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Full Length Article

# Parametric analysis and design of a screw extruder for slightly non-Newtonian (pseudoplastic) materials

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ABSTRACT

Extruders have found application in the food, polymer and pharmaceutical industries. Rheological characteristics of materials are important in the specification of design parameters of screw extruders. Biopolymers, which consist of proteins, nucleic acids and polysaccharides, are shear-thinning (pseudoplastic) within normal operating ranges. However, analytical models to predict and design screw extruders for non-Newtonian pseudoplastic materials are rare. In this study, an analytical model suitable to design a screw extruder for slightly non-Newtonian materials was developed. The model was used to predict the performance of the screw extruder while processing materials with power law indices slightly deviating from unity (the Newtonian case). Using non-dimensional analysis, the effects of design and operational parameters were investigated. Expressions to determine the optimum channel depth and helix angle were also derived. The model is capable of predicting the performance of the screw extruder within the range of power law indices considered ($1/\sqrt{2} \leqslant n \leqslant 1$). The power law index influences the choice of optimum channel depth and helix angle of the screw extruder.



## 1. Introduction

The increasing use, and inadequate recycling, of synthetic polymers has increased environmental concerns [1]. Biopolymers and biobased plastics have been considered as suitable replacements to synthetic, non-degradable polymers. Biopolymers being considered include starches, cellulose derivatives, chitosan/chitin, gums, proteins and lipids. The knowledge of rheological properties of food products is required for the design and process evaluation, process control, and consumer acceptability of products from biopolymers [2].

The major classes of biopolymers are proteins, nucleic acids and polysaccharides [3]. Mościcki and Zuilichem [4] stated that it is well known that within normal operating ranges, starches and protein-rich materials are shear thinning or pseudoplastic. The non-Newtonian, pseudoplastic behaviour is described by the power law: $\eta = m_o \gamma^{n-1}$. The power law index, $n$, is an indicator of a material's sensitivity to shear or the degree of non-Newtonian behaviour [5,6]. Slightly non-Newtonian materials have a power law index value between $1/\sqrt{2}$ and 1 but those classified as highly non-Newtonian have values between 0 and $1/\sqrt{2}$ [7].

Work done by Homaidan [6] on extrusion of fine-ground cellulosic slurries indicates that concentrated wood flour slurries with up to 67 wt% are slightly non-Newtonian. Nikoo et al. [8] observed that gelatin from Amur skin was slightly non-Newtonian and shear thinning with flow index between 0.82 and 1. Heyes et al. [9] noted that slightly non-Newtonian solutions of chitosan could be produced from solvents including aqueous solution of acetic, citric, formic, lactic, malic and tartaric acid [10]. Extrusion of chitosan and chitosan blends with other materials have been carried out by Quiroz-Castillo et al. [11], Quiroz-Castillo et al. [12] and Steckel and Mindermann-Nogly [13].

Li et al. [14] stated that although extrusion processing techniques for producing starch films have been developing for many years, there are a few commercial products in the market due to the influence of process variables and material properties. Willett et al. [15] and Della Valle et al. [16] found that waxy and normal corn starch exhibited pseudoplastic behaviour and becomes more Newtonian as either temperature or moisture content was increased. Xie et al. [17] noted that lower amylose-content corn starch has a more Newtonian behaviour in its melting state. Higher pseudoplasticity behaviour was due to an increase in entanglements between amylose chains. Amylopectin-rich starches were

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**Nomenclature**

| | |
|---|---|
| $D$ | diameter of screw, m |
| $g$ | acceleration due to gravity, m/s$^2$ |
| $G_z$ | non-dimensional pressure gradient, Equation (21) |
| $h$ | channel depth, m |
| $H$ | dimensionless channel depth, $h/D$ |
| $H_{opt}$ | optimum non-dimensional channel depth, Eq. (18) |
| $l$ | screw length, m |
| $L$ | dimensionless screw length, $L/D$ |
| $\dot{m}$ | mass throughput, kg/h |
| $m_o$ | consistency index, Pa.s$^n$ |
| $n$ | power law index (dimensionless) |
| $N$ | screw speed, rpm |
| $p$ | pressure, Pa |
| $P$ | non-dimensional pressure, $P/m_o\omega^n$ |
| $Q$ | non-dimensional volumetric throughput, Eq. (16) |
| $Q_n$ | non-dimensional volumetric throughput, $2Q/WHV$ |
| $t$ | Time, s |
| $U$ | dimensionless velocity, $v_z/v$ |
| $v$ | velocity, m/s |
| $x$ | distance on coordinate axis across screw channel, m |
| $y$ | distance on coordinate axis perpendicular to screw root, m |
| $Y$ | non-dimensional distance perpendicular to screw root, $y/D$ |
| $z$ | distance on coordinate axis down the screw channel, m |
| $Z$ | non-dimensional distance along screw channel, $z/D$ |
| $Z_s$ | non-dimensional distance along the screw length |
| $\eta$ | viscosity, Pa.s |
| $\overline{\eta}$ | non-dimensional viscosity, $\eta D^{n-1}/(m_o v^{n-1})$ |
| $\rho$ | density, kg/m$^3$ |
| $\tau$ | shear stress, Pa |
| $\phi$ | helix angle, deg |
| $\phi_{opt}$ | optimal helix angle, deg |
| $\omega$ | angular velocity of screw, rad/s |

