SIMULATION OF MATERIAL VISCOSITY UPON EXPRESSION OF VEGETABLE OIL IN EXTRUDER

Alexander V. Gukasyan

Kuban State Technological University, Moskovskaya Street, 2, Krasnodar, 350072, Russia

Abstract. At present it is impossible to simulate flows of non-Newtonian fluids complicated by compressibility, diffusion and mass transfer with sufficient accuracy for equipment designing on the basis of known methods of expression calculation. An engineering method of calculation of press variables based only on information of material viscosity during expression and geometry of screw flights has been developed. An adequate mathematical model upon extrusion of oil crops is based on up-to-date mathematical analysis of expression of plastically deformed porous medium saturated with oil via pressing cage which is a part of screw body. Press variables can be approximated by properties of viscous plastic material upon pressing by solving inverse problems of comparison of experimental and simulation data.

Key words: viscosity; expression; simulation; porous medium; filtration.

Introduction. Oil filtration via plastically deformed porous mixture and oil expression out of extruder channel via pressing cage lead to radial pressure drop in oil. Mathematical models of filtration [23] upon plastic motion of porous media in technological processes [18] are of significant theoretical [15] and practical value. Existing specialized applications do not permit to simulate flow of non-Newtonian fluids [9] complicated by compressibility, diffusion [20] and mass transfer [24] with sufficient accuracy for equipment designing [19]. This work is aimed at development of adequate mathematical model upon extrusion of oil crops on the basis of up-to-date mathematical methods of calculation [8] and analysis of expression of plastically deformed porous medium saturated with oil via pressing cage which is a part of screw body [11].

Methods

Press variables can be approximated by properties of viscous plastic material [22] upon pressing by solving inverse problems of comparison of experimental data [21] and simulation.

(1)

Taking into account that the width of pressure flight channel is significantly higher than its height, we do not consider in the first approximation the influence of side walls of trapezoid channel, thus, it is possible to rewrite Eq. (1) as differential equation in terms of total derivatives:

(2)

Similar differential equation (2) of the second order describing variation of flow rate over height of matrix channel can be solved on the basis of two initial or boundary conditions determined by selection of coordinates. The Cartesian coordinate system (the X axis along the channel width (b_m), the Y axis along the channel height (h_m), the Z axis along the channel length (l_m)) is applied. The coordinate origin is set at the middle of channel base cross section. Then the boundary conditions of differential equation of the second order are as follows:

(3)

Equation (1) is solved on the basis of the Laplace transform [10] permitting to transform the differential equation (original) to its algebraic analog (image). In this case the solution of algebraic equation will correspond to the solution of differential equation. Using the direct Laplace transform, we rewrite Eq. (2) as follows:

(4)

Solving the obtained Eq. (4) with regard to the image of the required function $L(s_L)$, we obtain the required dependence assuming that s_L is simple variable:

(5)

Using the inverse Laplace transform, we rewrite Eq. (5) as follows:

(6)

The integration constants V_0 and dV_0 are determined on the basis of adhesion conditions of viscous fluid to solid surfaces on plates (3) of the matrix:

(7)

While solving Eq. (7) it is established that $V_0 = 0$, and dV_0 is determined as follows:

(8)

The equation of velocity for laminar flow of non-compressible Newtonian fluid in a gap between two flat parallel walls [17] with accounting for Eq. (8) is as follows:

(9)

Knowing the velocity distribution over the gap cross section between two parallel walls, it is possible to calculate the specific flow rate [13, 16]:

(10)

In the first approximation the specific fluid flow rate in the matrix with the width $b_{m,}$ the height h_m and the length l_m can be presented as follows:

(11)

Equation (11) is a linear function of pressure drop on matrix and coefficient of geometry of former block . In order to estimate the coefficient of geometry of former block of the considered press [12], let us calculate the capacity of its outlet. Aiming at analytical construction of extruder property, it is required to solve a set of head-capacity equations of the former block (11) and injector. However, it is necessary to take into account that only a portion of material passes via the former block due to oil expression. In this case the set of equations is as follows:

(12)

Equations (12) can be simplified by introducing the respective coefficient of outlet and screw:

(13)

where is the coefficient of geometry of former block, ml; is the coefficient of geometry of injector direct flow, l; is the coefficient of geometry of injector counter flow, ml. Functional dependence of viscosity is established in the ranges of residual oil content of press cake during experiment:

(14)

In order to generalize data on viscosity variations, let us consider the ranges of applicability of Eq. (14). It is obvious that this equation describes adequately the viscosity variations in the limits of its identification:

(15)

Beyond the ranges (15) the equation can possess interpolation properties in the ranges of oil content from 0.224 to 1.0 since the oil viscosity is known (*f* = 1.0) [1, 2, 14]. Hence, the interpolation is based on the consideration of the derivative function (14):

(16)

Then the interpolation equation is as follows:

(17)

Solution of this equation determines the point of inflexion from Eq. (14) to linear interpolation of oil viscosity constant (0.0074 $Pa{\cdot}s$).

