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Influence of liquid food products viscosity on lobe pump performance (case of pumping fish oil)

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Abstract. Lobe pumps do not damage the structure of a highly viscous substance. Therefore, the lobe pumps are increasingly used for pumping the liquid food products, despite the high cost. For selecting the rotary lobe pumps, the dependences of the productivity on the pressure drop are necessary. Some manufacturers of the lobe pumps post online the dependences of these characteristics on the rotor speed. There is considered a method developed for calculating the performance diagrams of lobe pumps (*Q*–*P*) subject to the influence of the viscosity of pumped liquid food products based on the results of the tests. For example, the characteristics of WEB RF-024, Pomac PLP 1-1.5 when pumping fish oil are considered. The analysis of the test results showed the need to take into account in the calculations the minimum speed of rotation of the rotor n_0, at which pumping of the liquid begins. It is stated that the minimum rotational speed n_0 is a nonlinear function of pressure drop. The volume of liquid pumped in one revolution does not depend on the pressure drop. The volume of liquid with high viscosity pumped in one revolution does not depend on the pressure drop. An increase in the temperature of fish oil leads to a decrease in the performance of the lobe pump.

Keywords: lobe pump, performance, rotation speed of the rotor, pressure, load characteristics, fish oil, viscosity

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Научная статья

Влияние вязкости жидких пищевых продуктов на производительность кулачковых насосов (на примере перекачивания рыбного жира)

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Аннотация. Кулачковые насосы не повреждают структуру высоковязкой субстанции, поэтому они все чаще используются для перекачивания жидких пищевых продуктов, несмотря на высокую стоимость. Для подбора кулачковых насосов необходимы зависимости производительности от перепада давлений. Некоторые производители кулачковых насосов размещают в открытом доступе зависимости указанных характеристик от частоты вращения ротора. Представлен разработанный метод расчета диаграмм производительности кулачковых насосов (*Q*–*P*) с учетом влияния вязкости перекачиваемых жидких пищевых продуктов на основе результатов их испытаний. Для примера рассмотрены характеристики WCB RF-024, Pomac PLP 1–1,5 при перекачивании рыбного жира. Анализ результатов испытаний показал необходимость учитывать в расчетах минимальную частоту вращения ротора n_0, при которой начинается перекачивание жидкости. Установлено, что минимальная частота вращения n_0 является нелинейной функцией от перепада давления. Объем жидкости, перекачиваемой за один оборот, при большой вязкости не зависит от перепада давления. Повышение температуры рыбного жира приводит к снижению производительности кулачкового насоса.

Ключевые слова: кулачковый насос, производительность, частота вращения ротора, давление, нагрузочная характеристика, рыбный жир, вязкость

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Problem status

Large-capacity lobe pumps (LP) have been used to pump liquids of high viscosity for a long time [1]. However, they have not been as widespread for a long time as other volumetric pumps, for example, screw pumps (SP) or gear pumps (GP). It is known that LP have many positive properties important for food production (see [2, 3] and references in them). In rotary LP fluid flows through the inside of the housing, as in external gear pumps, but unlike them, the LP lobes do not come into contact. The support bearings of the LP shaft are located in the transmission box, outside the pumped liquid. Therefore, LPs are very reliable units with low wear. The particle size in the pumped liquid can be much larger than in SP or gear pumps. LPs can pump dense paste-like materials with very high viscosity, they have a high volumetric efficiency. This efficiency, as well as performance, varies depending on the viscosity of the liquid. LPs are easy to clean by circulating washing liquid through them. However, LPs have disadvantages. Among the main disadvantages is the inability to work with liquids that contain abrasive inclusions, LPs are afraid of hydraulic shocks. It is quite expensive, as it requires high precision in manufacturing. Despite this, in recent decades, the interest of the food industry in LP has increased markedly. One of the reasons is that LPs are characterized by careful pumping of liquid food products without damaging their structure.

A lot of papers have been published on studying the factors affecting the performance of LP [4-8]. In [4], a general flow formula for LP was obtained in terms of the pitch and deviation functions of the pump rotor. This formula is applicable to both circular and noncircular rotor pitch profiles. To associate the pump flow rate only with the rotor geometry, a dimensionless flow expression called “specific flow rate” is used. This enables the flow rate analysis of LP without the ad-hoc effects of individual pump size and rotor speed.

A numerical study of the LP hydrodynamics and the main factors that can affect the pump performance has been done in [5]. Reducing the size of the gap between the rotor and the housing wall from 1.25 mm to 0.5 mm leads to an increase in pressure by about 4 times. The gap between two rotors can vary from 0.12 mm to 0.15 mm without much effect on pump performance. Numerical modeling was carried out to determine the performance of a lobe pump in [7]. The study was conducted by using the commercial software Ansys. The system of Navier-Stokes equations determining the flow of liquid through LP was solved.

