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Research of thermal load in an energy efficient mechatronic truck transmission considering energy losses

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Abstract. The article examines the heating of a truck's energy efficient mechatronic transmission during operation of an electric motor in maximum power mode. Particular attention is paid to the process of modeling conjugate heat transfer and its impact on the energy efficiency of mechatronic transmission. To solve this problem, computational fluid dynamics (CFD) methods are used, in particular the finite volume method (FVM), which allows for an accurate assessment of heat flows between different environments inside the transmission. Analysis of thermodynamic processes occurring in mechatronic transmission is of great importance for optimizing its operation and increasing reliability. The simulation results demonstrate the influence of various factors, such as driving speed, loads and temperature conditions, on the efficiency of heat exchange and, as a result, on the energy efficiency of the entire vehicle. These research contribute to the development of more efficient cooling systems and improved performance of trucks.

1 Introduction

A mechatronic transmission [5], which combines mechanical and electrical components to drive the wheels of a vehicle, consists of an electric motor, a reduction gear, a gear engagement mechanism, an interwheel differential, a mechanism for locking the interwheel differential if available, etc. When an electric motor is operating, energy losses occur in it: part of the power consumed by the motor is spent on heating its windings, on heating the magnetic circuit from hysteresis and eddy currents, and on friction in the bearings. All this creates additional thermal load on the gears, lubrication system, bearing assemblies and crankcase parts. When designing a mechatronic transmission, it is necessary to conduct a research of the thermal load of the structure in order to determine the temperatures to which its elements are heated in the selected operating mode in order to assess compliance with the specified temperature limits. During long-term operation of the mechatronic bridge under conditions of high power levels developed by the electric motor, overheating of the structure may occur, which may lead to a reduction in the service life of the unit or even its failure, caused by jamming or destruction due to high thermal load.

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Due to the complexity of the geometry of the mechatronic bridge, obtaining the temperature distribution of the structural elements using analytical calculations is a complex task. For such studies in engineering practice, the use of numerical methods is more appropriate. When studying problems in which it is necessary to model conjugate heat exchange, i.e. heat exchange between different environments, computational fluid dynamics (CFD) methods are used [1-4]. The main one is the finite volume method (FVM).

2 Initial data for calculation

The main objective of the research is to determine the temperature of the transmission oil during operation. The geometry of the bridge under research is shown in Figure 1.

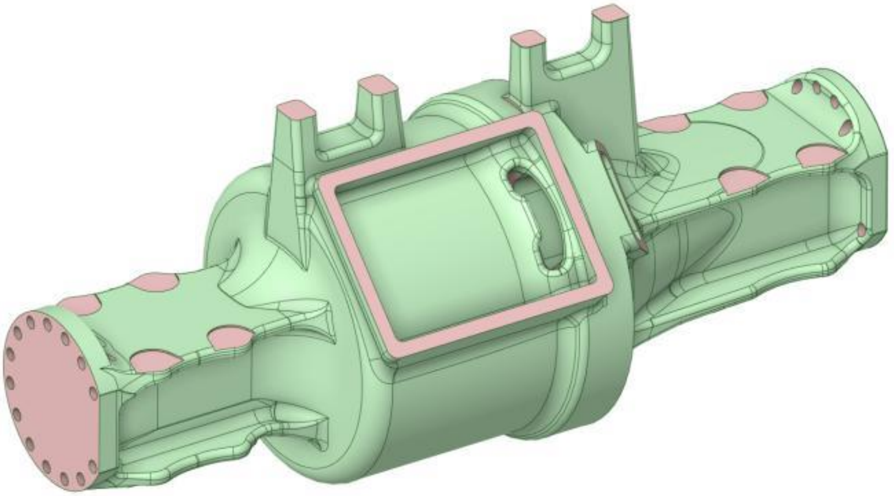

Fig. 1. 3D model of the mechatronic bridge.

To simulate conjugate heat transfer, the following regions are distinguished (Figure 2): the region of the solid body, the region of the environment and the internal cavity, part of which is filled with oil, as shown in Figure No. 2, and the rest is air.

Fig. 2. Calculation area in section.

The physical properties of air and oil adopted in the calculation are given in Table 1, the properties of the material of the solid body of the mechanism are given in Table 2.

Table 1. Physical properties of oil and air.

Parameter	Value	
	Oil	Air
Heat capacity, J/(kg·K)	1845	1005
Thermal conductivity, W/(m·K)	0.145	0.0271
Density at 40 °C, kg/m3	838	1.127

Table 2. Physical properties of metal.

Parameter	Value
Heat capacity, J/(kg·K)	466
Thermal conductivity, W/(m·K)	46
Density at 40 °C, kg/m3	7800

Figure 3 shows and identifies the main sources of thermal energy, the power losses of which are presented in Table 3.

