Computational Engineering and Physical Modeling 4-3 (2021) 19-28

Contents lists available at **CEPM**

Computational Engineering and Physical Modeling

Journal homepage: www.jcepm.com

Numerical Simulation of Stresses Produced on Hydraulic Clutch Discs Due to Heat Generated During Operation

J.A. Martins[1], R. Janghu[2], E.C. Romão[3*]

1. DESCH Ltd., Waterloo, Canada.
2. DESCH Ltd., Guelph, Canada.
3. Department of Basic and Environmental Sciences, Engineering School at Lorena, University of São Paulo, Brazil
Corresponding author: *mailto:estaner23@usp.br*

https://doi.org/10.22115/CEPM.2021.277513.1164

ARTICLE INFO

Article history:
Received: 15 March 2021
Revised: 23 June 2021
Accepted: 09 August 2021

Keywords:
Numerical simulation;
Hydraulic clutches;
Thermal stresses;
Static stresses.

ABSTRACT

Modern clutches are a critical component of a machine/equipment because they are designed to transfer and control torque, consequently producing movements, enabling safe operation, and controlling movement when necessary. When a clutch engages it transfers torque and allows a machine to produce mechanical work as a final result. The clutch engagement process generates heat due to the slipping of clutch discs. Although pressure applied on clutch discs generates stresses in the disc material, it was not clear how severe a combination of pressure and heat might raise the stresses. This study aimed to produce a numerical simulation to determine the impact of temperature also torque changes in the clutch discs when it transfers movement. Some static and thermal numerical simulations by Finite Element Analysis (FEA) (linear-elastic analysis) were performed, which considered two scenarios; (1) first with only pressures applied on clutch disc's face; (2) where heat was added to pressures. These mathematical simulations revealed that discs stresses are highly sensitive to thermal variations since for some cases the maximum von Mises stresses exceeded discs material mechanical strength leading it to failure. To overcome this problem it is compulsory to consider heat when designing a clutch and a cooling system for it.

How to cite this article: Martins, J. A., Janghu, R. S., & Romão, E. C. (2021). Numerical Simulation of Stresses Produced on Hydraulic Clutch Discs Due to Heat Generated During Operation. Computational Engineering and Physical Modeling, 4(3), 19–28. https://doi.org/10.22115/cepm.2021.277513.1164

1. Introduction

The main purpose of a machine and or equipment is to fulfill some human's need or desire [1]. In this context, engineers design and build machines and equipment by creating many parts with proper functionalities that altogether deliver a solution for a particular application. In many cases, a machine uses a source of energy (chemical or electrical) to produce work and transform the material into a product or to generate movement on a body, a driving part of a machine (drive system) has several components such as shafts, gears, coupling, clutches, etc. that are heavily loaded and react them by having high internal stresses. Likewise, all parts in a driving system transfer movement by controlling torque and power throughout the machine driving system [2–6]. In this sense, those parts deserve special attention and a meticulous examination of their application to end up as having a proper design [2].

Among several parts in a machine or equipment, clutches and brakes are undoubtedly one of the most important components which control speed, drive acceleration, and deceleration throughout a drive system. The importance of clutches is highlighted by Olszak et al. [7], who describes that hydraulic clutches are frequently used in drive systems of machines and vehicles, due to many advantages such as lack of a permanent connection between the input and output shaft, ability to start with a load or ability to damp torsional vibrations.

Not only hydraulic clutch is important but also oils, which play an important role due to their various benefits. Oils have been used for their many different attributes, for example, as a fluid capable to transfer torque, also as an incompressible liquid able to sustain pressure in hydraulic pistons, or lately to promote lubrication and cooling on mechanical parts. Furthermore, another application of oils is for transferring torque in hydrodynamic clutches [8]. Karamavruc et al. [9] for example optimized the clutch continuous slipping of a wet clutch by predicting the maximum temperature at the friction surface. In addition, the authors developed an accurate mathematical model of the heat transfer coefficient in and around the transmission oil grooves of the wet friction facing. Since excessive heat (poor cooling) causes thermal scratches or warping of the surface of discs of a clutch. Seo et al. [10] suggested a method to estimate a clutch temperature when under severe operation. In their study, a heavy-duty vehicle was used to run experiments. Later, Hebbale [11] successfully developed a model to estimate initial conditions of clutches during engine start-ups and validated it in a test cell environment in vehicles using slip ring and telemetry hardware. When it comes to clutches running at low speed, Marklund et al. [12] determined the thermal influence when transferring torque by using a boundary condition that takes into consideration operating conditions and clutches thermal history.

