Vol. 06, No. 2 (2024) 523-534, doi: 10.24874/PES06.02.010

Proceedings on Engineering Sciences

www.pesjournal.net

# NUMERICAL ANALYSIS OF A VISCOUS TRANSMISSION

Andrei I. Stoicescu[1]
Adrian Predescu

Received 12.09.2023.
Received in revised form 30.01.2024.
Accepted 24.03.2024.
UDC – 621.825

Keywords:

*Viscous Coupling, Viscous Shear, Fluid Film, Grooves, Numerical Simulation, Temperature, Torque*

A B S T R A C T

*A viscous coupling is a simple device that transmits torque by shearing an oil film between one or more pairs of discs that are moving in relation to one another. Due to their many advantages, viscous couplings are studied in many applications such as fan transmissions in vehicles, pumps, winches, belt conveyors, wind turbines, tunnel boring machines. Using a CFD Software, this study examined how grooves affected the performance of a viscous coupling. The main objective of the reported work is to study the flow of the fluid film, the total temperature and the torque of a viscous coupling that is operating in different conditions.*



## 1. INTRODUCTION

Viscous couplings are simple devices that present high interest in the auto industry due to their many advantages proven over the years. Other than the auto industry, viscous couplings are widely studied in different applications such as water pumps (Scott G.E., 2000), mechanism of belt conveyors (Meng, Q., & Hou, Y., 2008), (Cui, H., Zi-Sheng, L., Li, L., & Wang, Q., 2018), (Hao, N. N., Yu, Y., & Liu, H. W., 2011), winches (hydro-viscous winch) (Hou, Y. F., Wang, D. M., Meng, Q. R., & Du, B. 2011), (Meng, Q. R., Lin, S. F., & Wang, J. 2012), tunnel boring machines (TBM with viscous clutch) (Xie, H., Gong, H., Hu, L., & Yang, H., 2016), (Gong, H., Xie, H., & Yang, H., 2019), wind turbines (Yin, X., Lin, Y., Li, W., Liu, H., & Gu, Y., 2014), (Yin, X., Lin, Y., & Li, W., 2015), (Yin, X., Lin, Y., Li, W., & Gu, H., 2016).

Viscous couplings transfer torque by viscous shearing the oil film between one or more pairs of discs that are moving relative to one another. A viscous coupling operates best under complete film lubrication conditions and uses a viscous fluid as its working medium. The two surfaces that are moving relative to one another must always be covered in an oil coating. A viscous coupling can only transmit torque at its greatest level during this stage, when it is functioning under complete film lubrication conditions.

This paper proposes a study of the flow of the fluid film, the total temperature and the torque of a viscous coupling that is operating in different conditions.

The proposed viscous coupling model has 11 discs from which 6 discs that are stationary discs and 5 discs that are moving discs that has in between them 10 fluid films. The studied viscous coupling has moving discs

[1] Corresponding author: Andrei I. Stoicescu
Email: stoicescu_andrei_iancu@yahoo.com

that either may have surfaces with no grooves at all or surfaces that may have grooves at different degrees between them, grooves at different inclinations between them or grooves with different depths or different widths.

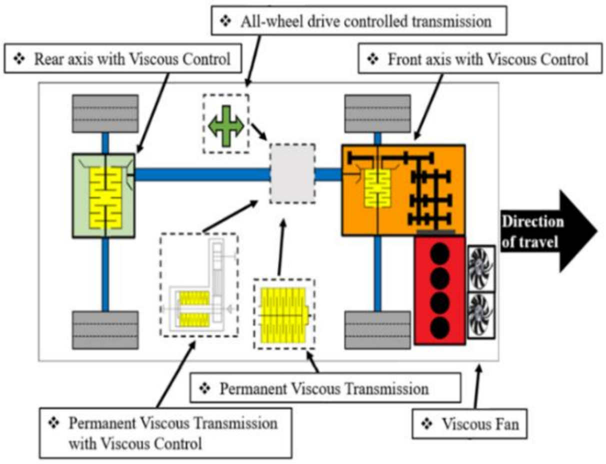


**Figure 1.** Various positions of a viscous coupling in a transmission

As seen in Figure 1. a viscous coupling can be used in the operation of the viscous fan of the vehicle (Bieberle, A., Schlottke, J., Spies, A., Schultheiss, G., Kühnel, W., & Hampel, U., 2015), (Yin, Z., Zhao, K., Shangguan, W., & Song, L., 2016) or in the transmission of the vehicle such as front or rear axis with viscous control and in all-wheel drive controlled transmission such as permanent viscous transmission with or without viscous control.

## 2. THE BASIC OPERATING PRINCIPLE OF A VISCOUS COUPLING

The basic operating principle of a viscous coupling is presented in Figure 2. below.

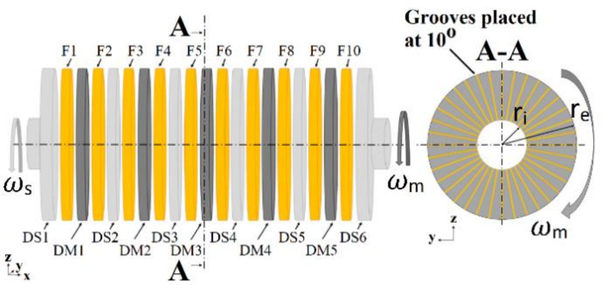


**Figure 2.** Schematic drawing of a viscous coupling

As shown in the image above in Figure 2. there are 10 fluid films that are coloured in yellow and 11 discs in total – 6 discs that are coloured in light grey that are stationary discs which have flat surfaces with no grooves and 5 discs that are coloured in dark grey that are moving discs which have grooves placed at 10°. That means 36 grooves on each side of every moving disc.

## 3. THE TORQUE CALCULATION MODEL OF A VISCOUS COUPLING

A viscous coupling performs due to Newton's law of viscosity, and does that by transferring the torque between the moving discs and stationary discs by shearing of the oil film between them. The torque calculation model of a viscous coupling is shown below and can be obtained by (Predescu A., 2011), (Cui, H., Zi-Sheng, L., Li, L., & Wang, Q., 2018), (Jin, L., Peng, X., Wang, D., Guo, D., & Chen, B., 2021), (Heuser, G., 1997):

$$M_t = \frac{1}{2} z\pi\eta \frac{(\omega_m - \omega_s)(r_e^4 - r_i^4)}{h}. \quad (1)$$

As shown in the above formula, the transmitted torque depends on: the total number of fluid films, the dynamic viscosity of the working fluid, the relative angular speed of the rotating grooved discs and stationary smooth discs, the radiuses of the discs (external and internal) and the thickness of the fluid film.

Due to the shear stress of the fluid film, the temperature of the fluid film between the friction discs will increase, which will cause the viscosity to decrease and the load capacities of the fluid film to vary. Thus, the effect of temperatures must be taken into account in the calculation of the load capacity of the fluid film (Meng, Q., Zhao, C., & Tian, Z., 2018). The thermal energy equation that describes the temperature distribution of the fluid film between the friction discs is as follows:

$$\rho C_v \left( q_z \frac{\partial T}{\partial z} + q_y \frac{\partial T}{\partial y} \right) = \frac{\eta}{h} \left[ (U_{1z} - U_{2z})^2 + (U_{1y} - U_{2y})^2 \right] + \frac{h^3}{12\eta} \left[ \left( \frac{\partial p}{\partial z} \right)^2 + \left( \frac{\partial p}{\partial y} \right)^2 \right]. \quad (2)$$

where $q_z$ and $q_y$ are the average flow of oil.

