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Effects of Screw Speed on Screw Pressure and Temperature: A Case of Non-Newtonian Non-Isothermal Flow †

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Abstract: This study uses ANSYS Polyflow to analyze the relationship between speed, temperature, and pressure. A wheat flour's viscosity, thermal conductivity, and heat capacity were found to be 12,000 cps, 0.375 W/m-K, and 2190 J/kg-K, respectively. The speed was increased from 5 to 100 RPM in five-step increments. The findings of pressure and temperature measurements were examined for statistical significance, as well as the link between change in screw speed and change in pressure and temperature. As the screw speed increased, so did the pressure and temperature, with a maximum of 41 bar and 372 K recorded at 100 RPM. Proper screw speed selection is critical for maintaining optimal pressure and temperature conditions in the extruder, which ensures great product quality and operating efficiency.

Keywords: ANSYS Polyflow; numerical simulation; extrusion

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1. Introduction

The extrusion technique is widely used in food manufacturing owing to its high throughput, energy efficiency, versatility, and environmental friendliness [1]. Extrusion processing enables the production of breakfast cereals, pasta, pre-packaged snacks, infant food, pet food, nutritional fiber, cereal-based modified starch, and traditional foods. As part of the processing, the ingredient mixture is pushed through a special extruder, which exposes it to high pressure, temperature, and shear. This alters the mixture's physiochemical and nutritional properties, influencing the quality of the final product by eliminating pathogens and increasing nutrient retention [2]. Figure 1 provides a schematic representation of a food extrusion handling production line [3]. The extruder receives the mixed ingredients, which are often in powder or pellet form. As they pass through the machine, the heat generated by friction and steam cooks and gelatinizes them. The extruder's screw transports and processes the mixture, forming a homogeneous mass [3].



Figure 1. Schematic depiction of a food extrusion handling production line.

The extrusion process relies significantly on several crucial factors, including the composition of the material being extruded, the speed at which it is rotated, the length of the

screw used, the temperature of the barrel, the pressure applied during processing, and the shape of the die, which are regulated according to the optimal item to maintain uniformity of output [4]. Extruded goods, such as puffed cereals, undergo structural changes due to the discharge of heat and moisture, as well as a decrease in screw extrusion force [5]. Extrusion of starches involves high temperatures, mechanical forces, and pressures of up to 0.7 MPa. The inclusion of moisture during the feeding process and the maintenance of a low die temperature lead to a decrease in the molecular weight of starch molecules [6]. Also, studies have shown that when wheat is heated, its dietary fiber content rises [7]. Speed, barrel temperature, and moisture all have an impact on extruded products' expansion ratios. When the input materials are more moist, the expansion ratio drops significantly [8]. Raising the screw's speed and barrel temperature results in sizable variations in expansion ratio due to the rise in moisture content [9]. As the extrusion temperature decreases, the end product's moisture content increases. Extruding at a higher temperature reduces the final product's moisture content [8,10]. The moisture content of a food product has a direct effect on its crispness.

The relationship between dough rheological properties and biscuit quality has been explored. It has been determined that the elastic recovery of the dough is the most precise indicator for predicting the textural quality of the biscuits [11]. A study mixer equipped with monitoring equipment has been used to assess the effect of specific mechanical energy and dough temperature on the quality of the biscuits [12]. Investigation has also been carried out on the impact of high-pressure processing on the microbiological load and performance of sugar-cookie dough [13].

Although there has been considerable success in researching the impact of temperature, pressure, and material composition on food product extrusion, there is an absence of a clear understanding of the impact of screw speed on temperature and pressure in food extrusion. The goal of this study was to close the gap by investigating the effects of screw speed on processing temperature and pressure by gradually increasing the screw speed from 5 to 100 RPM and recording the changes in pressure and temperature, which are two of the most important quality indicators that require optimal application for efficiency and quality production. A computer-aided model of the screw and barrel was created, and a fluid domain was generated to depict the flow of the material during extrusion. By specifying the viscosity, heat capacity, and thermal conductivity of the material at different RPMs, the resultant pressure and temperature were recorded, and an ANOVA and mean effect test were performed to determine the effects of screw speed on pressure and temperature.

2. Materials and Methods

2.1. Physical Properties of Wheat Dough

The thermo-physical properties of wheat dough, which was the product of choice in this study, were determined using data from the existing literature. The dough had a moisture content of 44.62% (db), a density of 970.90 kg/m^3, a thermal conductivity of 0.375 W/m-K, and a specific heat capacity of 2190 J/kg-K, with a viscosity of 12,000 cps [14]. These properties influence the system's flow and thermal conditions.

