THREE DIMENSIONAL SIMULATION OF OIL FLOW CHARACTERISTICS IN LUBRICATION SYSTEM OF ROTARY TILLAGE ENGINE

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旋耕发动机润滑系统中的油流特性三维仿真研究

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ABSTRACT

Taking the lubrication system of rotary tillage engine as the research object, this paper makes a three-dimensional simulation study on the oil flow characteristics in the lubricating oil passage. The oil supply of the oil pump shall be greater than the circulating oil required by the lubrication system to ensure the lubrication of the rotary cultivator. Lubrication system is an important part to ensure the reliability and durability of rotary cultivator. The key component to achieve its performance is the oil pump. The geometric model of lubricating oil flow field in rotary tiller lubrication system is established by using FLUENT software. The results show that the pressure drop in the lubricating oil passage of the main bearing is the largest under the same working conditions. In the oil passage of the cylinder head, the pressure drop of the front main oil passage is the largest and the oil discharge is the largest. Add 1.6 mm oil pump rotor on the basis of the thickness of the original oil pump rotor, the oil flow at the connecting rod nozzle reaches the flow index of the original rotary cultivator, and there is no cylinder pulling phenomenon of the rotary cultivator.

摘要

本文以旋耕发动机润滑系统为研究对象，对润滑油道中的油流特性进行了三维仿真研究。油泵的供油量应大于润滑系统所需的循环油量，以保证旋耕机的润滑。润滑系统是保证旋耕机可靠性和耐久性的重要组成部分。实现其性能的关键部件是油泵。利用 FLUENT 软件建立了旋耕机润滑系统润滑油流场的几何模型。结果表明，在相同工况下，主轴承润滑油道中的压降最大。在缸盖的油道中，前主油道的压降最大，排油量也最大。在原机油泵转子厚度的基础上增加 1.6mm 油泵转子，连杆喷嘴处的油流量达到原旋耕机的流量指标，旋耕机不存在拉缸现象。

INTRODUCTION

At present, agricultural land resources are extremely rich, and there are many rural farmers. Promoting the stable development of agriculture is closely related to the improvement of the living standards of rural population. At the same time, the improvement of the quality of life of the rural population will also promote the prosperity of various industries *(Savitska S., et al., 2020)*. The key task of the whole process of agricultural mechanization development is to focus on improving the comprehensive quality and benefit of agricultural mechanization of potato, corn, rice, soybean and other food crops. The core direction of the development of agricultural machinery industry is the intelligence and mechanization of agricultural machinery, which is also the main direction of realizing agricultural modernization *(Bukhtiyarova T.I. et al., 2021; Handler A.M. et al., 2020)*. Rotary tiller, as an important tillage machine, it is one of the important equipment to improve the tillage quality when it is used in field operation. Although some achievements have been made in the research and development of average depth control of agricultural machinery in the world, there is still a big gap compared with developed countries, and it is still in a relatively backward stage.

In the development project of rotary tillage engine, in order to better achieve the strategic goal of sustainable development, reducing oil consumption should be the first problem to be solved in the development and research of rotary tillage engine *(Siddique M. et al., 2021).* Under any working conditions, the oil supply of the oil pump should be larger than the circulating oil required by the lubrication system to ensure the lubrication of the rotary tillage engine.

If the oil supply of the oil pump is insufficient, the main bearing and connecting rod bearing of the rotary tiller will be worn, and the cylinder of the rotary tiller will even be damaged. At the same time, lubricating oil will deteriorate and fail quickly, which will seriously affect the normal operation of equipment and agricultural production efficiency. Therefore, the rational and effective design of lubrication system is of great significance to improve the power, economy and reliability of crusher *(Mukhametshin I. et al., 2020; Shevchenko A.N. et al., 2018)*.

Due to the complex structure and limited working environment of rotary tillage engine, we can't directly measure the lubrication parameters (such as crankshaft oil passage pressure, oil leakage, etc.) of some parts of the lubrication system through experiments. Using FLUENT simulation method to calculate and analyze the lubrication flow field of the lubrication system can not only get more accurate calculation results, but also save a lot of time and money and shorten its cycle *(Anand R. et al., 2021)*. Based on this, this paper will optimize the performance of engine lubrication system for rotary tillage based on FLUENT software, ensure the lubrication of piston and other parts, and ensure the oil supply of oil pump is sufficient, thus effectively avoiding the occurrence of cylinder pulling phenomenon, greatly shortening the development cycle of oil pump products, reducing product cost and improving product quality.