Decidedly, studies that evaluate clutches temperatures when operating are numerous and easily found in the literature. They reveal the importance of clutches in mechanical applications, indeed because it is a safety component that if it fails it can damage a piece of equipment or machine and consequently make it unviable to produce work. However, they did not use a heavy-duty clutch nor an applied heat on discs, instead, the authors estimated the result of heat as a consequence of torques applied. The question to answer in this paper is what would stress be when high torques are applied on clutch discs, and how different those stresses might change when different temperatures (heat flux) were also employed on clutch discs. To answer these questions this paper simulates numerically the impact of pressures on discs stresses and thereafter temperatures (heat flux) on clutch package discs when transferring movement. To do so, a multiphysics FEA software Autodesk A360 was used to run a static and thermal simulation. In summary, heat and pressure/torque were variables studied in this paper to understand how they influence discs' internal stresses (von Mises). This knowledge is very important because it presents as an input variable to design a hydraulic cooling unit that can thrive on removing a clutch's internal energy (heat).

2. Materials and methods

A package of four friction discs and four intermediate discs (Figure 1) was modeled in 3D domain to produce a numerical simulation based on pressure (torque) and different temperatures.

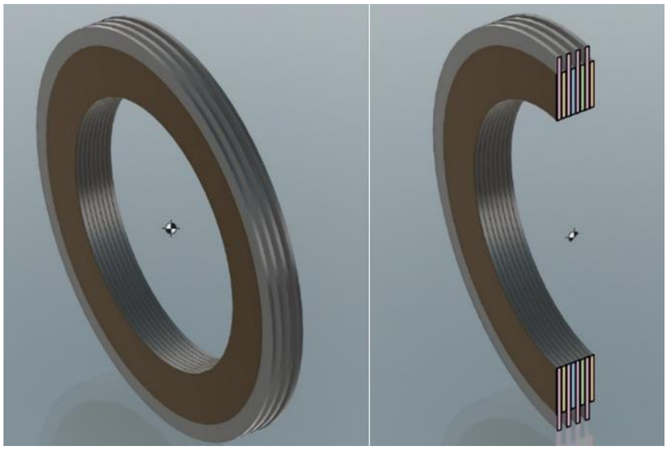

Fig. 1. Package of clutch discs (friction and intermediate discs).

The intermediate discs were designed to a diameter of 432 mm × 344.5 mm × 5 mm thickness while the diameter of the liner 518 mm × 344.5 mm × 5 mm thickness. The friction material attached on both sides of friction discs has a thickness of 1.0 mm and diameters of 432 mm × 344.5 mm.

The first step was to calculate analytically pressures by using Equations (1) to (6) and thereafter apply them on the frontal disc net friction area in the numerical simulation [13]. Pressures were based on the torque and dynamic friction coefficient for friction material. To calculate the axial pressure to apply on friction liners the first step is to determine the tangential force. The tangential force (Equation 1) is then calculated by the torque divided by the disc mid radius (Equation 2) as follows.

$$\tau = F_t . R_m \qquad \therefore \qquad F_t = \frac{\tau}{R_m} \tag{1}$$

for $$R_m = \frac{R_e + R_i}{2} \tag{2}$$

A second step is to rearrange the variables and calculate the Normal Force applied perpendicular to friction liner surfaces. This Normal force takes into consideration a friction coefficient and mid radius per seen in Equation 3.

$$F_t = \mu \cdot F_N = F_t = \frac{\tau}{R_m} \qquad \therefore \quad F_N \frac{\tau}{\mu \cdot R_m} . \tag{3}$$

Working (2) in (3) to reach final Normal Force equation is found as:

$$\mathrm{F_N} = \frac{2\cdot\tau}{\mu\cdot(\mathrm{R_e}+\mathrm{R_i})}. \tag{4}$$

