Original article
UDK 639:664.3.032:621.6
https://doi.org/10.24143/2073-5529-2024-3-95-101
EDN KBMFAC

Transportation of fish oil through a pipeline by a single-screw pump

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Abstract. Fish oil is processed from pelagic fatty fish species, in humans they are sources of fatty acids, especially omega-3. Fish oil differs in the composition of fatty acids. New sources of fish or fish oil are being studied. Increasing the efficiency of technological lines is associated with improving the interoperative transportation of fish oil. Manufacturers of processing lines use single-screw pumps for transporting fish oil. Single-screw pumps are advantageous for pumping highly viscous media and have a relatively low cost. The purpose of the article is to adapt to fish oil a method for calculating a continuous fish oil supply system, taking into account the characteristics of a process pipeline, a single-screw pump and rheological parameters of fish oil. The results of the analysis of the performance characteristics of single-screw pumps and the results of experimental work are used. The Buckingham-Rayner equation was used in calculating friction losses in the pipeline, as well as the modified Reynolds number. The flow rate, power, and the effect on them of the viscosity of the liquid for the Atlas W63-1B pump at different rotor speeds are estimated. As the frequency increases, the pressure at constant flow or the flow at constant pressure increases. Examples of determining the hydraulic and energy parameters of pumping systems when pumping fish oil are given. As the viscosity increases, the productivity decreases significantly, and the power consumed increases. As the diameter decreases, the hydraulic resistance of the pipeline increases. The presented algorithm for calculating the movement of fish oil in pipeline systems makes it possible to rationalize pumping systems, create energy-efficient technologies for working with fish oil, and ensure a scientifically sound pump choice.

Keywords: fish processing plant, fatty acids, performance characteristics, rotor speed

For citation: Velikanov N. L., Naumov V. A. Transportation of fish oil through a pipeline by a single-screw pump. *Vestnik of Astrakhan State Technical University. Series: Fishing industry*. 2024;3:95-101. (In Russ.). https://doi.org/10.24143/2073-5529-2024-3-95-101. EDN KBMFAC.

Научная статья

Транспортирование рыбного жира по трубопроводу одновинтовым насосом

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Аннотация. Рыбный жир перерабатывают из пелагических жирных видов рыб, у человека они являются источниками жирных кислот, особенно омега-3. Рыбный жир различается по составу жирных кислот. Изучаются новые источники рыбы или рыбьего жира. Повышение эффективности технологических линий связано с совершенствованием межоперационного транспортирования рыбного жира. Производители технологических линий используют одновинтовые насосы для транспортирования рыбного жира. Одновинтовые насосы выгодны для перекачивания высоковязких сред, обладают относительно невысокой стоимостью. Цель статьи – адаптация к рыбному жиру метода расчета системы непрерывной подачи рыбного жира с учетом характеристик технологического трубопровода, одновинтового насоса и реологических параметров рыбного жира. Использованы результаты анализа рабочих характеристик одновинтовых насосов, результаты экспериментальных работ. Использовано уравнение Букингэма – Рейнера при расчете потерь на трение в трубопроводе, а также модифицированное число Рейнольдса. Оценены расход, мощность, влияние на них вязкости жидкости для насоса Atlas W63-1B при разных частотах вращения ротора. При увеличении частоты увеличивается напор при постоянном расходе или расход при постоянном напоре. Приведены примеры определения гидравлических и энергетических параметров насосных систем при перекачивании рыбного жира. При увеличении вязкости производительность существенно уменьшается, а затраченная мощность увеличивается. С уменьшением диаметра гидравлическое сопротивление трубопровода возрастает. Представленный алгоритм расчета перемещения рыбного жира в трубопроводных системах позволяет рационализировать насосные системы, создавать энергоэффективные технологии работы с рыбным жиром, обеспечивать научно обоснованный выбор насоса.

Ключевые слова: рыбоперерабатывающий завод, жирные кислоты, рабочие характеристики, частота вращения ротора

Для цитирования: *Великанов Н. Л., Наумов В. А.* Транспортирование рыбного жира по трубопроводу одновинтовым насосом // Вестник Астраханского государственного технического университета. Серия: Рыбное хозяйство. 2024. № 3. С. 95–101. https://doi.org/10.24143/2073-5529-2024-3-95-101. EDN KBMFAC.