One of the few studies devoted to the study of the effect of viscosity on the performance of LP [8]. To reveal the influence of the viscosity of the medium on the characteristics of the flow in the LP, in [8] the flow rate of five media with different viscosities in the range from 1 cst to 110 cst was studied. The results show that the viscosity has a significant influence on the LP performance. The fluid flow in the rotor cavity tends to be stable with increasing viscosity. Viscosity can prevent leakage of the water into the rotor cavity. The output flow rate of medium 110 cst is 40% higher than that of medium 1 cst. When the rotation speed is reduced from 400 rpm up to 100 rpm, the output flow rate decreases by 95% at 11 cst and by 80% at 72 cst.

All the LP manufacturers [9-12] place the technical parameters of their units in the public domain. For example, Table 1 shows a part of the Dellmeco MPL series (designations in Table 1: Q_R – supply range (capacity); P_M – maximum allowable pressure drop; N_E – power of the electric motor; n_R – recommended range of the rotor speed; V_1 – volume of liquid pumped in one revolution; D_0 – dimeter of the nozzles (input/output)).

Table 1

Technical parameters of the Dellmeco MLP series*

Type	**Q_R, m^3/h**	**P_M, MPa**	**N_E, kW**	**n_R, rpm**	**V_1, dm^3**	**D_0, mm**
MLP-20	1-3	0.9	1.1	100-450	0.150	25
		1.2	1.5			
		1.5	2.2			
		2.0	3.0			
MLP-23	2-5	0.5	1.1	100-450	0.212	40
		0.9	1.5			
		1.2	2.2			
		1.5	3.0			
…						
MLP-100	25-50	3.0	5.5	100-360	2.922	100
		6.0	7.5			
		10.0	11.0			

*See data of resource [9].

Some LP manufacturers, in addition to the technical parameters, publish the test results in the public domain [11, 12]. In particular, graphs of dependence of the flow rate *Q* on the rotor speed *n* at various values of the pressure drop *P*. There are no dependencies (*Q*–*P*) necessary for a reasonable choice of the unit in given conditions of the technological line of food production.

The purpose of the research is to develop a method for calculating the performance diagrams of an LP (*Q*–*P*) taking into account the influence of the viscosity of pumped liquid food products based on the results of their tests (a case of fish oil).

Materials and methods

The initial materials were the results of the LP tests published in the public domain by Waukesha Cherry-Burrell [11] and Pomac Pumps [12] in the form of graphs of *Q*-*n* dependencies. In contrast to [11], the LP flow rate *Q* is converted from gpm to dm^3/s, the rotor speed *n* is converted from rpm to rps (s^{-1}).

LPs refer to volumetric rotary pumps, as well as to SP. The method of constructing the load characteristics of the SP was developed earlier [13, 14]. It includes a number of stages and serves as the basis for the development of the calculation method in this article. However, these stages for LP have certain differences, which will be discussed in the next section.

In order to assess the effect of the viscosity of the pumped liquid on the LP performance, it is necessary to set its rheological parameters. Let us consider pumping the fish oil as an example. Here are used the results of experimental work [15]. The effective viscosity of catfish oil was investigated at a temperature of $t = 25$°C and by using various processing methods. The shear rate varied from zero to 1 200 s^{-1}. Using the Bingham plastic model showed good results (see Table 2):

$$\mu = \mu_p + \tau_0/\omega, \qquad (1)$$

where μ – is the coefficient of effective dynamic viscosity, Pa · s; μ_p – Bingham consistency coefficient, Pa · s; τ_0 – yield stress, Pa; ω – shear rates, s^{-1}.

Table 2

Parameters for catfish oils using the Bingham plastic model

Oil	τ_0, Pa	μ_p, Pa·s	R^2
Crude	4.79	0.042	0.991
Degummed	2.41	0.033	0.992
Neutralized	2.42	0.030	0.995
Bleached	2.08	0.026	0.993
Deodorized	1.40	0.024	0.995

*See data of resource [15].

According to Table 2, it can be seen that crude oil has the highest viscosity. Deodorized oil has the lowest viscosity. In all the considered conditions [15] the determination index is very high $R^2 > 0.99$.

We write formula (1) in dimensionless form, taking into account $\omega = 2\pi n$:

$$\eta = \mu / \mu_0 = f_1(n) = \mu_p / \mu_0 + \tau_0 / (2\pi n \cdot \mu_0),$$

where μ_0 – is the coefficient of dynamic viscosity of water at 20°C.