Through the three-dimensional fluid simulation analysis of Aprilia diesel engine oil pump, the three-dimensional fluid simulation software pmpplix is used to simulate, and the cavitation phenomenon of relevant fluid in the calculation is considered *(Chiavola O. et al., 2021)*. They compare the experimental data obtained from the hydraulic test-bed with the simulation analysis results, and find that there is a good correlation between them. It can be proved that the oil pump can be simulated by 3D fluid simulation software when selecting or optimizing the oil pump. Flowmaster software can call models with different complexity in different internal combustion engine lubrication systems, and build and show the interaction of diesel engine fluid systems through these models, and then use one-dimensional fluid simulation software to complete different design tasks *(Samiezadeh S. et al., 2021)*. When studying the oil pump and lubricating oil circuit, the researchers used the three-dimensional model of external gear pump and flow pulsation for experimental evaluation. *(Corvaglia A. et al., 2021)*. Through the three-dimensional simulation model of oil pump, the internal structure of oil pump is optimized, the phenomenon of trapped oil and cavitation is improved, and the pressure loss at the corner and joint of complex casting oil channel is accurately predicted, which provides an important basis for the setting of oil pump *(Li D. et al., 2021).*

With the improvement of computer level, the numerical simulation method was used to study the flow characteristics of square section elbow, which provides a new method for the study of fluid in the pipe. In reference *(He M. et al., 2020)*, the flow characteristics of gas-liquid two-phase flow in a 180° bend were studied by numerical simulation. The numerical results are in good agreement with the experimental results, which proves the correctness of the numerical method. The lubrication of crankshaft bearing in internal combustion engine lubrication system is deeply analyzed and studied, and put forward a complete set of software implementation scheme from mathematical modeling, analysis and calculation to simulation results, but unfortunately, only the crankshaft bearing was analyzed *(Zhang Y. et al., 2020).* With the development of a set of simulation analysis software for internal combustion engine lubrication system, *Simisinov et al.* put forward a brand-new graphical modeling method for internal combustion engine lubrication system by using modular programming idea *(Simisinov D. et al., 2020)*. *Singh et al*. used FLUENT software in CFD tool to solve and analyze the pressure of sliding bearing, and calculated and analyzed the influence of bearing distribution and the size of upper and lower bearing slots on sliding bearing *(Singh R. et al., 2020)*.

MATERIALS AND METHODS

Brief introduction of FLUENT solution process

Computational Fluid Dynamics (CFD) is a systematic analysis method and tool for simulating fluid flow, heat transfer and related transfer phenomena by computer. Because of complicated partial differential equations, most problems in fluid mechanics and heat and mass transfer cannot be solved accurately, and can only be dealt with by experience or experiment, which makes the application of fluid mechanics in engineering technology very limited. Among commercial CFD software packages, Fluent is the most popular, and its utilization rate is very high in countries with high design level such as America and Europe. FLUENT has developed a variety of flow simulation software, which can simulate various complex physical phenomena and meet the needs of various users. It is precisely because of its powerful function that greatly facilitates users and is welcomed by users.

The process of CFD simulation solution is complex. The solution process of different problems is roughly the same and can be divided into several steps. The solution process can be represented by flow chart as shown in Figure 1.