## 4. THE GEOMETRICAL MODELS THAT WERE CHOSEN FOR THE CFD ANALYSIS

A pre-processing software was used to create the geometrical model of the viscous coupling. There were 6 geometrical models that were chosen for the CFD analysis as follows:

1. Radial placement of the grooves at different grades between them on the surfaces of the moving discs;
2. Radial orientation of the grooves that have different inclinations on the surfaces of the moving disks;
3. Grooves depth on the surfaces of the moving disks;

4. Grooves width on the surfaces of the moving disks;
5. Thickness of the fluid films between the pairs of discs;
6. Viscosity of the fluid used to operate the viscous coupling.

## 5. THE BOUNDARY CONDITIONS

The boundary conditions were assigned in the pre-processing software as shown below in Figure 3. and was analysed using Computational Fluid Dynamics Software.

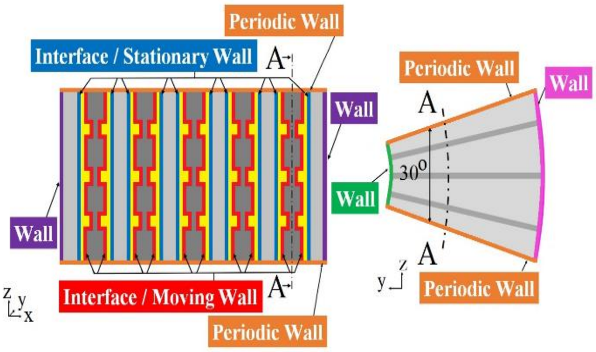


**Figure 3.** Setting up the boundary conditions for the simplified model

In order to better study the phenomenon, the geometrical model of the viscous coupling was simplified as follows: the entire volumes of the 10 oil films and the 11 discs, representing 6 discs that are stationary discs which have flat surfaces and 5 discs that are moving discs which have grooves placed on their surfaces, were reduced to 1/12 representing 30° of the full model in order to preserve the power and the resources of the computing machine.

The boundary conditions are assigned to the model in a pre-processing program as follows:

- Wall - Boundary condition was set to the outer surfaces of stationary discs at both ends of the viscous coupling (surfaces drawn in purple) and to the all surfaces of discs and fluid films representing the internal and the external radius of the viscous coupling (surfaces drawn in green for the internal radius and pink for the external radius).

- Periodic Wall - Boundary condition assigned to the simplified geometric model representing 30° of the complete model of the viscous coupling in order to conserve computing resources. This boundary condition was assigned to both the mobile and stationary discs of the viscous coupling and all its 10 fluid films (surfaces drawn in orange on either side of all sections of the discs and fluid films).

- Interface - Boundary condition assigned to the surfaces between discs and fluid films (surfaces drawn in red and blue). Once the Interface boundary condition is assigned, the surfaces between the stationary discs and the fluid films are defined as Stationary Wall (surfaces drawn in blue) and then the surfaces between the mobile discs and the fluid films are defined as Moving Wall (surfaces drawn in red).

## 6. THE PRE-PROCESSING OF THE MODEL

Using CFD software, a 3ddp precision numerical simulation was performed (three-dimensional double precision). After scaling the model to its proper original size, the boundary conditions were reviewed and conditions were set. The entire study was carried out using speeds ranging from 10 up to 150 ($rad \cdot s^{-1}$). A fluid was selected from the material database but with the viscosity changed from constant to power-law with Three Coefficient Method using 4 reference viscosities 0.02, 0.58, 0.81 and 1.06 (Pa·s). In every instance, the reference temperature was set at 300. (K). Also, in this stage the Energy Equation was selected. Moreover, the Laminar Model was used to analyse the simplified viscous coupling model. The model's initialization and iteration came next, once all the conditions had been specified. The study was carried out using both a constant viscosity and also a variable viscosity in each and every discussed case. For the variation of viscosity with temperature, it was considered a variant of Slotte's relation of the form (Predescu A., 2011):

$$\eta(T) = \eta_0\left(\frac{T_0}{T}\right)^2. \quad (3)$$

The current study is based on the Latin principle "ceteris paribus" translating as "other things being equal" thus trying to distinguish an effect of one type of change from any other by analysing the variation of temperature and the transmitted torque according to angular velocity for 6 cases of variables such as: the radial arrangement of grooves at different degrees, the radial orientation of the grooves having different inclinations, the depth of the grooves, the width of the grooves, the thickness of fluid films, the viscosity of the fluid.

## 7. CFD SIMULATION RESULTS

The results of the CFD simulation will be presented next with full explanations of the findings regarding the 6 geometrical models that were chosen for analysis.

For the Temperature and Torque analysis in the case of a viscous coupling with grooves at different degrees between them on the surface of the moving discs, a total of 5 variants of viscous couplings were taken into account, of which 4 variants with discs with grooves placed radially at different degrees between them (5°, 10°, 15°, 30°) and a variant with discs with flat surfaces (no grooves provided on the disc surfaces).

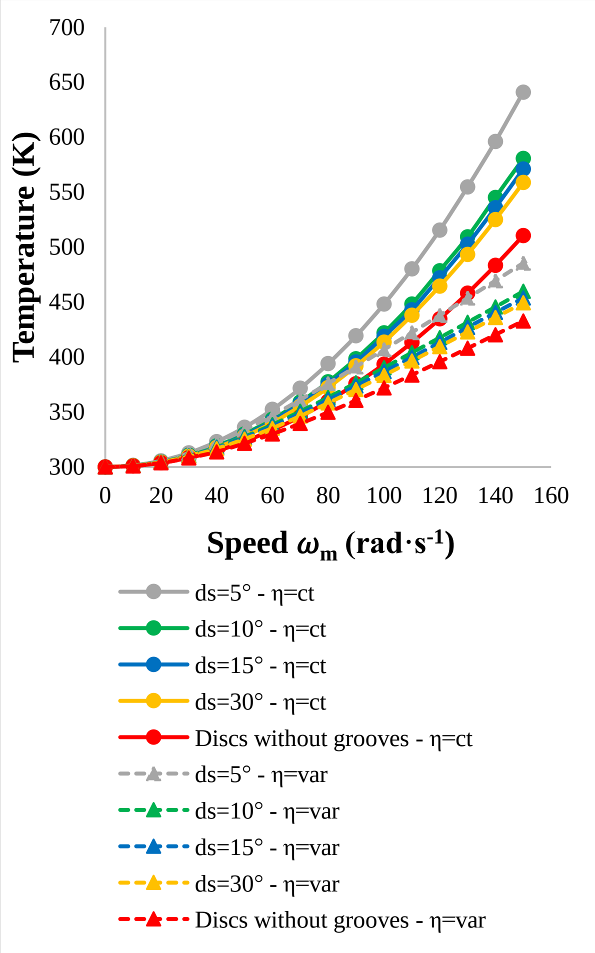


**Figure 4.** Temperature vs. speed analysis in the case of grooves placed at different degrees between them in radial direction at η=ct vs. η=var

