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PERFORMANCE ANALYSIS OF PUMPING VISCOUS FLUIDS WITH COMPLEX RHEOLOGICAL PROPERTIES USING A SCREW CONVEYOR

Summary

The work concerns analysis of a single screw feeder working in special conditions as a conveyor of fluids with high viscosity and pseudoplastic properties. The research was carried out on the transport of Newtonian and non-Newtonian pseudoplastic fluids using the original construction of the screw conveyor depending on the angular velocity of the screw and the rheological properties of the fluids being pumped. The testing material involved honey in its liquid i.e. non-Newtonian form and partially crystallized one (power-law fluid). The dynamic viscosity of the pumped medium (Newtonian fluid) was in the range $\eta \in (1.66; 4.43)$ Pa s. The value of the non-Newtonian power-law fluid consistency coefficient was contained within $m \in (2.562; 9,422)$ Pa sn, and the flow index $n \in (0.856; 0.975)$. As a result of comparative analysis, a significant difference between the performance of the conveyor was shown as a function of the rheological properties of the pumped medium. The special effect of the research concerns the determination of the impact of the angular velocity of the screw and the force of inertia on the actual performance of the feeder. It was found that each viscosity value of the medium has its corresponding minimum angular velocity of the screw at which the fluid transport is carried out. It was demonstrated that the screw feeder can act as a conveyor of high viscosity fluids.
***Key words**: screw conveyor, Newtonian fluid, pseudoplastic fluid, hydraulic transport, rheological properties*

ANALIZA WYDAJNOŚCI TRANSPORTU PŁYNÓW O ZŁOŻONYCH WŁAŚCIWOŚCIACH REOLOGICZNYCH ZA POMOCĄ PRZENOŚNIKA ŚLIMAKOWEGO

Streszczenie

Praca dotyczy analizy działania przenośnika jednoślimakowego w nietypowych warunkach - jako transportera płynów o dużej lepkości i właściwościach pseudoplastycznych. Przeprowadzono badania transportu płynów newtonowskiegi i nienewtonowskiego pseudoplastycznego przy wykorzystaniu oryginalnej konstrukcji transportera ślimakowego w zależności od prędkości kątowej ślimaka i właściwości reologicznych przetłaczanych płynów. Jako materiał transportowany zastosowano miód w postaci płynnej (płyn newtonowski) oraz częściowo skrystalizowanej (płyn potęgowy). Lepkość dynamiczna przetłaczanego medium (płyn newtonowski) należała do przedziału $\eta \in (1,66; 4,43)$ Pa s. Wartość współczynnika konsystencji płynu nienewtonowskiego (potęgowego) zawierała się w granicach $m \in (2,562; 9,422)$ Pa sn, a wskaźnik płynięcia $n \in (0,856;0,975)$. W wyniku analizy porównawczej wykazano istotne różnice pomiędzy wydajnością przenośnika w funkcji właściwości reologicznych przetłaczanych mediów. Różnice były tym większe im niższa była lepkość przetłaczanej cieczy. Szczególnym efektem pracy jest określenie wpływu prędkości kątowej ślimaka i siły bezwładności na wydajność tłoczenia. Wykazano, że każdej wartości lepkości medium odpowiada minimalna prędkość kątowa ślimaka, przy której następuje transport płynu. Dowiedziono tym samym, że przenośnik ślimakowy może pracować jako transporter cieczy o dużych lepkościach.
***Słowa kluczowe**: przenośnik ślimakowy, płyn newtonowski, płyn pseudoplastyczny, transport hydrauliczny, właściwości reologiczne*

Nomenclature

$\dot{Q}_d$ - volumetric flow rate [10^{-3} m^3 s^{-1}];
$\dot{m}_d$ - mass fluid flow rate [kg s^{-1}];
e - width of screw blade [10^{-3} m];
H - height of the screw channel [10^{-3} m];
m - fluid consistency coefficient [Pa s^n];
M=(t cosφ - e) - width of the channel [10^{-3} m];
n - power flow index [-];
R_b - inner radius of the transport barrel [10^{-3} m];
t - pitch of the screw [10^{-3} m];
φ - screw helix angle [°];
$\dot{\gamma}$ - liquid shear rate [s^{-1}];
d - gap width [10^{-3} m];
η - dynamic viscosity of the fluid [Pa s];
τ - shear stress in the rheological measurements [Pa];
ω - angular velocity of the screw [s^{-1}];
d_z - outer diameter of the screw [10^{-3} m];
d_w - inner diameter of the screw [10^{-3} m];
D - inner diameter of the barrel [10^{-3} m];
T - temperature of fluid [°C];
α - significance level [-].

