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Mechanical Design Aspects of Single Screw Extruders using Finite Element Analysis

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***Abstract*—This paper presents a method to investigate the characteristics of single screw extruders and evaluate the performance of various types of screw under different working conditions using finite element analysis. Finite element analysis is used to master a technique to evaluate the radial displacement of the used screw, while analytical solution is used to clearly describe the polymer behavior affecting the proposed screw. This performance is of great importance to determine the chance of the screw lock up in the barrel. A finite element model of two types of screw extruder is presented, taking into account bearing support contact, pressure and temperature profiles generated along the screw. The results show that the minimum displacement occurred at the metering zone, while the maximum displacement occurred at the feed zone moving to the compression zone for traditional screw**.

***Index Terms*— Extrusion, Single screw extruder, Screw Design, Finite element analysis, Screw displacement.**

I. INTRODUCTION

Many theoretical, experimental, and simulation studies have already described the polymer behavior in Extrusion process focusing on the polymer flow inside the barrel [1-4]. However, the mechanical behavior of the screw shaft itself during extrusion does not draw much attention [5, 6], although non proper design and selection of this device, which is present in large part of industrial processes, could mean poor performances, excessive power, severe wear of screw and degradation of the conveyed material. When a screw is installed in an extruder, the typical radial clearance between the screw and the barrel is 0.001 D, where D is the diameter of the extruder [7]. This is the clearance at room temperature. When the machine is in operation the actual clearance between the screw and the barrel can be quite different. There are two main reasons for the change in clearance under actual processing conditions. One reason is temperature; the other is compressive load on the screw [8]. The change in clearance between the screw and the barrel can cause the screw to bind which usually results in considerable damage to the extruder and screw break. The goal of this paper is to present a simulation for the diagnosis of a screw shaft behavior results under a range of processing conditions.

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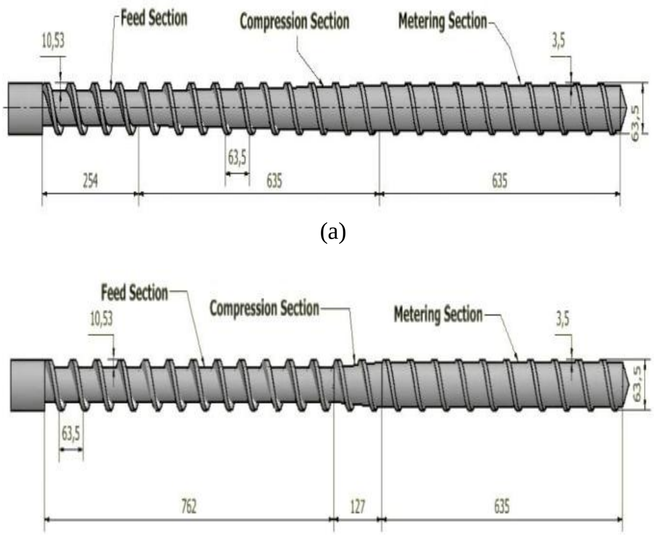
II. Extruder Screw Design

The most important mechanical element of a screw extruder is the screw. The design of screw is mainly depends on the material to be extruded as well as the amount of pressure that has to be developed by the screw. Two sets of single-screw extruders were used throughout this analysis and the geometrical configurations of the screws are shown in Fig.1. For the screw model under working loads, the elastic and plastic properties of the material must be defined. Screw material is 4140 steel, which is a medium carbon, relatively low-cost material and its properties is indicated in Table 1.



(a)

(b)

Fig.1 Schematic representation of 24:1 L/D Screws a) Traditional screw b) Rapid compression screw

Table 1: Material Properties

Property	**AISI 4140**
Density (kg/mm3)	7850
Coefficient of thermal expansion (1/°C)	1.27 E-5
Thermal Conductivity (W/m. °K)	42.5
Poisson's Ratio	0.3
Modulus of Elasticity (GPa)	200
Yield Strength (MPa)	655
Ultimate Strength (Mpa)	1020

