24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017- 0311
TRANSIENT THERMAL ANALYSIS OF A MR CLUTCH FOR KNEE PROSTHESES AND EXOSKELETONS

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Abstract. *Magneto-rheological (MR) fluids are smart materials which can have their properties controlled by an induced magnetic field. MR fluids have been used in devices with multiple purposes. Despite the great characteristics and benefits, the MR fluid properties are strongly dependent on temperature. When the fluid temperature reaches certain limit, its additives begin to deteriorate and the viscosity of the carrier fluid starts to change, which can lead to irreversible changes on the MR fluid and uncontrollability of its rheology. This paper presents a transient thermal analysis of a high torque and low weight MR clutch used in a knee actuator for prosthesis in order to determine the conditions of safe operation without loss of fluid properties. Two thermal analyses are developed, the first one is in the no slip condition, which occurs during a ground walk, in this case the heat generation is caused by Joule effect in its coil. The second analysis is developed based on the full slip condition, when knee actuator is used to walking down steps, in this situation the heat generation is caused by friction and by Joule effect. Since the heat generation caused by friction is very higher, full slip condition is the most important operating condition and requires attention.*

Keywords: *Magneto-Rheological Actuator, prostheses, exoskeletons, biomechanics, thermal analysis.*

1. INTRODUCTION

Magnetorheological fluid (MR) is a suspension of micro-sized of magnetizable particles mixed with insulated carrier fluid, usually mineral based or silicone-based (Chen et al., 2015). The weight percentage of particles in suspension can reach about 80% (Zipster et al., 2001). When the fluid is subjected to an external magnetic field, particles begin to form columnar structures parallel to the magnetic flux lines. This behavior changes the rheological properties of the fluid, principally the yield stress, that can attain values in order of kPa. The time to form the columnar structures is in order of milliseconds (Yang, 2001).

Due to these characteristics, MR fluids have been used in dampers, allowing modulate the damping level imposed by the magnetic field, and in power transmission systems that require adjustment of the output torque, as clutches. MR devices are used in various applications in engineering and industry: vehicle suspensions (Sung and Choi, 2008), clutches (Kavlicoglu et al., 2006), brakes (Nguyen and Choi, 2010), intelligent prosthesis (Andrade et al., 2015, Andrade et al., 2016), (Dong et al., 2006), and others.

The properties of the MR fluid strongly depends on temperature, for this reason, the fluid shows different performances with the temperature variation (Chen et al., 2015). The main reason for this variation is the temperature sensitivity of the carrier fluid. The viscosity of the carrier fluid changes with the temperature variation, which results in variation of the MR fluid shear stress. Additives are applied in the MR fluid to decrease the sedimentation rate and increase the particles dispersion on carrier fluid (Wang et al., 2014). However, these additives are also sensitive to temperature variation, some are decomposed at about 100 °C. The cyclic operation under high and low temperature can lead to irreversible changes on the MR fluid. It can cause the reduction of the rheological properties and uncontrollability of the shear stress by the influence of the chaining of the material under magnetic field (Chen et al., 2015). To account these properties changes with the temperature, Chen et al. (2015) proposed an experimental setup for evaluation of a MR transmission (which works on the shear mode of the MR fluid) under different temperatures, obtaining a set of curves for torque and temperature with different current inputs. Zipster et al (2001) proposed an experimental setup which analyzes the MR fluid in the flow mode under different temperatures. Wang et al (2014) made a complete characterization of the MR fluid under different temperatures. Lee et al (2015) accounted the temperature rise of the variable inductor for magnetorheological fluid under high-frequency pulsed voltage source. The variation, mainly due the eddy current, has an influence on the MR fluid temperature rise.