Introduction

Increasing the productivity and energy efficiency of technological lines is impossible without improving the interoperative transportation of fish oil (FO) [1-7]. However, hydraulic calculations of the process pipeline are often performed without taking into account the performance characteristics of pumping units. Only a few publications analyze the operation of pumps when pumping FO. Thus, in [8], the effect of FO viscosity on the performance of cam pumps (CP) was studied. It was found that the performance of CP when pumping FO is noticeably higher than when pumping water; an increase in the temperature of FO leads to a decrease in CP performance. At the same time, the characteristics of the pipeline were not taken into account.

Process line manufacturers prefer to use single screw pumps (SSP) for interoperable transportation of FO (see, for example, [9]). This is due to the well-known advantages of SSP when pumping high-viscosity media [10] and the relatively low cost [11-18].

In [16], the characteristics of the process pipeline were not taken into account, which makes it difficult to use the results for design calculations.

The purpose of this article is to develop a method for calculating a continuous FO supply system taking into account the characteristics of the process pipeline, SSP and rheological parameters of FO.

Materials and methods

The results of the analysis [16] can be used for the performance characteristics of the SSP. The supply (Q, m^3/s) and the consumed power (N, kW) of the SSP pumping water at 20 °C can be calculated using the formulas:

$$Q_0 = (a_0 - a_1 \cdot \Delta p)\,(n - a_2 \cdot \Delta p); \quad (1)$$

$$N_0 = n\,(b_1 + b_2 \cdot \Delta p) \quad (2)$$

where a_0, a_1, a_2, b_1, b_2 are empirical constants, the values of which are determined from experimental data; Δp is the pressure drop, Pa; n is the rotor speed (RS), s^{-1}. For example: $a_0 = 0.0020225$ m^3; $a_1 = 3.50 \cdot 10^{-7}$ m^3/kPa; $a_2 = 1.88 \cdot 10^{-6}$ s^{-1}/kPa; $b_1 = 0.4755$ kJ; $b_2 = 0.001492$ kJ/kPa (Atlas W63-1B pump).

According to formula (2), the spent power of the SSP increases linearly both with an increase in both RS and pressure drop. According to formula (1), the dependence of the SSP supply on RS is linear, and on Δp is nonlinear. However, such non-linearity is manifested only at large pressure drops.

Taking into account [16]:

$$\varphi_1(vb) \equiv Q / Q_0 = 1 - 0.000789 \cdot (vb - 1); \quad vb = v / v_0; \quad (3)$$

$$\varphi_2(vb) \equiv N / N_0 = 1 + 0.001765 \cdot (vb - 1) \quad (4)$$

where $\varphi_{1,2}$ – dimensionless coefficients; v_0, Q_0, N_0 is the kinematic viscosity, supply and power for water; $1 \le vb \le 534$ with determination index $R_2 = 0.97$. Then for FO with a dimensionless viscosity coefficient, vb can be written as follows

$$Q = (a_0 - a_1 \cdot \Delta p)\,(n - a_2 \cdot \Delta p)\,(1 - 0.000789 \cdot (vb - 1)). \quad (5)$$

To evaluate the effect of the viscosity of FO on the characteristics of SSP, it is necessary to set its rheological parameters. The results of experimental work can be used for the rheological model of FO [17, 18]. The effective viscosity of catfish fat (Catfish oils) at a temperature of $t = 25$ °C and various processing methods was investigated. The shear rate varied from zero to 1,200 s^{-1}. The use of the Bingham plastic model showed good results (see Table 1):

$$\mu = \mu p + \tau_0 / \omega \quad (6)$$

where μ is the coefficient of effective dynamic viscosity, Pa·s; μp is the coefficient of plastic viscosity of Bingham, Pa·s; τ_0 is the limiting shear stress, Pa; ω is the shear rate, s^{-1}.

According to the Table 1 it can be seen that untreated Fish oil has the highest viscosity. FO has the lowest viscosity after deodorization. In all the conditions considered [19], the determination index is very high $R_2 > 0.99$.

Table 1

Parameters of catfish fish oil using the Bingham model

Processing FO	τ_0, Pa	μp, Pa·s	R_2
Without processing (FOW)	4.79	0.042	0.991
Neutralization (FON)	2.42	0.030	0.995
Deodorization (FOD)	1.40	0.024	0.995

* Compiled according to [19].