Since pressure is force divided by the area, it gives:

$$\mathrm{p} = \frac{\mathrm{F_N}}{\mathrm{A}} = \frac{\mathrm{F_N}}{\pi\cdot(\mathrm{R_e}-\mathrm{R_i})^2}. \tag{5}$$

Then, inserting Equation (4) into (5) it is possible to calculate the final pressure to apply on axial disc area by Equation (6) as it follows:

$$\mathrm{p} = \frac{2\cdot\tau}{\mu\cdot\pi\cdot\left(\mathrm{R_e^3}-\mathrm{R_e}\cdot\mathrm{R_i^2}+\mathrm{R_e^2}\cdot\mathrm{R_i}-\mathrm{R_i^3}\right)}. \tag{6}$$

being p = pressure (MPa), τ = torque N.mm, R_e = outside friction disc radius (mm), R_i = internal friction liner radius (mm) and μ = dynamic friction coefficient [2].

To run the static stress simulation, an equation based on part stiffness as well as Hooke's equation was used as demonstrated in Equation (7).

$$F = k\cdot x \quad \text{and} \quad \sigma = E\cdot\varepsilon \tag{7}$$

where F = force (N), k = constant stiffness (N/mm), x = extension or compression distance (mm), σ = stress (MPa), E = Young modulus (MPa) and ε = strain (dimensionless). In the numerical simulation, only von Mises stress was analyzed.

When it comes to thermal analysis, a few temperatures and pressures were imposed directly on the first disc frontal area of the clutch. The thermal calculations were governed by Equation (8) to (9). Further up, the analysis ends with Equation (10) to determine the final von Mises stressed present on friction discs. To determine the thermal conduction [14,15] of the components of the clutch Equation (8) was used as follow:

$$\mathrm{Q} = \mathrm{k}\cdot\mathrm{A}\cdot\frac{\Delta\mathrm{T}}{\mathrm{L}}. \tag{8}$$

For Q = heat flow (J/s), A = cross sectional area (mm^2), ΔT = temperature difference (°C) and L = length normal to discs area (mm).

For the heat flux calculation for multi-dimensional, Equation (9) [15] was utilized as below:

$$\phi_\mathrm{q} = -\mathrm{k}\cdot\nabla\mathrm{T}. \tag{9}$$

Where: ϕ_q is the heat flux density (W.m^{-2}), k is the thermal conductivity (W·m^{-1}·K^{-1}), (The negative sign shows that heat flux moves from higher temperature regions to lower temperature regions), ∇T is the temperature gradient (K.m^{-1}).

Finally, the stress caused by thermal expansion is governed by Equation (10) [15,16].

$$\sigma = E\cdot\alpha\cdot\left(T_f - T_o\right) = E\cdot\alpha\cdot\Delta T \tag{10}$$

for T_f = final temperature (Celsius), T_o = initial temperature (Celsius), α = thermal expansion coefficient (°C^{-1}).

The material used for friction discs as well as for intermediate discs is high-strength steel (SAE 4340). The thin friction material attached on both sides of friction discs was considered bronze. Both materials' mechanical and thermal properties are described in Table 1 [15].

Table 1
Properties of steel and bronze.

Material	σ_y Yield Strength (MPa)	σ_t Tensile Strength (MPa)	Thermal expansion µm/m°C	Thermal conductivity W/mK
High strength steel (ref SAE 4340)	470	745	12.3	44.5
Bronze	125	255	17.5	71.9

Concerning numerical simulation of the clutch, Autodesk F360 software was utilized, particularly static and thermal stress Multiphysics platform [15]. Initially, a correlation between torque and pressure was settled by Equation (6) to provide values of pressure necessary to apply on discs during numerical simulation. It is important to highlight that the torques chosen were based on a heavy-duty hydraulic clutch for special applications.

When it comes to constraint, the back of the last disc, which opposes the pressure direction, received a fixed constraint through axis x, y, and z (ux, uy and uz) for all simulations. In addition, the center of mass of discs was determined and a gravity force of 9.81 kg/m^2 applied at that point.

3. Results

Table 2 shows the correspondent torques and specifically the pressures used as inputs for the numerical simulation. Also, it shows the maximum von Mises stresses experienced by friction due to pressure, described as “von Mises stress (MPa)”. As can be seen, von Mises stresses increased linearly from 0.8 MPa to 4.0 MPa, corresponding to torques from 2,000 Nm to 10,000Nm.