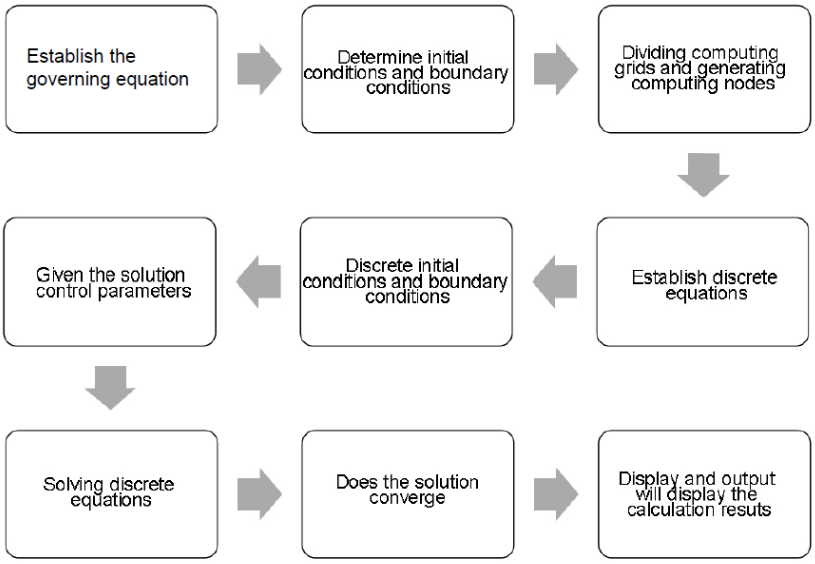


Fig. 1 - Flow chart of FLUENT analysis

Establishment of mathematical model of oil pump

Circulating oil quantity of oil pump is an important parameter of oil pump performance, and its size depends on the lubrication system of rotary tillage engine and the structural arrangement of rotary tillage engine. In the modern internal combustion engine, the circulating oil quantity of the oil pump is generally calculated by the heat transferred from the rotary tillage engine to the engine oil namely:

$$V_c = \frac{Q_o}{\gamma \cdot c \cdot \Delta t} \tag{1}$$

in which: V_c is the circulating oil quantity of oil pump, L h^{-1}; γ is the density of engine oil, kg·L^{-1}; c is the specific heat capacity of engine oil, k·J (kg·℃)$^{-1}$; Δt is the temperature between the inlet and outlet of engine oil, °C; Q_0 is the heat absorption of engine oil, kJ·h^{-1}. When there is no piston cooling nozzle, Q_0 is 1.5% ~ 2.0% of the total fuel heat; piston cooling nozzle, Q_0 is about 6.0% of the total fuel heat, where the total fuel heat is:

$$Q_f = \frac{3600\, N_e}{\eta_e} \tag{2}$$

in which: N_e is the calibration power of internal combustion engine, kW; η_e is the effective efficiency of internal combustion engine.

Actually, the calculation of oil supply of the oil pump is determined according to the layout structure of the rotary tillage engine and the parts to be lubricated, that is, the oil supply of the oil pump is the sum of the lubrication flow required by each part.

Pipeline model

The flow of engine oil in pipeline belongs to viscous flow, and there are two different flow patterns in viscous flow: laminar flow and turbulent flow. These two flows have different natures and manifestations, and their velocity distribution, shear stress size and distribution, energy loss and diffusion properties are different under various specific boundary conditions. Therefore, first of all, it is necessary to determine the flow state of oil in the pipeline.

The along-way loss of engine oil is expressed by h_λ, which is caused by the along-way resistance, that is, the frictional resistance along the flow path. The characteristic of loss along the route is that the loss is evenly distributed along the process, and its size is proportional to the length of the process. Along-way loss analysis is to calculate the pressure loss of engine oil after passing through the pipeline according to the extracted structural parameters of the pipeline and the flow rate of engine oil in the pipeline.

When the fluid flows through various local obstacles, the movement pattern in the obstacle zone changes sharply, such as vortex, liquid flow deformation, velocity redistribution, impact and secondary flow, etc., and then the force hindering the fluid movement is generated, which is called local resistance.

The resulting energy loss is called local loss. Usually, the spoon is used to express the local head loss per unit weight of fluid, and its calculation formula is:

$$h_f = \xi \frac{v^2}{2g} \tag{3}$$

in which:

ξ -- local resistance coefficient;

h_f -- local resistance loss.

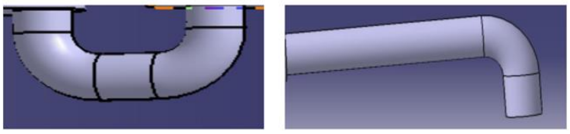
It can be seen from this formula that the key to calculate the local loss lies in how to determine the local resistance coefficient ξ. Generally speaking, ξ depends on the geometry of local obstacles and the Reynolds number R_e of flow. The relationship between the former and the latter is different in different areas divided by flow pattern, and its relationship is as follows:

(1) Laminar flow area, at this time, $\xi=A/R_e$; The A value needs to be determined by experiments, and it depends on the specific types of local obstacles.

