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Effect of mixer geometry and operating conditions on mixing efficiency of a non-Newtonian fluid in a twin screw mixer

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ABSTRACT

The effect of mixer speed, fluid inflow rate, and paddle angle was examined in a shortened geometry. 3D FEM simulation of non-Newtonian 2 g/100 mL carboxymethyl cellulose aqueous solution in the mixing region of a Readco continuous mixer was performed. Data gathered included velocity vectors, shear rate, and mixing index. Increasing mixer speed increased velocity magnitudes in the horizontal and vertical directions. Fluid inflow rate had little impact on velocity in the horizontal and vertical directions, but increased velocity in the axial direction and elongational contribution to the mixing index. All configurations showed areas of simple shear flow where the fluid experienced high shear rates. Staggering paddles increased the maximum axial velocity and shear rate. When successive paddles on the same screw are parallel, a zone was seen between the center of the paddle and the barrel wall which demonstrated efficient dispersive mixing.

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1. Introduction

Mixing is an important process in the production of foods, polymers, and pharmaceuticals. It is used to blend different components, to develop desirable product attributes and to introduce air. All of these processes are important to mixing of wheat flour with water and other ingredients resulting in wheat flour doughs. In this system, water must be distributed and flour particles must be broken to release starch and protein to allow gluten formation. Additionally, mixing is used to stretch glutenin promoting molecular alignment and the formation of non-covalent bonds giving dough elasticity, imparting machinability and gas retention. Bubbles introduced during mixing become nuclei for carbon dioxide formed in fermentation and allow for expansion of the dough during proofing (Connelly and Kokini, 2007).

Various kinds of mixers promote different types of mixing. These include batch and continuous mixers and those with both fixed and variable geometries. Effective mixers often have complex geometries and several moving parts. Numerical simulation can provide velocity, shear rate, shear stress, temperature, and moisture content distribution within the mixer in a non-destructive manner which is a distinct advantage over experimental measurements that often disturb the fluid while acquiring data. One major limitation of numerical simulation is the increased computational requirement for more complicated simulations. Using a more complex mixer geometry and fluid increases the equipment and time cost, especially when the fluids being mixed are very viscous or viscoelastic.

In determining mixing efficiency, one can examine both dispersive and distributive mixing. Distributive mixing spreads particles throughout the mixer volume and is influenced by fluid stretching and reorientation. Measures of distributive mixing include length of stretch, stretching efficiency, and segregation scale. Dispersive mixing separates clumps or aggregates in the mixer through shear and elongational stresses (Alsteens et al., 2004). It is measured by the Manas-Zloczower mixing index.

Muzzio and his research group (Alvarez et al., 2002; Lamberto et al., 2001; Zalc et al., 2001; Portillo et al., 2008, 2009) have studied stirred tank reactors, static mixing flows, and mixing in laminar to turbulent flow regimes with generalized Newtonian fluids. These investigations have involved experimental and computational fluid dynamics (CFD) work. Lamberto et al. (2001) used a rotating reference frame technique to examine laminar mixing of a Newtonian fluid in an unbaffled stirred tank with an impeller. This study was comparable to simulations performed using a classical geometry and varying time-periodic boundary conditions. The objective was to observe the effect of varying speed on mixing performance. They found the toroidal structures which form at a constant impeller speed periodically relocated if the speed varied between two values. This relocation caused an exponential increase in stretching. Increasing the frequency of the speed fluctuation also increased the stretching rate. Simulation results were a close match to data obtained by particle image velocimetry (PIV) in a seeded glycerin solution.

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Nomenclature

v_x	velocity in the *x* direction (horizontal)	n	power-law index
v_y	velocity in the *y* direction (vertical)	λ_{MZ}	Manas-Zloczower mixing index
v_z	velocity in the *z* direction (axial)	$\boldsymbol{\Omega}$	vorticity tensor
$\mathbf{T}$	extra stress tensor	H	step function
$\mathbf{D}$	rate of deformation tensor	$\mathbf{v}$	velocity
η	dynamic viscosity	$\bar{\mathbf{v}}$	local moving part velocity
T	temperature	$\mathbf{a}$	acceleration
$\dot{\gamma}$	local shear rate	p	pressure
K	consistency factor	ρ	density
t	natural time	β	compression factor

More recently, Portillo et al. (2008) examined the mixing of acetaminophen and lactose in a continuous convective blender. Their goal was to see the effect of blade design, mixer rotation rate, and processing angle on mixing efficiency. Blended samples were taken at the blender outlet and analyzed using NIR to determine their composition. Relative standard deviation (RSD) of tracer concentration was used as a measure of homogeneity. Lower RSD was taken as an indicator of less sample variability and therefore better mixing. The variance reduction ratio (VRR) which is the ratio of the calculated variance for the material entering and exiting the mixer measures the ability of a mixer to eliminate variability found in the product before entering the mixer. The upward processing angle (where the exit of the mixer was positioned higher than the entrance) resulted in the largest mean residence time as well as the lowest RSD and highest VRR providing the best mixing performance. Increasing mixer rpm decreased the powder residence time but increased the number of blade passes it experienced resulting in more variability with increasing speed. Increasing the blade angle from 15° to 60° decreased the RSD, but above 60° the axial transport was not strong enough to continue the trend.

