Theoretical study on the leakage characteristics of Disc-Seal Single Screw Pump used in oily sludge waste heat source absorption refrigeration system

Z L Wang*, H W Shi, S Y Wang, Z M Wang, M M Hao and J Wang

College of New Energy, China University of Petroleum (East China), Qingdao 266580, China
Email address: wangling25@ upc.edu.cn
* Corresponding Author

Abstract. The disc-seal single screw pump (DSSP) used in the field of oily sludge transport has a huge advantage. However, there is no research on the leakage characteristics of the DSSP at present, which makes its application limited. Therefore, the mathematical calculation model of leakage amount of each leakage channel was established in this paper according to the geometric model of the leakage channel. By using this mathematical model, the influence rule of working parameters on the leakage characteristics was analyzed. The results show that the total leakage amount per unit time of the DSSP varies periodically with the rotation of the screw, and the total leakage per unit time of the DSSP will increase with the increase of outlet pressure and screw rotation velocity. When the dynamic viscosity coefficient of the medium increases, the corresponding leakage will be reduced, in which the transmission medium dynamic viscosity is the main factor affecting the total leakage of the DSSP. The study of the leakage characteristics of the DSSP can provide a theoretical basis for the optimal design of its structure in the future.

1. Introduction
With the rapid development of economy and society, the demand for oil in all countries has increased greatly. All kinds of petrochemical enterprises to produce a large amount of sewage sludge and the oily sludge composition is complicated that mainly contains crude oil and solid impurities [1-3]. The large solid particles of impurities may be blocked and accelerated wear of pumping unit in the process of pumping. In addition, as the growth of the world's energy needs, the amount of oil transported by sea has increased rapidly, and the risk of oil spill pollution from oil tankers, especially VLCCS, has increased [4-6]. Once offshore oil spill occurs, the huge offshore oil film will seriously block the oxygen exchange between seawater and atmosphere, break the original stable Marine ecological balance, cause ecological pollution and serious economic losses that are difficult to recover, and eventually endanger human beings ourselves. Therefore, efficient cleaning and rapid recovery of offshore oil spill is particularly important for ecological environment and human beings. In addition, in the current situation of energy shortage, power supply shortage and environmental problems becoming more and more serious, absorption refrigeration technology with its unique advantages has been widely concerned. So the absorption refrigeration system uses waste heat recovered from oily sludge as heat source will have great application prospects. During the oily sludge waste energy recovery process in the absorption refrigeration system, the oil sludge need to be pumped. Due to the high viscosity of oily sludge, and many large particle impurities such as gravel, garbage, animal
carcasses contained in the oily sludge, the traditional fluid pump does not meet its pumping needs. The traditional pumping device is difficult to be applied to the high-viscosity and multi-impurity sewage oil transport on the sea due to the disadvantages such as narrow working chamber and easy wear [7-9], so it is in urgent need of a fluid pumping device with strong medium adaptability and large discharge capacity. For this reason, Johansson put forward the DSSP for the first time in 1991 [10]. This new type of screw pump is widely used in high-viscosity, multi-impurity sewage sludge transportation field and other industrial fields due to its advantages such as large displacement, compact structure and strong adaptability to solid particles.

The DSSP is mainly composed of sealing disc, screw rotor, pump shell and driving gears (as shown in figure 1), and its core working parts are meshing pair formed by sealing disc and pressurized section groove [11]. The pressurization process is realized by the change of the volume of the pressurization cavity formed by the engagement of the sealing disc and the pressurization groove and the DSSP has been widely studied for its unique advantages in the field of high viscosity and multi-impurity sludge transport. The surface equations of meshing pair was obtained by Wang et al. through space meshing principle and the coordinate transformation method [12]. The influence of working parameters on meshing characteristics of the DSSP was studied and the mathematical calculation model of suction capacity of the DSSP was established through the mesh characteristic analysis model [13]. The formula of the volume of the groove in the pressurized section was obtained and the numerical calculation model of the theoretical displacement of the DSSP was established by Wang et al. by using the calculus method [14]. However, the leakage characteristic is a key factor that affecting the conveying capacity of the DSSP, and there are no published papers on the leakage characteristic of the pump. Therefore, it is necessary to establish a mathematical model for calculating the leakage rate of the DSSP and conduct a thorough study on its leakage characteristics, so as to lay a theoretical foundation for improving the pump delivery efficiency and optimizing the structure of the pump.

Based on this, the leakage characteristics of the DSSP were studied in this paper. The mathematical calculation model of the leakage rate of each leakage channel was established according to the geometric model of the leakage channel. And the variation law of the leakage rate of each leakage channel and the total leakage rate of the screw pump during the rotation process was obtained. Finally, the influence of the working parameters of the DSSP on its leakage characteristics was analyzed.