Since the MR fluid has limited temperature of operation, the thermal analysis of the MR components has a great importance in almost all applications. Kowol and Pilch (2015) analyzed the temperature rise on a MR clutch on the full slip state, which is the most dangerous state for the MR fluid in shear mode. Wang et al (2013) proposed a cooling water method for dissipation for a high torque MR brake. An extensive investigation of the MR brake temperature distribution and fluid irreversible changes caused by excessive heat are made in Wang et al (2015). Although it is a very important analysis for the MR fluid device implementation in a real environment, few transient analyses were made on a MR fluid device to evaluate the time limit of operation under full slip state or under certain temperature condition. In our last work (Andrade et al., 2016) we made a transient analysis for the MR knee actuator for prosthesis and exoskeletons only under walking ground operation. In that work, the worst operating condition for the MR fluid was the full slip.

In this paper, the temperature distribution of a low weight and high torque MR clutch used in the MR actuator is analyzed under two operating condition. First one, when the knee actuator is used during a ground walk, in this case no slip occurs and the heat generation is caused only by Joule effect in its coil. Second, when knee actuator is used to walking down steps, in this situation the torque required is greater than the clutch induced torque and the heat generation is caused by Joule effect in its coil and by friction between the discs and MR fluid. Since the heat generation caused by friction is very higher, full slip condition is the most dangerous condition for the clutch.

2. MAGNETO-RHEOLOGICAL CLUTCH

Figure 1 shows the MR clutch. The clutch operation comprises on apply current in the coil set (03 and 04), consisting of a carbon steel SAE 1020 core, a copper winding and an aluminum cover, which generates a magnetic field. The coil set is connected to the inner steel discs (07) and to the inner support (02). The outer discs (06) are connected to an aluminum cover (08) and this to the upper support (01). MR fluids are filled between the outer and inner discs; they are used in shear mode. The coil core and side discs (05) direct the magnetic field to the MR fluid. Under the magnetic field, the fluid begins to behave as a semi-solid. This behavior leads to an increase friction in the discs, so with a sufficiently high magnetic field, the inner and outer discs rotate together with the same speed. The chosen fluid is the MRF-140DG provided by LORD corporation. All the design process is made thinking of a way to combine magnetic and mechanical requirements of the actuator and feasibility of the manufacturing. The clutch weight is about 500g and its can withstand up to 60 N.m. The inner and upper supports are considered in the simulations, because they are used in experimental tests.

In the MR clutch dynamic model, the current input is converted into magnetic field force on the MR fluid region. Magnetic field relates with the MR fluid yield stress through the experimental curve provided by the manufacturer. MR fluid yield stress and output torque are related through Eq. (1).

$$T = N\pi \int_{ri}^{ro} (\tau_Y + \eta\dot{\gamma}) r_D (r_D dr_D) = N\pi \left[\frac{\tau_Y}{3}\left(r_o{}^3 - r_i{}^3\right) + \frac{\omega\eta}{4g_D}\left(r_o{}^4 - r_i{}^4\right) \right] \tag{1}$$

Where τ_Y is the yield stress related to the applied magnetic flux density obtained by consulting the MR fluid datasheet provided by the manufacturer, η is the off-field viscosity and $\dot{\gamma}$ is the shear rate as a function of the radius, the length of the working gap (g_D) and the angular velocity (ω).

