot{Y})\, dr$ (8)

For single disk the contact is made on 2 opposite sides (n)

$T_b = 2n\pi r^2(\tau_y(H) + \mu\ddot{Y})\, dr$ (9)

For entire cross section of the disc, integrating

$T_b = \int_{r1}^{r2} 2n\pi r^2(\tau_y(H) + \mu\ddot{Y})dr$ (10)

Shear rate ($\ddot{Y}$) is the rate of change of shear strain with respect to time along the gap. The curve between τ_y and B is drawn first and from the BH curve of the MR fluid the corresponding H values are found out and the curve between τ_y and H is drawn and is approximated to an exponential curve of the form y = ax + b. The relation between τ_y and H is found and is given by

$\tau_y = 0.2976H + 2505.504\ N/m^2$ (11)

Finally the relation for torque (T_b) in terms of H can be established as

$T_b = \left(2/3\right) n\pi(0.2976H + 2505.504)(r_2^3 - r_1^3) + \left(n\pi\omega/2h\right)(6.496)(r_2^4 - r_1^4)$ (12)

Where,

n = number of surfaces (2 for single disk)

H= Applied magnetic field (A/m)

r_1= Inner radius of disc (mm)

r_2= Outer radius of disc (mm)

h= MR fluid filling gap (mm)

ω= Angular speed of disc (rad/s)

The disciplines which are involved in the operation of a magneto-rheological brake are magneto statics, fluid flow, and heat transfer. Due to the multidiscipline and the presence of nonlinearities (magnetic saturation and non-Newtonian fluid behavior) and the absence of closed-form solutions, the analysis of MR brakes is to be carried out using finite element modeling. Hence, in order to

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obtain meaningful solutions with the weak formulation, it is necessary to divide the original problem domain (the system being analyzed) into many small domains (the elements), so that the "average" introduced by the weak formulation does not introduce significant errors in the solution. In this COMSOL Multiphysics® is used for the Finite Element Analysis. It is a flexible platform that allows users to model all relevant physical aspects of any type designs [7].

Since the MR fluid's viscosity is controlled by the magnetic field, the first step in the analysis of an MR brake system is a magnetostatics analysis that determines the magnetic field distribution. The electromagnetic analysis results in the magnetic field intensity distribution within the MRB design configuration is analyzed. The relationship between applied electric power and the braking torque can be determined using electromagnetic analysis. This is a non-linear problem and requires an iterative approach. In order to determine the magnetic field distribution, a 2D axisymmetric Finite Element Model of the brake is created using COMSOL Multiphysics®.

The response of a system depends not only on its geometry and the properties of the materials it is made of but also on the loads that are applied and on any constraints imposed (boundary conditions) on the problem. The load in the present problem is the current flowing through the coil, responsible for the magnetic flux. After meshing, the FEM was solved using a parametric nonlinear solver and the magnetic field distribution onto the MR fluid was obtained. Finally, the braking torque using eq.11 was calculated [8].

Once the magnetic field distribution is known, the shear stress can be obtained from the fluid's specifications and, together with the no-field viscosity, describes the behavior of the fluid flow. Thermal analysis can then be done to obtain the distribution of temperature within the brake. The temperature change is mainly due to the joule heating effect.

5. Optimization and fabrication of MRB

Optimum design for the MRB should be done to findout the significant geometric dimensions of MRB that maximizes the torque and minimizes the weight. The objectives for the Optimization problem are:-

1. Maximize the braking torque (T)
2. Minimize the weight (W)

Objective function is chosen using the utility function method (weighted sum method) as

$F = T - W$, after giving weightage factors of 0.8 and 0.2 for torque and weight respectively, the objective function is as follows

$F = 0.8T - 0.2W$

$F = 0.8(T/T_0) - 0.2(W/W_0)$

where,

T_0 =1010 Nm and W_0 = 65 kg, taken as reference values

Above is a maximization problem, which is solved by using Nelder Mead method (Simplex method) with the aid of the COMSOL Multiphysics®. The global objective is given as input in the optimization module and the optimization is carried out.

Nelder mead optimization has reduced number of function evaluations in each iteration. For N variables, (N+1) points are used in initial simplex. At each iteration, the worst point in the simplex is found first. The centroid of all but the worst point is determined. Worst point in the simplex is reflected about the centroid and new point X_r is found. If functional value at this point is better than the best point in the simplex, expansion along the direction from the centroid to the reflected point is performed. If the functional value is much worse than the worst point in the simplex.

Then contraction in the direction from the centroid to reflected point is made. The process continues until the termination criterion is satisfied [9]. The results obtained from the optimization process are given in table 3.

Table 3

Optimum Design Parameters

Parameter	Initial value	Optimum value
th_disk	0.01 m	0.0141 m
rad_disk	0.17 m	0.18 m
rad_th_coil	0.01 m	0.0134 m
rad_th_casing	0.015 m	0.01 m
ax_th_casing	0.019 m	0.015 m
length_disk	0.14 m	0.1382 m

After an optimum design is found by solving the defined optimization problem for the MRB then the MRB is slightly modified for ease of manufacturing and additional details such as bearings, seals and the surface finishes were defined. Silicone gel sealant is used for the sealing purposes. In addition, deep groove ball bearings, 6816ZZ, were used. The fabricated model is shown in the fig. 8 and the final specifications of the MRB is shown in table 4.