Results and discussion

Fig. 1 shows the results of pumping water at 20°C.

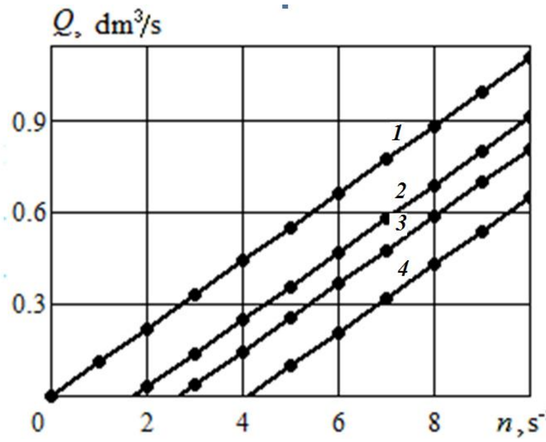

Fig. 1. Dependence of the LP WCB RF-024 performance on the rotor speed at different pressures:
1 – $P = 0$; *2* – $P = 172.4$ kPa; *3* – $P = 345.7$ kPa; *4* – $P = 689.5$ kPa.
Points are test data [11], lines are calculation by (2)

According to Fig. 1, the linear dependence of water flow Q_W on *n* can be represented by the same formula as in [13] for SP:

$$Q_W = f(n, p) = V_1\,[n - n_0(p)], \qquad (2)$$

where V_1 – volume of liquid pumped in one revolution; n_0 – minimum rotational speed at the start of liquid pumping, s^{-1}; $p = P / P_A$ – dimensionless pressure drop; P_A – atmospheric pressure.

The test results are well described by the exponential function

$$n_0 = B \cdot p^{\alpha}, \qquad (3)$$

where the empirical coefficients for LP WCB RF-024 are: $\alpha = 0.619$; $B = 1.246\ \text{s}^{-1}$. The determination index, corrected for a small number of experimental points, is 0.998.

The lines in Fig. 1 are parallel, as in [13]. This means that V_1 in formula (3) does not depend on the pressure drop. For the considered LP model $V_1 = 0.10\ \text{dm}^3$. Whereas the minimum rotational speed n_0 from the pressure drop is a non-linear function of pressure (Fig. 2).

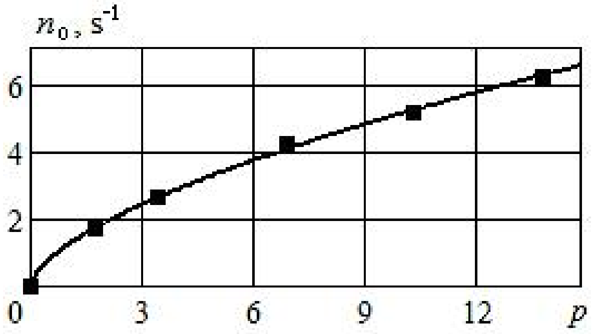

Fig. 2. Minimum rotational speed at which water pumping starts.
Points are experimental data [11], the line is calculation by formula (3)

The effect of pressure drop and viscosity of the pumped liquid on the performance of a rotary LP was experimentally studied in [11]. It was found that the highest LP performance Q_M is achieved when pumping water and there is no pressure drop ($P = 0$, line *1* in Fig. 1). An increase in P leads to a drop in performance. But an increase in the viscosity of the liquid entails an increase in performance. Moreover, $Q \to Q_M$ with growth $\eta = \mu / \mu_0$, where μ, μ_0 are the coefficient of dynamic viscosity of the pumped liquid and water at 20 °C, respectively. This is the fundamental difference between an LP and an SP. An increase in the viscosity of the liquid leads to an increase in the volumetric efficiency of the LP and its performance. A similar result was obtained in [8].

The specified effect can be described by the following formula:

$$Q = f(n, 0) - (f(n, 0) - f(n, p))\ \varphi(\eta), \qquad (4)$$

here $\varphi(\eta)$ is a decreasing function with the following properties:

$$\varphi(1) = 1;\ \eta \to \infty \Rightarrow \varphi(\eta) \to 0.$$

Such properties are possessed by the functions $\varphi(\eta) = \eta^{-\beta}$. The highest determination index for LP WCB RF-024 (0.978) was obtained at $\beta = 0.50$. Substituting $\varphi(n)$ into formula (4), we obtain

$$Q = f(n,0) - (f(n,0) - f(n,p))\eta^{-0.5}. \qquad (5)$$

It can be seen that the calculation results, according to formula (5), are in good agreement with the experimental data in Fig. 3.