III. Screw Temperature Profile Prediction

The temperature of the screw was measured by several investigators [9, 10]. The measurements were performed by mounting thermocouples in an axial hole bored in the center of the screw or by protruding the thermocouples into the melt flow. The studies showed also that rotational speed has a little effect on the screw temperature distribution. In order to predict the axial screw temperature in a single-screw extruder, heat conduction along the screw has to be modeled. An empirical model that describes the axial temperature profile was developed by Cox and Fenner [11] based on the research performed by Edmondson. A recent experimental study [12] showed that the axial screw temperature profiles are consistent with the general trends that would be predicted using the Cox and Fenner model. The model is as follows:

$$T_s = T_b(1-e^{\lambda l}) + T_{so}e^{\lambda l} \quad (1)$$

$$\lambda = \left[\frac{\ln\left[\frac{T_s(l_2)-T_b}{T_{so}-T_b}\right]}{l_2} \right] \quad (2)$$

Where T_s is the axial screw temperature, l is the independent variable for the axial location on the screw, T_b is the barrel temperature in the metering section, T_{so} is the material feedstock temperature, λ is a fitting parameter defined in Eq.(2), and l_2 is the axial location where the melt film first forms on the screw. $T_s(l_2)$ is equivalent to the melting point temperature of the polymer.

The initial extruder barrel temperatures were selected based upon common practice for an LDPE resin. The extruder was equipped with three barrel temperatures using three heaters through this study along the extruder, Table 2 summarize the temperature sets for the three heaters. Fig. 2 shows the temperature distribution along the traditional screw for the three different sets of temperature and Fig. 3 shows the sets for rapid compression screw using Cox and Fenner model.

.Table 2: Temperature sets for the two types of screw

Set No.	Traditional Screw	Rapid Compression Screw
1st	120°-140°-170° C	100°-140°-170° C
2nd	120°-140°-185° C	100°-140°-185° C
3rd	120°-140°-200° C	100°-140°-200° C

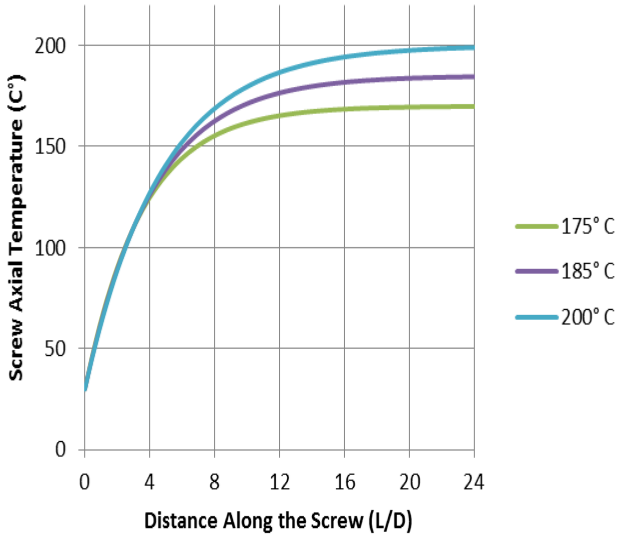


Fig.2 Temperature distribution for Traditional screw

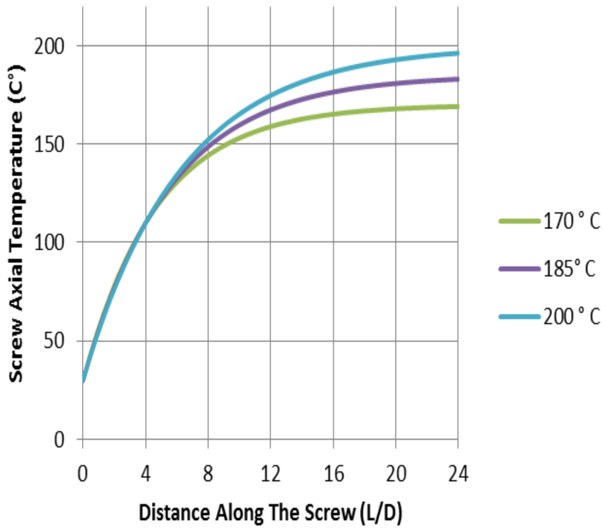


Fig.3 Temperature distribution for Rapid Compression screw

IV. Model Analysis

Forces applied to the extruder screw due to working pressure, temperature distribution, and screw weight generate stresses which lead to increase the probability of screw binding. Finite element method has been used as an important tool in the design and analysis of total screw displacement. In this study, single screw models will be analyzed using commercial finite element analysis code ANSYS. Static analyses were conducted under working loads.

