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Original Paper

Study on the Performance Characteristics of Centrifugal Pump with Drag-reducing Surfactant Additives

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Abstract

The performance characteristics of centrifugal pump were measured experimentally when running with tap water and drag-reducing surfactant (Octadecyl dimethyl amine oxide (OB-8)) solutions. Tests have been performed on five cases of surfactant solutions with different concentrations (0ppm (tap water), 200ppm, 500ppm, 900ppm and 1500ppm) and four different rotating speeds of pump (1500rpm, 2000rpm, 2500rpm and 2900rpm). Compared with tap water case, the experimental results show that the total pump heads for surfactant solution cases are higher. And the pump efficiency with surfactant solutions also increases, but the shaft power for surfactant solutions cases decreases compared to t hat for tap water. There exists an optimal temperature for surfactant solutions, which maximizes the pump efficiency.

Keywords: centrifugal pump, surfactant solutions, drag reduction.

1. Introduction

Adding a minute amount of drag-reducing polymer or surfactant additives may cause a dramatic frictional drag reduction (the so-called Toms' effect) [1]. Turbulent drag reducing effect can be used to increase flow rate or reduce the pipeline diameter and other equipments size so as to reduce the energy consumption of pumping, i.e., save energy. Polymer additives are susceptible to an irreversible degradation of the drag-reducing ability in high shear flows (e.g., when driven by a pump), whereas surfactant additives are not. Therefore, surfactants are more appropriate for fluid circulating systems, such as district heating and cooling systems, in which pumping power is necessary. There are many researches on drag- reducing surfactants in pipe and channel flows through experiments [2-4] and numerical simulations [5]. As is known, pump is an important part in district heating and cooling systems, so significant energy saving of the systems can be obtained due to the decrease of pump energy consumption. Early in 1970, Virk [6] predicted that the pump power is only one-fifth of the original power under the ideal running conditions.

Up to now, there have been several studies about the influence of drag-reducing surfactant solutions on the pump performance. Gasljevic and Matthys [7] carried out the experiments using a single suction centrifugal pump with 153mm and 45mm impellers both driven at 3450rpm and aqueous solution of a cationic surfactant (Ethoquad T13-50 by Akzo Chemical) with NaSal as counterion (from 2000ppm to 4500ppm) as working fluid. The results showed that the head-flow characteristics were unaffected for both pumps with different impellers, the requiring pump power decreased up to 10% in some cases and the cavitation onset was delayed in some cases. However, they didn't measure the pump shaft power and investigate the effect of surfactant solutions on the pump efficiency. And the reduction of pump power was about 30% at normal flow rate [7,8]. Because the frictional resistance of an enclosed rotating disk is used to estimate the pump performance generally, Ogata and Watanabe [9] proposed that drag reduction could occur by measuring the torque acting on the enclosed rotating disk with surfactant solutions (Ethoquad O/12 by Lion) with NaSal as counterion. The maximum drag reduction percentage was about 30% when $Re_w>3\times10^5$. This sufficiently indicated that the addition of surfactants could improve the pump characteristics by decreasing the energy consumption. However they didn't show the concentrations and temperature effect on the pump performance. In order to investigate this effect, Ogata et al. [10] carried out another experiment. The results showed that the pump efficiency increased as the concentrations of surfactant solutions increase and there existed an optimum temperature, which maximized the pump efficiency. Based on above analysis, some studies have focused on the influence of surfactant solutions on pump performance. However, the effect on rotating speed of an impeller is not known clearly presently.

In this paper, our goal is mainly to research the centrifugal pump performance when experimentally running with drag-reducing surfactant solutions (OB-8) in a closed system. The concentrations and temperature effect of surfactant solutions and the rotational speed effect of an impeller on pump performance were analyzed.

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2. Overview of the Experiment

The performance characteristics of centrifugal pump were measured experimentally when running with tap water and drag-reducing surfactant (Octadecyl dimethyl amine oxide (OB-8)) solutions. The experimental apparatus is sketched in Fig. 1.