1. Introduction

In food industry there is often the need to transport liquids which exhibit complex rheological properties, e.g. a two-phase liquid-solid suspension often sensitive to mechanical impact or high temperature [12, 4, 5, 7, 8, 9, 12, 14, 16, 21]. These characteristics make the hydraulic transport of such media cumbersome and, as a result, new designs of devices to pump the liquids are either being developed or unconventional solutions such as screw feeders and screw conveyors are being applied [3, 4, 5, 6, 9]. To transport of bulk materials either vertically or horizontally, standard screw conveyors are most commonly used [3, 6]. Another use of screws is in the plasticizing system of plastic extrusion machines and in extruders [1, 10, 15, 17, 20]. A screw with a diffuser is used also in mixers for mixing liquids of high viscosities [13, 18, 19]. In this application the screws show special feature (in contrast to arm, propeller or turbine mixers), a screw with a diffuser will increase its pumping intensity (circulation of liquid) with a corresponding increase in liquid viscosity [18, 19].

2. The aim of the research

The aim of the work was to investigate the influence of the angular velocity of auger screw working in a vertical system on the transport efficiency of fluids with high viscosity and pseudoplastic properties as a function of changes in their rheological properties.

3. Research methodology

The screw flow tests were conducted on an original screw conveyor system designed by the author, as illustrated in Fig. 2. It consists of pipe (9) with right-handed screw (8) inside with outer diameter $d_z=58\cdot10^{-3}$m, inner diameter $d_w=25\cdot10^{-3}$m , and operating length 1.4 m. The width of the screw's blade $e=1\cdot10^{-3}$m, screw's pitch t=0.05 m, number of blades z=27, screw helix angle $\varphi=15°$ and the value of the gap between the screw's outer diameter and the inner diameter of the transport barrel $\delta=1.15\cdot10^{-3}$ m, channel height $H=17.65\cdot10^{-3}$m and channel width $M=47.3\cdot10^{-3}$m (the ratio of M/H = 2.68). Pipe (9) has inner diameter D=60.30 m^{-3} and length of 1.4 m. In its lower part at height of 0.18 m and 0.24 m there are six inlet openings (12) with diameter of $0.02\cdot10^{-3}$ m through which the working fluid was sucked into the conveyor's transporting space. Screw (8) was driven by 5.5 kW system consisting of an asynchronous three-phase motor (7) of the synchronous rotational speed $n_s=23.67$ s^{-1} powered by the inverter (10), which allowed for a smooth change of the screw's rotational speed. The pumped fluid after leaving pipe (9) flowed down gutter (6) into a container positioned on an electronic balance (13), which allowed the readout with 1g accuracy. The reservoir (2) with the test medium was thermally insulated by insulation (1) and heated by coiled pipe (3) from ultrathermostat (4).

In order to determine the impact of rheological properties on the pumping performance, the working fluid was chosen in such a way as to enable easy change of its rheological properties in a repeatable way. For this purpose, honey with water content of 17.8% whose viscosity varied strongly with temperature was used. It is known from the literature that liquid honey is a Newtonian fluid and when crystallized it becomes crystalline suspension possessing pseudoplastic properties (power-law fluid) [2]. The research was carried out at three different temperatures, namely 24°C, 30°C, 40°C which ensured the rheological properties of the medium, i.e. dynamic viscosity of liquid honey (Newtonian fluid), consistency coefficient *m* and the flow index *n* for honey in the crystallized form (non-Newtonian power-law fluid).

