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Review paper

A review of dough rheological models used in numerical applications

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Abstract
The motivation for this work is to propose a first thorough review of dough rheological models used in numerical applications. Although many models have been developed to describe dough rheological characteristics, few of them are employed by researchers in numerical applications. This article reviews them in detail and attempts to provide new insight into the use of dough rheological models.

Nomenclature

A'	Relative increase in viscosity due to gelatinization, dimensionless	η	Apparent viscosity, $Pa.\sec$
b	Index of moisture content effects on viscosity, dimensionless	$\dot{\gamma}$	Shear rate, $\sec^{-1}$
D	Rate of deformation tensor	φ	Strain history, dimensionless
k_a	Reaction transmission coefficient, $°K^{-1}\sec^{-1}$	ψ	Time-temperature history, $K.\sec$
MC	Moisture content, dry basis, decimal	σ_0	Yield stress, Pa
MC_r	Reference moisture content, dry basis, decimal	u	Velocity, m/s
m	Fluid consistency coefficients, dimensionless	τ	Stress tensor
n	Flow behavior index, dimensionless	ΔE_v	Free energy of activation, cal/g mol
R	Universal gas constant, $1.987\ cal/g\,mol-K$	σ	Stress, Pa
α	Index of molecular weight effects on viscosity, dimensionless	λ	Relaxation time, sec

1. Introduction

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Bread is the most important daily meal of people in the world. Furthermore, improving the quality of bread baked products and the development of relevant apparatuses completely depend upon a comprehensive knowledge of dough rheology. Therefore, it is essential to gain a deep knowledge of dough behavior and to ensure the accuracy of the measured rheological data. However, finding a constitutive model that has all accurate molecular and structural arguments to simulate the linear and non-linear properties of wheat flour dough is a tough challenge due to the complicated nature of wheat flour doughs 0. The challenge is due to the fact that once water, wheat flour dough and small amount of ingredients such as salt, yeast, preservatives, etc. are combined, a cohesive viscoelastic substance is produced called dough. All of these ingredients can considerably change the rheological properties of the dough during mixing, and make it rheologically complex. In fact, the combination of these ingredients produces a three dimensional network called gluten which has a crucial role in complex viscoelastic behavior of wheat flour dough 0.

Despite these complexities, the rheology of wheat flour dough has been an important of scientific researches topics. Over the years, several efforts have been made to experimentally and theoretically evaluate dough properties that affect its flow behavior. In this approach, Schofield and Scott Blair [2-5] might be considered as pioneer researchers who studied the flow behavior of the wheat flour doughs. They also demonstrated that dough behaves both like a Hookean solid and also like a Newtonian liquid.

In order to provide information on the rheological properties of wheat flour dough, the measurement of dough material properties has been obtained using empirical instruments such as Farinograph, Alveograph, Extensigraph and Mixograph [6-8] and capillary rheometry (shear and extensional viscosities for dough) [9,10]. Kokini et al. have attempted to simulate and compare dough-like rheological materials using the Bird Carreau model [6, 8], the Wagner model [11], the White-Mezner model, the Giesekus-Leonov model [1,12] and the Phan-Thien-Tanner model [1,12,13]. In these studies they often employed the Brabender Farinograph to predict the measured rheological behavior of wheat flour dough at different moisture contents.

However, the limited application of their results and difficulties encountered in correlation between the quality of the baked products and values obtained from them complicate the task of characterizing the flow behavior of dough.

In 1954, Cunningham and Hlynka [14] tried to characterize the linear viscoelastic properties of dough using distribution of relaxation times. In order to characterize the viscoelastic properties of flour dough, Bagley and Christianson [15] used the BKZ elastic fluid theory. Thereafter, the upper convected Maxwell model was used by Bagley et al.[16]. Till 1990, the aim of studies had been to simulate the rheological properties of wheat flour dough without considering its non linear behavior. Dus and Kokini [6], therefore, tried to describe the steady state shear viscosity and oscillatory shear properties of hard flour dough using the five-parameter Bird-Carreau model. Bagley [17] used of the upper-convected Maxwell model to explain the dough behavior in biaxial extension flow.