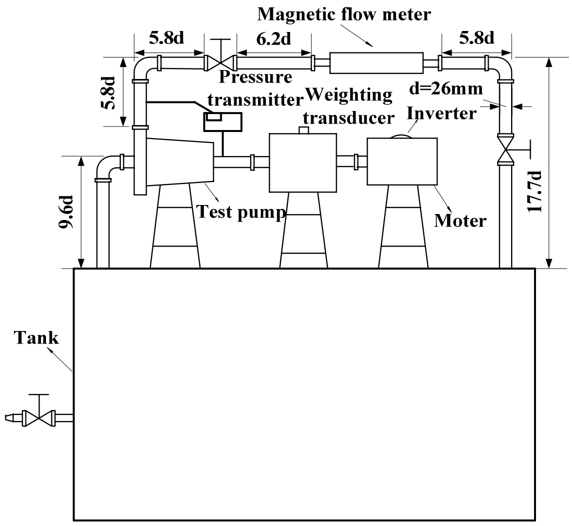

Fig. 1 Schematic diagram of experimental apparatus

A tank with volume of 355 L was used to be the storage for the surfactant solutions. The test pump is a single-suction centrifugal pump with the specifications D=130mm. The flow rate, the total head, the pump rated efficiency and the rated rotating speed of the test pump are 11m^3/h, 17m, 55% and 2900rpm, respectively. And the specific speed is calculated as follows:

$$n_s = \frac{3.65\sqrt{q}}{(H/i)^{3/4}} = 69.89 \qquad (1)$$

The suction and discharge pressure, flow rate, the torque and the rotating speed were measured by the pressure transmitter, an electromagnetic flow meter, a weighing transducer installed between the pump and the motor and a digital tachometer, respectively. A frequency inverter was used to control the impeller rotating speed.

Before the experiments, the water quality monitoring has been done, as shown in Table 1. Octadecyl dimethyl amine oxide ($C_{20}H_{43}NO$, trade name: OB-8) is used as drag reducing surfactant additive. Surfactants need to be adequately stirred with high-temperature water so as not to produce clots. Some bubbles, which may influence the experimental results, are generated in the stirring process. So surfactant solutions must be put for some time to eliminate the bubbles (2.5 hours for the present test) before the experiments. The whole system must be cleaned between two running cases and the validity of the data with tap water is confirmed before several tests. Because the viscosity of surfactant solutions is complicatedly dependent on many parameters, the Reynolds number is calculated based on the viscosity of tap water (Re_w) so as to compare with the results of tap water expediently.

Table 1 The results of water quality monitoring

Element	Al	Fe	Na	S	Sn
Content(mg/L)	0.06434	73.90	1.949	7.068	4.544

In this paper, five different concentrations of OB-8 solution (0ppm (tap water), 200ppm, 500ppm, 900ppm and 1500ppm) at 2900rpm rotating speed of the pump were selected as experimental condition. The rotating speeds at 1500rpm、2000rpm and 2500rpm were also selected so as to investigate the effect of rotating speed of impeller on centrifugal pump performance. And also the experimental temperature was at 36±2℃, 45±2℃ and 60±2℃.

In all experiments, the pressure transmitter, the electromagnetic flow meter and the weighing transducer are with ±0.5%, ±1% and ±5.8% uncertainty, respectively. Because the bearing and grand torque loss are usually difficult to estimate, the torque is directly calculated from the force F measured by the weighing transducer and the arm length L which is from the axis of the centrifugal pump to the weighing transducer. The shaft power is estimated by the torque.

3. Results and Analysis

3.1 The Effect of Surfactant Solutions on Pump Head and Shaft Power

In the experiments, five cases of surfactant solution with different concentrations (0ppm (tap water), 200ppm, 500ppm, 900ppm and 1500ppm) were running at 36±2℃、45±2℃、60±2℃ when the rotating speed of the pump was 2900rpm. We only give the results at 45±2℃ to investigate the concentration effect, as shown in Figs. 2 and 3.