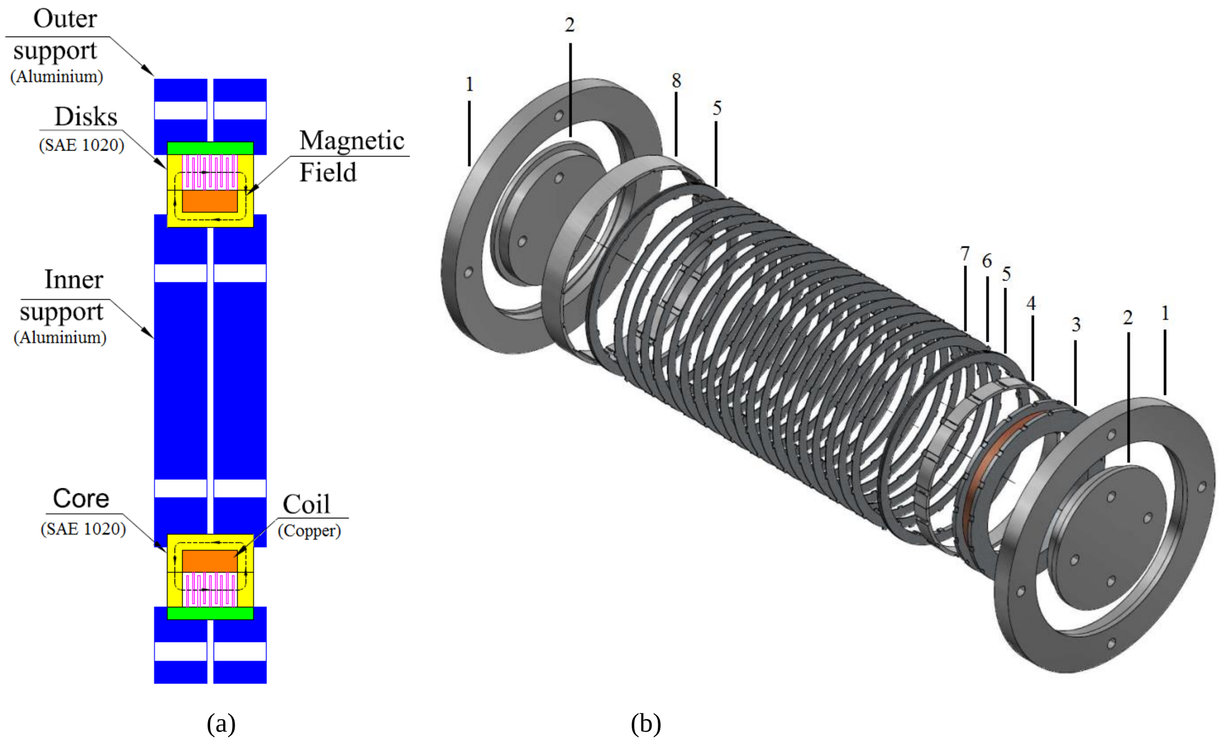


Figure 1. MR clutch. (a) Schematic view. (b) Exploded view of the MR clutch with supports for performance test.

3. COMPUTATIONAL PROCEDURE

The temperature variation during the MR Clutch (Figure 1) operation is evaluated through a finite element analyses. ANSYS Workbench 17.2 is employed for the transient thermal analysis with the Mechanical APDL solver.

Almost all input power on the MR fluid is converted into thermal power (Kowol and Pilch, 2015). Equation (2) presents the volumetric slip power loss, assuming that all slip power loss is converted to heat generation (Wang et al., 2015).

$$\dot{\Phi} = \frac{T\Delta\omega}{V} \tag{2}$$

Where $\Delta\omega$ is the angular velocity, T is the MR clutch induced torque and V is the MR fluid volume.

The electric power loss is applied to the model through the Joule effect on the coil. Eq. (3) presents the volumetric electric power loss.

$$\dot{\Phi}_C = \frac{I^2 R_C}{V_C} \tag{3}$$

I is the coil current, R_C is the coil wire resistance and V_C is the coil volume. The adopted natural convection coefficient for static surface is hs = 9,7 W.(m^2.°C)$^{-1}$(Wang et al., 2015).

Initial temperature and ambient temperature are 25ºC. In order to reduce processing time, a 1/360 part of the MR clutch was used for model, as presented in Figure 2. The mesh was generated using the MultiZone method to create hexahedral elements. Mesh controls were then applied to create different elements sizes to achieve an acceptable accuracy of the results in the most important areas. The elements size varies from 0.3 mm, in the MR fluid region, to 3 mm, in the supports.