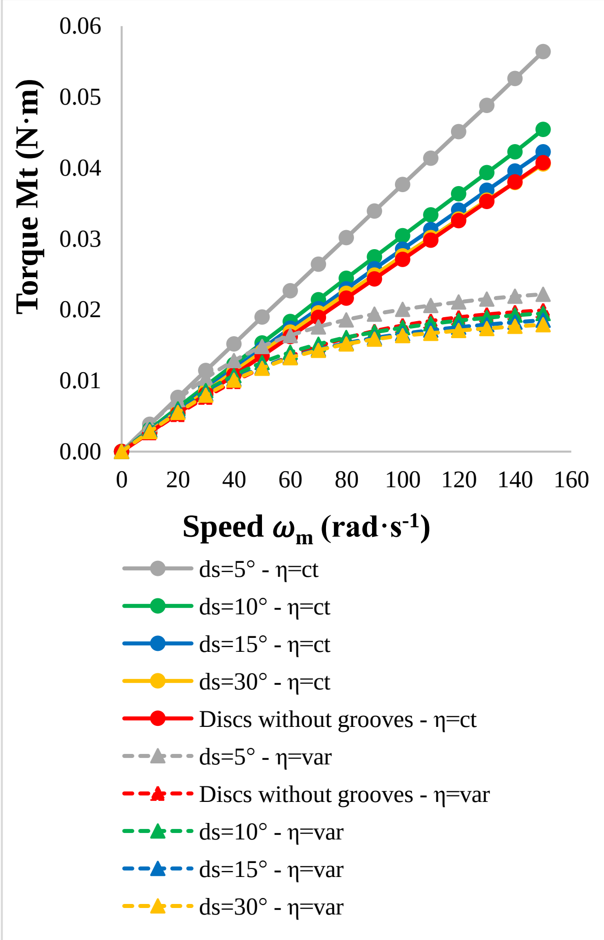


**Figure 5.** Torque vs. speed analysis in the case of grooves placed at different degrees between them in radial direction at η=ct vs. η=var

In all the analysed cases 11 discs with a thickness of 2 mm each with inner radii of 10 mm and outer radii of 30 mm were considered. A total of 10 fluid films with a thickness of 0.1 mm each with a viscosity of 0.02 Pa·s were considered. The effect of the groove was studied before but in regard of the flow between plates (Huang, J., Fan, Y., Minxiu, Q., & Fang, W., 2012), (Wei, B., He, Y., Wang, W., & Jianbin, L., 2018).

In the case of the 4 variants of viscous couplings, where the grooves are arranged at different degrees between them, these being straight and radially oriented on the surfaces of the mobile disks, the depth of the grooves is 0.05 mm and their width is 0.1 mm.

It can be seen from Figure 4. that the total temperature increases with the increase of the angular velocity. Also, the total temperature increases with the increasing number of grooves for both constant viscosity and variable viscosity.

From Figure 5. below, it can be easily seen that the transmitted torque increases with the increase of the angular velocity.

Also, it can be seen that the transmitted torque increases with the increasing number of grooves that are placed on the surface of the moving discs. When the viscous coupling with flat surfaces operates with variable viscosity this generates a maximum moment smaller than in the case of the viscous coupling which has discs with grooves placed radially from 5° to 5° but higher than all the rest of the viscous couplings studied in this case (couplings viscous with grooves placed at 10°, 15° and 30°).

For the Temperature and Torque analysis in the case of a viscous coupling with grooves at different inclinations between them on the surface of the moving discs, a total of 4 variants of viscous couplings were used, of which 3 variants with discs with radially oriented grooves at different inclinations 10°, 20°, 30° and a variant with discs with radially oriented straight grooves (grooves without inclinations). The effects of grooves orientation were studied before (Razzaque, M. M., & Kato, T., 1999), (Behzad, M., Saxena, V., & Schafer, M., 2018), (Gong, H., Xie, H., Hu, L., & Yang, H., 2019), (Wu, P., Xu, J., & Zhou, X., 2019) but not as it was studied in this article.

In all the analysed cases, 11 discs with a thickness of 2 mm each, with inner radii of 10 mm and outer radii of 30 mm, were considered. A total of 10 fluid films with a thickness of 0.1 mm each with a viscosity of 0.02 Pa·s were considered.

All the variants of viscous couplings studied in this case have provided on the surfaces of the mobile disks radial grooves arranged from 30° to 30° with a depth of 0.05 mm and a width of 0.1 mm.

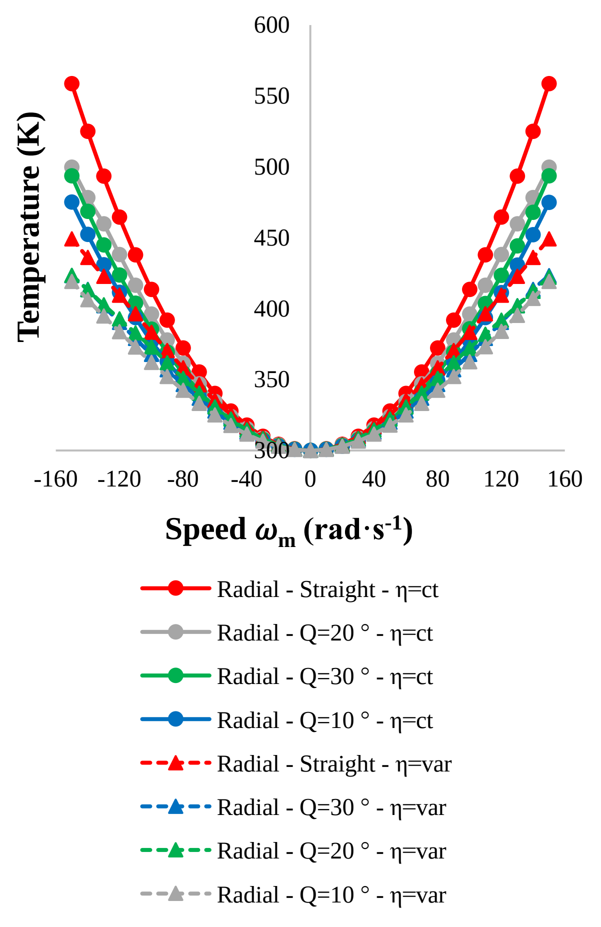


**Figure 6.** Temperature vs. speed analysis in the case of grooves placed at different inclinations between them at η=ct vs. η=var

It can be seen from Figure 6. that the inclination of the grooves leads to a significant decrease in the total temperature. Also, it can be seen from the same figure that the direction of rotation of the moving discs does not affect the total temperature at all.

From Figure 7. below, it can be easily seen that the increase of the inclination of the grooves leads to a decrease in the transmitted torque. Also, it can be seen that the direction of rotation of the moving discs does not affect the transmitted torque at all.