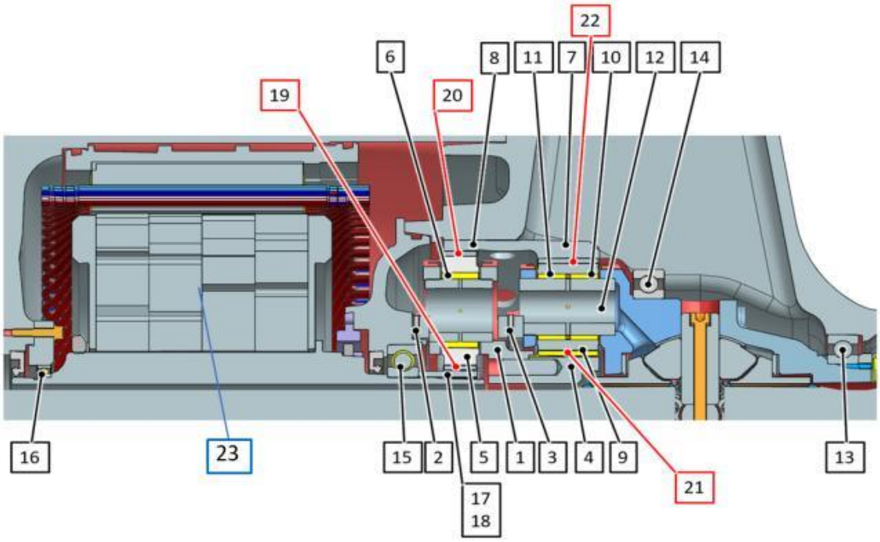

Fig. 3. Heat sources of mechatronic transmission.

The boundary conditions in this calculation are specified as thermal power sources on the surfaces of the traction electric motor, bearings and gears, the characteristics of which are presented in Table 3. The heat generation powers were obtained using the calculation in the KISSsoft software package. The initial temperature of all areas in the calculation model was 40 ℃.

Table 3. Thermal power sources.

№	Element name	Heat dissipation power. W
1	Losses from mixing of the carrier of the first planetary row	1.3342
2	Losses in the thrust bearing of the first planetary row	170.98
3	Losses in the thrust bearing of the second planetary row	214.77

4	Losses from mixing of the sun gear of the second planetary row	1.0583
5	Losses from mixing of the first planetary gear set satellite	36.32
6	Losses in needle bearings of the first planetary gear set satellites	226.66
7	Losses from mixing of the crown gear of the second planetary row	0
8	Losses from mixing of the crown gear of the first planetary row	0
9	Losses from mixing of the second planetary gear set satellite	1.5828
10	Losses in needle bearings of the second planetary gear set	51.828
11	Losses in needle bearings of the second planetary gear set	51.763
12	Losses from mixing of the second planetary gear carrier	0.067995
13	Losses in the small ball bearing of the differential	18.639
14	Losses in the large ball bearing of the differential	33.767
15	Electric Motor Ball Bearing Losses	294.63
16	Electric Motor Ball Bearing Losses	120.46
17	Losses from mixing of the sun gear of the first planetary row	6.2889
18	Compaction losses	0
19	Losses in engagement of the sun gear of the first planetary row with the satellites	561.91
20	Losses in engagement of the crown gear of the first planetary row with the satellites	117.38
21	Losses in engagement of the sun gear of the second planetary row with the satellites	823.63
22	Losses in engagement of the crown gear of the second planetary row with the satellites	255.52
23	Losses that make up the difference between losses in the active part of the traction electric motor and losses removed by the traction electric motor cooling system	493

The flow in the inner region of the mechatronic bridge is chaotic due to intensive mixing of rotating elements. The multiphase nature of the flow in combination with a wide range of turbulent structures significantly increases the time and machine resources required for numerical modeling. The accepted assumption of the immobility of the transmission elements, on the one hand, gives a large increase in the calculation speed, on the other hand, it reduces convective heat transfer, which will lead to an increase in the values of the calculated temperatures. Since the purpose of this research is to determine the maximum temperatures, the calculation with a guaranteed certain reserve is an acceptable condition that ensures the execution of calculations with a limited amount of machine time [6-16].

Also, the assumption of the absence of radiant heat exchange will not lead to a noticeable change in the results, due to the expected relatively low temperature values.

In this regard, the main assumptions adopted in the modeling are:

- the movement of transmission elements is not modeled;
- the natural convection model is adopted for the heat exchange of the mechanism with the environment;
- heat exchange by radiation is not taken into account;
- the calculation is performed in a stationary setting.