![Figure 1. The structure of the disc-seal single screw pump](image)

2. The leakage channel of DSSP

2.1 Backflow pressurized leakage channel
The geometric model of the backflow pressurized leakage channel is shown in figure 2. The leakage channel is mainly the leakage hole formed between the screw slot, the outer edge line of the sealing disc and the inner wall surface of the casing. The flow pattern of fluid leakage through orifice plate depends on the type of orifice plate. According to the geometric structure, the fluid is almost in line contact with the hole wall when the fluid flows through the suction and backflow pressurized leakage channel, so the leakage channel can be regarded as a model of thin-walled orifice plate.

![Figure 2. Backflow pressurized leakage channel](image)

2.2 Sealing line gap leakage channel
Sealing line gap leakage channel is the gap between sealing disc and screw rotor in meshing movement. During the meshing movement of the screw rotor and the sealing disc, the contact parts of both take on the shape of curves. Therefore, the clearance leakage model of the sealing line gap can be simplified to the flow model of the zoom nozzle (as shown in figure 3).

![Figure 3. Sealing line gap flow model](image)

During the working process of the screw pump, the relative velocity between the screw groove and the sealing disk is $u$ (the velocity direction of the sealing disc is perpendicular to the paper surface, and the screw velocity direction is along the tangent direction of the groove surface). The upper part of the sealing disc is the high-pressure area and the lower part is the low-pressure area. The average pressure and velocity of the fluid medium in the high-pressure area are respectively shown by $p_1$ and $u_1$, and the average force and velocity of the fluid medium in the low-pressure area are respectively represented by $p_2$ and $u_2$. The relative motion velocity of the screw rotor is equal to the velocity in the low-pressure region. The width of engagement gap leakage between the sealing disc and the screw rotor is expressed by $\delta$, and the length of the leakage channel is expressed by $L$. By ignoring the influence of the height of the two sections, the equation can be obtained as follows:
Local loss \( p + \rho g h + \frac{1}{2} \rho \alpha_1 u_1^2 = p_2 + \rho g h_2 + \frac{1}{2} \rho \alpha_2 u_2^2 + p_{\text{Local loss}} \) \( (1) \)

Where \( \alpha_1, \alpha_2 \) respectively represent the correction coefficients of liquid kinetic energy on two different sections. The main function of \( \alpha_1, \alpha_2 \) is to correct the pressure loss caused by pipe diameter shrinkage in the shrinkable tube flow. In the flow model of the zoom nozzle, the pressure energy loss mainly caused by the sudden reduction of the liquid cross section, and the liquid viscosity could be ignored in this case, the value of \( \alpha_1, \alpha_2 \) is 1 here. \( p_{\text{Local loss}} \) represents the local pressure loss in the flow process, and its mathematical expression can be obtained as:

\[
p_{\text{Local loss}} = K \cdot \frac{1}{2} \rho u_2^2
\] \( (2) \)

Where \( K \) represents the local loss factor of the rounded inlet, which is determined by the ratio of the radius of the sealing disc to the clearance distance. After looking up the table1, \( K \) is selected here as 0.04.

| \( r/D \) | 0.02 | 0.06 | \( \geq 0.15 \) |
|---|---|---|---|
| \( K \) | 0.28 | 0.15 | 0.04 |

Combined with the geometric model of the sealing line gap leakage channel, then the mathematical expression of sealing line gap leakage can be obtained.

2.3 The leakage channel between the inner wall of the pump shell and the screw rotor/the seal disc

All of the leakage channel between the inner wall of the pump shell and the screw rotor/the seal disc can be equivalent to a parallel plate model. In this paper, the leakage channel between the inner wall of the pump shell and the screw rotor is taken as an example to illustrate. As shown in figure 4, in combination with the working principle of the DSSP, there are two flow forms in the leakage zone formed by the gap between the inner wall of the pump shell and the screw rotor. One is a differential pressure flow caused by the pressure difference between a high pressure area and a low pressure area, the other part is the shear flow leakage caused by the relative movement of the screw rotor and the sealing disc.

