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Evaluation of effect of paddle element stagger angle on the local velocity profiles in a twin-screw continuous mixer with viscous flow using Finite Element Method simulations

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ABSTRACT

The effect of paddle element geometry, specifically a systematic change in stagger angle, on the velocity distribution of a Newtonian corn syrup was evaluated in the mixing region of a 2″ Readco continuous processor using 3D FEM simulations. Local velocities and regions of backflow were compared for three configurations of the paddle elements in the mixing region consisting of nine pairs of paddle elements with the central three being in a neutral (FLAT), staggered 45° forward (45F) or staggered 45° reverse (45R) configuration. The total material flow rate through the mixer was independent of the paddle element stagger but increased with screw speed when the mixer was operated with the barrel fully filled. The stagger angle variation caused only local disturbances in axial flow. The overall magnitudes of velocity were highest for the FLAT configuration followed by 45F and 45R. The local *X* and *Y* velocity components in the region of stagger showed no significant variation with paddle element stagger while the *Z* velocity component varied significantly in this region. Increased forward flow was seen for the 45F configuration while significant local backflow was seen for the 45R configuration at all positions of the paddle element rotation. The FLAT configuration had greater levels of pressure in the intermeshing region, suggesting a squeeze flow while there were not significant variations in pressure for the 45F and 45R configurations, suggesting a predominantly conveying/leakage flow in the axial direction. Variation in local flows is critical to good mixing.

1. Introduction

A mixing process involves blending or distribution of ingredients, creation of structure and dispersion/size-reduction of ingredients. When highly structured materials such as dough and heavy pastes are involved, the mixing process of these often highly viscous materials is usually in the laminar region and requires mixing elements that are carefully designed to create the desired flow to optimize the efficiency of the mixer. Twin screw continuous mixers, although being similar in design to twin screw extruders, are primarily used to attain a good degree of mixing and homogeneity in viscous food materials whereas twin screw extruders are generally designed to melt, cook, plasticize and shape food materials. In the food industry the twin screw mixers, like the Readco® continuous processor, are used for chewing gum base manufacture (Song and Townsend, 1996), melt crystallization of sugar alcohols like xylitol and mannitol (DuRoss, 1991, 1992), chocolate conching (Zeigler and Aguilar, 2003), etc.

The efficiency of a mixing device can be evaluated through the flow profiles generated in the mixer volume. In particular the geometry and arrangement of kneading/mixing elements is of specific importance to flow in continuous mixer geometries because they cause local and overall variations in axial flow which can affect mixing efficiency.

With recent advances in computational fluid dynamics, it is possible to evaluate the flow in complex mixing geometries like the twin screw continuous mixers using numerical simulation techniques, particularly the Finite Element Method (FEM). FEM has been widely used to study flow in batch mixers and dough kneaders with complex geometries. Connelly and Kokini (2006a) modeled the flow of a Newtonian, a power law and a cross-model fluid in the filled bowl of the Farinograph. A 41,860 element mesh was used for the Farinograph bowl while the two sigma blades were meshed with 6232 and 6166 mesh elements, respectively. The mesh superposition technique was used to calculate the velocity, shear rate and mixing data. FEM simulations were used to compare the flow and mixing in a 2D single screw mixer to a twin screw mixer, both modeled after the cross-section and paddle

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shape of the Readco continuous processor. However since the simulations were 2D, axial flow was not considered (Connelly and Kokini, 2004). Much of the published literature dealing with FEM simulation of flow in continuous mixing geometries pertains to twin screw extruders used in polymer processing and the effect of screw design on the flow in the mixing region of twin-screw extruders. Gotsis et al. (1990) found that the use of 30° reverse staggered (left-handed) kneading blocks caused the ratio of local backflow to forward flow to be five times greater than that seen in a 30° forward staggered (right-handed) configuration. FEM simulations were used to solve the 3D flow of a Newtonian fluid. The study stopped at measuring velocity values and reported only velocity contours. The small backflow in the forward configuration was attributed to a block up action caused by the adjacent kneading block while this effect was greatly enhanced in the reverse stagger due to the formation of a reverse flow channel on the surface. Yao and Manas-Zloczower (1998) analyzed the effect of 'pushing' and 'counter-pushing' units on the flow profile (among other mixing parameters), in an LCMAX 40 axial discharge continuous twin-screw mixer using the FIDAP CFD analysis package. While no backflow was observed in the cross-sections analyzed,