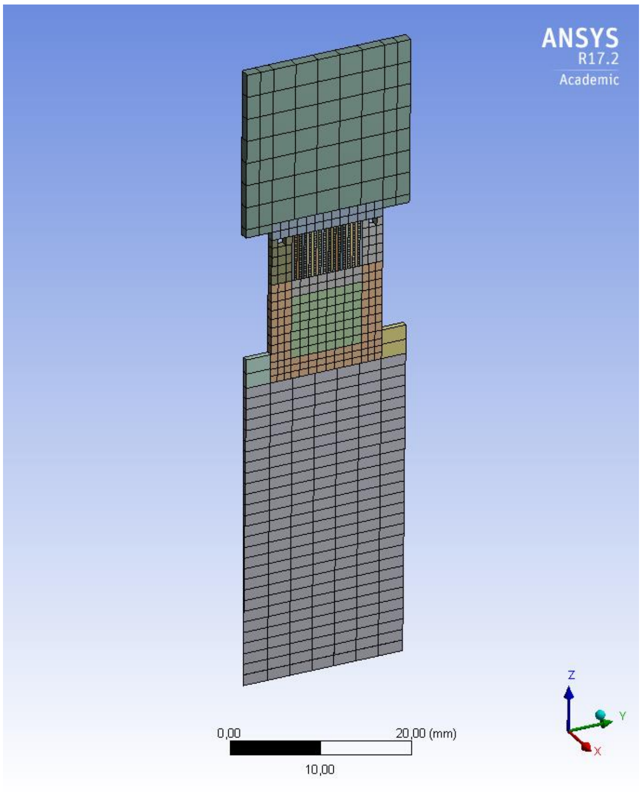


Figure 2. Mesh model used in the simulation.

To estimate the energy dissipation in the MR clutch it is necessary to calculate the current level in its coil and the heat generated in the region of MR fluid. The developed clutch presents a torque constant of 30,0 N.m / A. When the knee actuator is used during a ground walk, no slip occurs and the heat generation is caused only by Joule effect in its coil. The current level reached in the clutch during the gait is measured in the test bench using as input the torque reference developed in the knee during ground walk (Kapti and Yucenur, 2006). Figure 3 presents the current variation on the MR clutch coil during the gait cycle.

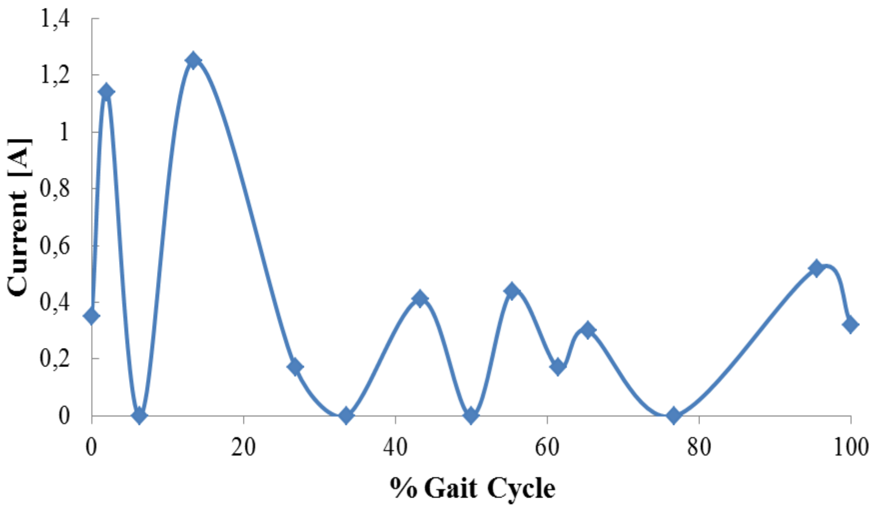


Figure 3. Current variation during the gait cycle on the coil.