A. Model Meshing

The screw consists of core and flights which have different meshing area with mesh gradient in the expected stress concentration area to improve the results. Fig. 4 shows generated mesh used for this analysis and expected number of elements ranging from 220,000 to 240,000 with maximum skewness of 0.78.

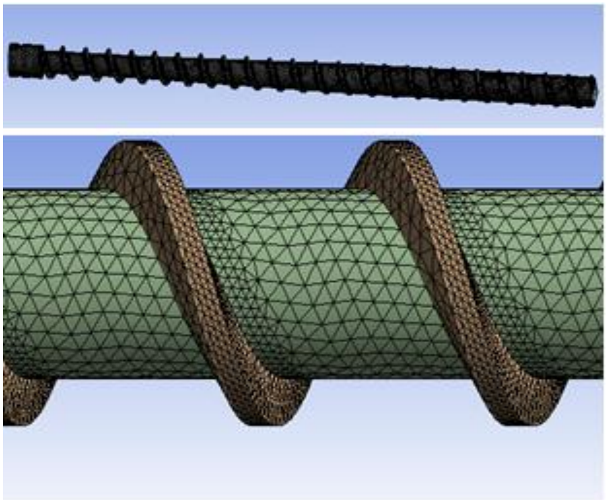
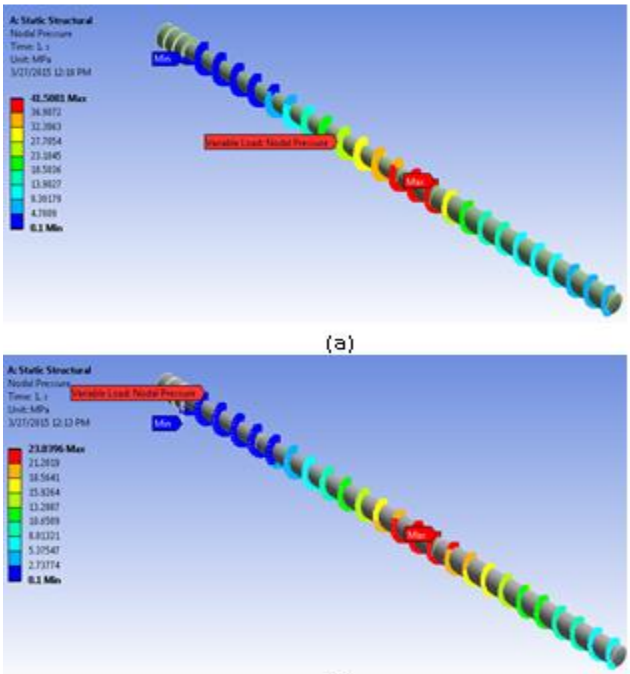


Fig.4 Mesh Configuration for Single screw extruder

B. Model settings

The present work takes into consideration the following conditions:

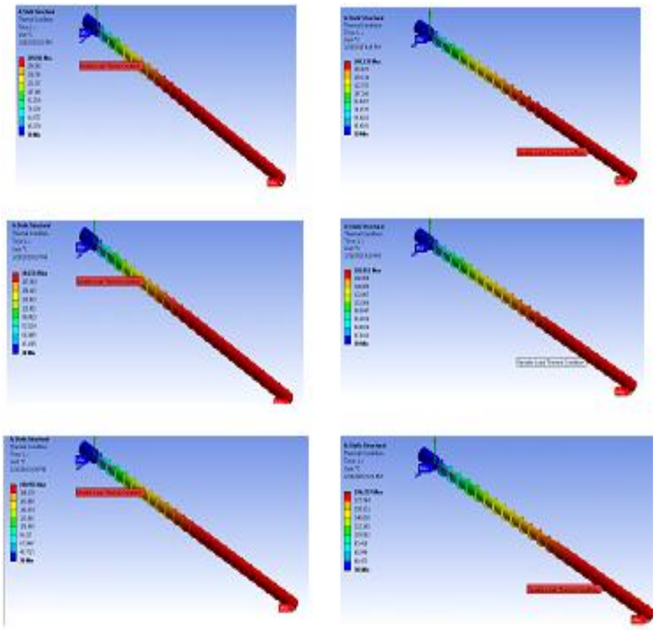
- Nodal Pressure distributed axially along the screw flights for both traditional and rapid compression screws. W.E. Abdel-Ghany et al. [13] studied the pressure distribution along the proposed screws and The output generated using the numerical analysis which can be transferred to Ansys in order to simulate the proposed screws as shown in Fig. 5.
- Maximum generated Torque on screws.
- Screw weight.
- Temperature distribution along the screws as shown on Fig. 6.
- Cylindrical supports for both axial and radial reactions.