*Subscripts*

| | |
|---|---|
| $x$ | coordinate direction across screw channel |
| $y$ | coordinate direction perpendicular to screw root |
| $z$ | coordinate direction down the screw channel |

also observed to exhibit increased Newtonian behaviour. Tajuddin et al. [18] also stated that during plasticisation of thermoplastic starch with mainly water, the behaviour observed tended towards being more Newtonian.

The food, ceramics, polymer, pharmaceutical and metallurgical industries widely employ equipment such as extruders and roll mills. Extrusion is also useful in the processing of biopolymers [19]. Forces are transmitted to the processed materials via the walls of the equipment [20]. Womer [21] discussed the basis of good extrusion screw design noting that the plasticating screw is the heart of the extruder which has to perform four main functions including feeding or axial forwarding; uniform melting; steady, consistent pumping of the melt; and homogenous mixing of melt pool. Generally, an extruder is made of many components including a gear box, a drive motor which drives the box, an integral thrust bearing, a feed throat section, an electrically heated barrel and the plasticating screw.

Ozsipahi et al. [22] noted that the flow phenomena in single screw extruders has evoked the attention of many researchers since non-Newtonian type of fluid transport by an extruder is utilized in many industrial applications. Vlachopoulos and Strutt [23] presented an overview of polymer processing focusing on the most important processes for thermoplastic materials, namely extrusion and injection molding. Khatry and Abbulu [24] also presented an overview of melt extrusion as it applies to the pharmaceutical industry noting that proper optimization of the process is essential for the assurance of product quality and performance.

Vignol et al. [25] presented simplified models for the prediction of mass flow rate and pressure at the exit of single-screw extruders as functions of material properties and extruder operating conditions. The models which were based on experimental values combined linear terms with some well-known nonlinear relations, such as the dependence of the mass flow rate on viscosity. Rao and Schumacher [26] presented design formulas for dimensioning extrusion screws and dies, which enable the optimization of coating processes. The study showed that the resin rheology can be reliably taken into account by means of the power law exponent which can be conveniently obtained from melt flow curves.

Koç and Demiryürek [27] investigated the hydrodynamic performance of a single-screw extruder with special reference to the metering region. They stated that the theoretical model was capable of estimating the hydrodynamic behaviour of the extruder metering region and also able to predict extruder geometry and polymer flow rate under different operating conditions. Yamsaengsung and Noomuang [28] carried out a study on the design of a single-screw extruder for starch-based snack products using 3-D finite element modelling to simulate the flow of rice dough through an extruder.

Covas and Gaspar-Cunha [29] investigated the influence of the rheological characteristics of a polymer on the predicted performance of a typical single screw extruder. A global modelling package was developed in order to yield important process responses such as axial pressure, melting rate, melt temperature, power consumption and degree of mixing. The study also involved the effect of power law constants both in terms of the general process behaviour and of the sensitivity of the extruder to small changes of the input conditions.

Li [30] developed a one-dimensional computer model of extrusion cooking which can simulate and predict extruder behaviour (such as pressure, temperature, fill factor, gelatinization, residence time distribution, shaft power) under various processing conditions (such as feed rate, screw speed, feed temperature/moisture, barrel temperature). Janssen and Mościcki [31] presented the fundamental knowledge of design and modelling of the most simple, inexpensive food extruders, which are still often used in feed and food sectors. The mass flow theory and process phenomena were given for predicting the operation of the extruders. Abdel-Ghany et al. [32] derived simple governing algebraic equations to simulate the performance of a single screw extruder. The pressure developed in the barrel was found to be directly linked to the screw geometry and the processing conditions.

Gabriele et al. [33] investigated the rheological behaviour of liquorice extract to design properly and to optimize a single-screw extruder dedicated to liquorice production. The study determined a stress-shear strain law and a simplified analysis of the extruder performance was carried out. A power law relationship between either the flow rate or the power consumption and the screw speed was established. Tadmor and Gogos [34] stated that it is impossible to have analytical solution for channel flows of a non-Newtonian fluid. They, however, noted the problem solved by Hirshberger [35] which illustrates the relative complexity introduced in dealing analytically with the absolute sign in the power

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