Before 1995, less attention was paid to the measurements of uniaxial and biaxial extensional rheological properties of wheat flour doughs in the strain rates region [12]. Therefore, Wang and Kokini [11], showed that one can profit by using the Wagner model to predict transient shear properties and uniaxial and biaxial extensional rheological properties of gluten doughs and also to simulate nonlinear shear properties. Dhanasekharan and Kokini [13] used the Phan-Thien Tanner model as a more realistic model describing dough-like fluids for 3-D numerical modeling of viscoelastic flow in a single screw extrusion and then analyzed the effect of viscoelasticity considering a stationary screw and rotating barrel. Phan-Thien and Safari-Ardi [18] derived relaxation spectra from both dynamic and relaxation data for Australian strong flour-water dough and reported dynamic oscillatory and stress relaxation data [1,19].

Till that time, most of the reported models simulating the rheological properties of wheat flour doughs or their protein components had been either linear differential viscoelastic models like the generalized Maxwell models or nonlinear integral viscoelastic models such as the Bird-Carreau and Wagner models [19].
Using the Phan-Thien Tanner, White-Metzner model and the Giesekus model applied by Dhanasekharan et al. [12] to study whole wheat flour doughs, Dhanasekharan et al. 0 compared the validity of these models to predict the steady shear and transient shear properties of gluten dough. Using the theory of rubber elasticity, Leonard et al. [19] studied the rheology of wheat flour doughs at large extensional strains and reported an intermediate behavior between rubber elasticity and plastic flow for dough.
In order to evaluate the constitutive eqations introduced by Phan-Thien et al. [20], the large-strain oscillatory shear flow of flour dough was studied by Phan-Thien et al. [21]. Their results indicated that a model with a shear-rate dependent viscosity alone is inadequate to describe the response of flour dough since the material response is significantly non-linear which is mainly due to the strain softening behavior of the material. Furthermore, in order to be able to differentiate between different flour types, tests at large-strain deformations are required.
Although, the literature has explored numerous papers dealing with both theoretical and experimental methods of characterizing dough like materials, there are only a few scattered references devoted to evaluating the application of reported constitutive equations of wheat flour dough in numerical simulations. In characterizing dough behavior and its effects on different flow patterns, the most notable works belong to Kokini et al. [13, 22, 23, 24 and 26] and Phan-Thien et al. [18, 21, 25 and 26]. A numerical modeling of viscoelastic flow in a single screw extrusion conducted by Dhanasekharan and Kokini [13] can be considered as one of the earliest dough numerical simulations. Thereafter, Connelly and Kokini [23] conducted a simultaneous scale-up of mixing and heat transfer analysis of dough behavior in such a single screw extruder. In this study, in order to take into account the variations in the rheology of wheat flour dough, the Mackey and Ofoli viscosity model was applied. With regards to attempts to examine the mixing ability of single and double screw mixers, significantly Kokini et al. [23,24,26,27] examined the effects of shear thinning and differential viscoelasticity on dough mixing behavior.
For the first time, Binding et al. [28] examined the combination of numerical and experimental studies of dough kneading in a partially filled cylindrical mixer, with either one or two eccentric stirrers. The numerical procedure utilized a parallel numerical method based on a finite element semi implicit time-stepping Taylor-Galerkin/pressure-correction scheme. The same approach was then employed [29,30,31] to analyze the wetting and peeling of dough like material on solid surfaces considering the free surfaces, kinematics and stress fields produced by variations of stirrers' speed and changing geometry mixer. For fluid rheology, Carreau–Yasuda, constant viscosity Oldroyd-B and two shear-thinning Phan-Thien/Tanner constitutive models were employed. Velocity profiles and relevant peeling stress were calculated using laser scatter technology, Laser Doppler Anemometry (LDA) and a video capture technique. Results revealed good agreements between the numerical and experimental studies.
It is not feasible here to even attempt to review many of efforts that have been made to explore both theoretical and experimental ways of characterizing and evaluating dough; however, Bagley [9], Kokini [19] and Phan-Thien et al. [21] have cited some useful references.
Despite all these attempts, there is still a great need to understand the necessary constitutive equations to accurately describe wheat flour dough behavior. According to the author's knowledge, there is no work in the literature that has reviewed the rheological models used in numerical applications of dough like materials. Therefore, this study aims to review the constitutive equations applied in numerical simulations of dough flow behavior during, approximately, the period 1987-2007. The