(a)

(b)

Fig.5 Pressure developed along the screw for
(a) Traditional screw (b) Rapid Compression Screw



(a) (b)

Fig.6 Temperature Distribution along the screw for the three sets for (a) Traditional Screw (b) Rapid Compression Screw

V. Results

The screw performance at different operating temperatures and pressure for both traditional and rapid compression screws could be analyzed and compared from finite element results. It shows the relation between screw length and the corresponding displacement occurred on each screw. For traditional screw, Fig.7 shows the finite element model at 170°C while Fig.8 shows the variation of displacement along the screw length. From the finite element results shown in Fig.9 and Fig.11, the displacement of screw is affected by changing the working conditions and by means of changing barrel temperature. The displacement at different barrel temperature is shown on Fig.10 and Fig.12. It is clear that changing the temperature on traditional screw increase flights subjected to maximum displacement but with the same value as indicated on Fig.13.

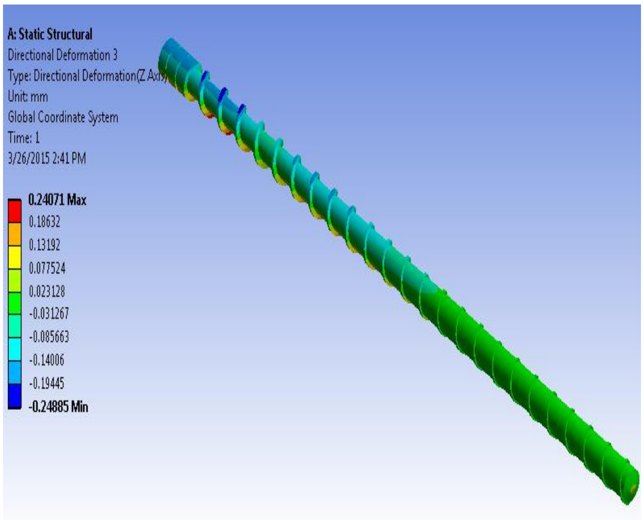


Fig.7 Finite element model for traditional screw at 170°

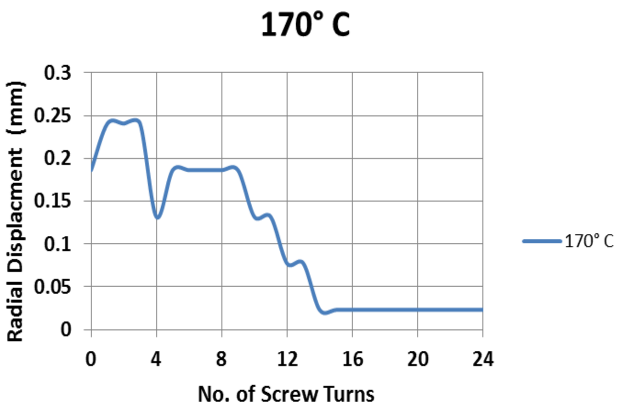