Figure 8. Fabricated MRB

Table 4
Specifications of MRB

Weight	38.2 kg
Diameter	416.8 mm
Height	46.1 mm
Number of Disks	1
Amount of MR Fluid to be used	210.856 cm^3
Coil Wire Size	AWG 21
Number of Turns	60
Magnetic Materials Used	Steel AISI1018
Non-Magnetic Materials Used	SS 304
Sealant used	Anabond® 666 RTV Silicone sealant

6. Results and Discussions

For the optimum design, the magnetic field distribution plot obtained by giving input current as 1.5 A is shown in fig. 9. The results obtained from the magneto static analysis for the magnetic flux density within the MR brake for an input current of 1.5 A along the coil is given in the fig.10. The shear stress distribution and temperature distribution in the MRB when 1.5 A current is given to the coil is given in fig.11 and fig.12 respectively. Eventhough the simulation result shows that 383.532 Nm braking torque can be achieved by the present design, in practice this value may not be reached.

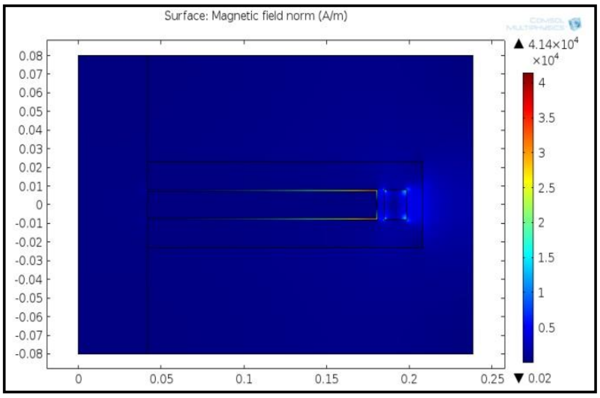

Figure 9. Magnetic field distribution along the MRB

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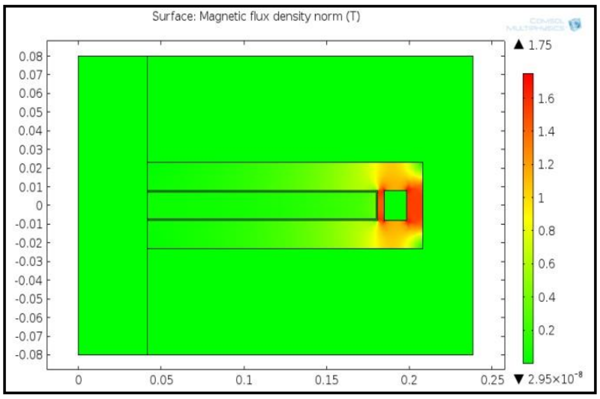

Figure 10. Magnetic flux density in MRB

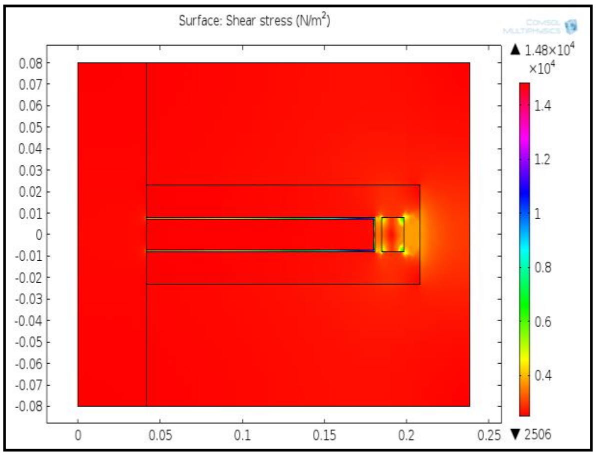

Figure 11. Shear stress distribution along the MRB

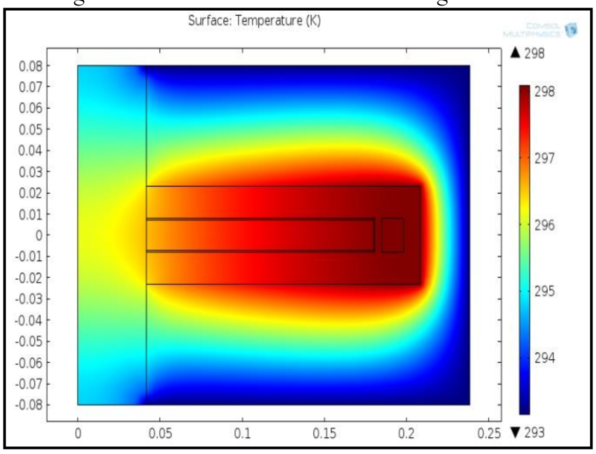

Figure 12. Temperature distribution along the MRB

7. Conclusion

In this paper, a magneto-rheological brake (MRB) with single disk design has been introduced as an alternative to the current conventional hydraulic brake (CHB) device. Analytical modeling results in the expression of torque for the MRB in terms of Magnetic field intensity. Optimization of design parameters to improve the torque and reduce weight was then carried out by Nelder Mead optimization technique using COMSOL and Finite element model for optimum design of MRB was created to simulate the steady-state magnetic flux flow within the MRB domain using COMSOL Electromagnetic module and solved for the magnetic field intensity distribution. In addition to the detailed electromagnetic analysis, a simple thermal analysis was also carried out to monitor the temperature distribution within the brake.

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The multiobjective optimization of the MRB was also carried out for minimizing the weight and maximizing the braking torque using the Nelder Mead optimization technique. For a vehicle travelling at a speed of 80 kmph, the shaft speed is found as 1040.88 rpm. When the brake is applied the torque generated is found to be 383.532 Nm with the help of the COMSOL Multiphysics®. The weight of the brake is found to be 39.158 kg. The MRB is also fabricated and the specifications are noted. Further testing procedure can be done to find the experimental results of braking torque for various speeds.

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