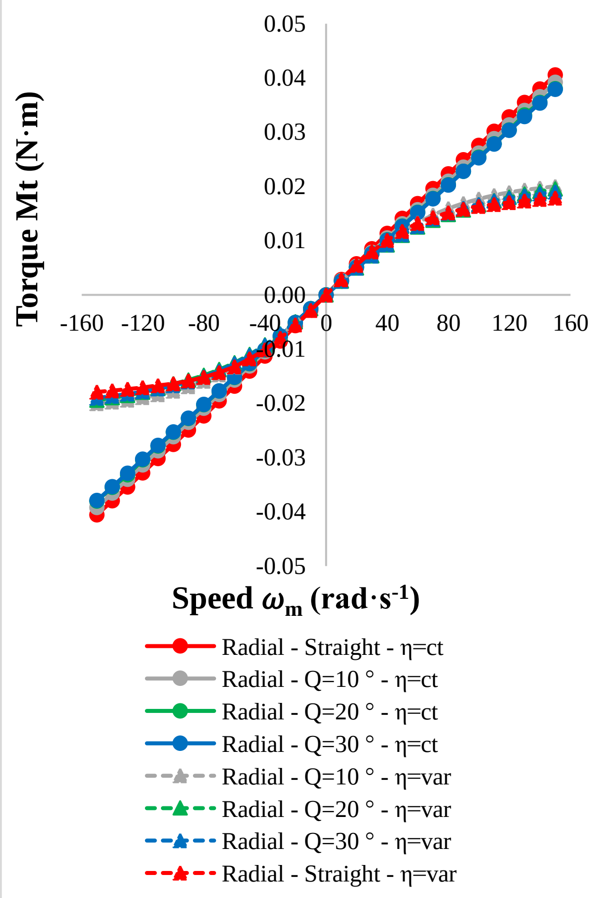


**Figure 7.** Torque vs. speed analysis in the case of grooves placed at different inclinations between them at η=ct vs. η=var

For the Temperature and Torque analysis in the case of a viscous coupling with grooves with different depths on the surfaces of the moving discs, 6 variants of viscous couplings were used, of which 5 variants with discs with grooves with different depths (0.01 mm, 0.02 mm, 0.03 mm, 0.04 mm, 0.05 mm) and a variant with discs with flat surfaces (without grooves provided on the surfaces of the discs).

In all the analysed cases, 11 discs with a thickness of 2 mm each, with inner radii of 10 mm and outer radii of 30 mm, were considered.

A total of 10 fluid films with a thickness of 0.05 mm each with viscosity of 0.02 Pa·s were considered.

In the case of the 5 variants of viscous couplings where the depth of the grooves on the surfaces of the moving discs varies from 0.01 mm to 0.05 mm, the grooves are straight, radially oriented and are arranged from 10° to 10° with a width of 0.1 mm.

It can be seen from Figure 8. that the increase of the depth of the grooves leads to a slight increase in the total temperature with the mention that the temperature values are somewhat close.