Flow efficiency was determined by measuring the mass of the transported fluid per unit of time $\dot{m}_d$ as mass flow rate. Then fluid density was calculated from the relationship described by Oraian (depending on the temperature used in the pumping process) [11]:

$\rho=1423-1,009T$ (1)

and the volumetric flow rate was determined as:

$\dot{Q}_d = \frac{\dot{m}_d}{\rho}$. (2)

a)

b)

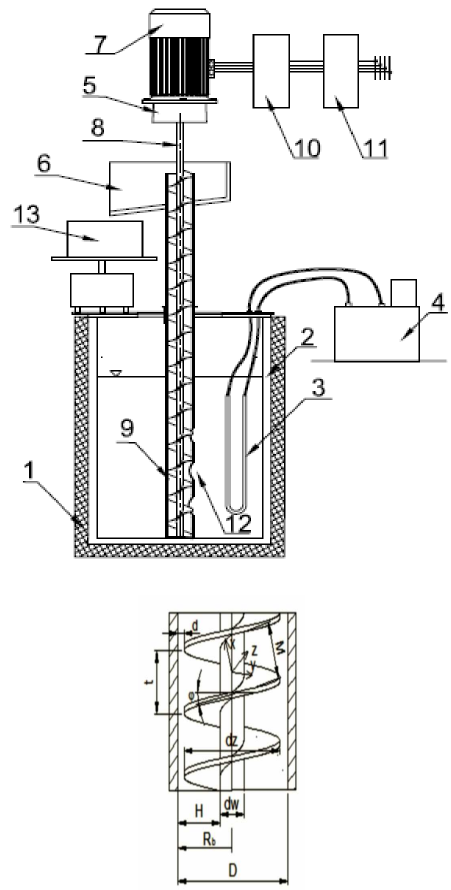

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Fig. 1. Diagram of the test stand (a): 1 - insulation,, 2 - reservoir , 3 - coiled pipe, 4 - ultrathermostat, 5 - clutch, 6 - gutter, 7- motor, 8 - screw, 9 - pipe, 10 - inverter, 11 - power meter, 12 - inlet openings, 13 - electronic balance, (b) of the screw conveyor's geometric system

Rys. 1. Schemat (a) stanowiska badawczego wykorzystywanego w badaniach: 1 – izolacja, 2 – zbiornik, 3 – wężownica, 4 – ultratermostat, 5 – sprzęgło, 6 – rynna, 7 – silnik, 8 – ślimak, 9 – rura, 10 – falownik, 11 – miernik mocy, 12 – otwory wlotowe, 13 – waga, (b) układu geometrycznego badanego transportera ślimakowego

The rheological tests of fluids were carried out using Anton Paar I rheometer in the range of shear rates $\dot{\gamma} \in$ (1.5-243) s^{-1} (liquid honey) and $\dot{\gamma} \in$ (0.16-145) s^{-1} for the honey in the form of crystal suspension. Rheological identification of the medium was carried out at the temperatures corresponding to the pumping temperatures, i.e. at 24°C, 30°C and 40°C. The determined flow curves of liquid honey were approximated to the Newtonian model determining the value of dynamic viscosity [2]:

$\tau = \eta \cdot \dot{\gamma}$. (3)

The flow curves of honey in the form of a crystalline suspension was approximated to Ostwald de Waele model [2]:

$$\tau = m \cdot \dot{\gamma}^{n} \tag{4}$$

determining the rheological parameters of the model, namely consistency coefficient m and melt flow index n. The approximation was performed using Statistica 10 software basing on regression analysis at the assumed significance level α = 0.05.

Experimental volumetric characteristics of pumping $Q_d=f(\omega)$ of the Newtonian and power-law fluid was determined for the range of the angular velocity ω∈ (4.16-14.27) s^{-1}.The resultant dependencies were approximated using a linear model based on regression analysis at the significance level α = 0.05 in the Statistica 10. In this way, the obtained efficiencies were compared in reference to the rheological properties.

4. Research results

Figs. 2 and 3 present a summary of the measurement results of the rheological properties of the fluids used for the research in the function of temperature. The statistical analysis of linear correlation made it possible to conclude that the liquid honey was a Newtonian fluid with dynamic viscosity η_1=4.433Pa s at 24°C and η_2=1.933Pa s at 30°C (Fig. 2).

