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Thermodynamic modeling, simulation and experiments of a water hydraulic piston pump in water hydraulic variable ballast system

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ABSTRACT

The water hydraulic variable ballast system (WHVBS), which is used to adjust buoyancy, pitch angle and underwater hovering, has become more and more popular in submersible vehicles. Water hydraulic piston pump with driving parts lubricated by oil (WHPLO) is one of the key components of WHVBS. Since the lubricating oil is enclosed in a sealed chamber without circulation, its temperature rises sharply during the operation process of the pump. The high oil temperature is detrimental to pump. However, there are few literatures on the thermodynamic analysis of this kind of pump. In this paper, an integrated thermodynamic model of the WHPLO has been proposed to predict the change of oil temperature. Based on the model, the oil temperature-time curve has been obtained, and the distribution of heat production and dissipation has also been analyzed. The equilibrium oil temperature of the WHPLO in simulation and experiment under different operating conditions has been conducted. The results showed that the difference of the equilibrium oil temperature of WHPLO between the simulation result and the experimental result is less than 3 °C. Therefore, the model is effective to predict the oil temperature of WHPLO.

1. Introduction

With the development of industry and the expansion of population, more and more countries have focused their attention on ocean exploitation in recent years. The submersible vehicles, such as manned deep-sea submersible vehicles and autonomous underwater vehicles (AUVs), are very useful tools in exploring and utilizing the resources in the ocean (Ba et al., 2013; Kopman et al., 2012; Liu et al., 2015; Pebody, 2008; Roman and Mather, 2010). The variable ballast system, which is used to adjust buoyancy, pitch angle and underwater hovering, is a key part of the submersible vehicle. In recent years, the water hydraulic variable ballast system (WHVBS) has become more and more popular in submersible vehicles owing to its advantages of environmental friendliness, simple construction and simple seal (Zhao et al., 2016). Moreover, WHVBS is the best choice for deep-sea manned submersible vehicles such as Jiao long, New ALVIN and SHNKAI6500 (Liu et al., 2010; Nanba et al., 1990; Walden and Brown, 2004).

The water pump, used to transmit the water between the ballast and surroundings, is one of the key components of WHVBS. Especially, a piston water pump is feasible to water hydraulics due to its low contacting stress and well seal (Liu et al., 2014; Qiu, 2008; Tangirala and Dzielski, 2007). In addition, as the WHVBS is an open-circuit system, numberless silt laden in natural water is difficult to filter finely. Appropriate structure of the water pump is favor to improve its anti-wearability.

The water hydraulic piston pump with driving parts lubricated by oil (WHPLO), which distributes the flow by port valves, is used in the WHVBS due to its excellent abrasion resistance structure. For this type pump, the pumped fluid is sealed by seal ring placed in the cylinder, and other moving parts are lubricated by lubricating oil. Besides, the gap between cylinder and plunger can be appropriately enlarged to strengthen the anti-pollution ability. Different from the WHPLO, the water hydraulic piston pump with moving parts lubricating by water (WHPLW) distributes the flow by a port plate instead of port valves. WHPLW is commonly used in water hydraulic system onshore due to its compact structure (Trostmann, 1995). However, WHPLW is unsuitable for WHVBS because it is required to work in clean water (the water must be filtered by a 10 μm filter with a $\beta_{10} > 5000$ or better). The principles of abrasion wear in the two water pump by silt suspended in natural water are shown in Fig. 1 (Wu et al., 2017), the numbers of tribopairs in the WHPLW lubricated by silt-laden water is more than that in the WHPLO. Therefore, the WHPLO is more suitable than WHPLW for the WHVBS.

However, in the WHPLO, lubricating oil is enclosed in a sealed

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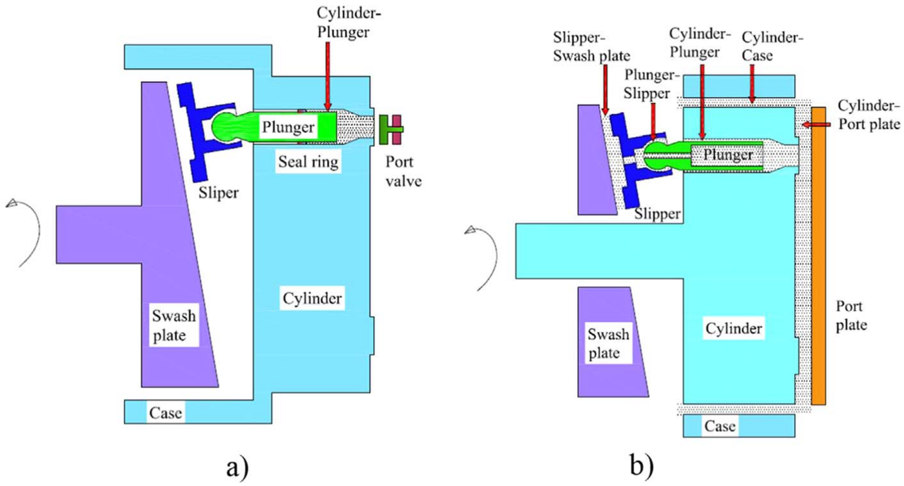