Fig.8 Traditional screw displacement at 170°

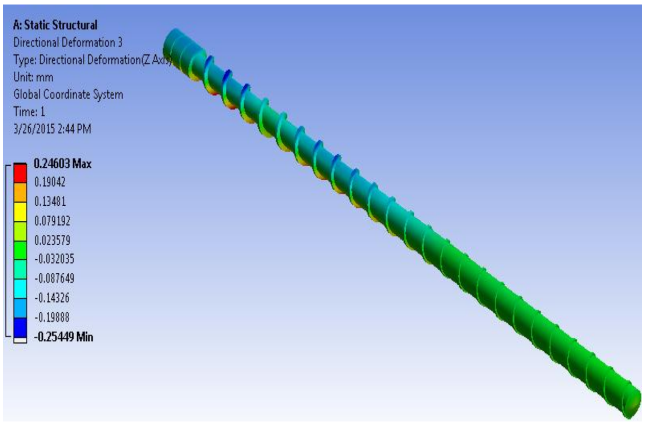


Fig.9 Finite element model for traditional screw at 185°

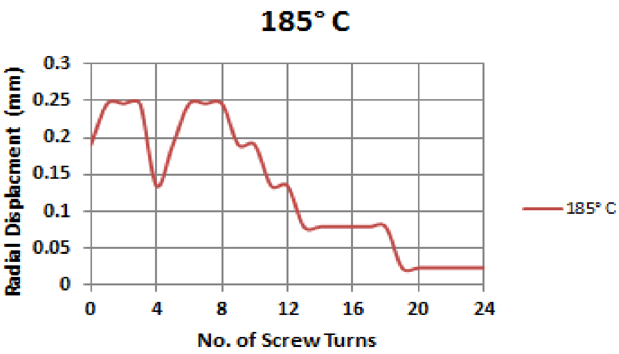


Fig.10 Traditional screw displacement at 185°

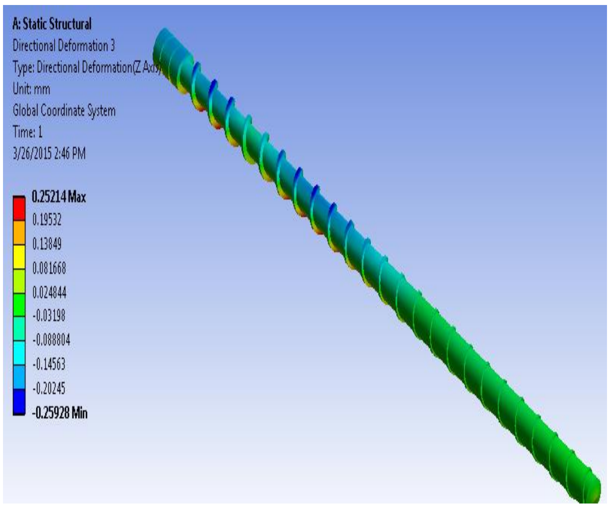


Fig.11 Finite element model for traditional screw at 200°

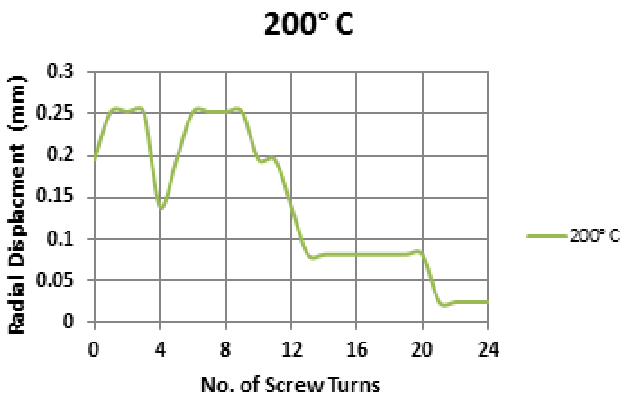


Fig.12 Traditional screw displacement at 200°

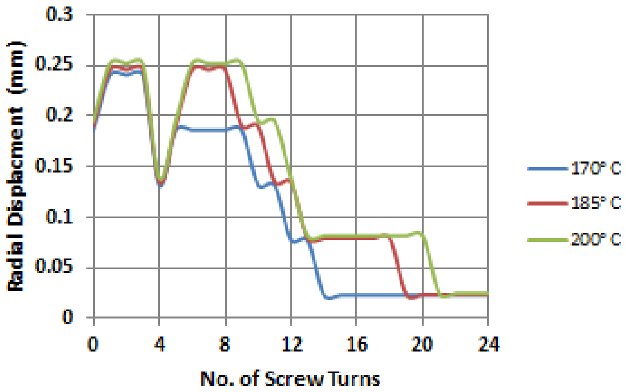


Fig. 13 Comparison for traditional screw radial displacement at different temperatures

The same boundary conditions applied to rapid compression screw with the values of pressure predicted by W.E. Abdel-Ghany et al. [13] and temperature as stated on Fig. 3 and the same sets of temperature were applied. The below figures indicate both finite element analysis and the corresponding displacement for rapid compression screw. While the behavior of traditional screw was increasing the flights subjected to maximum displacement, rapid compression screw had different behavior. The value of maximum displacement increased by increasing the barrel temperature while the same number of flights have subjected to maximum displacement as shown in Fig. 20.