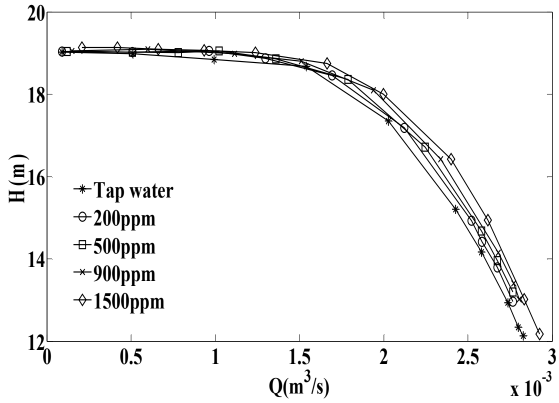

Fig. 2 The pump head vs. the flow rate

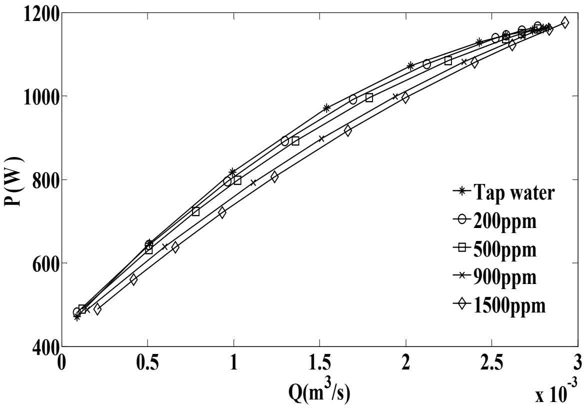

Fig. 3 The shaft power vs. the flow rate

Figure 2 shows that the total pump head for the surfactant solutions cases is higher in comparison with that for tap water case at the same flow rate over the high flow rate range and increases as surfactant solutions concentrations increase. As is known, the shaft power is also an important factor. It is clearly seen that the shaft power for 200ppm and 500ppm surfactant solutions cases slightly decreases from Fig. 3. However, for 900ppm and 1500ppm surfactant solutions cases, the shaft power obviously decreases at the same flow rate over the entire range of flow rate. Due to the limit of experimental apparatus, it is hard to measure the maximum flow rate in this study. However, Ogata et al. [10] reported the maximum flow rate of the pump also increased as surfactant solutions concentrations increase (Ethoquad O/12 by Lion with NaSal as counterion) compared to that for tap water case.

In order to show the concentrations effect on the total pump head, an increased ratio of the pump head I_H is defined as follows:

$$I_H = \frac{H_S - H_T}{H_T} \times 100(\%) \tag{2}$$

where H_T and H_S are the total pump head for tap water and surfactant solutions cases, respectively.

In Fig. 4, it is shown that I_H goes up as surfactant solutions concentrations increase. This sufficiently suggests that the pump total head grows as surfactant solutions concentrations increase at the same flow rate.

3.2 The Change of Pumping Operation Point

As is known, there exists a relationship between the total head and the system head curve of the pump, which finally determines the pump running state. Figure 5 shows this relationship for both tap water and 1500ppm surfactant solution cases at T=45±2℃. Due to the reduction of pressure loss, the system head curve of the pump for surfactant solution case declines compared to that with tap water case. This pressure loss was ever mentioned by Zakin and Chang [11]. They suggested that the reduction of pressure loss when Reynolds number Re>2300. Besides, the drag reduction percentage increased as surfactant solutions concentration and temperature increase.