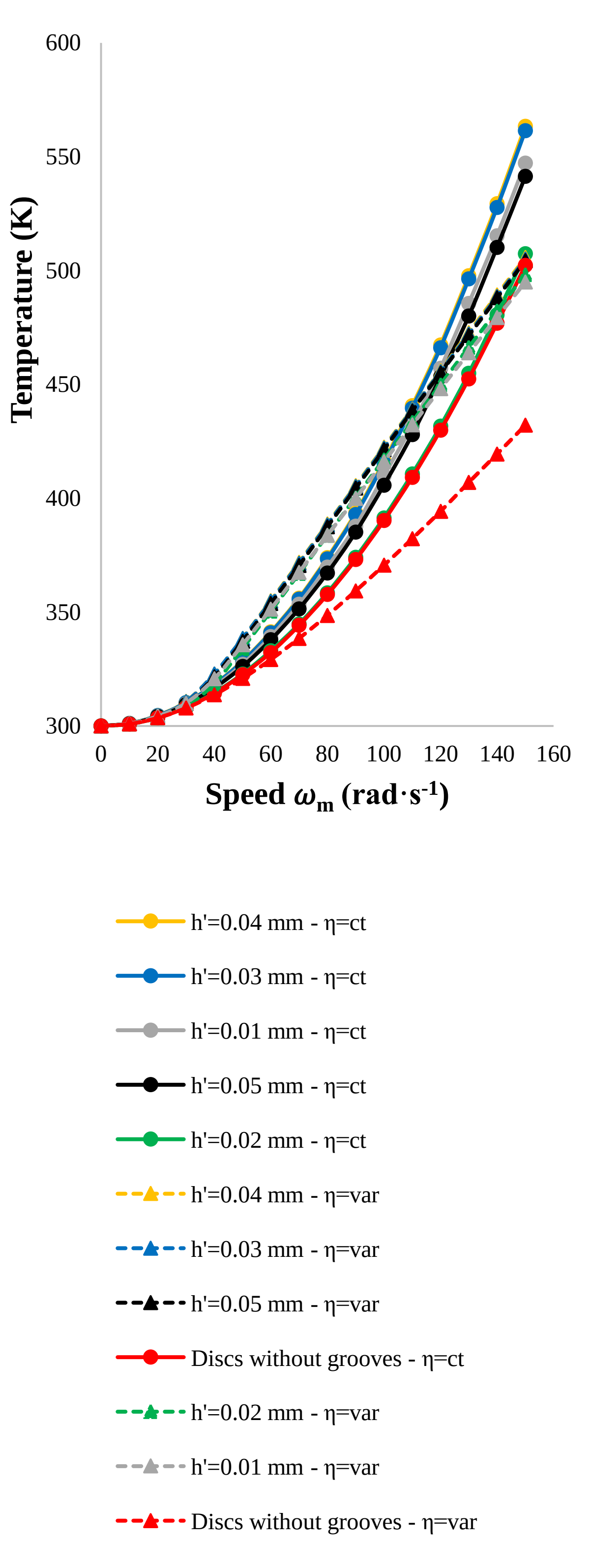


**Figure 8.** Temperature vs. speed analysis in the case of grooves with different depths at η=ct vs. η=var

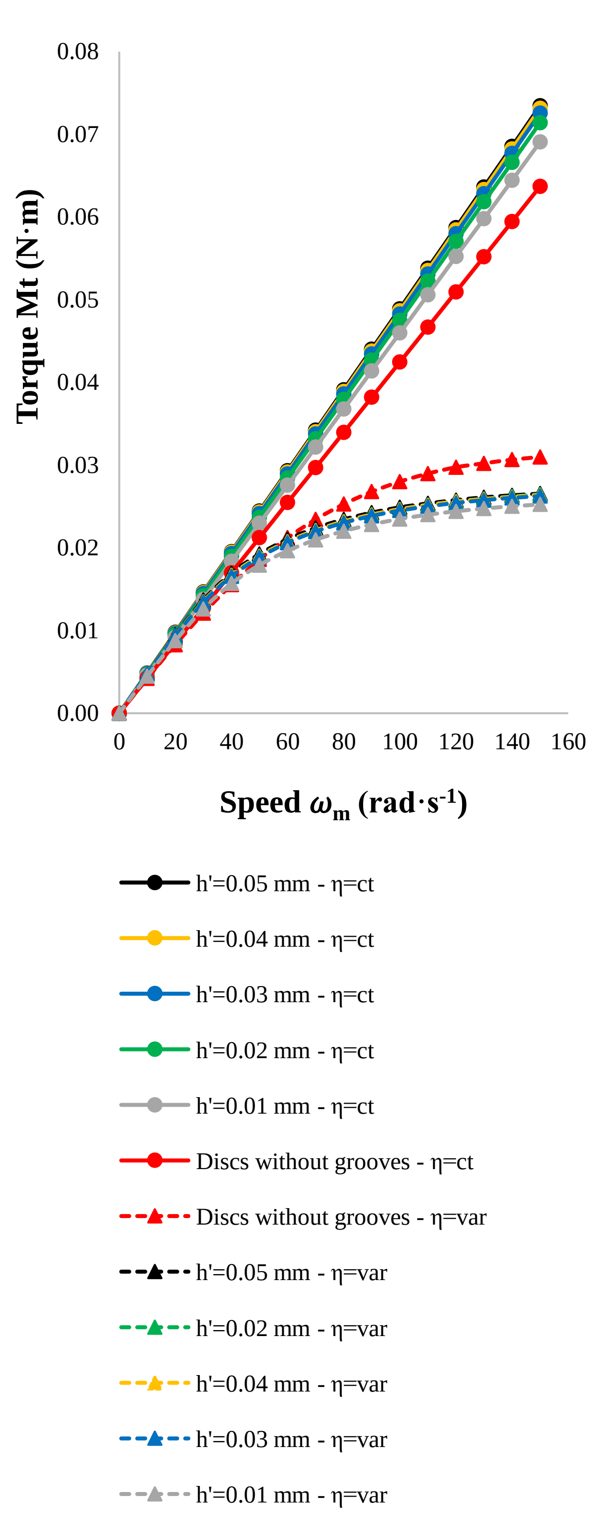


**Figure 9.** Torque vs. speed analysis in the case of grooves with different depths at η=ct vs. η=var

From Figure 9. below, it can be easily seen that the increase of the depth of the grooves leads to a slight increase in the transmitted torque with the mention that the torque values are somewhat close for both constant viscosity and variable viscosity. The optimal value of the grooves depth is 0.05 mm.

For the Temperature and Torque analysis in the case of a viscous coupling with grooves with different widths on the surfaces of the moving discs, 6 variants of viscous couplings were used, of which 5 variants with discs with grooves of different widths (0.1 mm, 0.2 mm, 0.3 mm, 0.4 mm, 0.5 mm) and a variant with discs with flat surfaces (without grooves provided on the surfaces of the discs).

In all the analysed cases, 11 discs with a thickness of 2 mm each, with inner radii of 10 mm and outer radii of 30 mm, were considered. A total of 10 fluid films with a thickness of 0.1 mm each with a viscosity of 0.02 Pa·s were considered. In the case of the 5 variants of viscous couplings where the width of the grooves on the surfaces of the moving discs varies from 0.1 mm to 0.5 mm, the grooves are straight, radially oriented and are arranged from 10° to 10° with a depth of 0.05 mm.

It can be seen from Figure 10. that the total temperature decreases as the width of the grooves increases. The optimal value of the grooves width is 0.1 mm and 0.5 mm for both constant viscosity and variable viscosity.

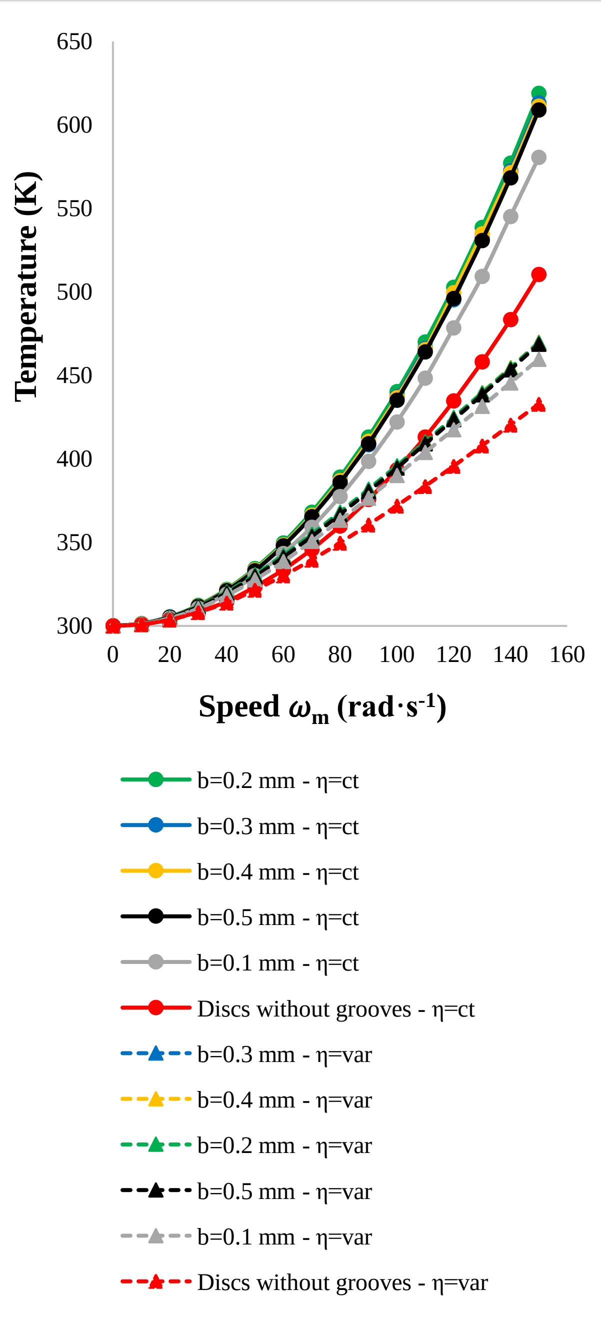


**Figure 10.** Temperature vs. speed analysis in the case of grooves with different widths at η=ct vs. η=var

From Figure 11. below, it can be easily seen that the transmitted torque has very close values regardless of the width of the grooves. The optimal value of the grooves width is 0.04 mm for both constant viscosity and variable viscosity.

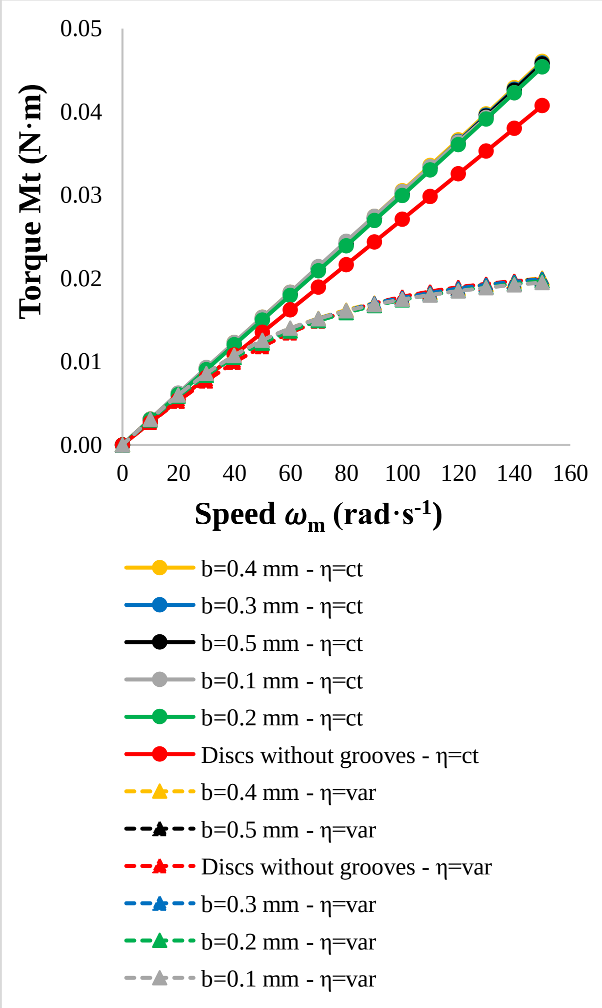


**Figure 11.** Torque vs. speed analysis in the case of grooves with different widths at η=ct vs. η=var

For the Temperature and Torque analysis in the case of a viscous coupling with grooves with different film thicknesses, a total of 4 variants of viscous couplings with different fluid film thicknesses (0.5 mm, 1.0 mm, 1.5 mm, 2.0 mm) were used.