In comparing different blenders, Portillo et al. (2009) found that the effectiveness of a mixer was affected by the design of the impeller and blades. The blade angle relative to the shaft affected mixing performance Impeller rotation rate caused the most significant effect on relative variance, followed by powder cohesion, and then vessel angle. Rotation rate and processing angle significantly affected residence time, with rotation rate having a greater influence. A direct correlation was found between improved mixing and higher residence time.

Zhang et al. (2009) examined residence time distribution (RTD) of a co-rotating twin screw extruder using CFD and compared the data obtained with experimental results. They analyzed the distributive mixing performance of different kneading disc types by measuring the area stretch ratio, instantaneous efficiency and time-averaged efficiency. The researchers found that local RTD was affected by both operating conditions (screw speed and feed rate) and the geometry of the kneading discs used. Mean RTD increased while axial mixing decreased with increasing stagger angle of the kneading discs. Generally, kneading discs with a disc gap, small disc width, and large stagger angle produce good distributive mixing performance.

Previous numerical simulation work has frequently examined mixing behavior of simple fluid in simplified geometries. In our lab, geometries resembling those in industrial mixers have been used with Newtonian and non-Newtonian fluids (Connelly and Kokini, 2003, 2004, 2006a, 2006b, 2007; Connelly, 2004; Ashokan et al., 2003; Ashokan, 2008; Vyakaranam, 2012; Vyakaranam and Kokini, 2012; Vyakaranam, et al., 2012). Mixing in a Brabender Farinograph was explored numerically by Connelly (Connelly, 2004; Connelly and Kokini, 2004; Connelly and Kokini, 2006a, 2006b) using mesh superposition and particle tracking with a Newtonian fluid. The results were validated against laser Doppler anemometry (LDA) values obtained by Prakash and coworkers (Prakash, 1996; Prakash and Kokini, 1999, 2000; Prakash et al., 1999). Twin-screw mixers have also been simulated with more complex fluids. Successful simulation of mixing in a twin-screw mixer was performed using 2D finite element method (FEM) techniques; and these results were compared to those from previous 2D simulation of a single screw mixer (Connelly and Kokini, 2007). A generalized Newtonian Carreau fluid model was used in a mixed Galerkin FEM simulation.

Variation of mixing index with mixer operating conditions and configuration was not found to be significant (Cheng and Manas-Zloczower, 1997) but changing fluid rheology had an impact. The influence of rheology increased with non-Newtonian behavior (Prakash and Kokini, 1999). Viscoelasticity enlarged the areas of high mixing index, those with more elongational flow. Increased shear thinning caused greater areas of plug flow with low mixing index values. Shear stress was shifted in a viscoelastic fluid so that high shear stresses increased ahead of the blade and low shear stress moved behind the blade. Adding high values of shear stress to areas with elongational flow increased the dispersion ahead of the paddle. Conversely, increased shear stress magnitudes near the paddle tip increased the area of dead zones, thus hindering dispersion (Connelly and Kokini, 2004).

Recent work by Vyakaranam et al. (2012) has examined mixing in a Readco continuous mixer both experimentally and numerically. A high viscosity Newtonian corn syrup was used as the model fluid. Experimental measurements were made using LDA to determine fluid velocity and compared to values obtained via numerical simulation. Stagger angle of the mixer paddles caused local disruption but did not change global forward or reverse flow. Flow rate was found to be independent of stagger angle, but varied with screw speed. The axial component of velocity (v_z) was affected by stagger angle, but the horizontal component (v_x) and the vertical component (v_y) were unaffected.

2. Material and methods

2.1. Fluid rheology

This research focused on a non-Newtonian power-law fluid. Fluids that follow the power-law relation have a viscosity dependent on shear rate as found in the following equation:

$$\mathbf{T} = 2\eta(\dot{\gamma}, T)\mathbf{D} \tag{1}$$

where $\mathbf{T}$ is extra stress tensor, $\mathbf{D}$ is the rate of deformation tensor and η is dynamic viscosity, here a function of temperature T and local shear rate $\dot{\gamma}$ as seen below in Eq. (3). The extra stress tensor is isotropic and represents the effects of deformation on a material while being dependent on the gradient of fluid velocity and fluid

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