2.2. Numerical Simulation

Inventor CAD software was used to develop a CAD extruder model with an 800 mm screw length encased in a barrel with a tapered die of 100 mm. The model was imported into ANSYS spaceclaim where the fluid domain depicting the material flow in the extruder was extracted and solved using the general non-Newtonian solver (ANSYS Polyflow, 19.0) with the finite element method (F.E.M.) task and evolution problems usually used in the extrusion of paste material, such as glass and concrete [15,16]. The study made the

following assumptions: there were no chemical reactions in the extruder, the dough was filled in the barrel, and there was no heat loss through the barrel. These assumptions are meant to simplify the study by eliminating the complications associated with air gaps, increasing computing efficiency, and improving model stability. The temperature (298 K), input screw speed (varied from 5 to 100 RPM), and flow rate were specified at the flow inlet. The wall was thermally insulated, and the flow outlet had normal flow with tangential forces exerted.

Polyflow is a computational method that solves the equations of momentum, incompressibility, and energy for non-isothermal flows in generalized Newtonian flow. The momentum equation has the following form:

$$-\nabla p + \nabla \cdot T + f = \rho a \tag{1}$$

where T represents the extra-stress tensor, ρ is the density, p represents pressure, f is the volume force, and a is the acceleration. The formula for incompressibility is

$$\nabla \cdot v = 0 \tag{2}$$

where v represents velocity. The energy equation is denoted below:

$$\rho C_P \frac{DT}{Dt} = r - \nabla q + (\sigma D) \tag{3}$$

where σ represents the Cauchy stress tensor, D is the rate-of-deformation tensor, and (σD) is the sum of the diagonal terms of σD. DT/Dt is the material derivative of the temperature:

$$\frac{DT}{Dt} = T : \nabla v + r - \nabla q \tag{4}$$

2.3. Mesh Generation, Sensitivity Analysis, and Verification

Mesh generation and mesh sensitivity analysis were carried out with mesh sizes of 1.5, 1.2, 0.9, 0.6, and 0.3 mm. A mesh size of 0.6 mm and 102,960 total elements were selected due to their minimal change in the result. The model was verified from the literature due to its similar characteristics and behavior with the study conducted on the investigation of ideal soap extrusion parameters using numerical modeling [17]. Twenty runs were performed with screw speed increments of 5 from 5 to 100 RPM, which is the speed range of the majority of operating extruders, and the resulting pressure and temperature were measured.

3. Results and Discussion

Mains effects were investigated to assess the influence of varying speeds on temperature and pressure. Figure 2 displays the variation in pressure with changes in the screw speed. The vertical axis shows the mean values of pressure while the horizontal axis shows the values of screw speed. The figure indicates a rise in pressure with a rise in screw speed. This can be attributed to the rise in energy requirement for material flow as the screw speed increases [18]. Increasing screw speeds causes the fluid or material being processed to flow more quickly, resulting in a higher amount of kinetic energy transferred to the fluid. A rise in kinetic energy results in an increase in pressure within the system [19]. Higher screw speeds can result in greater frictional heating. This can influence the viscosity of the material being processed, which in turn affects the pressure of the system [4].