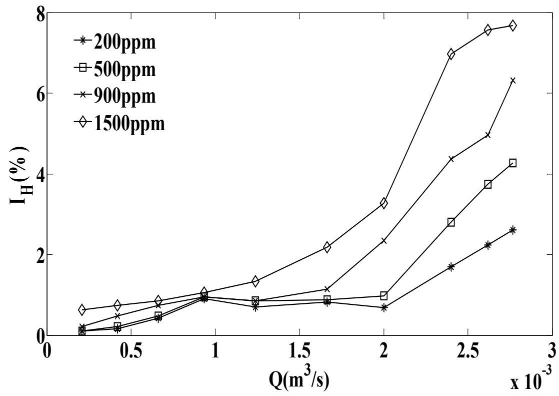

Fig. 4 An increased ratio of the pump head vs. the flow rate

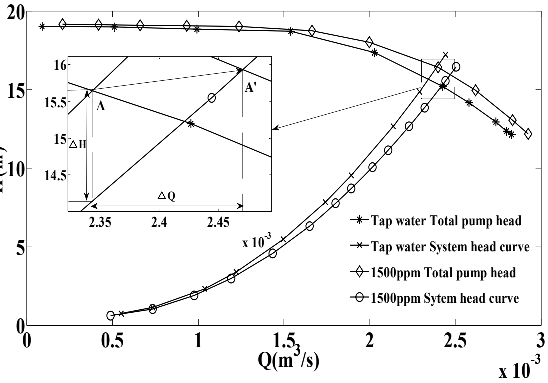

Fig. 5 The pump running state at T=45±2℃

It is clearly seen that the pump total head rises for 1500ppm surfactant solution, as shown in Fig. 5. And the running state (A) for tap water case moves to the new running state (A$'$) for surfactant solution case. The reduction rate of pressure loss △H and the increase rate of flow rate △Q are 9.58% and 5.42%, respectively.

3.3 The Effect of Rotating speed of Impeller on Centrifugal Pump Performance

In order to express the influence of the rotating speed of impeller on centrifugal pump performance clearly, three coefficients (flow coefficient φ, head coefficient ψ and power coefficient τ) defined by Ogata et al. [10] were used. These dimensionless coefficients were defined as follows [10]:

$$\varphi = \frac{Q}{(D^3 N)} \tag{3}$$

$$\psi = \frac{H}{(D^2 N^2)} \tag{4}$$

$$\tau = \frac{P}{(\rho D^5 N^3)} \tag{5}$$

where Q, H, P, and N are the flow rate, total pump head, shaft power and rotating speed of impeller, respectively; D is the diameter of impeller.

From Figs. 6 and 7, we can conclude that the three coefficients defined above for surfactant solution case are dependent on the rotating speed of impeller, unlike tap water case. In Fig. 6, the head coefficient increases as the rotational speed of impeller increase at the same flow coefficient for surfactant solution case. Figure 7 shows that the power coefficient for surfactant solutions case at 1500rpm is very close to that for tap water case. However, the power coefficient for surfactant solutions cases at 2000rpm and 2500rpm decreases at the same flow coefficient. Besides it decreases with a rise of the rotating speed. But the shaft power for surfactant solutions decreases with a decline of the rotating speed at the same flow coefficient, which is due to the large variation

As is known, drag reduction in pipe and channel flows can occur due to the addition of surfactants. So it is considered that the friction loss of the impeller and pump decreases so as to increase the head coefficient for surfactant solutions cases. In addition, Ogata and Watanabe [12] suggested that surfactant solutions cases declined the frictional resistance of a rotating disk. So the reduction of power coefficient is due to the effect of surfactants.