Results and Discussion

Taking into account the aforementioned, data array was generated for plotting of functional spline-approximation of material viscosity as a function of oil content and screw rotation velocity [3, 4, 5, 6, 7]:

((18)

The calculation results of this block (18) are presented in the form of surface diagram (Fig. 1) with the viscosity axis (Z) in logarithmic scale.

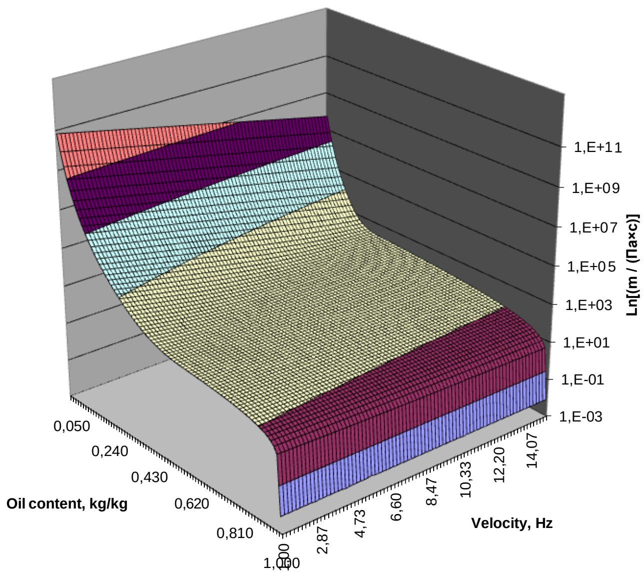

Fig. 1. Viscosity as a function of oil content and rotation velocity.

Using this data array (Fig. 1) we developed smooth functional spline approximation as a function of these parameters:

(10
)

The obtained dependence (19) of viscosity makes it possible to analyze the expression on flights. Contrary to a conventional screw, in this case the flights 1…7 are equipped with molder, thus facilitating oil expression on flight out of transported material. This process is related with variations of oil flow and pressure along the flight length . Since the flight geometry remains the same along , these variations are described by the following set of differential equations:

(20)

where C is the filtration constituent of flight pressing cage:

(21)

where is the viscosity of oil released from pressing cage determined by the equation. In order to determine rheological properties of material in the equation, lets us consider the pressing kinetics on flight. Solution of the set (20) is based on integral transform:

(22)

of this system to the algebraic image (22) which after reduction with regard to the image of required functions:

(23)

is inverted to the required solution:

(24)

Therefore, variations of pressure and flow rate along the flight length are determined as follows:

(25)

At the end of the seventh flight the molder is terminated, hence, the flow equals to zero . This permits to determine the integration constants P_o and Q_{Mo} from the set of boundary conditions:

(26)

The solution gives the following integration constants P_o and Q_{Mo}:

(27)

Then the oil flow from molder along the flight length Q_{M7} under the pressure P_K in the flight end is determined as follows:

(28)

The pressure along the length of the seventh flight P_{M7} in this case is as follows:

(29)

Hence, the oil flow from molder at the start of the seventh flight Q_{mo7} is determined as follows:

(30)

The pressure in this point is determined as follows:

(31)

Determining the average oil flow from the seventh flight molder:

(32)

we obtain the lower limit of expression with regard to pressure according to the following equation:

(33)

Solving this equation with regard to P_K, we obtain infimum of head and rate property according to the following equation:

(34)

Therefore, Eq. (34) determines the lower limit of solutions of the expression equations (20) with regard to pressure. At the same time can be determined by experimental data, if to convert weight capacity into volumetric flow rate of press with accounting for material density **ρ(f)** as a function of its oil content (**f**):

(35)

The calculation is based on dependence of material flow:

(36)

and pressure drop:

(37)

with consideration for viscosity of oil material. The major concept is based on pressure drop as a function of viscosity and the absence of such dependence for material flow. In this case variation of oil content on the flight (x) is determined by solution of the equation:

(38)

where j = 1,…,7 is the number of pressing cage flight. Equation (38) permits to calculate variation of oil content on flights starting from the first flight on the basis of initial oil content of seeds. In fact, in this case the forward algorithm is applied. The program module makes it possible to perform consecutive calculations for all press flights starting from the first and to the seventh one inclusively:

(39)

Similarly, the backward algorithm is applied on the basis of residual oil content of cake as initial value. In this case variation of oil content on the flight (x) is determined as follows:

(40)

The program module makes it possible to perform consecutive calculations for all press flights starting from the seventh and to the first one inclusively:

(41)

A drawback of these calculations is the necessity to preset initial values of oil content. However, if coincidence of calculations for flights is required, this constraint can be eliminated by introducing the following objective function:

(42)

In this case minimization of Eq. (42) makes it possible to determine not only oil content at inlet and outlet but also distribution of flows upon pressing.

Conclusion. Therefore, on the basis of Eqs. (36), (37) it is possible to determine variation of oil content on screw flights. On the basis of these variations using Eq. (38) we determine by forward algorithm the variations of oil content, pressure and material consumption on flights and verify the obtained values by backward algorithm using difference scheme (40) by means of resolvers (39) and (41), respectively. Therefore, we developed an engineering method of calculation of press variables based only on information of material viscosity during expression and geometry of screw flights.

References

1. Gukasyan, A.V. (2017). Identification of rheological dependencies of oil material processed in a screw press. International Journal of Mechanical Engineering and Technology (IJMET), 8(10), 708–718.
2. Gukasyan, A.V. (2017). *Analiz faktorov protsessa otzhima rastitel`nogo masla v shnekovom presse* [Analysis of expression of vegetable oil in screw press]. Izvestiya vysshikh uchebnykh zavedenii. Pishchevaya tekhnologiya, 4(358), 64-68.
3. Gukasyan, A.V. (2017). *Modelirovanie napornogo dvizheniya vyazkoi zhidkosti v pryamougol`nom kanale* [Simulation of pressure flow of viscous fluid in rectangular channel]. Technologies, tools and mechanisms of innovative development. Proceedings of International workshop of Povolzhye Research Corporation, 44-46.
4. Gukasyan, A.V., Koshevoi, E.P., Kosachev, V.S., Tarbin, A.N. (2016). *Techenie maslichnogo materiala v vypusknom ustroistve pressa* [Flow of oil material in press outlet]. In: Transfer processes in apparatuses of chemical and food industries. Proceedings of the 2nd International Workshop, 146-150.
5. Kosachev, V.S., Gukasyan, A.V. (2017). *Chislennoe modelirovanie napornogo dvizheniya vyazkoi zhidkosti v pryamougol`nom kanale* [Numerical simulation of pressure flow of viscous fluid in rectangular channel]. In: Challenges of scientific researches. Proceedings of the 4th International Workshop. Ed. by O. N. Shirokov et al., 278-280.
6. Kosachev, V.S., Gukasyan, A.V. (2017). *Analitika skorosti sdviga v pryamougol`nom kanale s nepodvizhnoi kryshkoi* [Analytics of shear rate in rectangular channel with end plate]. In: Education and science in present day realities. Proceedings of the 3rd International Workshop. Ed. by O. N. Shirokov et al., 146-148.

7. Kosachev, V.S., Gukasyan, A.V. (2017). *Reologicheskaya model` techeniya maslichnogo materiala v ekstrudere* [Rheological model of oil material flow in extruder]. In: Challenges of scientific researches. Proceedings of the 4th International Workshop. Ed. by O. N. Shirokov et al., 193-195.

8. Kosachev, V.S., Orlov, B.Yu. (2016). *Odnomernyi metod konechnykh elementov* [Univariate finite element method]. Al`manakh mirovoi nauki, 2-1(5), 61-62.

9. Koshevoi, E.P., Blyagoz, Kh.R., Shalyahov, A.A., Kosachev, V.S., Zaslavets, A.A. (2012). *Kriterial`nye zavisimosti gidrodinamiki formirovaniya kapli v vide splain-approksimatsii* [Criterion dependences of hydrodynamics of droplet formation by spline approximation]. Novye tekhnologii, 1, 28-32.

10. Koshevoi, E.P., Kosachev, B.C., Meretukov, Z.A. (2004). *Teoreticheskoe rassmotrenie deformirovaniya materiala na vyhode ekstrudera. Izvestiya vysshikh uchebnykh zavedenii* [Theoretical consideration of material deformation at extruder outlet]. Pishchevaya tekhnologiya, 5-6, 86-88.