To use formulas (3), (4), it is necessary to calculate the ratio of kinematic viscosities vb. Formula (6) is written in dimensionless form as follows:

$$vb = f_1(\omega) = \mu p / (\rho \cdot v_0) + \tau_0 / (\omega \cdot \rho v_0) \qquad (7)$$

where ρ is the density FO, kg/m^3. The velocity shift in SSP is approximately estimated as follows: $\omega \approx 2\pi nr / \delta$ (r is the radius of the screw, δ is the average gap value).

For example, for FON by (7) it turns out

$$vb \approx 45.41 + 824.6 / n. \qquad (8)$$

During the flow of FO, hydraulic losses are present in the pipe. The coefficient of hydraulic friction losses along the length of a round pipe (CHFL) λ during the flow of a pseudoplastic liquid (Bingham model) obeys the well-known Buckingham-Reiner equation:

$$\lambda = (64 / \mathrm{Re})\,(1 + \mathrm{Bi} / 6 - (64 / 3)\,\mathrm{Bi}\,4 / (\lambda \cdot \mathrm{Re})^3);$$

$$\mathrm{Bi} = \tau_0\, d / (v\, \eta_A);\;\; \mathrm{Re} = v\, \rho\, d / \eta_A$$

where η_A – absolute viscosity coefficient; Bi is the Bingham number; Re is the Reynolds number; d is the inner diameter of the pipe, m; v is the velocity of the liquid, m/s; $v = Q / S$, S is the cross–sectional area of the pipe, m^2, $S = \pi d^2 / 4$.

In [19] it was shown that in the laminar flow regime of a non-Newtonian fluid, CHFL can be calculated using the approximate formula

$$\lambda n = 64 / \mathrm{ReM}, \qquad (9)$$

as for a Newtonian fluid, but using a modified Reynolds number ReM, where the modified Reynolds number of the Bingham liquid is determined by the formula

$$\mathrm{ReM} = \mathrm{Re} / ((3m + 1) / (4m) + \mathrm{Bi} / 8); \qquad (10)$$

$$m = 1 / (1 + \mathrm{Bi} / 8). \qquad (11)$$

Convert the expression in the denominator of formula (11) as follows:

$$1 / m = 1 + \mathrm{Bi} / 8;\; (3m + 1) / (4m) = 0.25\,(3 + 1 / m) = 0.25\,(4 + \mathrm{Bi} / 8) = 1 + \mathrm{Bi} / 32. \qquad (12)$$

When substituting (12) into (10) and then into (9), it turns out

$$\mathrm{ReM} = \mathrm{Re} / (1 + 5 \cdot \mathrm{Bi} / 32);\;\; \lambda n = (64 / \mathrm{Re})\,(1 + 5 \cdot \mathrm{Bi} / 32).$$

It was shown in [20, 21] that the pressure loss coefficients (PLC) in local hydraulic resistances can also be calculated using formulas used for laminar flow of a Newtonian fluid, replacing the usual Reynolds number with a modified one. So in the tap (smooth turn), the PLC is calculated using the formula:

$$\zeta = A / \mathrm{ReM}$$

where the value is $A \approx 200$ if the radius of rounding is $2d$.

The characteristics of the pipeline in this form:

$$\Delta p \equiv fT\,(Q) = \Delta pS + 0.5\rho \cdot (4Q / \pi d^2)^2\,(zA + 64L / d) / \mathrm{ReM} \qquad (13)$$

where z is the number of pipeline bends, ΔpS is the static pressure drop.

Formula (5) for a given supply value Q can be considered a quadratic equation with respect to the pressure drop Δp. Its solution is a form of SSP load characteristic:

$$\Delta pL = fL(Q) \qquad (14)$$

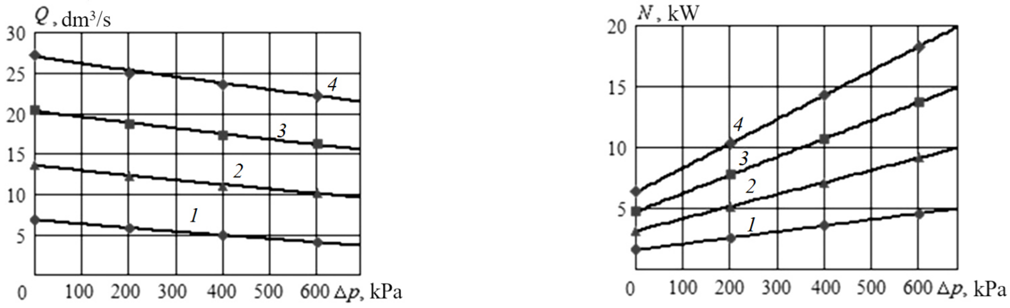
where fL – load characteristic of the pump.