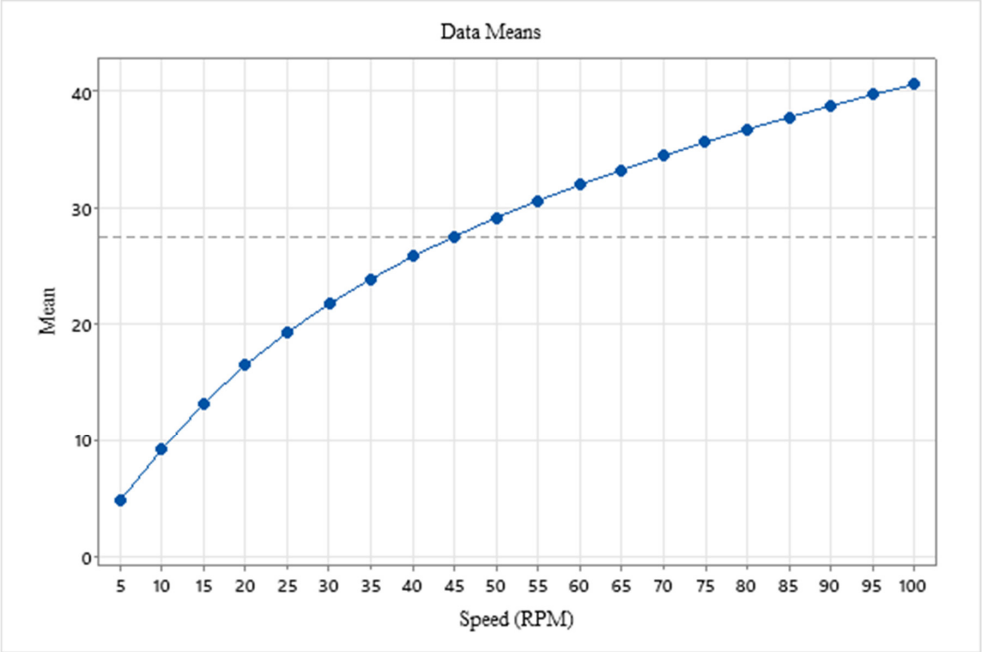


Figure 2. Main effect plot for pressure.

The force applied by the screw affects the quality and uniformity of the extruded dough. Increased pressure can lead to a more condensed and tightly packed product, while decreased pressure may result in a lighter and more porous composition. The optimal pressure is often determined based on the chosen quality of the end product [19]. Effective pressure control ensures unwavering dispersion of ingredients and moisture across the entire dough. Inadequate pressure can result in irregular blending, resulting in alterations in the quality and visual characteristics of the extruded product [20]. By applying the appropriate force, the dough can be effectively blended, leading to a uniform outcome [21]. Figure 3 shows the flow visualization of pressure at a speed of 50 RPM. It is evident that the pressure is high at the entry point and reduces as the material flows towards the exit.

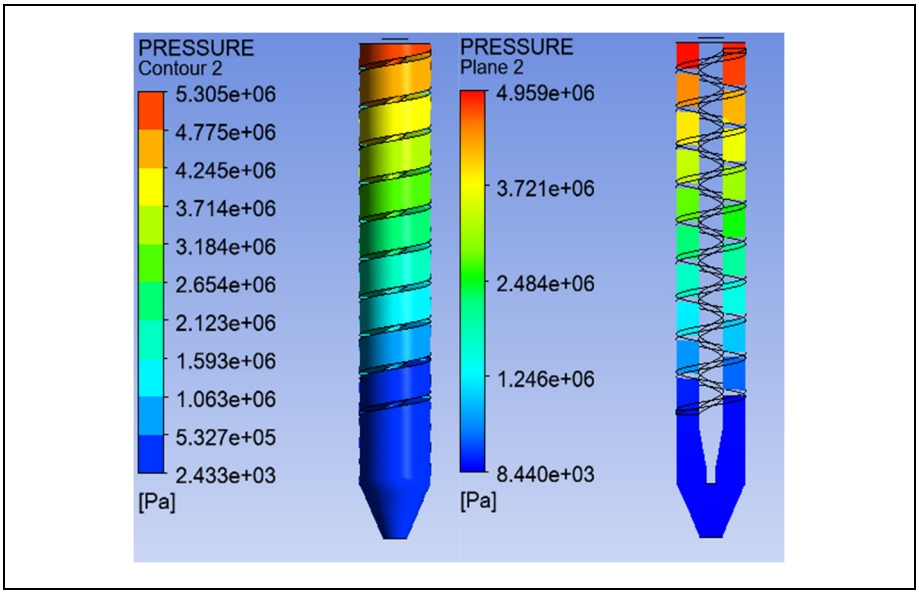


Figure 3. Flow visualization of pressure at a speed of 50 RPM.

The model is statistically significant, as shown by its very low *p*-value of 0.000. Changes in screw speed account for 99.45% of the pressure fluctuations in the model. This explains

a lesser proportion of the fluctuation in pressure than the major effect of speed, which accounts for 5.09%. The unexplained variability in pressure after accounting for predictor effects is 0.55%, which is modest and thus acceptable. The higher predicted R-squared value (99.02%) suggests a low likelihood of model overfitting. Overall, the ANOVA result shown in Table 1 suggests that both the main effect of screw speed and its interaction are highly significant predictors of pressure.

Table 1. Analysis of variance for pressure.