(2) Smooth area, at this time, $\xi=B/R_e^{0.53}$; the value of B is determined by experiment.

(3) The resistance square area, in which the local loss coefficient has no relationship with R_e, but is only determined by the geometric shape of the local obstacle.

In this paper, according to the actual measurement of structural dimensions of related parts of rotary tillage engine, the oil circuit is simplified into a through pipe of corresponding size for convenience of drawing. The simplified oil circuit model of the engine lubrication system for rotary tillage is established by FLUENT (Figure 2). For the oil radiator and oil filter, because the internal structure is too complex, they are built into solid entities, and porous media are used instead in the calculation process. Because of the special structure and complicated flow, the bearings, intake and exhaust valves and lubricating oil passages of single pump are equivalent to oil drain holes.



(a) U-shaped tube structure (b) Outlet of oil pump to cooler

Fig. 2 - Special pipeline model

Calculation model of flow resistance of valve

There are two pressure limiting valves in the lubrication system of rotary tillage engine studied in this paper. The primary pressure limiting valve is installed at the outlet of the oil pump, and the secondary pressure limiting valve is installed at the outlet of the filter, which is connected in parallel with the whole lubricating oil circuit to limit the maximum oil pressure of the lubricating system. In the hydraulic valve, the influence of gravity is negligible. Because of $H_1=H_2$, the influence of gravity potential energy is not considered. At the same time, the flow of fluid at the valve port is turbulent, and the kinetic energy coefficient is $a_1=a_2=1$.

Therefore, Bernoulli equation of flow sections 1 and 2 is:

$$\frac{P_1}{\gamma} + \frac{v_1^2}{2g} = \frac{P_2}{\gamma} + \frac{v_2^2}{2g} + h_s \tag{4}$$

in which:

P_1, P_2 -- pressure of sections 1 and 2, MPa;

v_1, v_2 -- the velocity of sections 1 and 2, m/s.

The energy loss h_s can be expressed by the product of the resistance coefficient ξ of the valve port and the speed, i.e.:

$$h_s = \xi \frac{v_2^2}{2g} \tag{5}$$

$$\frac{P_1}{\gamma} + \frac{v_1^2}{2g} = \frac{P_2}{\gamma} + \frac{v_2^2}{2g} + \xi \frac{v_2^2}{2g} \tag{6}$$

According to the principle of fluid continuity

$$Q = A_1 v_1 = A_2 v_2 \tag{7}$$

where: A_1 is the area at the overcurrent section 1, m^2;

A_2 is the area at the overcurrent section 2, m².
Available:

$$\frac{v_1^2}{2g}(1+\xi)-\frac{v_1^2}{2g}\left(\frac{A_2}{A_1}\right)^2=\frac{P_1}{\gamma}-\frac{P_2}{\gamma} \tag{8}$$

Solving equations:

$$v_2=C_v\sqrt{\frac{2(P_1-P_2)}{\rho}} \tag{9}$$

in which, $C_v=\frac{1}{\sqrt{1+\xi-(A_2/A_1)^2}}$. C_v is the velocity coefficient, and it is determined by experiments that C_v=0.96-0.98. It can be approximated as 1 in calculation. Add a shrinkage coefficient $C_0=A_2\text{-}A_1$, where A is the flow area at the valve port, then:

$$Q=A_2v_2=C_0A_2v_2=C_VC_0A\sqrt{\frac{2(P_1-P_2)}{\rho}}=CA\sqrt{\frac{2(P_1-P_2)}{\rho}} \tag{10}$$

In this formula, $C=C_vC_0$ is called flow coefficient. The flow coefficient is different for different orifice shapes. In hydraulic valves, slide valve type sliding port and cone valve port often appear. The flow coefficient $C\approx0.65$ of the slide valve port is determined by experiments. Flow coefficient $C\approx0.77\text{-}0.80$ of conical valve port. The cross-sectional areas in front of and behind the valve port are equal, so the relationship between pressure drop and flow rate of the valve is:

$$\Delta P=P_1-P_2=\left(\frac{Q}{CA}\right)^2\frac{\rho}{2} \tag{11}$$

RESULTS

Analysis of lubrication system in cold start

At cold start, the rotational speed of the rotary tillage engine is 609r/min, and the measured pressure of the engine oil at the outlet of the filter is 0.15MPa. Fig. 3 shows the overall pressure nephogram of internal oil from the main oil passage to each outlet, and fig. 4 shows the oil pressure values of the main parts between the main oil passage and each oil injection point.

