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Numerical analysis of enhanced heat transfer by incorporating torsion elements in the homogenizing section of polymer plasticization with the field synergy principle

Ranran Jian, Weimin Yang, Lisheng Cheng, Pengcheng Xie *

College of Mechanical and Electrical Engineering, Beijing University of Chemical Technology, Beijing 100029, China

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ABSTRACT

The polymer plasticizing process is one of the most important stages in an extruder plasticizing unit. 3D numerical simulations have been carried out in order to investigate the heat transfer and fluid flow characteristics of an extruder plasticizing unit equipped with various screws. The use of screw elements with a twisted groove (namely torsion elements) has been proposed for the first time. The magnitude of radial temperature fluctuations is within 10 K in the position of torsion elements, while it is more than 25 K in other positions. The simulation results reveal that screws with such torsion elements give rise to a more uniform temperature distribution and better heat transfer performance than conventional screws without torsion elements. The mechanism by which the torsion elements enhance the heat transfer was also analyzed using the field synergy principle. The Nusselt number is negatively correlated with the field synergy angle, and the correlation coefficient increases with the screw speed in the range of faster than 60 r/min. The local field synergy angle and heat transfer coefficient have the minimum and maximum respectively at the position where the swirling flow appears. The periodic changes in the flow field induced by the torsion elements are able to improve the synergy between the temperature gradient and the velocity fields, which increases the Nusselt number and the coefficient of local heat transfer, and consequently enhances the overall heat transfer.

1. Introduction

As a device for the plasticization of polymers, screw plasticizing systems are widely used in processes such as extrusion, injection molding, and internal mixing [1,2]. The performance of the screw plasticizing unit can directly affect the quality of products and production efficiency. Therefore, it is very important to optimize the structural parameters and working characteristics of the screw in order to enhance plasticization of polymers, especially for high-end plastics, such as micro lenses and microfluidic chips.

Taking precision injection molding as an example, uneven plasticization of polymers gives rise to defects in the products [3,4]. In general, the temperature distribution is not uniform in the process of plasticization; this is due to significant friction heating and the low thermal conductivity of polymers. Previous efforts to enhance screw plasticization can be classified into two categories: developing new types of screws and optimizing working conditions. Table 1 summarizes reported studies of screw plasticization and highlights the advantages and disadvantages of different approaches. Four novel screw types have been proposed in the literature—distribution screws, barrier screws, separator screws and channel screws with variable sections—for use under different extrusion conditions, and each type has been developed in a variety of structural forms. Dray [5] has compared nine historically significant barrier screws, and modeled melting capacity based on the biggest single factor, solid channel area. This gives a quick way to evaluate barrier screw designs. Abeykoon et al. [6] compared the melt quality in terms of melt temperature fluctuation across the melt flow when using three different screw geometries. Their results showed that the radial location at which the highest melt temperature fluctuation occurred across the melt flow depends particularly strongly on the screw geometry. In order to obtain perfect melting, an adequate melt temperature, and sufficient metering pressure, Lee et al. [7] optimized the screw geometry using an orthogonal array with four factors—feeding zone length, feeding zone depth, melting zone length, and compression ratio. Verbraak

* Corresponding author.
E-mail address: xiepc@mail.buct.edu.cn (P. Xie).

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Nomenclature

ρ	density, kg/m^3	Re	Reynolds number
C_p	specific heat capacity, J/(kg·K)	Pr	Prandtl number
λ	thermal conductivity, W/(m·K)	Nu	Nusselt number
T	temperature, K	θ	intersection angle/synergy angle, °
x, y, z	cartesian coordinates, m	P	pressure, Pa
??$_{??}$	thermal boundary layer thickness, m	η	apparent viscosity, Pa·s
$\overline{U}$	velocity vector, m/s	η_0	zero shear viscosity, Pa·s
$\overline{\nabla T}$	temperature gradient vector, K/m	t	natural time, s
μ	viscosity, Pa·s	β	temperature sensibility coefficient, K^{-1}
α	heat transfer coefficient, W/(m^2·K)	n	non-Newtonian index

