Extrudate dehydration rate increase by modernization of the extruder vacuum chamber

A A Kurochkin¹, D I Frolov¹ and V M Zimnyakov²

¹ Penza State Technological University, 11, Gagarin Str., Penza, 440039, Russia
² Penza State Agricultural University, 30, Botanicheskaya Str., Penza, 440014, Russia

E-mail: fbt@penzgtu.ru

Abstract. This paper proposes to upgrade the vacuum chamber of the extruder to enhance the impact of thermovacuum effect on extrudate due to dispensing air into the working volume of the vacuum chamber of the extruder. An air valve is installed in the upgraded extruder chamber. This valve allows faster removal of the wet steam with the extrudate surface. Analytical expressions, which allow determining the volumetric flow rate of intake air of the machine in the vacuum chamber and determining its influence on the basic design and technological parameters of the system, were obtained. The obtained results can be useful and taken into account in the process of subsequent theoretical studies of extruders with a vacuum chamber and will improve the efficiency of machines that perform thermal vacuum extrusion of plant materials.

1. Introduction

The working process of the extruder is based on the use of heat, which is generated inside the machine due to the dissipation of mechanical energy. An intermediate link in the conversion of electrical energy is the mechanical energy of shear and the friction force of the processed raw materials. Most of the energy goes to raising the temperature of plant materials. The technological process of such extruders is based on the multiple conversion of one type of energy into another (figure 1).

![Figure 1. Energy conversion in an extruder.](image)

Analytical models of screw extruders for non-Newtonian pseudoplastic materials are rare. In the study [1], an analytical model was developed suitable for designing a screw extruder for non-Newtonian materials.

The effect of thermal vacuum impact on the product at the time of its exit from the die of the
machine matrix is described in the study [2]. The study of the basic laws of the formation of the capillary-porous structure of extrudates from plant materials made it possible to theoretically substantiate the method. Experimental studies have confirmed that the working process of extruders, based on the vacuum effect, provides the desired coefficient of explosion of the extrudate at lower pressure and temperature [3].

Researchers [4] provided an overview of polymer processing, focusing on extrusion and injection molding. Simplified models were presented for predicting the mass flow rate and pressure at the outlet of a single-screw extruder depending on the material properties and operating conditions of the extruder [5]. The influence of temperature, vacuum and preliminary pulses for the intensity of the extraction process [6]. Many other studies have reported effects of different process variables and extruder configuration on properties of different blends of extrudates [7, 8, 9, 10, 11].

A theoretical analysis of the structural-technological scheme of an extruder with a vacuum chamber [3] revealed the disadvantages:

- Insufficient dehydration of the extrudate.
- The dependence of individual indicators of the extruder on the ambient temperature.

The basic disadvantage associated with the insufficient efficiency of dehydration of the ex-work is due to the relatively low air flow rate at the surface of the ex-work. This phenomenon limits the transfer rate of the liquid removed from the extrudate by means of wet steam moving from the vacuum chamber of the extruder into a vacuum-balloon. The solution to this problem requires a more complex approach and is associated with theoretical studies of the relationship between the flow rate of the air extruder admitted into the vacuum chamber and the basic structural and technological parameters of the machine.

The purpose of the study is the theoretical justification for increasing the efficiency of extrudate dehydration by supplying air to the vacuum chamber of a modernized extruder with a thermal vacuum working process.

The objectives of the study are to obtain analytical relationships that allow us to assess the effect of additional air supply into the vacuum chamber of a modernized extruder on its efficiency.

2. Materials and methods
Theoretical calculations relied on the properties and thermodynamic characteristics of water vapor. The mass balance equations for the raw materials located inside the barrel of the experimental extruder and in the vacuum chamber were compiled.

3. Results and discussion
The results of previous theoretical studies allowed us to justify and propose a new technical solution for the extruder, which ensures more efficient dehydration of the extrudate during its operation. To this end, it is proposed to equip the extruder's vacuum chamber with an air valve to supply a certain volume of air to it, which in turn intensifies the process of removing wet steam from the surface of the extrudate and its further movement into a vacuum cylinder. At the same time, it is rational to place the air valve on the opposite side from the pipe connecting the chamber with the moisture removal and condensation system.