Then the SSP supply at the operating point (OP), equating (13) and (14):

$$fL(Q_{OP}) = fT(Q_{OP}).$$

Results and discussion

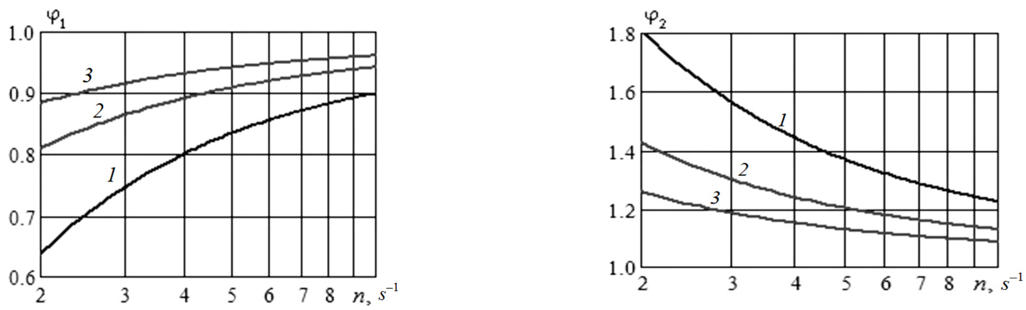
Dependences (1), (2) correspond to experimental data [22] obtained by supplying water using SSP (Fig. 1).



a *b*

Fig. 1. The dependence of the supply (*a*) and the consumed power (*b*) Atlas W63-1B single screw pump from pressure drop at different rotor speed: *1* – 200 rpm; *2* – 400 rpm; *3* – 600 rpm; *4* – 800 rpm.
The points are experimental data [22], the lines are calculated according to (1) and (2)

Substituting (6) into (3) and (4), one can estimate the effect of the viscosity of FO on the operation of SSP. According to Fig. 2 it can be seen that with a decrease in RS, the effect of the viscosity of FO on the characteristics of SSP increases.



a *b*

Fig. 2. Assessment of the effect of fish oil viscosity on the operation of the Atlas W63-1B single-screw pump depending on the rotor speed: *a* – reduction in feed; *b* – increase in power consumption;
1 – untreated fish oil; *2* – neutralized fish oil; *3* – deodorized fish oil

FOW has the highest coefficient of kinematic viscosity, therefore its influence is the greatest, and FOD has the least. If $n = 3$ s^{-1}, then SSD performance decreases by 25% when pumping FOW, power consumption increases by 56%, and when pumping FOD, respectively, by 8 and 19%.

It is possible to select SSP parameters for transporting FO with the specified properties. Suppose it is necessary to supply FOW $Q_0 = 6$ dm^3/s using SSP Atlas W63-1B. The length of the pipeline is $L = 30$ m, $z = 3$.

In Fig. 3, according to the formula (13), the characteristics of the pipeline are constructed at three diameter values (lines *1-3*).

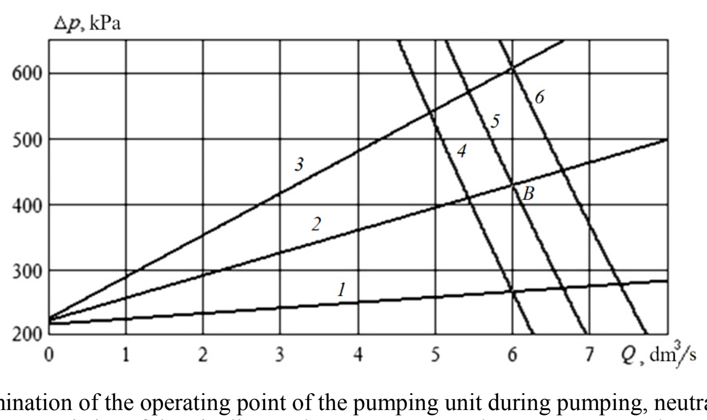


Fig. 3. Determination of the operating point of the pumping unit during pumping, neutralized fish oil:
1 – characteristics of the pipeline at $d = 50$ mm; *2* – at $d = 35$ mm; *3* – at $d = 30$ mm;
4 – pressure characteristic of the turboprop pump at $n = 4.32$ s^{-1}; *5* – at $n = 4.68$ s^{-1}; *6* – at $n = 5.10$ s^{-1}

As the diameter decreases, the hydraulic resistance of the pipeline increases.

