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Hydrodynamics of a planetary mixer used for dough process: Influence of impeller speeds ratio on the power dissipated for Newtonian fluids

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ABSTRACT

The objective of this paper is to better characterize the influence of process parameters (impeller revolution speeds) on the performance of a planetary flour-beater mixer (mixer bowl P600 from Brabender) used in dough production.

Firstly, we have theoretically described the path followed by the impeller tip into the vessel and the variation of the absolute velocity during its trajectory. This gives us indications during the transient mixing action of the material induced by this mixer.

Secondly, we have theoretically and experimentally shown that for Newtonian fluids:

(i) The power dissipated by this mixer is strongly dependent on the impeller speed ratios.
(ii) It is possible to obtain for this planetary mixer a unique master power curve, gathering on the same characteristic the influence of the dual impeller speeds on power consumption. This requires the introduction of a characteristic velocity, known as the maximal impeller tip velocity, into power and Reynolds numbers. The constant K_p of the mixer bowl P600, determined as the product of the modified Reynolds and power numbers, was found to be equal to 48.6.

1. Introduction

Planetary mixers combining dual impeller revolution speeds are commonly used in the gluten network development but have rarely been investigated in depth as classical mixing systems (mixing equipments equipped in which the agitator is vertically and centrally mounted in the tank and performs a single revolutionary motion around the vertical axis).

Mixing wheat flour with water results in an even distribution of the ingredients and the development of a continuous network of gluten proteins within the dough (Sandstedt et al., 1954). According to Tipples and Kilborn (1975), mixing has three distinct functions in dough development: (i) distribution and homogenization of dough ingredients, (ii) hydration of flour particles, and (iii) energy input to develop the homogeneous protein structure. Several types of planetary mixers and off-centered double agitators are widely used in flour dough mixing processes. It is well known (Frazier et al., 1975; Jongen et al., 2003; Kilborn and Tipples, 1972; Lee et al., 2001; Oliver and Allen, 1992; Peighambardoust et al., 2006; Schluentz et al., 2000; Wilson et al., 1997; Zounis and Quail, 1997) that several process parameters strongly influence the gluten network and dough development: the design of mixing equipment, which mainly determines the type of dough deformation, the material properties and the mixing variables, such as mixing speed.

Among the mixing variables, we recently showed that the instantaneous power delivered to a dilute flour–water dough is a key parameter to control the process of dough development (Auger et al., 2008). This work was done using a particular planetary mixer, which combines two parallel revolutionary motions around a vertical axis: the mixer bowl P600 from Brabender that we used to mix flour doughs. Therefore, characterizing the power consumption of this particular mixer and, especially, quantifying its dependence on mixing speed is an essential step towards optimizing wheat dough development.

Characterizing the power consumption of a stirred tank requires the knowledge of the Newtonian power curve of the mixing

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Nomenclature

d	agitator diameter (m)
d_G	diameter of the gyrational motion
d_R	diameter of the rotational motion (m)
C	bottom clearance between the tank and the agitator (m)
H	height of the blade (m)
H_L	height of liquid in the vessel (m)
H_T	height of the impeller tip of the hook (m)
K_p	proportionality constant of the power number defined by Eq. (12) (–)
l	altitude of the point M in the reference frame R (m)
N	rotational speed of the drive shaft for classical mixing system (rev s^{-1})
N_G	rotational speed of the gyrational motion (rev s^{-1})
N_p	power number (–)
N_{pM}	modified power number for the mixer bowl P600 (–)
N_R	rotational speed of the rotational motion (rev s^{-1})
Ns	rotational speed of the drive shaft for planetary mixer (rev s^{-1})
P	power consumption of the mixer (W)
R_e	Reynolds number (–)
R_{eM}	modified Reynolds number for the mixer bowl P600 (–)
R_G	radius of the gyrational motion (–)
R_R	radius of the rotational motion (–)
t	time (s)
$u_{impellertip}$	instantaneous impeller tip speed of the hook (m s^{-1})
u_{ch}	characteristic velocity of the impeller (m s^{-1})
α	gyrational angle (Rad)
β	rotational angle (Rad)
μ	apparent dynamic viscosity (Pa s)
Γ	torque acting on the drive shaft (N m)
θ	temperature (°C)
ρ	fluid density (kg m^{-3})