When knee actuator is used to walking down steps, the torque required is greater than the clutch induced torque and the heat generation is caused by Joule effect in its coil and by friction between the discs and MR fluid. Data from Riener et al. (2002) are used to estimate heat generation in the MR fluid and current variation in the coil when clutch is used in this gait mode (Figure 4).

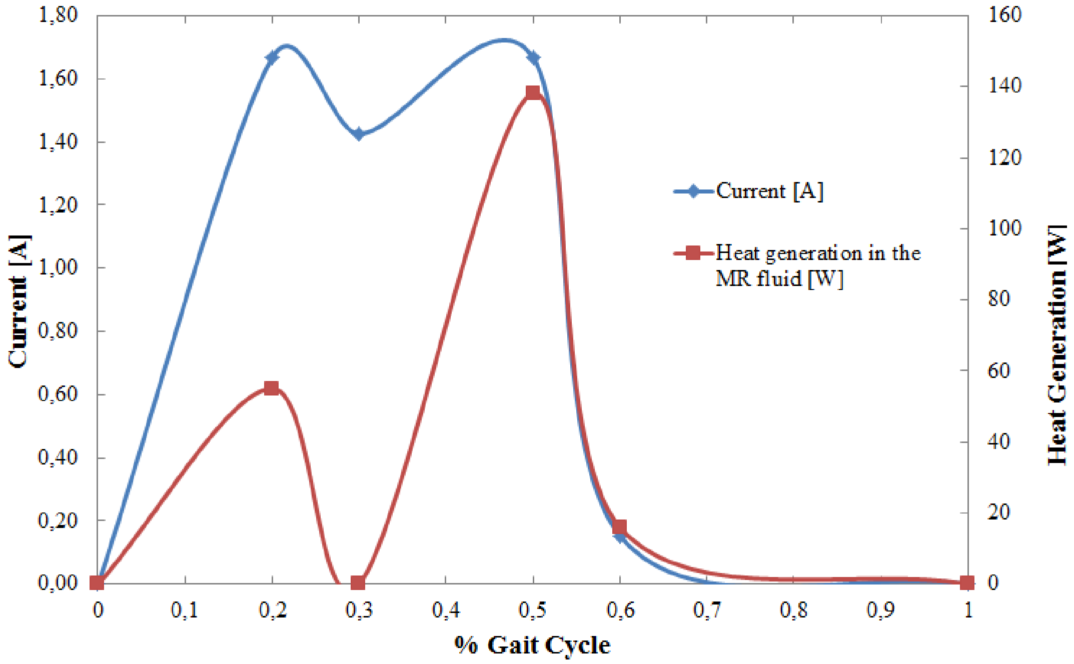


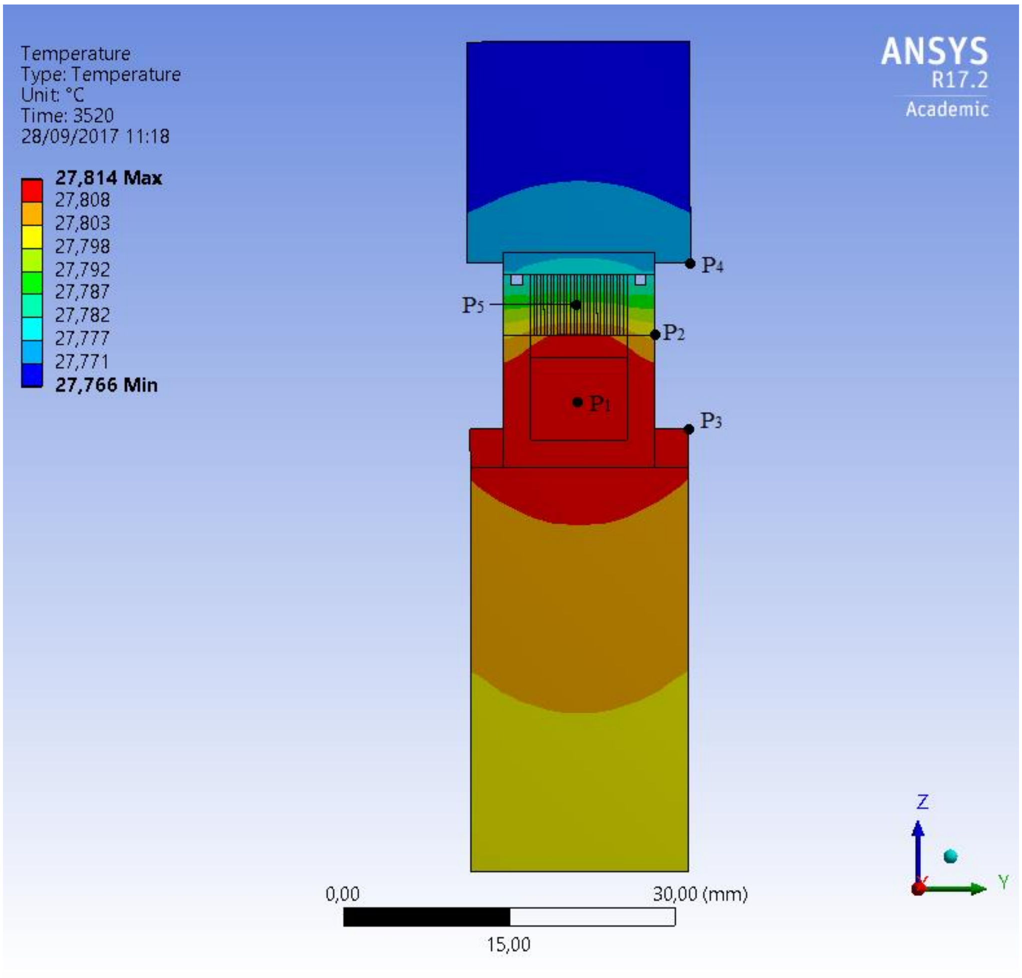
Figure 4. Current variation and heat generation in the MR fluid region when it's going down stairs.

The data from Figure 3 and Figure 4 are used as boundary conditions in the simulations. The results are shown in the next section.