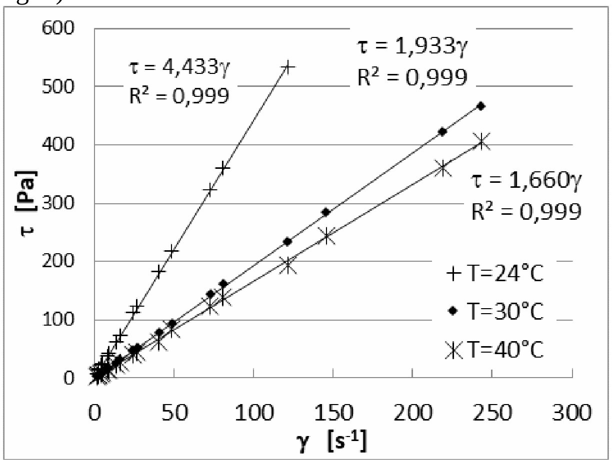

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Fig. 2. Flow curves of liquid honey

Rys. 2. Krzywe płynięcia miodu płynnego

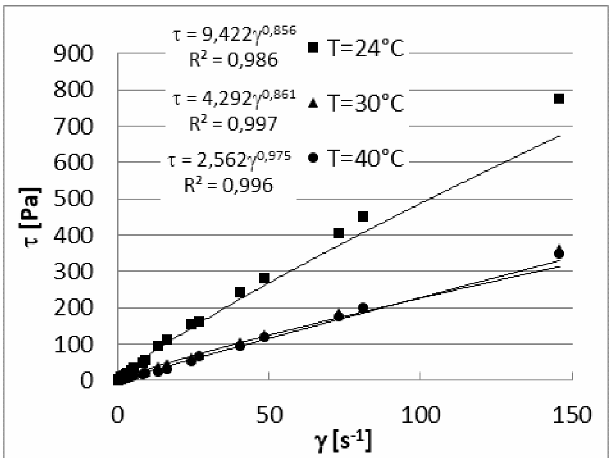

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Fig. 3. Flow curves of crystallized honey

Rys. 3. Krzywe płynięcia miodu skrystalizowanego

The flow curves of honey in the form of crystalline suspension were approximated to the Ostwald de Waele rheological model (Fig. 3). Variance analysis led to the conclusion at the significance level of p>α=0.05 that the adopted model had been properly defined. The rheological parameters resulting from the approximation are as follows:

- m_1=9.422 Pa s^n, n_1=0.856, at 24°C,
- m_2=4.292 Pa s^n, n_2=0.861, at 30°C,
- m_3=2.562 Pa s^n, n_3=0.975, at 40°C.

Fig. 4 shows the characteristic of the volumetric fluid flow rate determined experimentally for both Newtonian and non-Newtonian fluids in the function of the screw's angular speed.

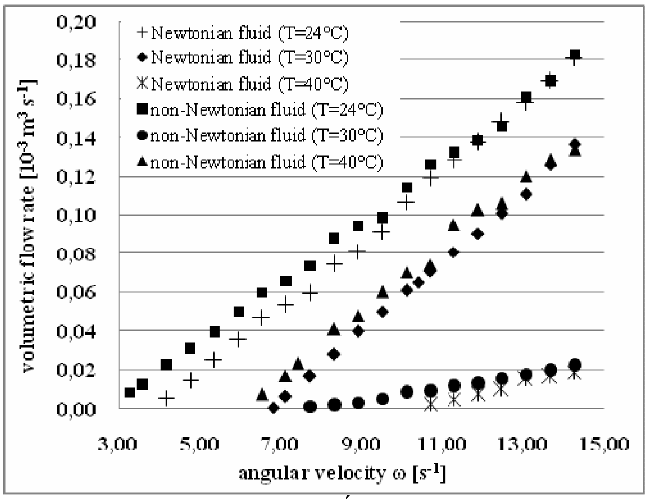

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Fig. 4. Characteristic $\dot{Q}_d = f(\omega)$ for both Newtonian and power-law fluids at 24°C, 30°C and 40°C

Rys. 4. Charakterystyka $\dot{Q}_d = f(\omega)$ dla płynu newtonowskiego i potęgowego o temperaturze 24°C, 30°C, 40°C

Regression analysis carried out for the flow curves allowed us to conclude that at the adopted significance level α=0.05, it is possible to approximate the curves describing the volumetric efficiency of the screw conveyor system for both Newtonian and non-Newtonian fluids to the linear model by the equations:

a) Newtonian fluid:

($\square_1$=4.433 Pa s): Q_{d1}=0,017 ω-0,068, R^2= 0,997 (5)

($\square_2$=1.933 Pa s): Q_{d2}=0,0187 ω-0,121, R^2= 0,999 (6)