In all the analysed cases, 11 discs with a thickness of 2 mm each, with inner radii of 10 mm and outer radii of 30 mm, were considered.

A total of 10 fluid films were considered, the fluid used in the operation of the viscous coupling has a viscosity of 0.02 Pa·s.

All the variants of viscous couplings studied in this case, where the thicknesses of the fluid film vary from 0.5 mm to 2.0 mm, have provided on the surfaces of the moving disks radial grooves arranged from 10° to 10° with a depth of 0.05 mm and a width of 0.1 mm.

It can be seen from Figure 12. Below that that the total temperature decreases at high thicknesses of the fluid film but also decreases at very small values of the fluid film when the viscosity is constant. If the viscosity is variable, the total temperature increases as the thickness of the fluid film decreases.

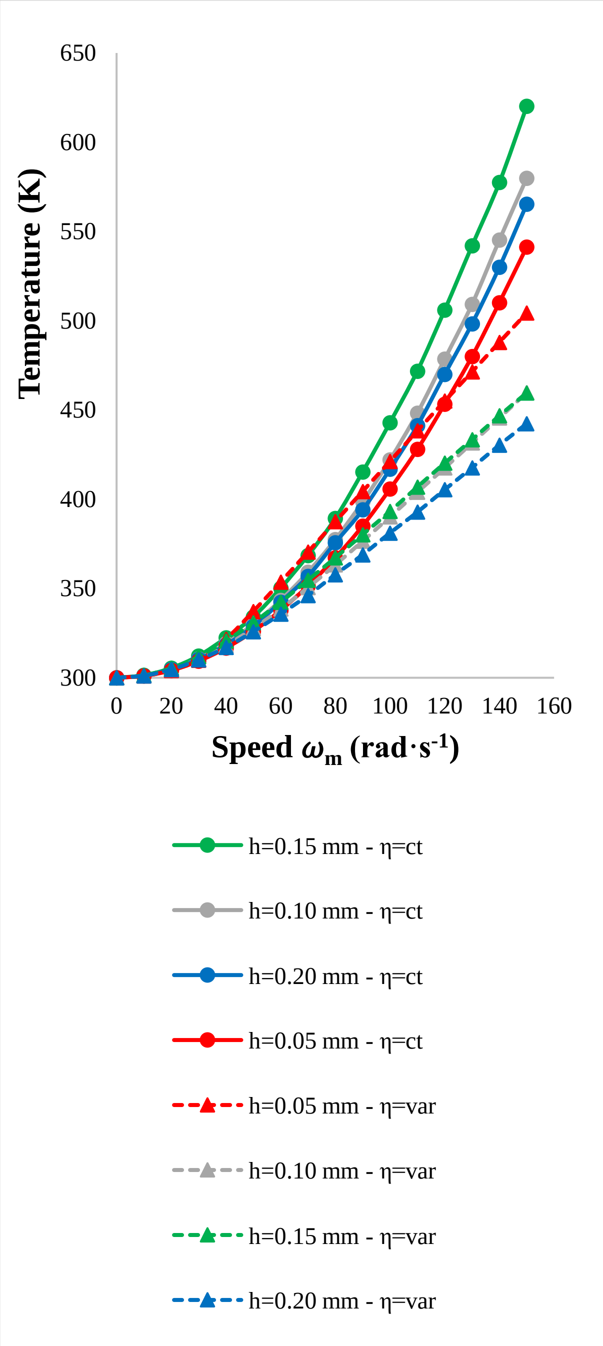


**Figure 12.** Temperature vs. speed analysis in the case of different fluid thicknesses between the moving disks and the stationary discs at η=ct vs. η=var

From Figure 13. it can be easily seen that the transmitted torque increases at small thicknesses of the fluid film, but increases abruptly at decreasing values of the fluid film for both cases when the viscosity is constant and when the viscosity is variable.

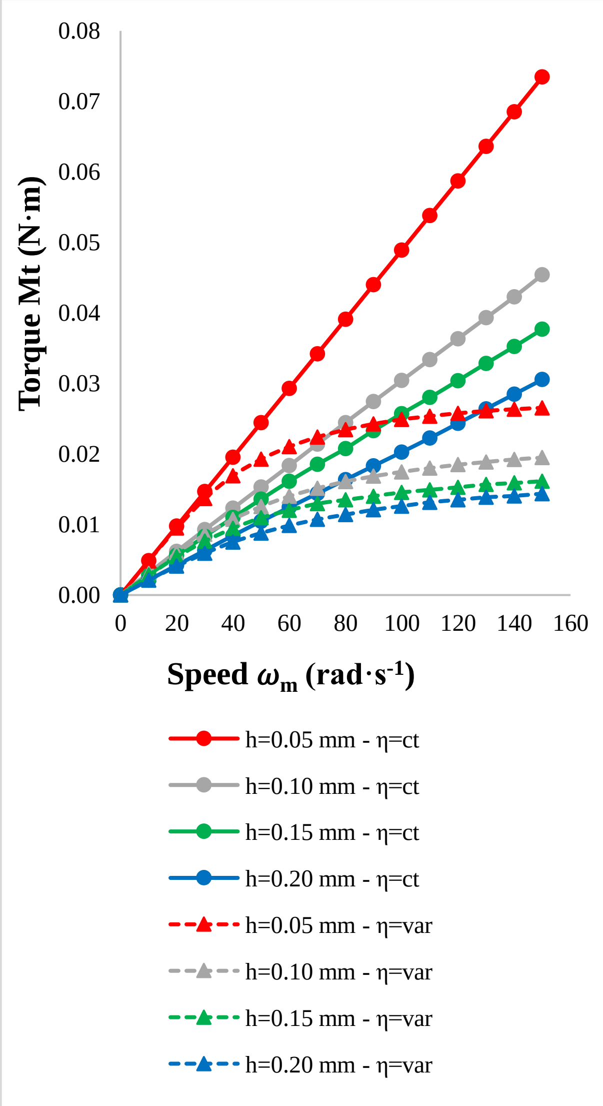


**Figure 13.** Torque vs. speed analysis in the case of different fluid thicknesses between the moving disks and the stationary discs at η=ct vs. η=var

For the Temperature and Torque analysis in the case of a viscous coupling that operates with different fluid viscosities, a total of 4 variants of viscous couplings were used that operate with different viscosities of the fluid film (0.02 Pa·s, 0.58 Pa·s, 0.81 Pa·s, 1.06 Pa·s). The effect of oil film temperature on hydro-viscous drive characteristics was studied before (Xie, F., Zhang, L., Wang, H., Yu, X., Tao, X., Song, X., Li, X., & Jian, L., 2011) but not with different viscosities as in the current article.