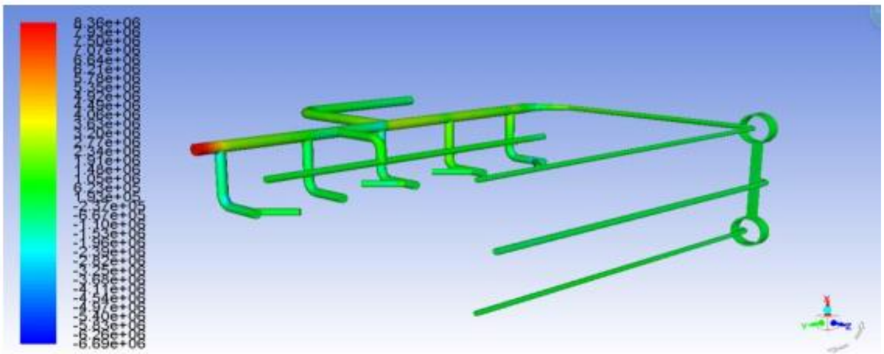


Fig. 3 - Pressure diagram at cold start

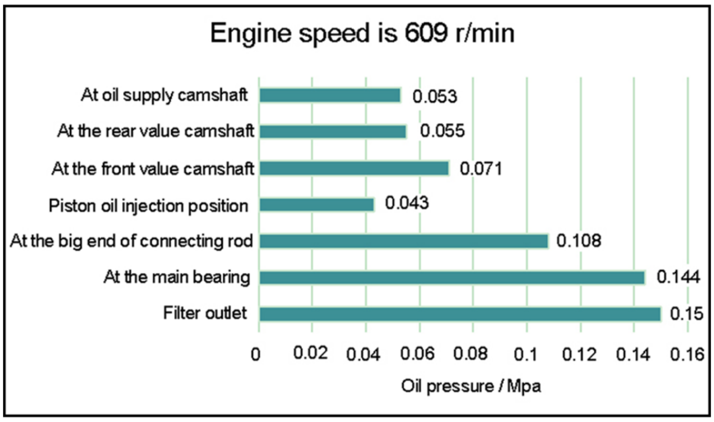


Fig. 4 - Pressure value of main parts

It can be seen from the data in the figure that the oil reaches the main bearing through a vertical elbow in the accessory bracket, and the oil pressure is 0.144 MPa. Part of the engine oil passes through the wetting place at the big end of the connecting rod connected with the main bearing, and the engine oil pressure is 0.108 MPa. At the nozzle of piston cooler, the pressure is 0.043 MPa. The engine oil passes through the nearby bracket and reaches the oil passage of the front valve camshaft, and the pressure is 0.071 MPa. In the oil passage of the rear valve camshaft, the pressure is 0.055 MPa. The pressure at the oil supply camshaft is 0.053 MPa.

According to the design experience, the circulating oil quantity of the rotary tillage engine with engine oil cooling piston, that is, the lubricating oil flow of the main oil passage, should meet $V_c=(0.42\text{-}0.57)N_e$, where N_e represents the power of the rotary tillage engine. Therefore, the circulating oil quantity of rotary tillage engine should be between 28-38L/min, while the oil supply quantity of oil pump is 54.3128L/min and the lubricating oil flow of main oil channel is 39.61L/min, which proves that the oil supply quantity of oil pump and the flow of main oil channel meet the design requirements. Fig. 5 shows the optimization process of engine lubrication system for rotary tillage.