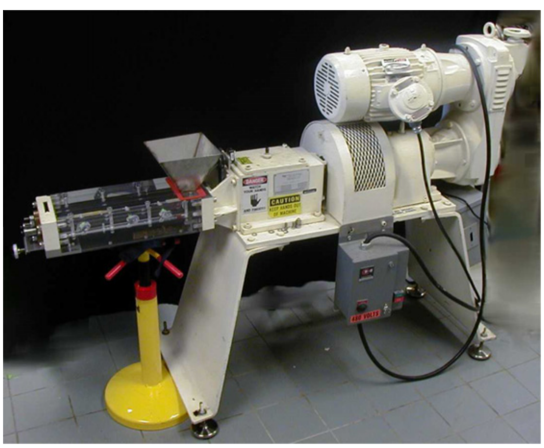

Fig. 1. The Readco® 2″ continuous processor (twin-screw mixer) shown here with a transparent Plexiglas barrel.

it was found that using three or more counter pushing units in a total configuration of six units affected the pumping capacity of the mixer. The absence of backflow could have been due to the fact that these elements consisted of a screw design that was a hybrid between fully-flighted screws and kneading block elements, unlike individually stacked kneading blocks where gaps between the staggered elements create channels for backflow. Bravo et al. (2004) compared the effect of the kneading element width on the flow in a five element kneading block region of a twin-screw extruder configured with a forward stagger angle of 45° between successive elements. An increase in the width of the disc elements generally increased the amount of backflow. While it was further hypothesized that an increase in the stagger angle between the kneading blocks would increase the backflow by creating larger gaps with local pressure gradients, no comparison was given between staggered and non-staggered arrangements. More recently, Zhang et al. (2009) used particle tracking in FEM flow simulations of kneading block region of a twin screw extruder to compute the residence time distribution and the distributive mixing efficiency. No information was presented on the velocity profiles.

Not much published work is available on the analysis of flow in continuous mixers. Although similar in design to the twin-screw extruder, the Readco Continuous processor significantly different in terms of (i) larger dimensions and greater barrel and flow channel volume; (ii) negligible axial pressure gradient and absence of constrained die at discharge end. With developments such as mesh superposition and more powerful numerical techniques it is appropriate to revisit the prediction of flow profiles and mixing efficiencies amongst kneading elements as a function of stagger angle. The objective of this study was to investigate the local pressure and velocity profiles developed in the kneading/mixing elements in the mixing region of the Readco 2″ continuous processor, which is a co-rotating continuous pilot size mixer built with larger screw and barrel dimensions and wider kneading/mixing elements exclusively aimed at viscous fluid mixing. The mixer's typical screw configuration consists of full flight conveying screw elements and kneading blocks or mixing elements. The conveying screw elements are always positive displacement elements that are needed for the net positive flow of the material through the barrel. Specifically a three part mixing element configuration was studied where a 45° forward or reverse stagger angle was introduced in the central part while keeping the beginning and end of the mixing region not staggered. Velocity profiles for an isothermal Newtonian vis-

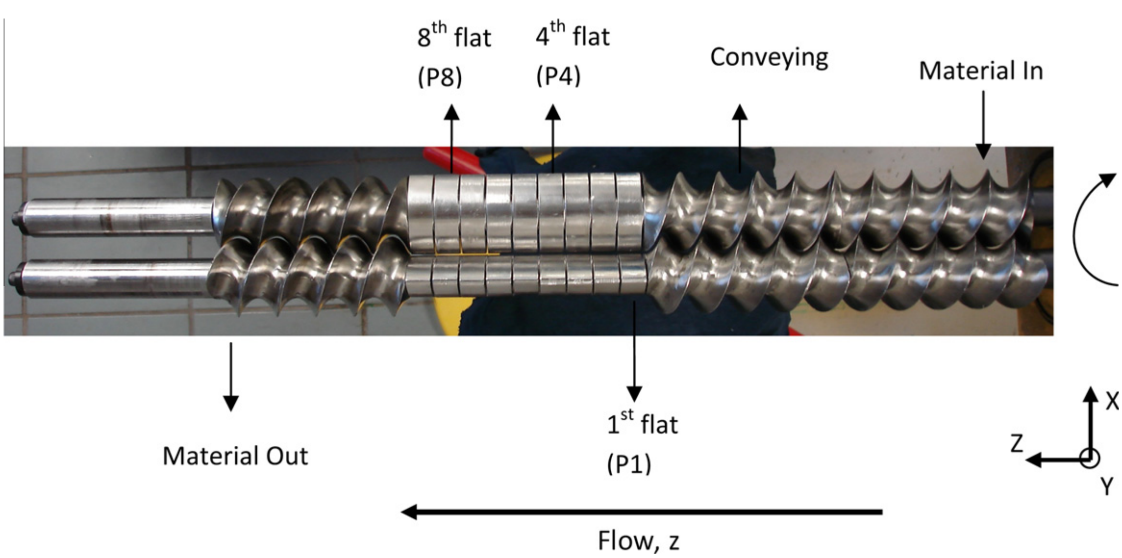

Fig. 2. Conveying screw elements and the 9 pairs of neutral paddle elements of the Readco twin-screw mixer shown here with the barrel removed.