system, which is the plot of the power number versus the Reynolds number. With classical mixing equipment, in which the agitator is vertically and centrally mounted in the tank and performs a single revolutionary motion around the vertical axis, the determination of such dimensionless numbers is actually well established from mixing torque/speed measurements obtained with known Newtonian fluids. Unfortunately, it is not yet the case for planetary mixers. Indeed, such a characteristic power curve does not exist, to our knowledge, for planetary mixers used in dough mixing in general, and not for the mixer bowl P600 in particular. This state of knowledge may be explained partially by the fact that planetary mixers are more recent mixing equipments, and that analysis of their mixing characteristics have appeared only recently in the literature. However, this mixing equipment is taking a big sweep in the processing industry, fulfilling the needs of consumers for complex products with specific functionalities.

Pioneer works have been conducted on planetary mixers by Tanguy et al. (1996), but scientific studies devoted to the performances of this mixing equipment are still scarce in the literature (Delaplace et al., 2004, 2005, 2007, 2011, 2012; Jongen, 2000; Tanguy et al., 1996, 1999). These experimental and numerical works have clearly highlighted the difficulties of comparing the mixing performances of planetary mixers with those of well-established conventional mixers. This is mainly due to the fact that dual revolutionary motions of the agitator, characteristic of a planetary mixer, induce an increase in the number of the relevant process parameters required to perform the dimensional analysis. To solve this difficulty, Delaplace et al. (2005, 2007) modified the dimensional analysis established for classical mixers and adapted it for non-conventional mixers. This was done for a particular planetary mixer: the TRIAXE® system, which combines two perpendicular revolutionary motions around a horizontal axis. These authors proposed modified Reynolds, power and mixing time numbers, which involved the maximum impeller tip speed as the characteristic velocity and a dimension perpendicular to the vertical axis of revolution as the characteristic length. These authors showed experimentally that such modified dimensionless numbers allowed us to obtain a unique power and mixing characteristics of the TRIAXE® system, regardless of a variation in speed ratio. Moreover, the modified dimensionless numbers proposed by these authors were consistent with the definition of classical Reynolds, power and mixing time numbers if the impeller was forced to perform only one motion around the vertical axis of the tank, as in the case for a classical mixing system.

To our knowledge, such an approach has not been applied for other planetary mixers, and not for the planetary mixer bowl P600. In this paper, we propose to use and develop the methodology proposed by Delaplace et al. (2005), on the particular mixer bowl P600 from Brabender. This mixing system was used in a previous paper to mix flour doughs (Auger et al., 2008). However, we can note that the revolutionary motion performed by the mixer bowl P600 is quite different from the one performed by the TRIAXE® system studied by Delaplace et al. (2005), since revolution axes of the hook shaped planetary mixer are parallel, whereas they are perpendicular in the case of the TRIAXE® system. Moreover, the geometry of the agitator is also strongly different. Consequently, the aim of this paper is:

(i) To propose a characteristic velocity for this planetary dough, such as the pi-space describing the power consumption of the hook shaped planetary mixer, is described only by a modified power and Reynolds numbers. In particular, attention will be paid to the ways of obtaining the characteristic velocity for this planetary dough mixer.
(ii) To ascertain the reliability of the modified dimensionless numbers proposed from experimental measurements of the power consumption obtained with the mixer bowl P600 by mixing several Newtonian fluids.

2. Materials and methods

2.1. Mixing equipment

The mixing equipment used was a planetary mixer bowl P600 (Brabender OHG, Germany) equipped with a helicoidal dough hook (Kenwood stirring insert, Brabender OHG, Germany) and thermostated with a water double jacket (see Fig. 1).

This mixer is usually used in non-food area for testing the properties of plastic powders, like their liquid absorption or their plasticizer absorption rate but we recently used it for mixing flour–water doughs. The mixer was coupled to a Plastograph lab-station (Brabender OHG, Germany) which allowed continuous torque, speed and temperature recording. The experimental temperature (25 °C or 40 °C) varied according to the tested fluid (Table 1).

The hook displacement is characterized by two parallel revolutionary motions, gyration and rotation, around the vertical central axis. Gyration is the revolution of the vertical axis of the hook