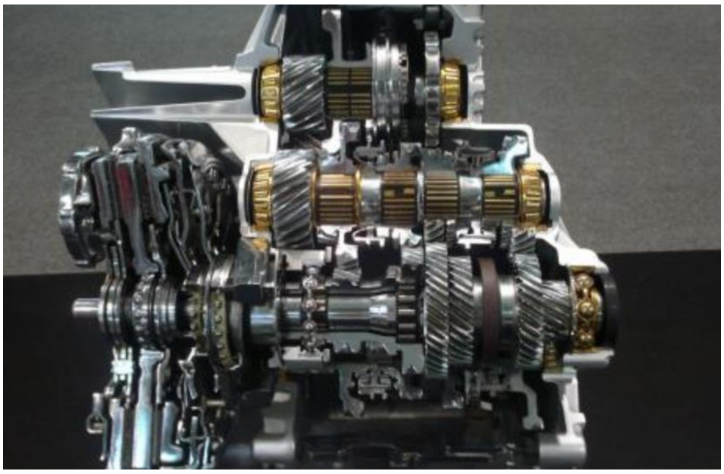


Fig. 5 - The optimization process of the engine lubrication system for rotary tillage

Fig. 6 is a graph showing the variation of lubricating oil distribution with rotating speed in several key parts, which lists the distribution of oil supply of oil pump, main oil passage flow, total flow of five main bearings, total flow of four connecting rod big end bearings and total flow of four cooling nozzles.

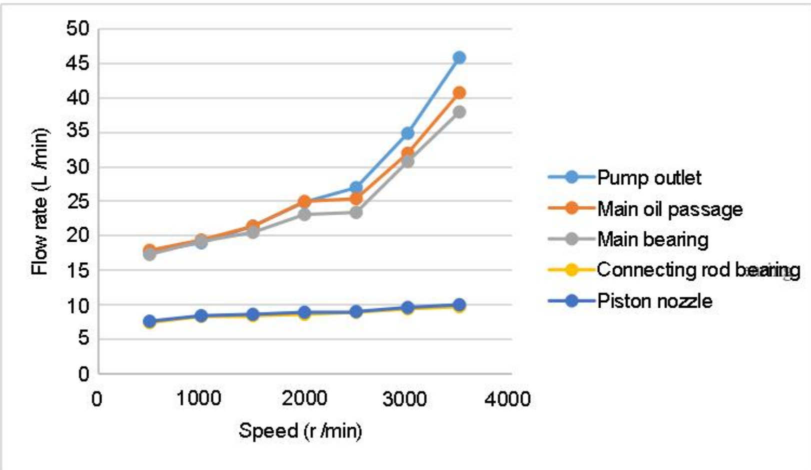


Fig. 6 - Variation diagram of lubricating oil distribution with rotating speed

Its distribution law has the following points:

(1) Generally speaking, the oil distribution of each part increases with the increase of rotating speed;

(2) In the medium and small speed range, the oil supply of oil pump increases linearly with the increase of speed, and its outlet flow all flows through the main oil passage without valve leakage.

In the middle and high speed region, the oil supply of the oil pump continues to increase linearly with the increase of the speed, but the oil supply of the main oil passage increases very little, because the pressure in the lubrication system has increased to the pressure of opening the safety valve at this time, and a large part of lubricating oil leaks back to the inlet of the oil pump through the safety valve when the safety valve is opened.

(3) Most of the lubricating oil after passing through the main oil passage is distributed to the main bearing, the rest is the connecting rod bearing and the piston nozzle again.

Optimization of lubrication system

Due to the complex structure, high manufacturing cost and high price of the raw oil pump, it cannot meet the economic requirements of the main oil passage, so a new pump is needed to replace the old one. The outlet pressure of the new oil pump is required to be greater than 2bar at the lowest speed. The minimum speed of oil pump is 425 r/min, and the maximum speed of oil pump is 1277 r/min. After improvement, it is required that the pressure in the main oil duct should be increased, and when the rotational speed of the rotary tillage engine reaches 1500 r/min, the pressure should be close to 0.7MPa. In this way, sufficient lubrication effect can be ensured, which not only reduces the friction between parts and the work lost due to friction, but also can better take away heat and adjust the temperature.

In normal operation, the engine oil inlet temperature for rotary tillage is 87.9-94.5°C, at which time the oil viscosity is 90-100SSU, 45-49SSU at 125.7 °C and 3600-8600SSU at 10 °C. There are two kinds of oil pumps that can be selected according to requirements: APV-5295-3 and APV-5183-3. These two kinds of oil pumps are respectively brought into the lubrication system model for simulation. For convenience of comparison, APV-5295-3 oil pump will be referred to as oil pump 1 and APV-5183-3 oil pump will be referred to as oil pump 2 hereinafter. Input the data of two new oil pumps into the model and run the module. The ratio of loss coefficient to Reynolds number of the introduced new oil pump is shown in Figure 7.