Table 2
von Mises stresses on discs with change on the pressure applied on friction disc, non-temperature added.

Torque applied (Nm)	Pressure applied on disc (MPa)	von Mises stress (MPa)
10,000	4.0	5.1
8,000	3.2	4.1
6,000	2.4	3.1
4,000	1.6	2.0
2,000	0.8	1.0

Based on Table 2, Figure 2 demonstrates a linear curve that fits for von Mises maximum stress with a raise on torque. However, stresses are far below the steel and bronze yield strengths shown in Table 1. Likewise, Figure 3 gives more details of von Mises stresses for an imposed 4.0 MPa pressure.

Further up, for thermal simulation, a pressure of 4.0 MPa was assigned constant - correspondent of 10,000 Nm - meanwhile temperatures varied from -20 to 160ºC. An expressive raise on maximum von Mises stress is verified in Table 3 and demonstrated in Figure 4.

To have a clearer picture of the values in Table3, Figure 5 show heat flux distribution for 80 ºC, while Figure 6 and 7 show the stress distribution with 120 ºC and 160 ºC. Given the circumstance that the temperature widely varies, it is important to highlight stress change within certain ranges. From -20 ºC to +20 ºC for example, there is a small decrease in von Mises maximum stress from 309 to 81 MPa, while a bit further, until 40 ºC, a timid raise occurs and it reaches 130 MPa. Thereafter, from 60 ºC to 160 ºC there is a steep and constant raise of von Mises stresses, reaching a maximum value of 958 MPa. It should be noted that a linear fit is possible to be traced from 60º C to 160º C. The equation that best fits with that region is represented by $s = 6.96786 \cdot T - 160.5$ where T represents temperature (ºC) and maximum von Mises (MPa). Considering the yield strength of bronze, used as friction material, the limit in terms of temperature to reach its yield strength is close to 40º C. Nevertheless, the temperature to denigrate the steel disc is higher and close to 90 ºC.

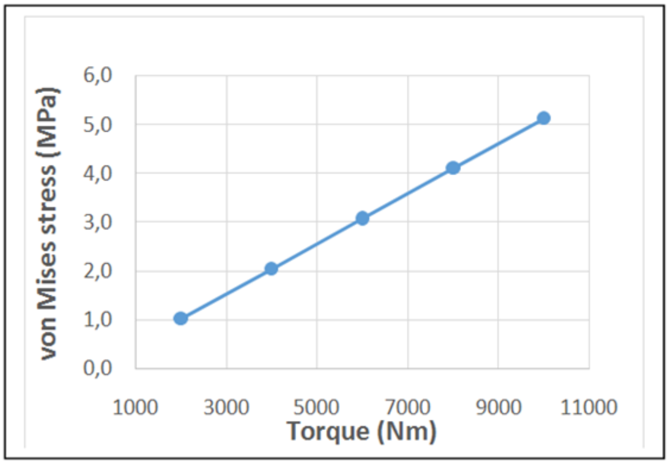

Fig. 2. Change on von Mises stress under pressure (torque) non-temperature.

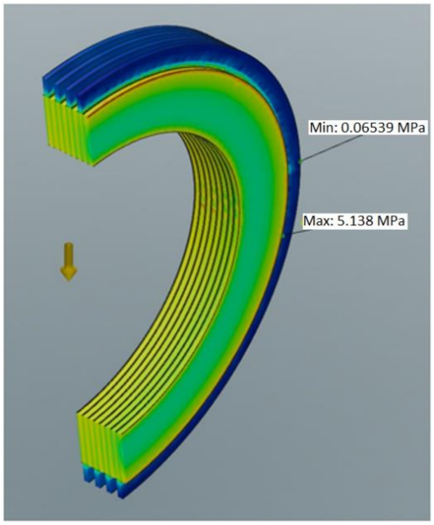

Fig. 3. von Mises stresses with a 4.0 MPa pressure applied – non-temperature.

Table 3
Change on maximum von Mises stresses with increase of temperature for the same pressure of 4.0 MPa.