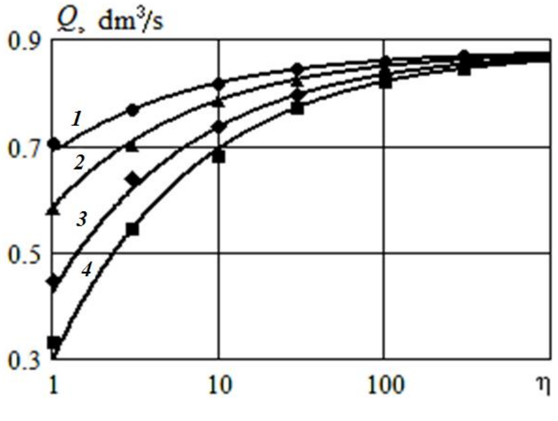

Fig. 3. Dependence of the performance of LP WCB RF-024 on the relative viscosity of the liquid $n = 8\ \text{s}^{-1}$ and various pressure drops: *1* – P = 172.4 kPa; *2* – P = 345.7 kPa; *3* – P = 689.5 kPa; *4* – P = 1 034 kPa. Points are test data [11], lines are calculation according to (5)

The performance diagram in coordinates (Q–p) is required for the hydraulic calculation of a liquid food supply system. It is easily constructed by formula (5). The flow rate of LP decreases markedly with a low viscosity and with an increase in the pressure drop (lines *1* and *2* in Fig. 4).

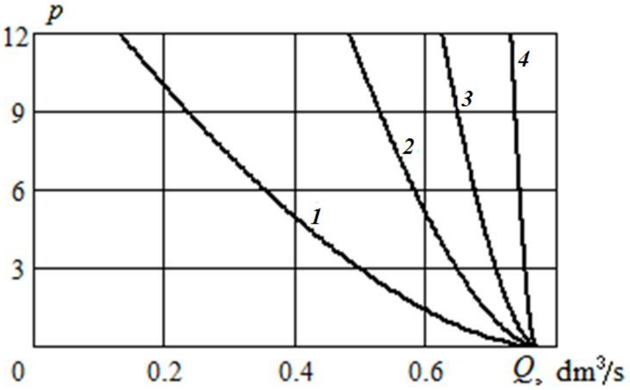

Fig. 4. Relationship between the performance of LP WCB RF-024
and the dimensionless pressure drop at $n = 7$ s^{-1} and different viscosity of the liquid:
1 – $\eta = 1$; *2* – $\eta = 5$; *3* – $\eta = 20$; *4* – $\eta = 300$

The LP performance is practically independent of the pressure drop at $\eta > 300$. It is equal to the performance of the LP Q_M when pumping water in the absence of a pressure drop.

A similar picture was obtained of the influence of the rotational speed, pressure drop and viscosity on the LP performance in the tests [12]. But the results are presented in a different form. Thus, the dependence on the speed of rotation is represented by one line $Q_M = V_1 \cdot n$, similar to line *1* in Fig. 1. That is, the limit value of the flow rate at a given value n.

It is proposed to take into account the decrease in performance using the correction Q_L ($Q = Q_M - Q_L$). We have selected a function to approximate the experimental data (see Fig. 5):

$$Q_L = (a_0 + a_1 \ln \eta + a_2 \ln^2 \eta)\, \eta^{\gamma}, \tag{6}$$

where empirical coefficients for PLP 1-1.5: a_0 = 0.267 dm^3/s; a_1 = –0.0615 dm^3/s; a_2 = 0.0028 dm^3/s; γ = 0.50.

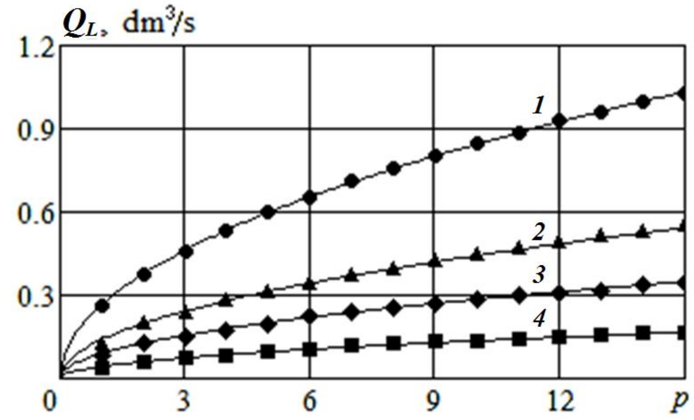

Fig. 5. Correction to the performance of Pomac PLP 1-1.5. Points are test data [12],
lines are calculation results by the formula (6)

Then

$$Q = V_1 \cdot n - (a_0 + a_1 \ln \eta + a_2 \ln^2 \eta)\eta^{\gamma}, \tag{7}$$

Let's pay attention to the similarity of the obtained formulas (5) and (7). We will construct graphs similar to Fig. 4 using formula (7).