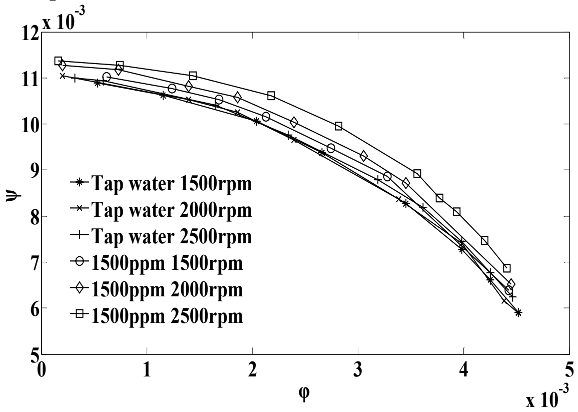

Fig. 6 The head coefficient vs. the rotating speed at 60±2℃

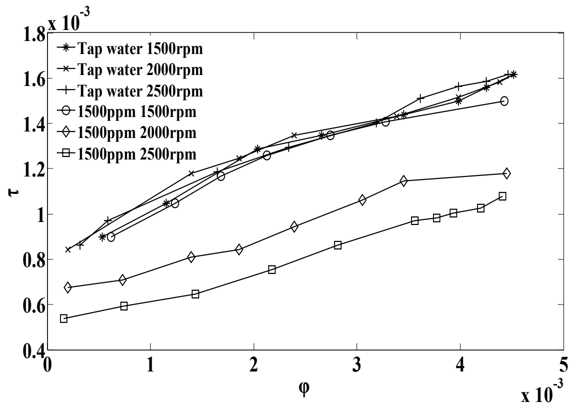

Fig. 7 The power coefficient vs. the rotating speed at 60±2℃

The loss of pump is divided into mechanical loss, volumetric loss and hydraulic loss. The mechanical loss contains bearing friction loss, sealing friction loss and disc friction loss. Among three kinds of friction loss, disc friction loss is the most important factor for the shaft power loss. So the shaft power depends on the Reynolds number Re_w based on the radius of the impeller.

In order to show the relationship between the Reynolds number Re_w and the shaft power for pump, the reduction ratio of shaft power is defined as follows:

$$K = \frac{|P_S - P_T|}{P_T} \times 100(\%) \tag{6}$$

where P_S and P_T are the shaft powers for surfactant solution and tap water cases at the maximum efficiency point respectively.

There is no clear boundary for Re_w to clarify the relationship between K and Re_w as shown in Fig. 8 for the case of 1500ppmsurfactant solution. This is due to the large variation of the rotating speed. But in the results of Ogata et al. [10], K would begin to decrease when Re_w reached to some value. And Ogata and Watanabe [9] reported the tendency of K was similar to the behavior for the frictional resistance of a disk in surfactant solution. So the disc friction loss can be seen as the most important factor for the shaft power.

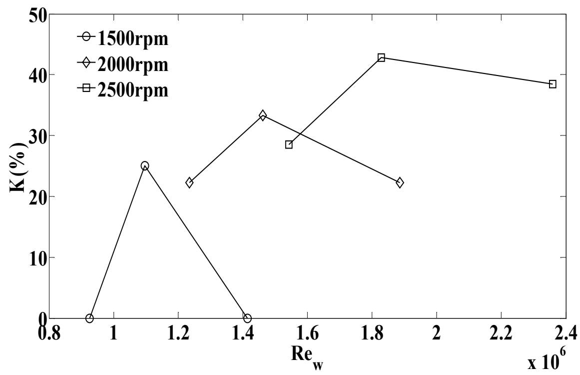

Fig. 8 Effect of Reynolds number on shaft power (1500ppm)

There are many studies about the effect of disc friction loss on the pump efficiency. To estimate the percentage of the disc friction loss occupied for the shaft power (i.e., DS), we use the equation proposed by Nixon and Cairney [13] when Re_w=2.12×10^6 (*N*=2900rpm) at the maximum efficiency point. The best empirical expression of the disc friction coefficient for turbulent flow mode is at 'hydraulically' smooth regime, so the non-dimensional torque coefficient C_m=0.0051. As a result, DS is about 15.3%. The decline of disc friction loss can be an important factor for the increase of pump efficiency. Because there was no result for the frictional resistance of the rotating disc at higher surfactant solutions concentration, the increase of pump efficiency can not be exactly calculated.

3.4 The Relationship among Temperature, Surfactant Solutions Concentrations and Pump Efficiency

In order to elaborate the temperature and concentration effect on the pump efficiency, the increase ratio of the pump efficiency *E* is defined as follows:

$$E = \frac{\eta_S - \eta_T}{\eta_T} \times 100(\%) \tag{7}$$

where η_S and η_T are the pump efficiencies for surfactant solutions and tap water cases at the maximum efficiency point, respectively.

From Fig. 9, there exists an optimal temperature corresponding to the maximum pump efficiency. And this optimal temperature is about 45℃. Beside, the maximum increasing percentages of pump efficiency are about 3.38%, 6.17%, 8.40% and 11.24% for 200ppm, 500ppm, 900ppm and 1500ppm surfactant solution cases, respectively.