Source	DF	Seq SS	%Cont	Adj SS	Adj MS	F-Value	*p*-Value
Regression	2	2112.39	99.45%	2112.39	1056.19	1523.17	0.000
Speed (RPM)	1	2004.30	94.36%	430.09	430.09	620.25	0.000
Speed (RPM) × Speed (RPM)	1	108.09	5.09%	108.09	108.09	155.88	0.000
Error	17	11.79	0.55%	11.79	0.69		
Total	19	2124.17	100.00%				
Model Summary							
S	**R-sq**	**R-sq (adj)**	**PRESS**	**R-sq (pred)**	**AICc**	**BIC**	
0.832716	99.45%	99.38%	20.8699	99.02%	56.85	58.17	
Regression Equation							
Pressure (bar) = 3.286 + 0.6768 Speed (RPM) − 0.003139 Speed (RPM) × Speed (RPM)							

The main effects of speed on temperature were determined. On average, it can be noted that the dough temperature increases as the screw speed increases, as shown in Figure 4. As the screw's rotational speed increases, it generates more friction with the material that it is in contact with. The frictional force converts mechanical energy into thermal energy, resulting in an increase in the system's temperature [22]. Increased screw speeds might result in higher shear forces exerted on the material. Shear heating occurs when adjacent layers of material experience differential movement, resulting in friction and the generation of heat [17]. Effective temperature control and management are essential for ensuring product quality and optimizing process efficiency.

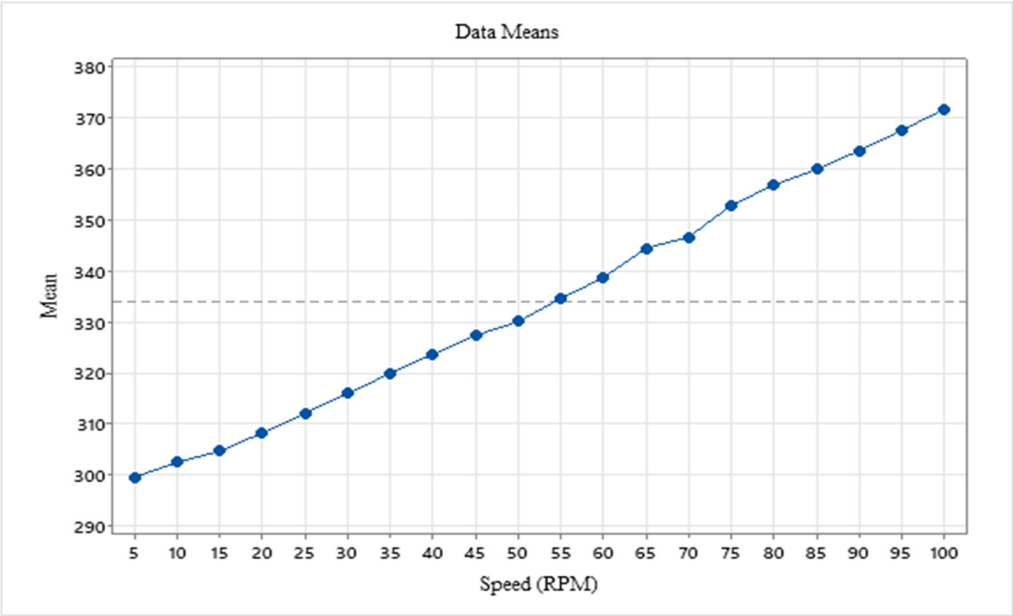


Figure 4. Main effect plot for temperature.

The temperature impacts the viscosity and elasticity of the dough. High temperatures decrease the viscosity of the dough, hence facilitating the process of extrusion. However, higher temperatures might excessively strain the gluten network of wheat dough, resulting in changes to its texture and structure. Regulating temperature facilitates the process of browning and enhances the formation of flavors, thus enhancing the overall taste of the product [23]. Nevertheless, excessive heat has the potential to cause burns or result in an unpleasant taste. Temperature has a significant impact on protein denaturation in dough. Optimal temperatures promote protein denaturation, leading to improved dough pliability and texture. High temperatures can cause proteins to degrade and lose their functionality, which can have a detrimental effect on the manipulation of dough and the overall value of the finished product [4]. Figure 5 shows the flow visualization of temperature at a speed of 50 RPM, which remains moderate with areas of localized high temperatures that can be attributed to the effects of friction heating and shear stresses.