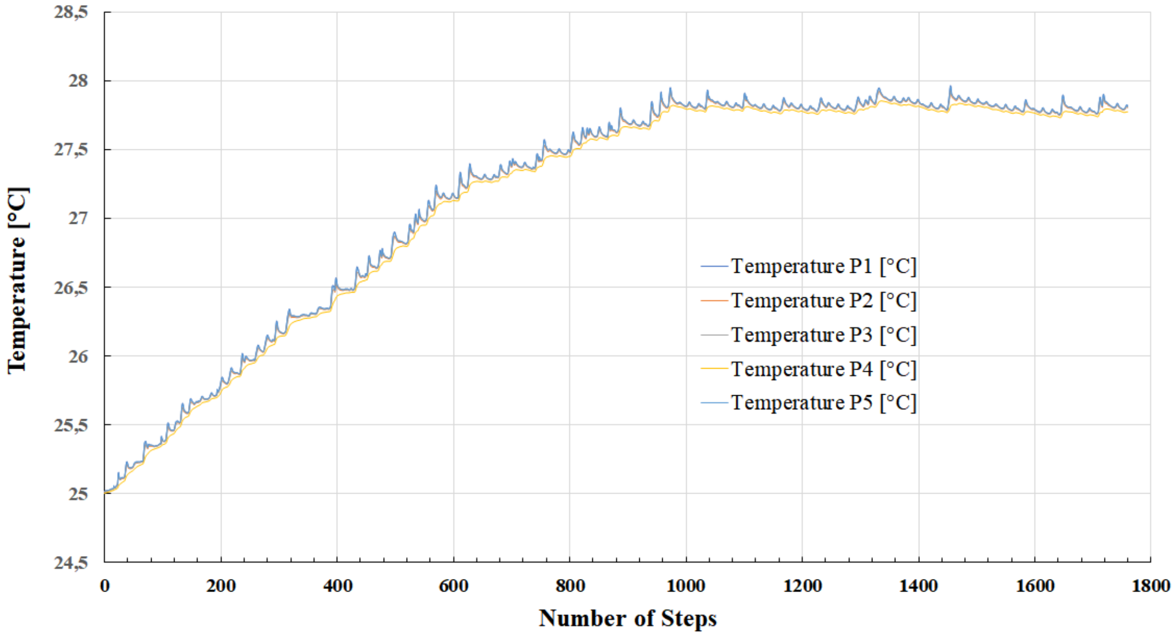
4. RESULTS AND DISCUSSION

The temperature distribution in the MR clutch is analyzed under two operating condition: ground walk operation, and descending stairs operation. The temperature of the MR fluid must be carefully evaluated. According to Chen et al. (2015), an operating temperature between 0 ~ 100 ° C has no significant influence on the fluid shear viscosity and shear stress. Although the manufacturer mentions an operating temperature up to 150 ° C for the MR fluid, it is safe to limit its operating temperature to 100 ° C. For safe operation, it is also important that the temperature of the copper wire does not exceed 150 ° C and the surface temperature of the clutch does not exceed 45 ° C, so it does not cause injuries to the user (Moritz e Henriques Jr., 1947).