The type of LP performance diagrams (Q–p) obtained in Fig. 4 and 6 differs significantly from those for SP in [13, 14].

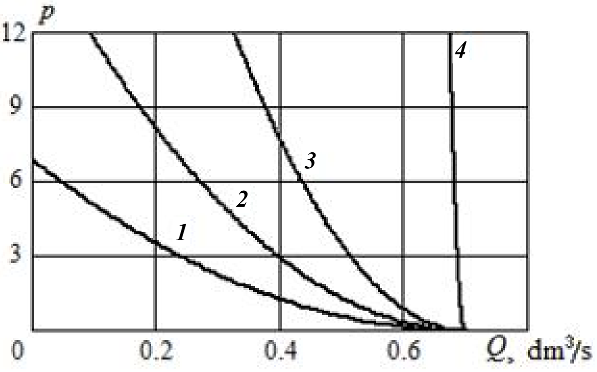

Fig. 6. Relationship between the performance of PLP 1-1.5 and the dimensionless pressure drop at $n = 7$ s^{-1} and different viscosity of the liquid: *1* – $\eta = 1$ (water); *2* – $\eta = 5$; *3* – $\eta = 20$; *4* – $\eta = 300$

Graphs of functions Q from p are concave, whereas SPs have convex graphs. A particularly noticeable difference is observed with small pressure drops and a decrease in viscosity. This must be taken into account when the temperature of the pumped liquid increases.

In [16], data are presented on the decrease in the coefficient of dynamic viscosity of fish oil with increasing temperature. Comparison with the results of experimental works [15, 17] made it possible to estimate such a decrease for Catfish oils using the empirical function:

$$\eta = f_2(n, t) = f_1(n)\,(2.304 - 0.0693 \cdot t + 7.564 \cdot 10^{-4} \cdot t^2 - 2.841 \cdot 10^{-6} \cdot t^3). \tag{8}$$

Formula (8) is used to determine the relative viscosity at given values of frequency and temperature. Table 3 presents the results of calculating the performance of PCB RF-024 when pumping Neutralized catfish oil for various values of rotation speed and temperatures.

Table 3

Pumping performance of LP WCB RF-024
Neutralized catfish oil, dm³/s

n, s^{-1}	Temperature, °C				
	20	**40**	**60**	**80**	**100**
4	0.405	0.390	0.366	0.343	0.321
6	0.620	0.602	0.574	0.547	0.522
8	0.835	0.816	0.785	0.756	0.728
10	1.052	1.031	0.999	0.967	0.937

The viscosity of fish oil increases markedly with decreasing temperature. Therefore, the LP performance increases. In this case, the power expended will increase significantly, as the test results say [11, 12].

Conclusion

There has been developed a method that allows constructing a diagram of LP performance (flow rate dependence on pressure drop) taking into account the influence of viscosity of liquid food products. The main stages of the calculation method are:

1. Obtaining analytical dependences of the performance of a given rotary LP (on water) on the rotor speed, including the calculation by the least squares method of n_0 for each value of pressure drop.
2. Finding the dependence of the LP flow rate (on water) on p for characteristic frequency values. Calculation of empirical parameters in the formula (4) by the least squares method.
3. Determination based on the results of experimental studies of the dependence of the dimensionless dynamic viscosity of the pumped liquid on the rotor speed under given conditions. These will be the parameters μ_p and τ_0 in formula (3) for the Bingham model. Other rheological models can also be used.
4. Evaluation of increasing the LP performance by formula (5) when pumping high-viscosity food products, compared with water.

The results of calculations using the proposed method for the load characteristics of LP when pumping non-Newtonian liquids of high viscosity showed quite satisfactory agreement with the published experimental data. However, formulas (3), (5), (8) need further refinement and experimental verification. In particular, whether the rheological type of the food liquid affects the characteristics of the pump under study. Therefore, the obtained estimates should be considered as a first approximation. Nevertheless, a number of conclusions can be drawn from them.

An increase in the temperature of the fish oil leads to a decrease in the LP performance. The test showed that the proposed engineering calculation method is also suitable for LP from other manufacturers. However, it is necessary to take into account the design features.

The LP performance when pumping viscous food products is noticeably higher than water pumping. At the same time, the power consumption increases significantly. But this is a topic of a separate study.

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