It is possible to determine the RS at which the required SSP supply will be. Let d = 35 mm (line *2* in Fig. 3). OP should be at the intersection point of line *2* with the vertical Q_0 = 6 dm^3/s (point B in Fig. 3). According to Q_0, formula (13) allows us to calculate the pressure drop in OP: Δp_{OP} = 428.3 kPa. If the obtained value of Δp_{OP}, Q_0 and formula (8) are substituted into (5), we obtain a nonlinear equation with one unknown – n. Solving it numerically leads to the desired value RS n = 4.68 s^{-1}. The parameters in the other two OP were calculated in a similar way in Fig. 3. The calculation results are presented in Table 2 (η – efficiency; E – pecific energy of the liquid).

Table 2

The results of calculating the parameters of the pumping unit at the operating point for neutralized fish oil

***d*, mm**	**Δp_{OP}, kPa**	***n*, s^{-1}**	**N_{OP}, kW**	**η_{OP}, %**	**E_{OP}, kJ/dm^3**
50	264.6	4.32	5.32	29.9	0.89
35	428.3	4.68	7.25	35.4	1.21
30	608.0	5.10	9.62	37.9	1.60

The results of similar calculations for pumping FOD are shown in Fig. 4 and in Table 3.

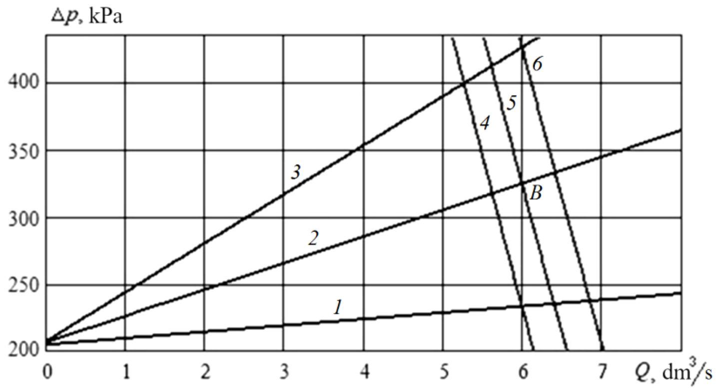


Fig. 4. Determination of the operating point of the pumping unit when pumping deodorized fish oil:
1 – characteristics of the pipeline at d = 50 mm; *2* – at d = 35 mm; *3* – at d = 30 mm;
4 – pressure characteristic of a single-screw pump at n = 7.76 s^{-1}; *5* – at n = 3.98 s^{-1}; *6* – at n = 4.23 s^{-1}

Table 3

The results of calculating the parameters of the pumping unit at the operating point for deodorized fish oil mm

***d*, mm**	**Δp_{OP}, kPa**	***n*, s^{-1}**	**N_{OP}, kW**	**η_{OP}, %**	**E_{OP}, kJ/dm^3**
50	232.9	3.76	3.58	39.0	0.597
35	324.6	3.98	4.40	44.3	0.733
30	426.7	4.23	5.38	47.6	0.896

Conclusion

Viscosity significantly affects the operation of the FO pumping system. FOW has the highest coefficient of kinematic viscosity, while FOD has the lowest.

When pumping FOW compared to pumping FOD, the performance is almost 3 times less, the power consumed is 3 times more for a constant SSP frequency.

The developed method for calculating the continuous FO supply system, taking into account the characteristics of the process pipeline, SSP and rheological parameters of FO, can be used in the development of technological processes for working with FO.

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The article was submitted 10.04.2024; approved after reviewing 10.06.2024; accepted for publication 06.09.2024
Статья поступила в редакцию 10.04.2024; одобрена после рецензирования 10.06.2024; принята к публикации 06.09.2024

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