3 Initial data and settings of the calculation model

The simulation consists of two consecutive stages. The first stage is the calculation of the conjugate heat exchange of the solid body of the mechanism with the environment, as a result of which the temperature field on the surface of the mechanism's contact with the surrounding air is calculated. The resulting field is specified as one of the boundary conditions for the second stage, in which the conjugate heat exchange of the solid body with the transmission oil and the air of the internal cavity is simulated. Conjugate heat exchange is the process of simulating the thermal interaction between solids and liquids. This method allows calculating the heat flux that is transferred through the boundaries between solid and liquid phases, taking into account both thermal conductivity in solids and heat transfer in liquids (convection).

The computational domain of the first stage is shown in Figure 4.

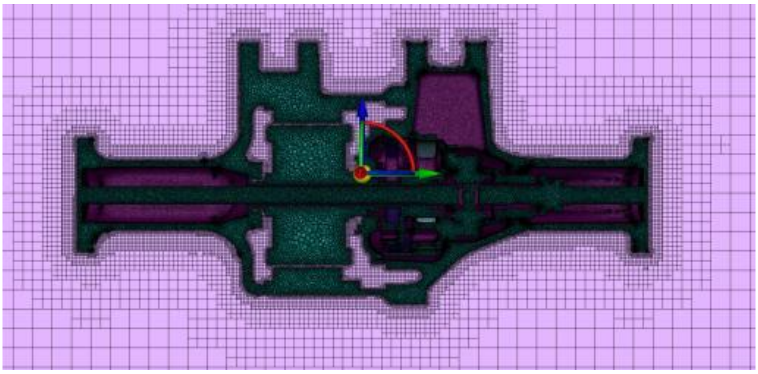

Fig. 4. Calculation area of the first stage.

Parameters of the computational domain grid:
- basic cell size: 3 mm;
- total number of cells: 11798097.

The grid quality allows performing the calculation with optimal accuracy.

Physical model settings for this calculation:

- laminar flow mode is selected, which implies the movement of a liquid or gas flow, in which the layers of matter move smoothly and parallel to each other without significant mixing;

- the model for air is an ideal incompressible gas. The ideal incompressible gas model describes a gas that has a constant density and does not change its volumetric properties with changes in pressure and temperatur].

The temperature distribution over the surface of the mechanism obtained as a result of the first stage of calculation is shown in Figure 5.

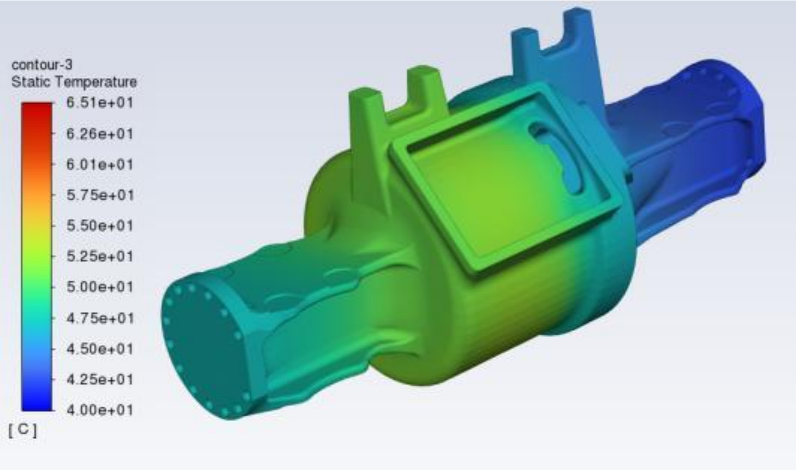

Fig. 5. Temperature distribution on the surface of contact of the mechanism with the surrounding air.

The calculated field values were saved in CSV format and exported to the second stage of calculation. CSV format is convenient for importing data into ANSYS Fluent due to its simple structure, versatility and ease of editing, which simplifies data preparation and exchange.

The hottest parts of the housing are the walls located closest to the traction motor. The obtained temperature field demonstrates the effective removal of heat flow into the atmosphere, since the temperature on the surfaces of the housing walls does not exceed 70 °C.

The calculation area of the second stage is shown in Figure 6.

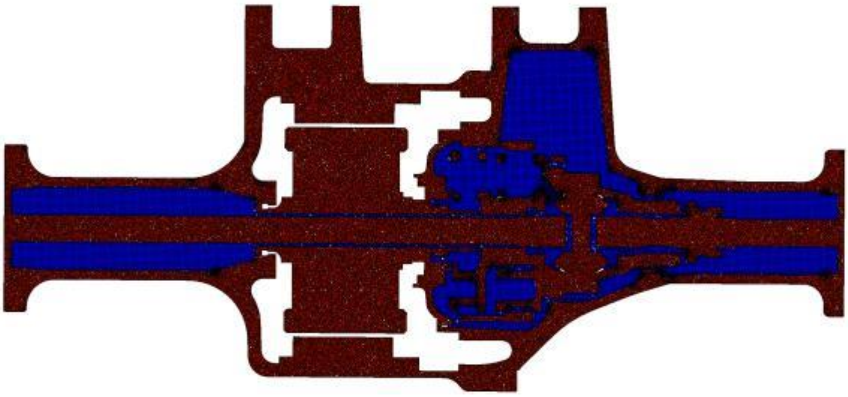

Fig. 6. Calculation area of the second stage.