($\square_3$=1.660 Pa·s): Q_{d3}=0,004 ω-0,049, R^2= 0,986 (7)

b) non-Newtonian Fluid:

(m_1=9.422 Pa s^n): Q_{d4}=0,015 ω-0,042, R^2= 0,997 (8)

(m_2=4.292 Pa s^n): Q_{d5}=0,016 ω-0,100, R^2=0,994 (9)

(m_3=2.562 Pa s^n): Q_{d6}=0,003 ω-0,025, R^2=0,991 (10)

Preliminary analysis of the flow characteristics of the screw conveyor (Fig. 5 and equations Eq. 29-34) shows that the volumetric fluid flow rate strongly depends on the fluid viscosity. The higher viscosity of the medium the greater the efficiency of a transporter and conversely a decrease in viscosity will result in a decrease in volumetric capacity of the screw conveyor system. Newtonian fluid viscosity drop by 56% from η_1=4.433 Pa s to η_2=1.933 Pa s reduces the transport efficiency by 45.7% and a further fall in viscosity to η_3=1,660 Pa s changes the transport efficiency by 95.9% compared to the transport of Newtonian fluid with a viscosity of η_1=4.433 Pa s. In the case of non-Newtonian fluid transport, a drop in the value of the consistency coefficient m by 54.4% to m_2=4.292 Pa s^n causes a decrease in transport performance by 47.6%. A decrease consistency coefficient to m_3=2.562 Pa·s^n reduces the transport efficiency by as much as 94.4% compared to the transport fluid consistency coefficient m_1=9.422 Pa·s^n. This occurs at a slightly higher flow rate for non-Newtonian fluids at low screw angular velocity than in the case of a Newtonian fluid at the same temperature. At a temperature of 24°C the flow rate value for non-Newtonian fluids is higher by 8.24%, at 30°C by 5.05% and at 40°C by 34.52% respectively. In all cases these differences decrease with a corresponding rise of the screw's angular velocity. A characteristic feature observed here is connected with the existence of a critical angular velocity at which the fluid transport through the screw conveyor occurs. These velocities are a function of the viscosity of the transported fluid. The higher the viscosity, the lower the critical angular velocity of the screw is (Tab. 1).

Table 1. The value of the critical angular velocity of the screw depending on the rheological properties of the fluid
Tabela 1. Wartość krytycznej prędkości kątowej ślimaka w zależności od właściwości reologicznych płynu

Type of fliud	ω_{kr} [s^{-1}]
Newtonian (η_1=4.433 Pa s)	4.00
Newtonian (η_2=1.933 Pa s)	6.27
Newtonian (η_3=1.660 Pa s)	12.25
Non-Newtonian (m_1=9.422 Pa s^n)	2.8
Non-Newtonian (m_2=4.292 Pa s^n)	6.25
Non-Newtonian (m_3=2.562 Pa s^n)	8.33

Source: own elaboration / Źródło: opracowanie własne

The analyzes carried out with the use of a geometrical system have shown that a screw conveyor comprising a barrel and a screw may be an effective screw transporter of high viscosity fluids of complex rheological properties**.** Such a system is characterized by a minimum deformation of the pumped fluid since it flows as a layer equal to the cross section of the rectangular channel between the screw blades without further deformation which typically occurs in positive displacement pumps. This results in lower losses in hydraulic flow and absence of liquid structure destruction, which is very important for many food liquids.

5. Summary

The results obtained in the studies have allowed us to draw conclusions listed below.

1. The screw conveyor is an efficient transport system of viscous liquid. The higher the volumetric viscosity of the fluid, the higher the efficiency of the screw conveyor is. There is a linear dependence of the conveyor's pumping performance on the angular velocity of the screw.
2. A new qualitative phenomenon observed here refers to the fact that for any viscosity of the pumped fluid there is a minimum angular velocity of the screw at which liquid flow through the conveyor occurs. The lower the fluid viscosity, the higher the angular velocity of the screw must be for the flow to occur.
3. The studies have shown general developments observed in the pumping process of Newtonian and non-Newtonian fluids with high viscosity in a particular geometrical system. It is advisable to continue research to determine the generalized dependences which could reflect the criterial numbers linking the analyzed parameters. This would allow us to design of a screw conveyor adapted to specific conditions.

6. References

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