et al. [8] investigated screws with pineapple or Maddock/Egan mixing elements, and one or two channel barrier sections. Their results indicated that Maddock elements are able to enhance the plasticization capacity and improve melt homogeneity. Spalding [9] presented a distributive melt-mixing type (DM2) high-performance screw combined with an Eagle mixer on the tip, which can increase the melting capacity and eliminate solid polymer particles from discharge. Yin et al. [10] proposed a novel extruder based on converging–diverging flow composed of four vane plasticizing and conveying units and three mixing units. Their results showed that the thermo-mechanical history of the material in this extruder can be significantly shortened. These previous studies all indicate that novel screw elements or plasticizing units can improve plasticating capacity and melt homogeneity. However, the corresponding mechanism is still not very clear. Tomasz [11] discussed the theoretical fundamentals underlying the construction of an autothermal screw-disc extruder. The autothermal effects occurred during extrusion at low screw speeds, which confirms the validity of the idea of an active feeding zone.

Previous efforts to optimize the working conditions have focused on high-speed extruders, electromagnetic dynamic extruders, and screws in a vibrational force field. Inspired by ultrasonic welding, Michaeli [2] developed a process of ultrasonic plasticising, which has potential applications in generating melts for micro injection molding. In addition, the crystal structure of the material plasticized using this process was also very uniform. Jiang [12] explored the heating mechanism for an amorphous polymer in ultrasonic plasticizing using both theoretical models and experiments. The results showed that the ultrasonic amplitude has a much greater influence on the heat generation rate than the ultrasonic frequency. Qu et al. [13] established an approximate analytical model of the plasticizing process under vibrational force fields in the melt conveying section of a single screw, and derived the influence coefficient of the vibrational force field on the apparent viscosity of the melt. Qu et al. [14–16] proposed a novel vane extruder based on extensional flow and volume transportation. Their results showed that the vane extruder had good plasticizing capacity and low power consumption. Diekmann [17] studied direct-drive single-screw extruders without gearing. It was shown that their use could increase the plasticization capacity of single-screw extruders, provided that a wide screw speed range is utilized effectively.

Table 1
Summary of recent studies on the improvement of screw plasticization.

Year	Authors	Method	Advantages and disadvantages
2006	Kelly et al. [1]	A barrier-flighted screw with Maddock mixer	Better melting Difficult processing
2004	Spalding [9]	A distributive melt-mixing type crew combined with an eagle mixer on the tip	Melting capacity increased
2009	Rydzkowski [11]	Autothermal screw-disc extruder	Autothermal effect occurred
2016	Jiang [12]	Ultrasonic plasticizing	Energy-saving
2002	Qu et al. [13]	Introducing a vibrational force field	Extrusion pressure reduced Mixing performance improved Complicated structure High cost
2009 2012	Qu et al. [14,15]	Vane plasticization extruder	Based on volume transportation Based on extensional flow Power consumption reduced Plasticizing capacity improved
2004	Diekmann [17]	Direct-drive single-screw extruders without gearing	Plasticization capacity increased
2008	Rauwendaal [22]	CRD elongational mixing devices	Based on elongational flow Distributive and dispersive mixing improved Melt temperatures fluctuation reduced Pressure fluctuation reduced
2008	Rauwendaal [22]	CRD barrier screws Adding a slanted section to the crest of the barrier flight	Elongational flow is created Mixing improved Power consumption reduced Viscous dissipation reduced
2008	Rauwendaal [22]	Floating sleeve intermeshing pin mixer	Highly effective distributive mixing Mixing capability improved Low cost
2008	Rauwendaal [22]	High heat transfer (HHT) screw design technology	Heat transfer increased Cooling capacity increased Distributive mixing improved