The design scheme of the extruder being upgraded consists of a loading hopper 1 (fig. 2), a housing 2, a screw 3, a die 4, an air valve 5, a vacuum chamber 6, a vacuum cylinder 7, a vacuum regulator 8, a vacuum meter 9, a vacuum pump 10 and airlock 11.

The lock gate 11 is used to discharge the extrudate from the vacuum chamber of the extruder. A vacuum pump 10 is used to create low pressure in a vacuum chamber. A vacuum cylinder 7 is necessary to normalize the pressure fluctuations in the vacuum chamber 6. The vacuum regulator 8 controls the necessary pressure in the vacuum chamber 6. The vacuum meter 9 is used to control the pressure in the vacuum chamber.

The extruder with a vacuum chamber operates as follows. The raw material enters the feed hopper 1 of the extruder. The screw 3 moves the raw materials through the pressing and dosing zones of the
There, the raw material is heated to a temperature of 120-130 °C and is discharged through the die plate of the extruder 4 into the vacuum chamber 6. When leaving the die, the extrudate is cut into particles of a given length. Entering from the high-pressure region (inside the extruder) into the low-pressure zone (into the vacuum chamber 6), the raw material undergoes a powerful decompression explosion. In the process of the transition of water into a gaseous state and evaporation from the surface of the extrudate layer, the product cools by about 20-30 °C. Steam using a vacuum pump 10 condenses in a vacuum cylinder 7 and flows like liquid into its lower part. In order to intensify the removal of wet steam from the surface of the extrudate, air is supplied to the chamber 8 using the air valve 5.

**Figure 2.** The structural scheme of the modernized extruder: 1 - loading hopper; 2 - case; 3 - auger; 4 - matrix die; 5 - air valve; 6 - a vacuum chamber; 7 - vacuum cylinder; 8 - vacuum regulator; 9 - vacuum meter; 10 - a vacuum pump; 11 - lock gate.

Figure 3 shows the operation diagram of the vacuum chamber of the extruder.

**Figure 3.** The design scheme of the vacuum chamber of the extruder.

From the chamber with a volume of $V$ through an opening with a cross-section $f_1$. The air is evacuated by a vacuum pump. In this case, the amount of air will decrease by $dG_1$. The amount of intake air through the hole with a cross-sectional area of $f_2$ by means of the air valve will increase; we will designate it through $dG_2$.

Humidity is denoted as the initial moisture content in the processed raw materials. During the extrusion process, part of the liquid from the feed passes into steam, and the other part remains in the product. The percentage of liquid passing into steam depends on the process parameters. We describe a model where water vapor in the amount of $dG_1$ enters the vacuum chamber of the extruder.
The amount of air pumped out of the vacuum chamber of the extruder is found from the expression:

$$dG_1 = P_v^{\frac{1}{K}} \cdot f_1 \cdot \mu \cdot a \cdot \sqrt{P_m^m - P_v^m} \, d\tau$$  \hspace{1cm} (1)$$

where $P_v$ is the pressure in the vacuum chamber; $K$ is the adiabatic index; $f_1$ is the sectional area of the vacuum wire; $\mu$ is the flow rate coefficient in the vacuum chamber; $a$ is the dimensionless coefficient equal to $\frac{2gK^{\frac{1}{K}}}{\sqrt{K-1} \cdot C^\frac{1}{K}}$;

$m$ is the coefficient characterizing the adiabatic process and equal to $\frac{K-1}{K}$; $C$ is a value characterizing the ratio of the working air pressure to its specific gravity ($\frac{P_v}{Y_v}$); $P$ is the working air pressure in the vacuum system of the extruder; $d\tau$ is an infinitely small period of time for the expiration of air in a vacuum chamber.