Figure 5 (a) shows the temperature distribution of MR clutch during ground walking. The region with the greater temperature is the coil; this is expected since the heat generation occurs by Joule effect in this region. The temperature distribution is almost equal in whole system, about 28ºC. Figure 5 (b) shows the MR clutch temperature variation as a function of the number of steps of the user during ground walk. The steady state temperature is attained after 1000 steps of walk. It is note that the temperature attained during walking ground is not dangerous for the fluid, copper wire or for the user.



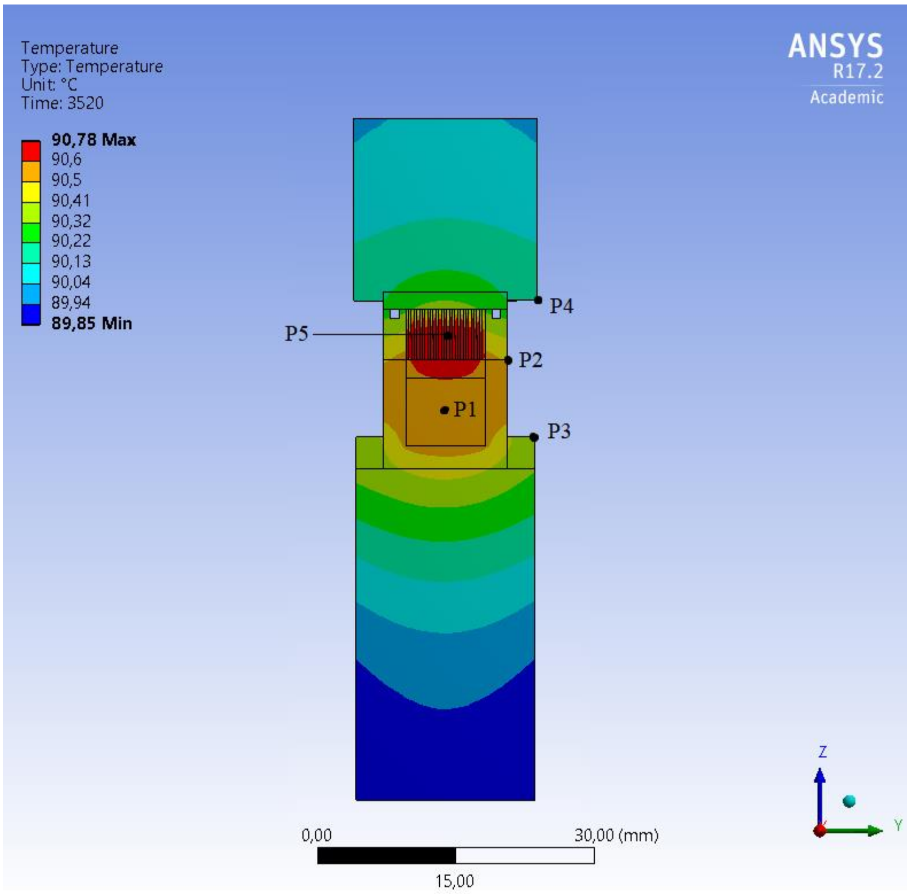
(a)