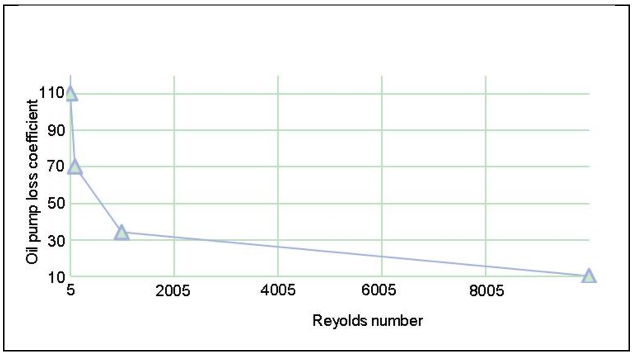


Fig. 7 - Ratio of oil pump loss coefficient to Reynolds number

The change of oil pump outlet pressure with rotary tillage engine speed is shown in Figure 8.

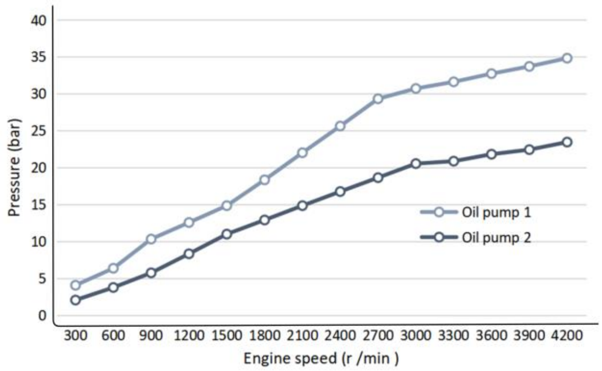


Fig. 8 - The change of oil pump outlet pressure with rotary tillage engine rotational speed

The change of oil pump flow rate with rotary tillage engine speed is shown in Figure 9.

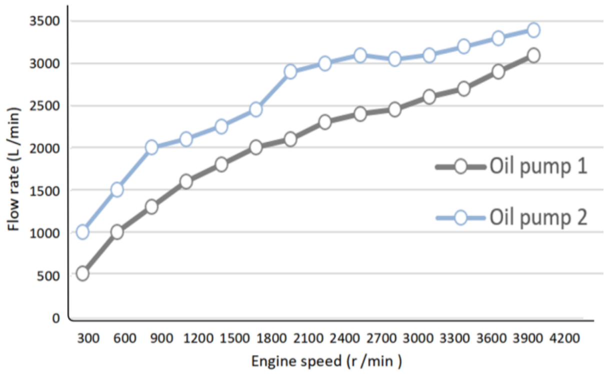


Fig. 9 - The change of oil pump flow rate with rotary tillage engine rotational speed

It can be seen from Figure 8 and Figure 9 that the changes of pressure and flow rate of both oil pumps increase with the increase of rotating speed. The increasing trend is approximately linear. This shows that the oil pump has good responsiveness, and can satisfy the lubrication of rotary tillage engine at various speeds, with corresponding changes. The No.1 oil pump is higher in pressure and flow than the No.2 oil pump, which is more effective and increases the amount of lubricating oil entering the main oil passage of the lubrication system. The analysis results are shown in Figure 10 and Figure 11.

Figure 10 is a comparison chart between the oil pressure test data of the main oil passage of the new rotary tillage engine using the new oil pump 2 and the simulation data. The error between the two is within 4%, and the maximum deviation is 0. 02 MPa, which confirms that the simulation calculation model of the new rotary tillage engine is accurate.