The amount of air entering the vacuum chamber of the extruder through the air valve can be determined by the formula:

$$dG_2 = P_a^{\frac{1}{K}} \cdot f_2 \cdot \mu \cdot a \cdot \sqrt{P_m^m - P_a^m} \, d\tau$$  \hspace{1cm} (2)$$

where $P_a$ is the atmospheric pressure; $f_2$ is the cross-sectional area of the air valve.

We substitute in the equation of the material balance of air in the vacuum chamber of the extruder (in differential form) $dG_1 = dG_2 + dG_3$ formulas for determining the flow rate during pumping (1) and air inlet (2). Let us determine the amount of water vapor that must be removed from the vacuum chamber of the extruder:

$$dG_3 = dG_1 - dG_2 = P_v^{\frac{1}{K}} \cdot f_1 \cdot \mu \cdot a \cdot \sqrt{P_m^m - P_v^m} \, d\tau - P_a^{\frac{1}{K}} \cdot f_2 \cdot \mu \cdot a \cdot \sqrt{P_m^m - P_a^m} \, d\tau.$$  \hspace{1cm} (3)$$

Analyzing equation (3), we can see that the amount of water vapor in the vacuum chamber of the extruder depends on the parameters:

- pressure in the vacuum system of the extruder ($P_v$);
- cross-sectional area of the vacuum pipe ($f_1$);
- coefficient of air flow in the vacuum chamber of the extruder $\mu$;
- air pressure in the vacuum system of the extruder ($P$);
- cross-sectional area of the air valve ($f_2$);
- atmospheric pressure ($P_a$).

In this case, the air flow coefficient in the vacuum chamber takes into account the interaction of the coefficients showing the resistance to the outflow of air from the holes, taking into account the shape of the air valve and the completeness of compression of the air stream.

Equation (3), taking into account the previously obtained results of the author’s research [2, 3], allows one with accuracy sufficient for practical application to determine and analyze almost all structural and technological parameters of the vacuum chamber. In this case, depending on the purpose and accuracy of the calculations, you should first determine the method of estimating the amount of water vapor generated in the vacuum chamber as a result of a decompression explosion of water in the processed raw materials.
For example, the amount of water vapor that must be removed from the vacuum chamber of the extruder can be determined from the equation for the mass balance of the extrudate, as the difference between the mass of the extrudate inside the extruder barrel (before exiting the die) and the mass of the extrudate after exiting the extruder die:

$$G_w = G_t - G_f = \rho_t \cdot V_t - \rho_f \cdot V_f$$

(4)

where $G_t$ and $G_f$ are the mass of the extrudate, respectively, before exiting and after exiting the extruder die;

$V_t$ and $V_f$ is the volume of the extrudate, respectively, before exiting and after exiting the die of the extruder;

$\rho_t$ and $\rho_f$ is the density of the extrudate before and after the exit from the die of the extruder.

Given $G_f = \varepsilon \cdot \Delta V_t$, we can write:

$$\varepsilon = \frac{V_f \cdot \rho_t - V_t \cdot \rho_w}{\Delta V_t}$$

(5)

where $\varepsilon$ is a coefficient that takes into account the influence of the thermal vacuum effect on the increment of the extrudate volume after it leaves the extruder die;

$\Delta V_t$ is an increment of the volume of the extrudate after it leaves the die of the extruder.

Then the amount of water vapor that must be removed from the vacuum chamber of the experimental extruder is determined by the following formula:

$$G_w = G_t - \varepsilon \cdot \Delta V_t.$$  

(6)

Another possible option for the practical application of the results obtained in this work may be the determination by experimental methods of the numerical values of the parameters included in formula (5) for each particular case of the proposed structural and technological scheme of the extruder.

4. Conclusion
The influence of additional air supply to the vacuum chamber of the modernized extruder improves its efficiency. Analytical expressions were obtained, with the help of which it is possible to determine the volumetric flow rate of air admitted into the vacuum chamber of the machine and determine its effect on the main structural and technological parameters of the system. The results obtained can be useful in the subsequent research of extruders with a vacuum chamber and will improve the efficiency of machines that perform thermal vacuum extrusion of plant materials.

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