![Figure 4](image)

A fluid element is selected as the research object between the leakage channels as shown in figure 4. The length, width and height of the fluid micro element are represented by \( dx, dy \) and \( dz \), where the direction of \( Z \) is perpendicular to the paper. During the working process of the DSSP, the inner wall of the pump shell is in a static state, the distance between the two plates is expressed as \( h \),...
the width of the parallel plate is $b$, and the length of the parallel plate is $L$. Taking the fluid microelement as the research object, the compressive stress acting on the $yz$ plane can be expressed as $p$ and $p + dp$, and the shear stress acting on the $xz$ plane can be expressed as $\tau$ and $\tau + d\tau$. The force analysis of fluid microelement is carried out and we can get the following expression:

$$p dy + d\tau dx = (p + dp) dy + (\tau + d\tau) dx$$

(3)

According to Newton’s law of internal friction, the expression of $\tau$ can be obtained as follows:

$$\tau = \mu \frac{du}{dy}$$

(4)

Substitute the expression for $\tau$ into equation 2 and the following formula can be obtained:

$$\frac{d^2 u}{dy^2} = -\frac{1}{\mu} \frac{dp}{dx}$$

(5)

By integrating the above equation, the velocity of the leakage fluid passing through the parallel plate can be obtained as follows:

$$u = -\frac{1}{2\mu} y^2 \frac{dp}{dx} + C_1 y + C_2$$

(6)

Where $C_1$ and $C_2$ are the integral constant.

Combined with the geometric model between the inner wall of the pump shell and the screw rotor, then the mathematical expression of the leakage quantity between the inner wall of the pump shell and the screw rotor can be obtained.

### 3. Result and discussions

In order to calculate the leakage of the DSSP, the structural parameters of the DSSP used for theoretical research are shown in table 2, and the working parameters are shown in table 3. Based on the mathematical model of the leakage channel, the influences of working parameters such as outlet pressure, screw speed and liquid dynamic viscosity on the leakage characteristics are analyzed.

**Table 2. The structural parameters of DSSP**

| Parameters               | Value |
|-------------------------|-------|
| Screw radius /mm        | 100   |
| Center distance /mm     | 100   |
| Radius of sealing disc /mm | 60   |
| Eccentricity /mm        | 30    |

**Table 3. The working parameters of DSSP**

| Parameters      | Value     |
|-----------------|-----------|
| Outlet pressure /kpa | 800       |
| Inlet pressure /kpa  | 101.315  |
3.1. Leakage characteristic analysis

There are many leakage channels in the working process of DSSP. In combination with the above analysis of the mathematical models of each leakage channel, 0.3s-0.4s cycle is selected to analyze and study the leakage amount, and the changes of leakage amount in different leakage channels during the rotation of screw pump are shown in figure 5.

![Figure 5. The amount of leakage in a cycle of different leakage channels](image)

It can be seen from figure 5 that the leakage amount of the backflow pressurization leakage channel is much higher than that of other leakage channels in a rotation cycle, so it can be explained that the backflow pressurization leakage channel is the leakage channel with the largest proportion in the working process of the DSSP, and is also the key factor to improve the pressure of the medium in the working cavity.

In order to further analyze the leakage characteristics of the DSSP in the working process, the total leakage amount of DSSP is obtained by adding the leakage amount of each leakage channel in figure 5. As shown in figure 6, according to the relationship between the leakage amount and the time step of the screw rotor in the figure, it can be seen that the total leakage amount changes periodically with the rotation of the screw rotor. The total leakage of screw pump in a rotation period decreases first, then increases and then decreases.
3.2. The influence of each working parameter on the leakage quantity

The change of working parameters during the operation of the DSSP will also have an influence on the change rule of the leakage quantity. In order to further study the leakage characteristics of the DSSP, this paper analyzes the influence law of outlet pressure, screw speed and medium viscosity of screw pump on the leakage quantity. In order to increase the contrast, a single variable was selected for each parameter based on the basic value. The results are shown in figure 7 to figure 9.

It can be seen from figure 7 that in the two rotation cycles selected, the variation trend of the leakage amount under different outlet pressures is similar. At the same time, the greater the outlet pressure, the greater the leakage, this is because that the DSSP is mainly dependent on the backflow leakage of the medium to achieve pressurization. When the inlet pressure is constant, the higher the outlet pressure is, the greater the pressure gradient along the axis direction of the screw rotor is, and the leakage amount caused by the pressure difference also increases accordingly.

![Figure 6. Variation law of total leakage](image)

The influence of screw speed on leakage of DSSP is shown in figure 8. It can be seen from figure 8 that the change trend of leakage quantity of DSSP is similar under different screw speeds. And the leakage quantity will increase with the increase of screw speed at the same time. This is because the shear flow caused by the relative velocity between the moving parts on both sides of the clearance will also affect the leakage amount. Therefore, the increase of screw speed will increase the

![Figure 7. Variation law of total leakage under different outlet pressure](image)
speed of the relative moving parts of each clearance, and the leakage amount caused by the shear flow will also increase accordingly.