Temperature °C	von Mises stress (MPa)
-20	309
0	169
20	81
40	130
60	257
80	379
100	536
120	677
140	817
160	958

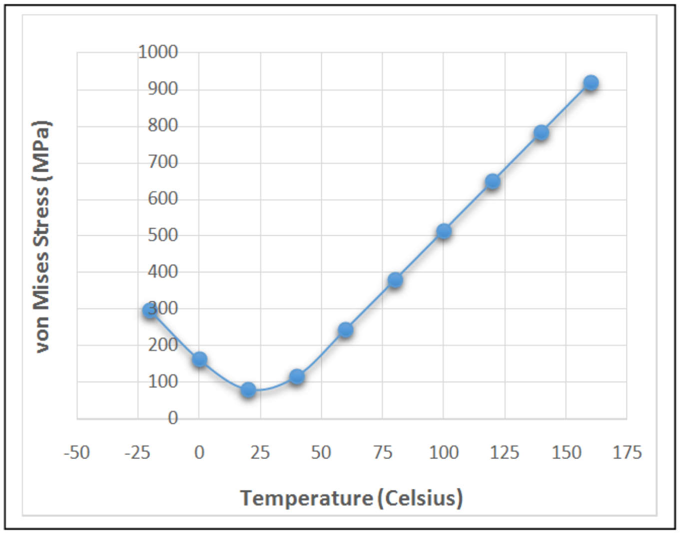

Fig. 4. Stress versus temperature on friction discs.

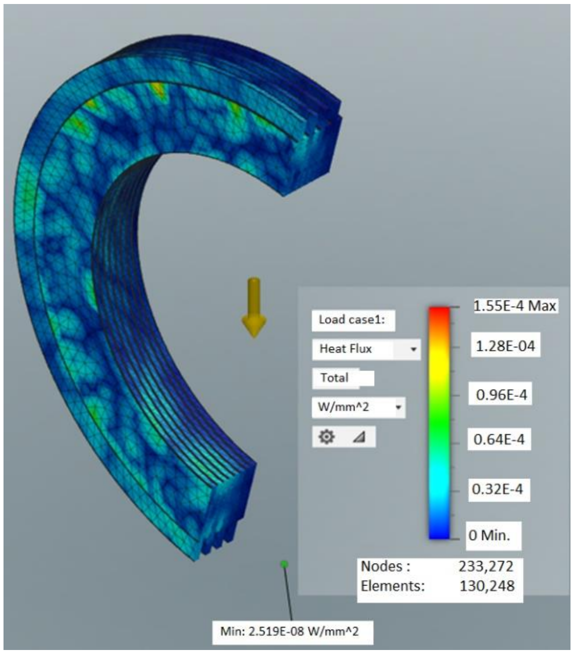

Fig. 5. Heat flow distribution for a fixed temperature of 80 °C.

To clarify the values obtained on the simulation and shown in Table 3, two graphs are presented in Figures 6 and 7 to reveal the stress distribution throughout discs cross-sections. It is clear by the Figures that the region with the highest von Mises stress is located on the opposite side to the face to which pressure is applied and close the disc more external diameter. The cause of this higher stress on those regions is justified when the heat flux is considered. This flux shown in Figure 5 for a constant temperature of 80 ºC illustrates that the maximum value of heat flux observed was 2.5×10^{-8} W/mm^2 and it is located close to friction liner outside diameter.