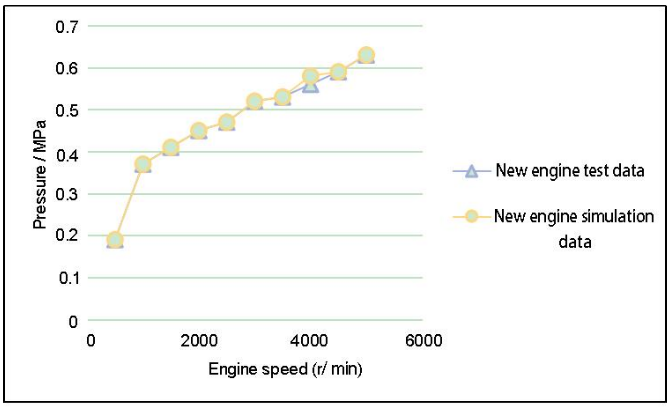


Fig. 10 - Comparison of pressure test and simulation data of main oil passage of rotary tillage engine

Figure 11 is a comparison between the flow rate of connecting rod nozzle produced by new rotary tillage engine at different speeds and the flow rate produced by original rotary tillage engine with original oil pump.

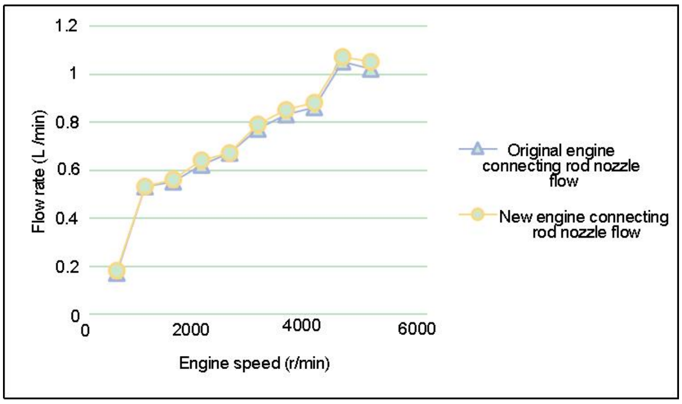


Fig. 11 - Comparison of connecting rod nozzle flow between original rotary tillage engine and new rotary tillage engine

It can be seen from Figure 11 that the flow rate of the connecting rod nozzle of the new rotary tillage engine is slightly lower than the original reference index at medium and low speed, which is mainly reflected in the three operating points of 1700 r/min, 2300 r/min and 3100 r/min. Therefore, according to these three speed operating points, the nozzle flow of the new oil pump connecting rods is simulated and calculated, and the results are shown in Table 1.

Table 1

Comparison of simulation results of nozzle flow of two new oil pump connecting rods

Rotation speed (min)	Connecting rod nozzle flow rate (L·min) (Original pump)	Connecting rod nozzle flow rate (L·min) (New pump 1)	Connecting rod nozzle flow rate (L·min) (New pump 2)
1700	0.624	0.617	0.571
2300	0.775	0.779	0.736
3100	0.862	0.893	0.852

It can be seen from table 1 that the flow requirement of connecting rod nozzle is higher when the rotational speed of rotary tillage engine is 1700 r/min, because 1700 r/min is the low-speed torque point, and VVT (Variable Valve Timing) requires higher oil pressure at the low-speed torque point. Under this rotational speed of rotary tillage engine, the oil pump pumps less oil and the leakage at VVT is large, resulting in lower flow at connecting rod nozzle. For the new oil pump 2, when the rotational speed of the rotary tillage engine is 1700 r/min, the flow rate of the original oil pump connecting rod nozzle cannot be reached, but the new oil pump 1 meets the requirements.

CONCLUSIONS

In this paper, the lubrication system of rotary tillage engine is studied, and the lubrication system model of the engine is simulated by FLUENT software. According to the calculation results, the working condition of the engine lubrication system for rotary tillage was analyzed, and the optimization scheme was put forward. The research results show that: according to the data of the new oil pump, the curves of pressure and flow changing with rotating speed are made. The result is approximately linear, which indicates that the new oil pump has better response. The flow rate of engine oil at the connecting rod nozzle reaches the flow index of the original rotary tillage engine, which meets the requirements of the rotary tillage engine lubrication system and solves the cylinder pulling problem. The analysis and test results achieved by this optimization method are consistent, which provides a theoretical basis for the performance optimization and engineering application of the rotary tillage engine lubrication system, and reduces the production cost and development cycle.

In this paper, the simulation optimization of engine lubrication system for rotary tillage mainly focuses on the analysis of pressure and flow rate of main structure, and there is still some work to be further studied. For example, the branches of lubrication system, such as camshaft rocker arm and tappet, need to be studied. The lubricating oil flow of these components is small, so it is necessary to analyze the influence of its tiny flow.

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