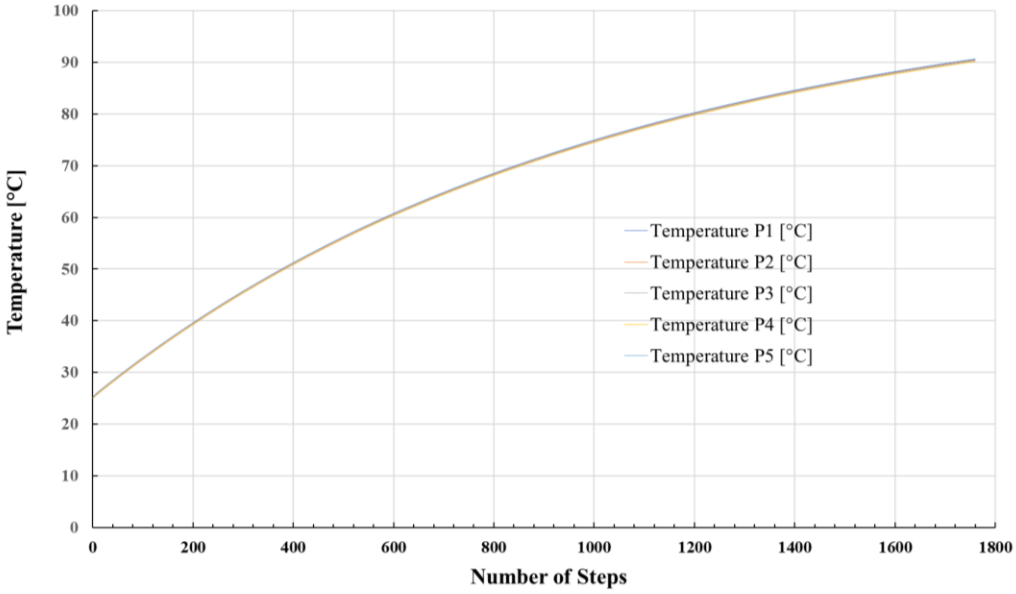
(b)

Figure 5. Temperature distribution of MR clutch during ground walking. (a) After 1760 steps, (b) Transient analysis.

Figure 6 shows the temperature distribution of the MR clutch when the MR knee actuator is used to walking down steps, working in full slip condition.



(a)



(b)

Figure 6. Temperature distribution of MR clutch during walking down steps. (a) After 1760 steps, (b) Transient analysis.

Figure 6 (a) shows that the temperature distribution in the clutch after almost 1 hour of walking down steps, is about 90 ºC. The fluid-disc interface in the region near to the coil, where the greater heat generation occurs, has a large increase in temperature, but still does not cause any damage for the MR clutch components. Figure 6 (b) shows the temperature variation with time.

It is important to note that the steady-state temperature, when the actuator is used to descend stairs, is not harmful to the user, since the temperature of 45ºC, in P2, P3 and P4 would only be reached in a walking of 300 steps down the stairs, unlikely condition to happen.

5. ACKNOWLEDGEMENTS

The authors wish to acknowledge FAPES and FAPEMIG for the financial support. The authors thank Reval Metalmecânica Ltda. for providing resources and manpower to start to build the MR actuator.

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