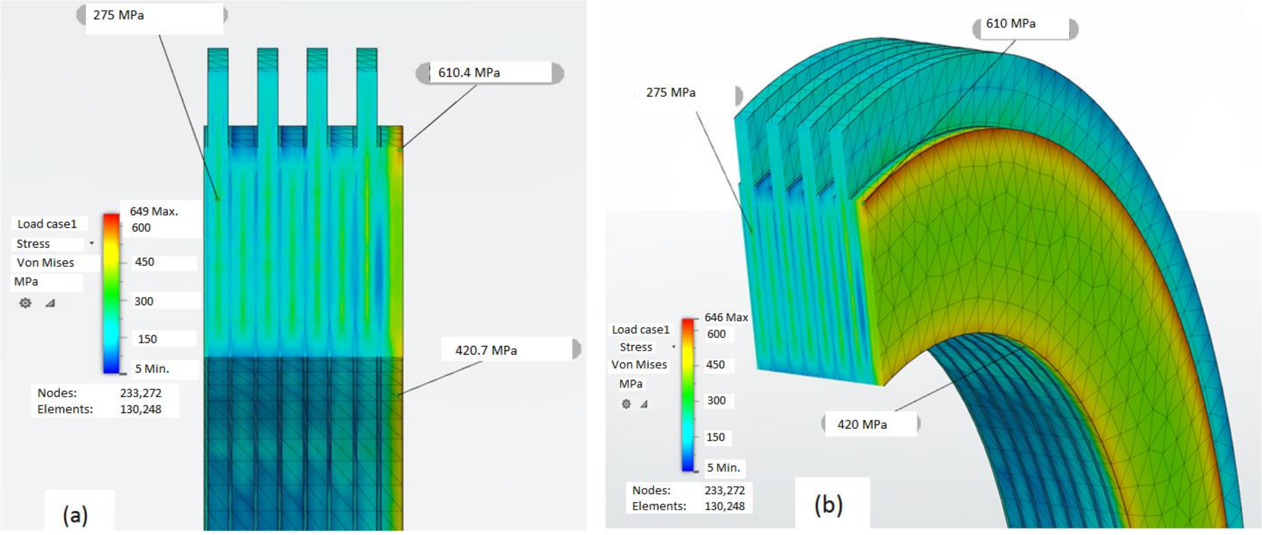

Fig. 6. (a) Cross-section of discs, (b) angular view of discs showing von Mises maximum stresses for a constant torque of 10,000 Nm (pressure 4.0 MPa) and temperature at 120 ºC.

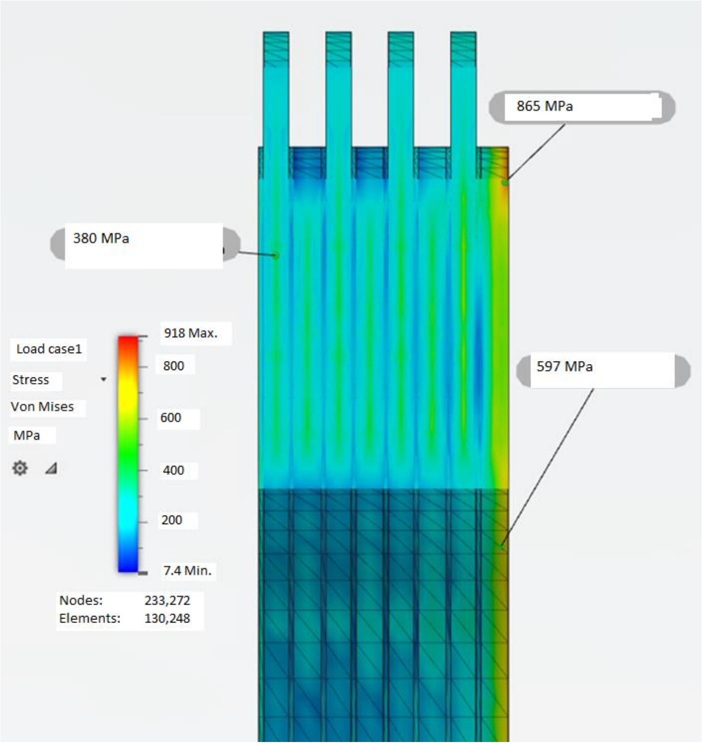

Fig. 7. Cross-section of discs showing von Mises stresses for a constant torque of 10,000 Nm (pressure 4.0 MPa) and temperature at 160 ºC.

4. Conclusion

To answer a very practical question - what would stresses be when high torques are applied on clutch discs and how different those stresses might be when different temperatures (heat flux) were also introduced - this research was produced. The research started with an analytical calculation to determine the pressures that were related to torques, thereafter it was possible to run static and thermal numerical simulations. The research was then conducted by running a numerical simulation by Autodesk F360 to determine the impact of pressures (torques) on clutch discs with and without temperature on them.

Results showed that when the temperature is not added on clutch discs stresses were very low when compared with materials mechanical strengths and particularly distant from their yield strengths. Whereas with a temperature in placed stresses went expressively high, sometimes exceeding material strength. The simulation was also possible to verify the distribution of stress throughout the package of clutch discs. It revealed that stresses stepped higher from the face where pressure is applied to the back surface where a constraint was placed. Namely, values obtained with the addition of temperature caused a steep increase in the stresses endured by intermediate and friction discs and in some cases, as mentioned, even able to damage discs.