It is clearly seen that *E* goes up as surfactant solutions concentrations increase as shown in Fig. 10, i.e., the pump efficiency shows this tendency. The increase ratios of the pump efficiency for 1500ppm surfactant solution case are 9.29%, 11.24% and 10.64% at 36±2℃, 45±2℃ and 60±2℃, respectively.

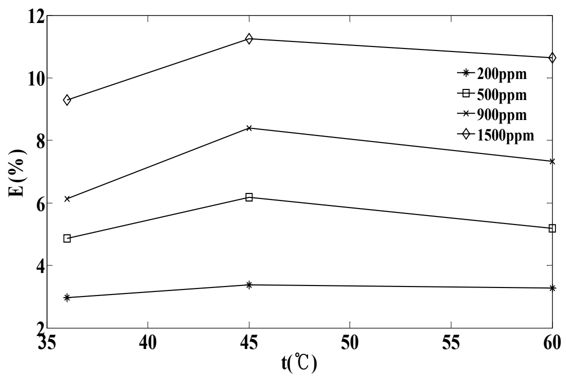

Fig. 9 Surfactant solutions temperature vs. pump efficiency for different concentrations at 2900rpm

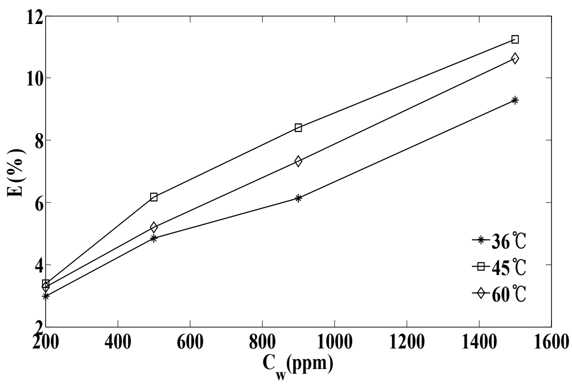

Fig. 10 Surfactant solutions concentrations vs. pump efficiency for different temperatures at 2900rpm

The pump efficiency is a product of mechanical efficiency, volumetric efficiency and hydraulic efficiency. Because the reduction of frictional resistance of the rotating disc causes the decline of disc friction loss with surfactant solutions, the mechanical efficiency increases. And due to the reduction of the hydraulic loss with surfactant solutions, the total pump head increases. However there are still some unknown points about hydraulic loss. And the studies about the volumetric loss are scare. So if we want to know the performance characteristics of the pump exactly, some advanced technologies are needed to examine the flow field inside the pump.

4. Conclusion

The performance characteristics of centrifugal pump were measured experimentally when running with tap water and drag-reducing surfactant (Octadecyl dimethyl amine oxide (OB-8)) solutions. Through analyzing the effect of surfactant solutions on pump performance, the change of pump running state, the concentrations and temperature effect, we draw the following conclusions.

(1) The total pump head increases with the increase of surfactant solutions concentrations, but the shaft power decreases. Besides, the head coefficient for surfactant solutions cases is also higher than that for tap water case, and increases with increasing of the rotating speed of impeller.

(2) The pump efficiency for surfactant solutions cases is higher than that for tap water case, increasing with the increase of surfactant solutions concentrations grow.

(3) For surfactant solutions cases there is an optimal temperature about 45℃, which maximizes the pump efficiency.

(4) There is a distinct deviation of the running state of the pump for surfactant solutions cases as compared with that for tap water case.

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Nomenclature

d	diameter of test pipe [m]
D	diameter of impeller [m]
H	total pump head [m]
N	rotating speed of an impeller [rpm]
P	shaft power [w]
Q	volumetric flow rate [m^3/s]
Re	Reynolds number based on pipe diameter $(=(4\rho Q)/(\pi\mu d))$
Re_w	Reynolds number based on impeller diameter $(=(D^2\rho\omega)/(4\mu))$
T	temperature of test fluids [°C]
η	pump efficiency (%)
μ	viscosity of test solution [$Pa \cdot s$]
ρ	density of test solution [kg/m^3]
τ	power coefficient
φ	flow coefficient
ψ	head coefficient
ω	Angular velocity of impeller [rad/s]

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