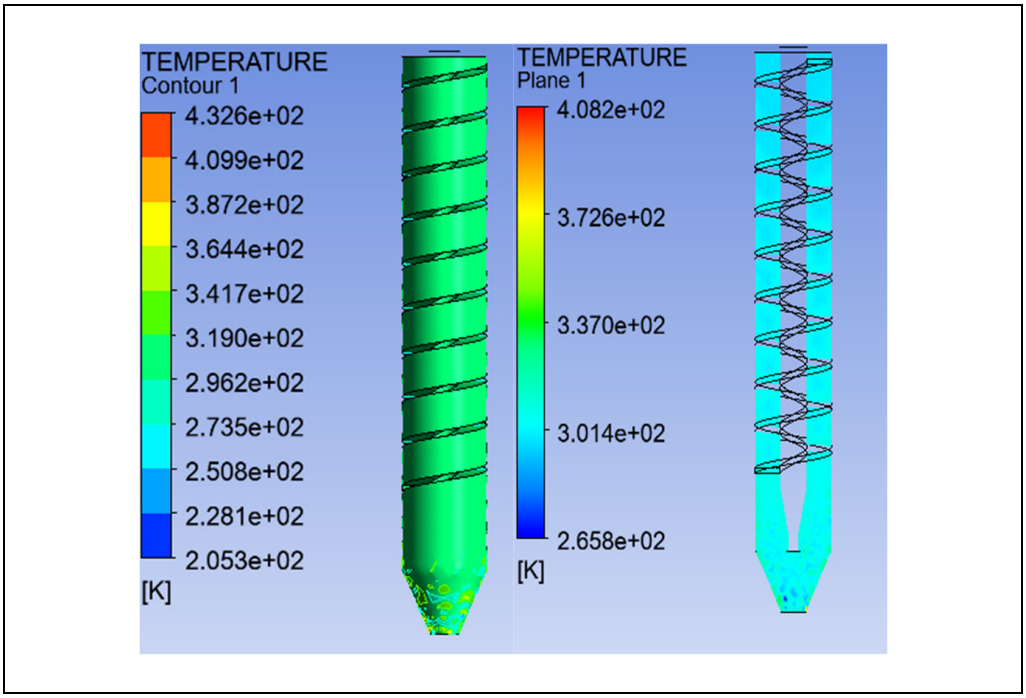


Figure 5. Flow visualization of pressure at a speed of 50 RPM.

The ANOVA analysis shown in Table 2 indicates that both the main effect of screw speed and its interaction have a strong influence on the temperature and are statistically significant predictors. The model accounts for a substantial portion of the temperature variations, specifically 99.88%, due to changes in screw speed. The interaction term is statistically significant, as evidenced by the extremely low p-value of 0.000. The contribution of this factor to the variability in temperature is rather small compared to the primary influence of speed, accounting for only 0.12%. The residual variability in temperature, which cannot be explained by the predictors, is 0.12%, indicating a reasonably low level of unexplained variation, which is considered acceptable. The greater value of the projected R-squared measure (99.82%) suggests that there is a small likelihood of the model overfitting.

Table 2. Analysis of variance for temperature.

Source	DF	Seq SS	%Cont	Adj SS	Adj MS	F-Value	*p*-Value
Regression	2	10132.7	99.88%	10132.7	5066.35	6818.60	0.000
Speed (RPM)	1	10120.7	99.76%	422.3	422.29	568.34	0.000
Speed (RPM) × Speed (RPM)	1	12.0	0.12%	12.0	11.96	16.10	0.001
Error	17	12.6	0.12%	12.6	0.74		
Total	19	10145.3	100.00%				
Model Summary							
S	**R-sq**	**R-sq (adj)**	**PRESS**	**R-sq (pred)**	**AICc**	**BIC**	
0.861985	99.88%	99.86%	18.5749	99.82%	58.23	59.55	
Regression Equation							
Temperature (K) = 295.032 + 0.6706 Speed (RPM) + 0.001044 Speed (RPM) × Speed (RPM)							

4. Conclusions

The investigation was conducted to study the influence of screw speed on temperature and pressure. It has been discovered that the speed at which the screw rotates has a substantial impact on both the pressure and temperature. Specifically, as the screw speed increases, there is a corresponding increase in both the temperature and pressure exerted by the screw. The highest pressure and temperature of 41 bar and 372 K, respectively, were recorded at a speed of 100 RPM. Obtaining the right temperatures and pressure is crucial for obtaining the desired dough rheology, texture, color, flavor, and microbiological safety throughout the wheat dough extrusion process. With the assumptions set, the results should be evaluated with caution because the model may not fully explain the physical processes taking place due to its inability to account for complex interactions. Ensuring product quality and consistent results involves close supervision and monitoring of all aspects involved in the industry.

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