Parameters of the computational domain grid:

- base size: 3 mm;
- total number of cells: 12658832.

The physical model settings for the second stage are as follows:

- laminar mode;
- free surface modeling methods – Volume of Fluid (used in CFD to model multiphase flows where it is necessary to track and accurately determine the boundary between liquids or phases, such as water and air, by solving the equations for conservation of volume of each phase in a grid cell);

Figure 7 shows the specified oil level selected based on the required for effective lubrication of the rubbing elements and a preliminary estimate of the required oil volume for effective heat dissipation.

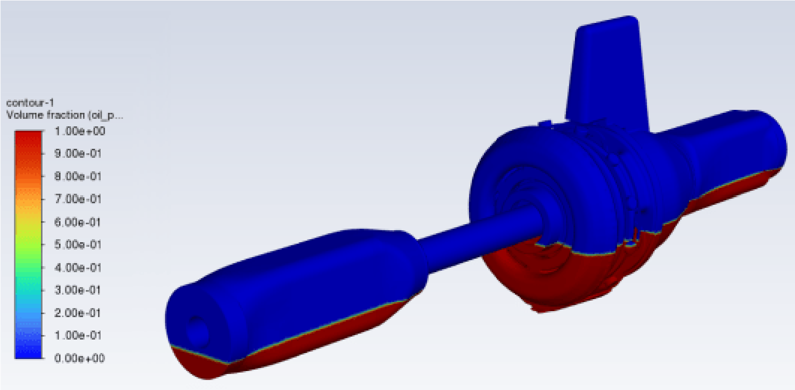

Fig. 7. Initialized calculation model: blue – air phase, red – oil phase.

4 Results

The calculated temperature field in the cross-section of the mechatronic bridge is shown in Figure 8.

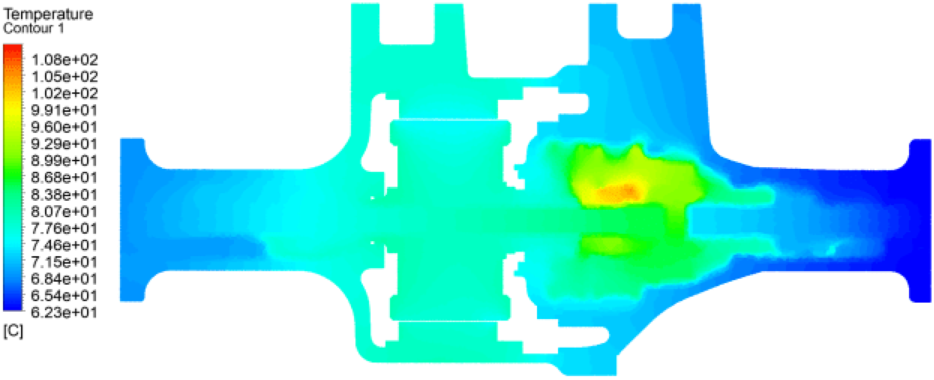

Fig. 8 Temperature distribution in the cross section.

The average value of the oil volume temperature was 76 °C. The maximum oil temperature was 93 °C. The hottest point according to the calculation results is in the area of the greatest losses, pos. 21 in Figure 3 and Table 3, in the contact zone of the solid with air, since the cooling properties of air are lower than those of oil.

The mechatronic bridge design functions effectively, since the analysis of the boundary conditions of heat emission on the friction surfaces was performed taking into account the most loaded operating mode of the car. Since local temperatures do not exceed the permissible ones, it can be concluded that losses in friction pairs are permissible, then the mechatronic bridge design does not require modification and effectively removes heat from heating sources.

5 Conclusion

In this research, the heating of the mechatronic transmission elements was analyzed. The method of modeling the conjugate heat exchange of the design elements with the ambient air and with the transmission oil was used. For this purpose, the calculation areas were identified, the boundary conditions were set and the conjugate heat exchange between the areas under consideration was calculated using CFD modeling. Based on the results obtained, it can be concluded that under the selected operating mode, the temperature of the oil and transmission elements is within the permissible limits, i.e. up to 150 °C. The mechatronic bridge design demonstrates efficient operation due to the analysis of thermal conditions, which is confirmed by permissible local temperatures and efficient heat removal, without requiring modifications.

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