This happens because the constraint on the back disc and a fixed pressure at the axial disc do not allow to disc to expand axially with temperature. Therefore, the discs have only a possibility to expand in the radial direction, which makes stresses increase substantially and for some temperatures exceeding material mechanical strength. To sum up, since heat is an important variable in the system because raises mechanical stresses, it is compulsory to address more oil flow in a few regions with higher stresses due to temperature. A very robust and precise cooling system is necessary for hydraulic clutches, in addition, grooves on the bronze material are of high importance unless the temperatures on the clutch discs are very low and lower than 45 ºC.

For future research, it is important to study the influences of adding grooves on the friction material surface to produce oil flow to remove heat and reduce local temperature. For this particular simulation, a CFD platform is necessary and will be used.

Acknowledgments

The authors would like to thanks DESCH Group for support, also CNPQ Brazil and FAPESP by Process 14/06679-8.

References

[1] Collins JA. Mechanical design of machine elements and machines: a failure prevention perspective. John Wiley & Sons; 2009.

[2] DESCH Clutch Brake Combination (CBC). Cambridge: Internal report, 2019.

[3] Aparecido Martins J, Pardal PCPM, Romão EC. Catastrophic Results for Equipment and Machine Driving Systems when High Impact during Operation Occurs. Appl Mech Mater 2015;775:329–33. doi:10.4028/www.scientific.net/AMM.775.329.

[4] Hohmann C, Schiffner K, Oerter K, Reese H. Contact analysis for drum brakes and disk brakes using ADINA. Comput Struct 1999;72:185–98. doi:10.1016/S0045-7949(99)00007-3.

[5] Martins JA, Romão EC. Analyzing 2D segment by Multiphysics in heat transfer and solid mechanics, pondering variables by Design of Experiment (DOE). Eng Sci Technol an Int J 2016;19:1929–35. doi:10.1016/j.jestch.2016.10.013.

[6] Martins JA, Ferreira I, Leite D, Romao EC. Failure analysis of a set of flapper valves under ALT with alternative test device. J Test Eval 2013;41:324–31.

[7] Olszak A, Osowski K, Kęsy A, Kęsy Z. Experimental researches of hydraulic clutches with smart fluids. Int Rev Mech Eng 2016;10:364–72.

[8] Yuan Y, Liu EA, Hill J, Zou Q. An Improved Hydrodynamic Model for Open Wet Transmission Clutches. J Fluids Eng 2007;129:333–7. doi:10.1115/1.2427088.

[9] Karamavruc A, Shi Z, Gunther D. Determination of Empirical Heat Transfer Coefficients via CFD to Predict the Interface Temperature of Continuously Slipping Clutches, 2011. doi:10.4271/2011-01-0313.

[10] Seo H, Zheng C, Lim W, Cha SW, Han S. Temperature prediction model of wet clutch in coupling. 2011 IEEE Veh. Power Propuls. Conf., IEEE; 2011, p. 1–4. doi:10.1109/VPPC.2011.6043013.

[11] Hebbale K, Samie F, Kish J. Dry Dual Clutch Transmission (DCT) Thermal Model, 2015. doi:10.4271/2015-01-1144.

[12] Marklund P, Mäki R, Larsson R, Höglund E, Khonsari MM, Jang J. Thermal influence on torque transfer of wet clutches in limited slip differential applications. Tribol Int 2007;40:876–84. doi:10.1016/j.triboint.2006.09.004.

[13] Serway RA, Vuille C. College physics. Brooks Cole; 11th edition. Cengage Learning; 2017.

[14] Dai WJ, Gan YX, Hanaor D. Effective Thermal Conductivity of Submicron Powders: A Numerical Study. Appl Mech Mater 2016;846:500–5. doi:10.4028/www.scientific.net/AMM.846.500.

[15] Autodesk. “Autodesk F360.” 04_Model. 11 28, 2020. https://myhub.autodesk360.com/ue29c9141/g/shares/SH7f1edQT22b515c761e015af81664fecb70.

[16] F., Carter, Giles and Paul, Donald E. Materials science & engineering. Material Park, Ohio: ASM International 1991.