In all the analysed cases, 11 discs with a thickness of 2 mm each, with inner radii of 10 mm and outer radii of 30 mm, were considered. A total of 10 fluid films were considered, the fluid used in the operation of the viscous coupling having both constant viscosity and variable viscosity.

All the variants of viscous couplings studied in this case, where the viscous coupling operates with different viscosities of the fluid film, have provided on the surfaces of the moving disks radial grooves arranged from 10° to 10° with a depth of 0.05 mm and a width of 0.1 mm.

It can be seen from Figure 14. that the total temperature increases with increasing viscosity of the fluid film.

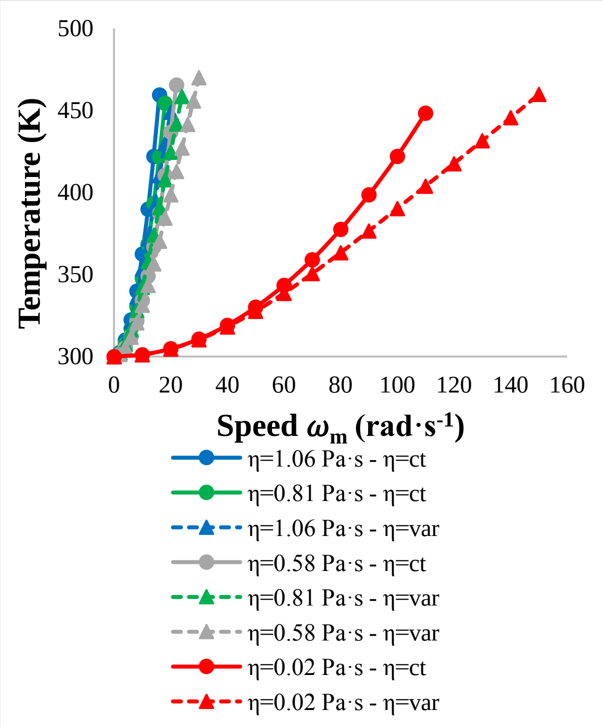


**Figure 14.** Temperature vs. speed analysis in the case of different fluid viscosities at η=ct vs. η=var

From Figure 15. below, it can be easily seen that the transmitted torque increases with the increasing viscosity of the fluid film.

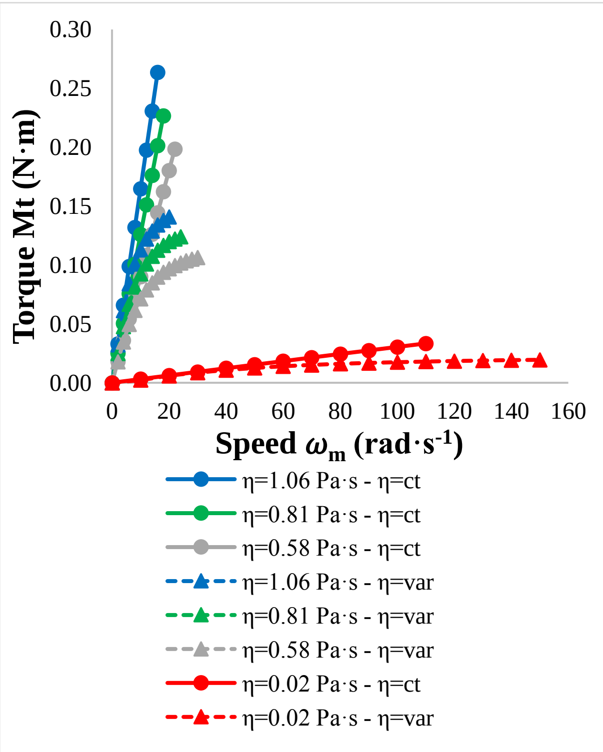


**Figure 15.** Torque vs. speed analysis in the case of different fluid viscosities at η=ct vs. η=var

## 8. CONCLUSIONS

This study is very important since viscous couplings are used in many applications due to their undeniable advantages such as: operational safety, small overall dimensions, easy assembly and disassembly, low manufacturing and operating costs, simple and robust construction, high reliability in operation, operation without any shocks and vibrations.

This paper proposes to establish a full introspection regarding viscous couplings by studying different cases and by studying the flow of the fluid film, the total temperature and the torque generated.

In all the studied cases, the total temperature increases exponentially with the increase of the angular velocity of the moving disks.

The cases in which the viscous couplings operated with fluid films with constant viscosity registered higher values of the total temperature as opposed to the cases in which the same variants of viscous couplings operated with fluid films with variable viscosity.

The total temperature increases with the increasing number of grooves on the surfaces of the moving disks.

The inclinations of the grooves on the surface of the moving disks lead to a significant decrease in the total temperature as opposed to the variant of the viscous coupling with the moving disks provided with straight radial grooves.

The direction of rotation of the moving discs does not affect the total temperature at all.

The increase of the depth of the grooves on the surfaces of the moving disks leads to a slight increase in the total temperature with the mention that the temperature values are somewhat close.

The total temperature decreases as the width of the grooves on the surface of the moving disks increases.

The total temperature decreases at high thicknesses of the fluid film but also decreases at very small values of the fluid film when the viscosity is constant. If the viscosity is variable, the total temperature increases as the thickness of the fluid film decreases.

The total temperature increases with increasing viscosity of the fluid film.

In all the studied cases, the transmitted torque increases exponentially with the increase of the angular velocity of the moving disks.

The cases in which the viscous couplings operated with fluid films with constant viscosity registered higher values of the transmitted moment as opposed to the cases in which the same variants of viscous couplings operated with fluid films with variable viscosity.

The transmitted torque increases at small thicknesses of the fluid film, but increases abruptly at decreasing values of the fluid film.

The transmitted torque increases with increasing viscosity of the fluid film.

**Acknowledgement:** I would like to express my sincere gratitude for the assistance and for the financial support of both the faculty and the coordinating professor.

## References:

Behzad, M., Saxena, V., & Schafer, M. (2018). Thermal-Hydrodynamic optimization of grooves in wet clutch. *ResearchGate*. Retrieved from https://www.researchgate.net/publication/335611945_Thermal-Hydrodynamic_Optimization_of_Grooves_in_Wet_Clutch

Bieberle, A., Schlottke, J., Spies, A., Schultheiss, G., Kühnel, W., & Hampel, U. (2015). Hydrodynamics analysis in micro-channels of a viscous coupling using gamma-ray computed tomography. *Flow Measurement and Instrumentation*, *45*, 288–297. https://doi.org/10.1016/j.flowmeasinst.2015.07.008

Cui, H., Zi-Sheng, L., Li, L., & Wang, Q. (2018). Analysis of influencing factors on oil film shear torque of hydro-viscous drive. *Industrial Lubrication and Tribology*, *70*(7), 1169–1175. https://doi.org/10.1108/ilt-05-2017-0137

Gong, H., Xie, H., & Yang, H. (2019, December 1). A Numerical Method for Extrication Characteristics of TBM Cutter-Head with the HVC. *Chinese Journal of Mechanical Engineering*. https://doi.org/10.1186/s10033-019-0413-z