Figure 8. Variation law of total leakage at different screw speed

The influence rule of the dynamic viscosity of the conveying medium on the leakage of the DSSP is shown in figure 9. According to the changing trend of the curve in the figure, the variation law of leakage amount is similar under different media conditions. And the larger the dynamic viscosity coefficient of the medium, the smaller the total leakage of the DSSP. This is because the leakage channels of disc seal single screw pump are narrow clearance, fluid through each leakage channel resistance loss will increase with the increase of medium viscosity. As a result, the pressure drop is reduced and the leakage of DSSP is eventually reduced.

Figure 9. The change law of total leakage under different dynamic viscosity coefficient of medium

4. Conclusion
In this paper, the theoretical calculation mathematical model of the leakage amount of each leakage channel is established according to the working principle and the leakage geometry model of the DSSP. Based on the above mathematical model, the leakage characteristics of DSSP were studied and the following conclusions can be drawn from the research:
1) In the working process of the DSSP, the total leakage of the screw pump varies periodically. In a rotation period, the total leakage of DSSP will show a trend of decreasing first, then increasing and then decreasing.

2) The leakage through the backflow pressurization leakage channel is much larger than that of other leakage channels, which has the greatest impact on the transmission efficiency of the DSSP.

3) The variation trend of leakage is similar under different working parameters. The total leakage amount per unit time will increase with the increase of outlet pressure and screw speed. When the transmission medium's dynamic viscosity coefficient increases, the corresponding leakage will be reduced, and the transmission medium's dynamic viscosity is the main factor that affecting the leakage of the DSSP.

Acknowledgements
This work is supported by National Natural Science Foundation of China [NO. 51706247] and the Fundamental Research Funds for the Central Universities and the Opening Fund of National Engineering Laboratory of Offshore Geophysical and Exploration Equipment [NO. 20CX02312A].

References
[1] Evans M N C, Chidinyane T M, Oluwademilade M F, et al. Biosurfactant assisted recovery of the C5-C11 hydrocarbon fraction from oily sludge using biosurfactant producing consortium culture of bacteria[J]. J Environ Manag, 2017, 196:261-269.
[2] Lin B C, Wang J, Huang Q X, et al. Effects of potassium hydroxide on the catalytic pyrolysis of oily sludge for high-quality oil product[J]. Fuel, 2017, 200: 124-133.
[3] Wang J, Han X, Huang Q X, et al. Characterization and migration of oil and solids in oily sludge during centrifugation[J]. J Environ Technol, 2018, 39(10):1350-1358.
[4] Zhang C, Han L, Shi X. Modified Assessment Methodology for Mechanical Recovery Capacity for Oil Spill Response at Sea [J]. Aquatic Procedia, 2015, 3:29-34.
[5] Yu F, Li J, Cui S, et al. A hindcast method to simulate oil spill trajectories for the Bohai Sea, Northeast China[J]. Ocean Engineering, 2016, 124:363-370.
[6] Singh A, Asmath H, Chee C.L, et al. Potential oil spill risk from shipping and the implications for management in the Caribbean Sea[J]. Marine Pollution Bulletin, 2015, 93(1-2):217-227.
[7] Du X H. Research on mechanics properties and the wear failure of the screw-bushing pairs of oil extraction progressing cavity pump[D]. Daqing: Daqing Petroleum Institute, 2010.
[8] Lin S D. Research on Mechanical analysis and wear of single screw pump[D]. Xian: Xi’an Shiyou University, 2014.
[9] Shi J Q, Fang J K, Guo Y, et al. Test research on oil screw pumps wear mechanism[J]. J Sci Eng, 2012, 12(05):1151-1154.
[10] Johansson A. Screw pump. WO 91/14869, 1991.
[11] Shen Y F. Study on the meshing characteristics and working mechanism of disc sealed single screw pump[D]. Qingdao:China University of Petroleum(East China), 2018.
[12] Wang Z L, Shen Y F, Wang Z M, et al. Research on the meshing characteristics of disc-seal single screw pump[J]. J Xian Jiaotong Univ, 2018, 52(05):69–74+101.
[13] Wang Z L, Wang H, Wang Z M, et al. Study on the suction capacity of disc-seal single screw pump used in energy recovery systems[J]. Int J Refrig, 2020, 112:333-340.
[14] Wang Z L, Shi H W, Wang S Y, et al. Study on the operating characteristic of disc seal single screw pump used in energy recovery systems[J]. Int J Refrig, 2020, 118:336-344.