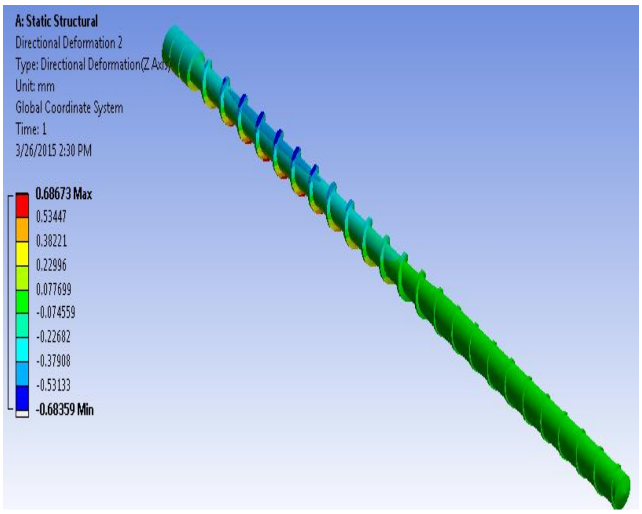


Fig.14 Finite element model for rapid compression screw at 170°

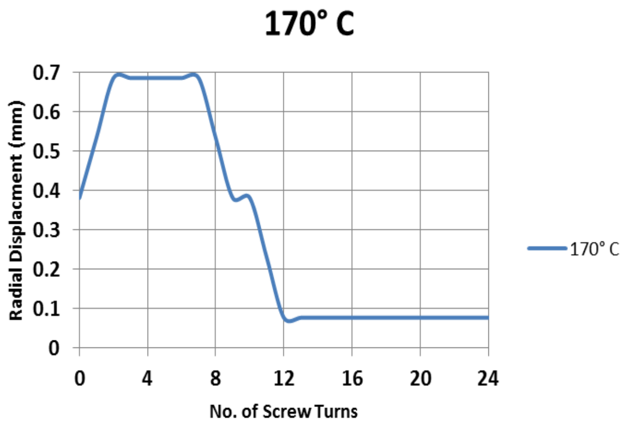


Fig.15 Rapid compression screw displacement at 170°

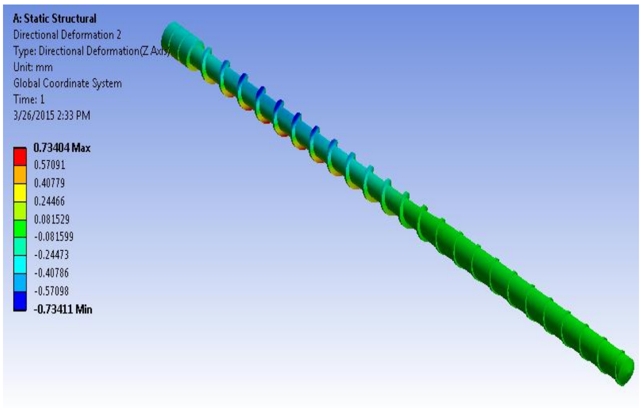


Fig.16 Finite element model for rapid compression screw at 185°

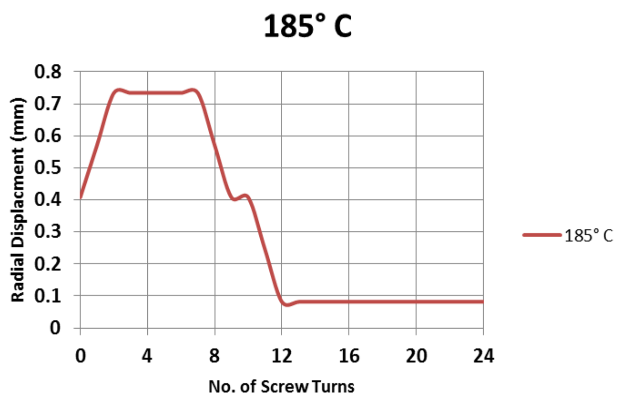


Fig.17 Rapid compression screw displacement at 185°

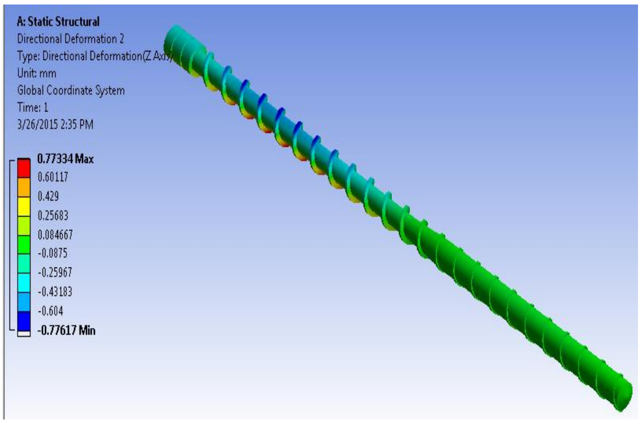


Fig.18 Finite element model for rapid compression screw at 200°

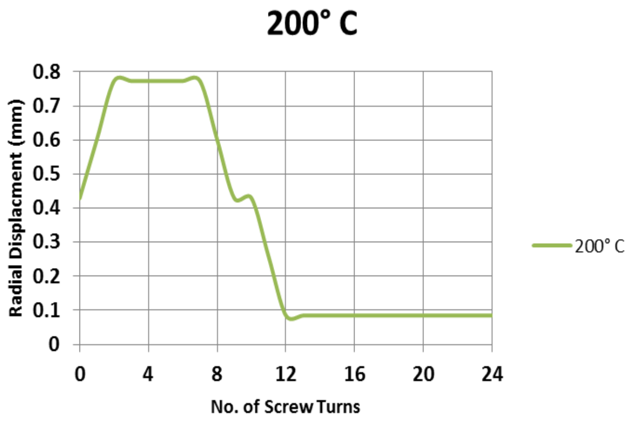


Fig.19 Rapid compression screw displacement at 200°

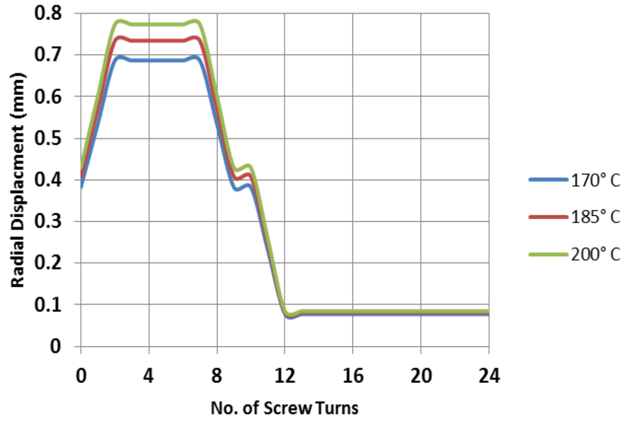


Fig.20 Comparison for rapid compression screw radial displacement at different temperatures

VI. Conclusions

The following conclusions are drawn on the basis of results obtained from Static structural simulations of single screw extruders:

- The higher screw temperature will cause the screw to expand much more specially in the feed throat, causing the screw to bind.
- Finite element analysis results confirm that minimum displacement occurring at the metering section for both traditional and rapid compression screws.
- The pressure for both screws has little effect on the screw displacement which didn't exceed 10 % of the total screw displacement.
- The maximum displacement for the feed and compression zones is 0.252 mm while minimum displacement occurred at metering zone is 0.024 mm. The rapid compression screw has more tendencies to increase the magnitude of displacement comparing with traditional screw. When changing heater temperature the maximum value is 0.773 mm but with the same flights subjected to maximum displacement.
- Increasing temperature in traditional screw lead to increase flights subjected to maximum displacement, while increasing Temperature in rapid compression screw lead to increasing the magnitude of maximum displacement.

- To reduce screw displacement (i.e. the chance of screw binding), the following should be taken into consideration:
    - Cooling of the screw at the feed section.
    - Reduce the temperature in the transition and metering sections.
    - Increase the clearance in the feed throat region.

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