Gong, H., Xie, H., Hu, L., & Yang, H. (2019). Effects of groove orientation on transmission characteristics of hydro-viscous film in the parallel-disk system. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, *234*(2), 183–192. https://doi.org/10.1177/1350650119858238

Hao, N. N., Yu, Y., & Liu, H. W. (2011). Theoretical research on Hydro-Viscous transmission to power equilibrium in Multi-Motored starting of belt conveyor. *Applied Mechanics and Materials*, *121–126*, 1677–1681. https://doi.org/10.4028/www.scientific.net/amm.121-126.1677

Heuser, G. (1997). An approximate solution for the flow in viscous couplings. *Forschung Im Ingenieurwesen-engineering Research*, *63*(6), 206–214. https://doi.org/10.1007/pl00010832

Hou, Y. F., Wang, D. M., Meng, Q. R., & Du, B. (2011, September 1). *Dynamic Analysis of a New Type of Hydro-Viscous Drive Winch*. Advanced Materials Research. https://doi.org/10.4028/www.scientific.net/amr.328-330.2243

Huang, J., Fan, Y., Minxiu, Q., & Fang, W. (2012). Effects of groove on behavior of flow between hydro-viscous drive plates. *Journal of Central South University*, *19*(2), 347–356. https://doi.org/10.1007/s11771-012-1011-8

Jin, L., Peng, X., Wang, D., Guo, D., & Chen, B. (2021). Calculation and verification of the Real-Time working characteristics of a viscous coupling. *Applied Sciences*, *11*(3), 1110. https://doi.org/10.3390/app11031110

Maurya, U., Kumar, A., Saini, V., Thakre, G., & Harmain, G. A. (2024). Unravelling the Effect of Chain and Branch Content on Viscosity of Polyisobutylene-Mineral Oil Blends by Modelling and its Tribological Properties. *Journal of Materials and Engineering*, *2*(3). https://doi.org/10.61552/JME.2024.03.005

Meng, Q. R., Lin, S. F., & Wang, J. (2012, December 1). Design and Analysis of Hydro-Viscous Winch Hydraulic System. *Advanced Materials Research*, Vols. 605-607, 1317-1321. https://doi.org/10.4028/www.scientific.net/amr.605-607.1317

Meng, Q., & Hou, Y. (2008). Mechanism of hydro-viscous soft start of belt conveyor. *Journal of China University of Mining and Technology*, *18*(3), 459–465. https://doi.org/10.1016/s1006-1266(08)60095-4

Meng, Q., Zhao, C., & Tian, Z. (2018). Effect of torque ratio on speed regulating start. *Industrial Lubrication and Tribology*, *70*(9), 1657–1663. https://doi.org/10.1108/ilt-02-2018-0062

Predescu A. (2011). *Cuplaje cu frecare vîscoasă*, Printech.

Razzaque, M. M., & Kato, T. (1999). Effects of groove orientation on hydrodynamic behavior of wet clutch coolant films. *Journal of Tribology*, *121*(1), 56–61. https://doi.org/10.1115/1.2833811

Scott G. E., Water pump driven by viscous coupling, United States patent, US6725812B1, 2000.

Wei, B., He, Y., Wang, W., & Jianbin, L. (2018). Simulation and experiment of viscous torque for disengaged wet clutches of tracked vehicle. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, *233*(4), 593–604. https://doi.org/10.1177/1350650118788143

Wu, P., Xu, J., & Zhou, X. (2019). Numerical and experimental research on engagement process of wet multi-plate friction clutches with groove consideration. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*. https://doi.org/10.1177/1350650119866045

Xie, F., & Hou, Y. (2010). Transient temperature field of a friction pair in a HVD device of a belt conveyor. *Mining Science and Technology (China)*. https://doi.org/10.1016/s1674-5264(09)60304-5

Xie, F., Zhang, L., Wang, H., Yu, X., Tao, X., Song, X., Li, X., & Jian, L. (2011). Effect of oil film temperature on hydro-viscous drive characteristics. *2011 International Conference on System Science, Engineering Design and Manufacturing Informatization*, Guiyang, pp. 246-249,. https://doi.org/10.1109/icssem.2011.6081289

Xie, H., Gong, H., Hu, L., & Yang, H. (2016, August 1). Improving the extricating performance of TBM cutter-head driving system with hydro-viscous clutch. *12th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications (MESA)*. https://doi.org/10.1109/mesa.2016.7587188

Yin, X., Lin, Y., & Li, W. (2015). Operating modes and control strategy for Megawatt-Scale Hydro-Viscous Transmission-Based continuously variable speed wind turbines. *IEEE Transactions on Sustainable Energy*, *6*(4), 1553–1564. https://doi.org/10.1109/tste.2015.2455872

Yin, X., Lin, Y., Li, W., & Gu, H. (2016). Hydro-viscous transmission based maximum power extraction control for continuously variable speed wind turbine with enhanced efficiency. *Renewable Energy*, *87*, 646–655. https://doi.org/10.1016/j.renene.2015.10.032

Yin, X., Lin, Y., Li, W., Liu, H., & Gu, Y. (2014). Output power control for hydro-viscous transmission based continuously variable speed wind turbine. *Renewable Energy*, *72*, 395–405. https://doi.org/10.1016/j.renene.2014.07.010

Yin, Z., Zhao, K., Shangguan, W., & Song, L. (2016). Analytical and experimental characterization of viscous fan clutch performances including thermal dynamics. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*. https://doi.org/10.1177/0954406215619448

**Andrei-Iancu Stoicescu**
Polytechnic University of Bucharest,
Bucharest,
Romania,
stoicescu_andrei_iancu@yahoo.com
ORCID 0000-0002-6977-3509

**Adrian Predescu**
Polytechnic University of Bucharest,
Bucharest,
Romania,
adrian_omtr@yahoo.com
ORCID 0009-0005-1798-3474

## Appendix

**Nomenclature:**

$M_t$ (Nm) - transmission torque
$\eta$ (Pas) - dynamic viscosity (oil)
$\eta_0$ (Pas) - initial dynamic viscosity (oil)
$\eta = var$ (Pas) - variable dynamic viscosity (oil)
$\eta = ct$ (Pas) - constant dynamic viscosity (oil)
$\omega_1$ ($rads^{-1}$) - angular speed of the rotating grooved disc
$\omega_2$ ($rad^{-1}$) - angular speed of the stationary smooth disc
$r_e$ (mm) - external radius of the disc
$r_i$ (mm) - internal radius of the disc
$h$ (mm) - thickness of the oil film
$z$ (mm) - number of oil films
ρ (kg/m3) - lubricant density
$C_v$ ($J \cdot kg^{-1} \cdot K^{-1}$) - lubricant specific heat capacity
$U_{i\,z,(y)}$ (m/s) - velocity components of the friction disc
$q_{z,(y)}$ ($m^3/s$) - average flow of oil components
p ($N \cdot m^{-2}$) - hydrostatic pressure (isotropic component)
$T_0$ (K) - initial temperature of 300 K
$T$ (K) - temperature
ds (°) - grooves at different degrees between them on the surfaces of the moving discs
Q (°) - grooves at different inclinations between them on the surfaces of the moving discs
h` (mm) - grooves with different depths on the surfaces of the moving disks
b (mm) - grooves with different widths on the surfaces of the moving disks