11. Koshevoi, E.P., Kosachev, V.S., Garus, A.A. (1998). *Model` otzhima zhidkoi fazy iz poristogo materiala s peremennoi pronitsaemost`yu* [Model of liquid phase expression out of porous material with variable permeability]. Food industry – 2000: Proceedings of the 2nd Interregional Workshop. Kazan, 6.

12. Koshevoi, E.P., Kosachev, V.S., Garus, A.A. (2011). *Otzhim zhidkoi fazy iz dispersnogo materiala s peremennoi naporoprovodnost`yu* [Liquid phase expression out of disperse material with variable flow rate]. In: Innovative food technologies in the field of storage and processing of agricultural products. Proceedings of Internatioanl workshop. Ed. by R. I. Shazzo, 226-231.

13. Meretukov, Z.A., Kosachev, V.S., Koshevoi, E.P. (2011). *Reshenie zadachi nelineinoi naporoprovodnosti pri otzhime* [Solution of flow rate capacity upon expression]. Izvestiya vysshikh uchebnykh zavedenii. Pishchevaya tekhnologiya, 5-6, 62-64.

14. Meretukov, Z.A., Koshevoi, E.P., Kosachev, V.S. (2011). *Plotnost` i vyazkost` rastvorov dvuokisi ugleroda v rastitel`nykh maslakh pri pressovanii maslichnykh materialov* [Density and viscosity of carbon dioxide solutions in vegetable oils upon pressing of oil materials]. Novye tekhnologii, 4, 62-65.

15. Meretukov, Z.A., Koshevoi, E.P., Kosachev, V.S. (2011). *Reshenie differentsial`nogo uravneniya otzhima* [Solution of expression differential equation]. Novye tekhnologii, 4, 54-57.

16. Meretukov, Z.A., Koshevoi, E.P., Kosachev, V.S., Vereshchagin, A.G., Sled`, N.I. (2011). *Proizvoditel`nost` transportera so spiral`nym shnekom* [Capacity of spiral screw conveyor]. Novye tekhnologii, 1, 20-24.

17. Meretukov, Z.A., Koshevoi, E.P., Sled`, N.I., Kosachev, V.S., Vereshchagin, A.G. (2010). *Modelirovanie struktury potokov v transportere so spiral`nym shnekom* [Simulation of flow structure in spiral screw conveyor]. Novye tekhnologii, 4, 33-37.

18. Meretukov, Z.A., Zaslavets, A.A., Koshevoi, E.P., Kosachev, V.S (2012). *Metody resheniya differentsial`nykh uravnenii gidrodinamiki* [Solution procedures of differential equations of hydrodynamics]. Novye tekhnologii, 1, 36-41.

19. Podgornyi, S.A., Kosachev, V.S., Koshevoi, E.P., Shalyahov, A.A. (2013). *Analiz tochnosti metoda konechnykh elementov* [Analysis of accuracy of finite elements method]. Novye tekhnologii, 4, 31-38.

20. Shalyahov, A.A., Kosachev, V.S., Koshevoi, E.P. (2009). *Matematicheskoe modelirovanie protsessa razdeleniya zhidkikh smesei v membrannom module s razlichnoi organizatsiei potokov* [Mathematical simulation of separation of liquid mixtures in membrane module with various arrangements of flows]. Izvestiya vysshikh uchebnykh zavedenii. Pishchevaya tekhnologiya, 2-3, 71-74.

21. Shorstkii, I.A., Koshevoi, E.P., Kosachev, V.S., Meretukov, Z.A. (2015). *Vyazkost` spirtovykh suspenzii izmel`chennykh semyan podsolnechnika* [Viscosity of alcohol suspension of crushed sunflower seeds]. Novye tekhnologii, 3, 40-44.

22. Shorstkii, I.A., Koshevoi, E.P., Kosachev, V.S., Meretukov, Z.A. (2015). *Reologiya suspenzii izmel`chennykh semyan podsolnechnika v etanole* [Rheology of suspension of crushed sunflower seeds in ethanol]. Novye tekhnologii, 2, 38-46.

23. Zaslavets, A.A., Shalyahov, A.A., Koshevoi, E.P., Kosachev, V.S., Koshevaya, S.E. (2013). *Gidravlika techeniya v membrane kontaktora* [Flow hydraulics in contactor membrane]. Novye tekhnologii, 1, 11-14.

24. Zaslavets, A.A., Shalyahov, A.A., Koshevoi, E.P., Kosachev, V.S., Koshevaya, S.E. (2013). *Gidravlika reversivnogo techeniya vnutri membrany kontaktora* [Revers flow hydraulics in contactor membrane]. Novye tekhnologii, 2, 91-94.