Fig. 1. The principles of abrasion wear in water pump by silt laden: a) WHPLO; b) WHPLW.

chamber without circulation, a mass of heat produced by friction pairs in the oil chamber will lead to the oil temperature rise sharply during the operation of the pump. The viscosity of oil decreases with the increasing temperature, which will reduce the oil performance and accelerate wear of friction pairs. Simultaneously, the extremely high oil temperature makes the clearance of piston pairs smaller, even jammed. Therefore, it is essential to carry out relevant research on the oil temperature of the WHPLO.

Over the years, many researchers have studied the thermal analysis of piston pump. Norgard (1973) created a method to determine the power loss of hydraulic components, which is based on thermodynamic theory. Rvachev et al. (1980) developed several calculations on cylinder block of piston pump, and obtained the three-dimensional temperature distribution of cylinder by means of numerical heat transfer. Olems (2000) and Pelosi and Ivantysynova (2009) have carried out many studies on the temperature distribution of key friction pairs in piston pump. Besides, a series of experiments were conducted to check the simulations. Li and Jiao (2008) proposed the integration methods for solving cross coupling equations in a thermal-hydraulic system. Kazama et al. (2010) designed several experiments to measure the temperature of bearing and seal parts of an axial piston pump. However, most of researches just discussed the oil temperature of hydraulic system or a single part of the pump, and the integrated thermodynamic model of piston pump has not been built.

Thus, in this paper, an integrated thermodynamic model of the WHPLO has been proposed to predict the oil temperature. Based on this model, a series of numerical simulations have been conducted. Besides, experiments are designed to evaluate the validity of the model.

2. Principle of heat transfer in piston pump

The structure schematic of the WHPLO is shown in Fig. 2. Its diameter and length are 150 mm and 298 mm, respectively. The WHPLO includes driving parts and flowing parts. The driving parts, which are lubricated by oil, consist of the shaft, slippers, swash plate and bearings, etc. The flowing parts, which contact with water, include the pistons, suction valves, discharge valves and cylinder, etc. In the WHPLO, each piston has two port valves: suction valve and discharge valve. The piston, which is held against the swash plate through the slipper and driven by the shaft, is reciprocating inside cylinder. The suction valve is opened and the discharge valve is closed when the piston chamber is enlarged to make the water suction in the pump. The discharge valve is opened and the suction valve is closed when the piston chamber is narrowed to make the water ported out the pump. The technical parameters of the WHPLO are shown in Table 1.

The leakage of water in cylinder/piston pair can be ignored because it is sealed by glyd rings. The leakage of water only occurs in port valves. In actual use, the leakage rate is less than 1.5% of the total flow rate in the WHPLO. The leakage power loss is less than 25 W (1500 rpm, 3.2 MPa) and taken away by water, which has little effect on oil temperature. Thus, in this paper, the mechanical power loss of the WHPLO contributes to heat production.

The sources of heat production in the WHPLO are shown in Fig. 3. The moving parts, including mechanical seal, bearings, swash plate/slipper pair, cylinder/piston pair and shaft, are the sources of heat production during the working process of the WHPLO. The shaft rotating in lubricating oil causes viscous friction, which produces heat. Fig. 4 shows the roadmap of heat transfer in the WHPLO. Part of heat is absorbed by the lubricating oil and related components in oil chamber of the WHPLO. The rest is taken away by the following three kinds of heat transfer path: convection process between pump shell and air, radiation of pump shell, conduction process of cylinder and convection process between cylinder and water. The oil temperature will rise until heat production is equal to heat dissipation.

Thus, for the purpose of predicting the oil temperature in the oil chamber, an integrated thermodynamic model is essential and every process of heat transfer should be taken into account. To establish the thermodynamic model, some assumptions are made as follows.

Assumption 1. The temperature of air and water are regarded as constant during the working process of the WHPLO.

Assumption 2. Since the cylinder/piston pair is sealed by glyd rings, leakage of lubricating oil can be ignored in the WHPLO.

3. Thermodynamic model

3.1. The analysis of heat production

3.1.1. Heat production of mechanical seal

The mechanical seal has two friction faces, which is used for sealing oil. One face is fixed on the pump, while the other rotates with the shaft. Some heat will be produced by the friction between the two relative motion surfaces. The heat production power is equal to the power loss of mechanical seal, which can be expressed as follows (Li et al., 2001):

$$P_{ms} = \frac{1}{2} F_{ms} \cdot f_{ms} \cdot \omega \cdot d_{ms} \tag{1}$$

where F_{ms}, f_{ms} and d_{ms} are the force, friction coefficient and average radius between the two faces of mechanical seal, respectively, ω is the rotational angular velocity of shaft.