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Model emulsions to study the mechanism of industrial mayonnaise emulsification

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ABSTRACT

Mechanistic understanding of industrial food-emulsification is necessary for optimal operation and design. Industrial mayonnaise production is yet poorly understood, partly due to a lack of experimental data and partly due to the complexity of the product.

This study suggests a systematic method for building mechanistic insight, by investigating successively more complex model emulsions in industrial rotor–stator mixers, comparing to idealized theories identifying points of departure. As a first step, a high volume fraction (>50%) and high viscosity (>100 mPa s) model emulsion with a non-ionic surfactant acting as emulsifier is investigated in two industrial-scale mixers (one batch and one continuous inline mixer) at varying rotor tip-speeds.

The resulting drop diameter to rotor tip-speed scaling suggest turbulent viscous fragmentation of the model emulsion in both mixers despite the high volume fraction of disperse phase which could be expected to lead to significant non-idealities such as extensive coalescence and concentration effect-dominated fragmentation. If the other non-idealities (e.g. egg yolk emulsifying system and non-Newtonian rheology) would not influence the emulsification, this suggests the same mechanism for mayonnaise emulsification. An outline for continued work on successively more complex model-emulsions is discussed in order to further enhance understanding.

1. Introduction

Mayonnaise is a high volume fraction ($\varphi_D \approx 80\%$ (v/v)) oil-in-water (o/w) food emulsion (McClements, 2005; Walstra, 2005). It is one of the commercially most important food emulsion in terms of production volume due to its use as ingredient in dressings and sauces. Due to high product viscosity, industrial production takes place in batch or continuous rotor–stator mixers (RSMs) (Schultz et al., 2004). Despite substantial research on how composition influences product characteristics (Depree and Savage, 2001; Harrison and Cunningham, 1985; Wendin et al., 1997), mechanistic understanding of mayonnaise emulsification is limited, especially for non-laboratory scale equipment.

For less complex products (i.e. low disperse phase volume fraction emulsions with an excess of emulsifier), mechanistic insight has been obtained from experimental investigations of the scaling between resulting emulsion drop sizes and operating conditions (e.g. rotor tip-speed), and from comparing these to theoretical scaling laws (Boxall et al., 2012; Rueger and Calabrese, 2013a,b; Santana et al., 2013).

Fragmentation dominated emulsification is described as taking place in different regimes (Hinze, 1955; Walstra, 2005) depending on local hydrodynamic conditions and emulsion

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Abbreviations: LV, laminar viscous; RSM, rotor–stator mixer; TI, turbulent inertial; TV, turbulent viscous.

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Nomenclature

Symbols Latin

A	empirical constant (–)
A_{jet}	turbulent stator-jet base area (m^2)
D_{max}	maximum drop diameter (m)
D_{vx}	limiting drop diameter, xx % of the drop volume belong to smaller drops (m)
G	shear rate (s^{-1})
K	flow consistency index (Pa s^n)
L_{jet}	turbulent stator-jet length (m)
n	flow behavior index (–)
P	mixer power input (W)
q	scaling parameter in Eq. (7) (–)
Q_{slot}	volumetric flow through a stator slot (m^3/s)
U	rotor tip-speed (m/s)
V_{diss}	dissipation volume (m^3)

Greek

δ	rotor–stator clearance (m)
ε	dissipation rate of turbulent kinetic energy (m^2/s^3)
η	Kolmogorov length-scale (m)
λ	viscosity ratio (–)
ρ	density (kg/m^3)
σ	interfacial tension (N/m)
φ_D	volume fraction (–)
μ	viscosity (Pa s)

Sub- and superscripts

C	continuous phase
D	disperse phase
E	emulsion

properties; by laminar viscous (LV), turbulent inertial (TI) or turbulent viscous (TV) fragmentation. Theoretical correlations between the dissipation rate of turbulent kinetic energy (ε) and the maximum stable drop diameter (D_{max}), is available for each (Boxall et al., 2012; Davies, 1985; Hinze, 1955; Taylor, 1934; Vankova et al., 2007; Walstra, 2005):

$$D_{max}^{(TI)} = A_{TI}\rho_C^{-3/5}\varepsilon^{-2/5}\sigma^{3/5} \tag{1}$$

$$D_{max}^{(TV)} = A_{TV}(\lambda)\,\mu_C^{-1/2}\rho_C^{-1/2}\varepsilon^{-1/2}\sigma \tag{2}$$

$$D_{max}^{(LV)} = A_{LV}(\lambda)\,\mu_C^{-1}G^{-1}\sigma \tag{3}$$

where σ is the interfacial tension, ρ_C is the continuous phase viscosity, μ_D and μ_C are dynamics viscosities of disperse and continuous phase respectively and $\lambda = \mu_D/\mu_C$). The constant A_{TI} is approximately 1 (Hinze, 1955), and at low disperse phase to emulsion viscosity, both A_{TV} and A_{LV} are approximately 1 (c.f. Vankova et al., 2007, p. 377). For concentrated emulsions such as mayonnaise, the continuous phase viscosity in Eqs. (1)–(3) should be substituted with the emulsion viscosity (Jansen et al., 2001; Tcholakova et al., 2011).

However, simply comparing scaling of resulting drop diameter with operating conditions is not expected to give significant insight for the mayonnaise system since it departs on so many points from the assumptions of the theoretical models, e.g. mayonnaise displays non-Newtonian rheology (Cedergårdh, 2014; Pons et al., 1994; Singla et al., 2013), has a high volume fraction of oil expecting to give rise to substantial re-coalescence during emulsification (Håkansson et al., 2016; Niknafs et al., 2011), and the emulsifier system is a complex mixture of colloidal egg proteins (Magnusson and Nilsson, 2011; Nilsson et al., 2007), not easily described using a static interfacial tension. Since neither of the models (Eqs. (1)–(3)) describe these non-idealities found in mayonnaise, it is far from obvious that they would apply. Furthermore, the idealized models (Eqs. (1)–(3)), assume that the emulsification can be accurately described using the dissipation rate of turbulent kinetic energy only and that the intricate details of mixer and vessel design (Mortensen et al., 2011; Utomo et al., 2008) does not influence the result except through this measure.

An alternative methodology for gaining mechanistic insight, a first step of which is presented here, is to study a set of experimental model systems with increasing complexity in order to find where the models start to deviate from the simplistic models and stepwise build an understanding of the whole system. The objective of this first study is to investigate the mechanism of a high-volume fraction mayonnaise model emulsion produced in two different industrial-scale batch and continuous RSMs (with similar dissipation rate of turbulent kinetic energy) in order to discuss implications on the mechanism of mayonnaise production and clarify directions towards further investigations.

2. Materials and methods

2.1. *Rotor–stator mixers and emulsification experiments*

Model emulsions were processed in two industrial rotor–stator mixers, a 25 L batch RSM (Tetra High shear mixer, Tetra Pak Scanima, Aalborg, Denmark), and a continuous inline RSM (Tetra High shear mixer, Tetra Pak Scanima, Aalborg, Denmark), both run at rotor tip-speeds between 10 and 30 m/s.

Batch RSM model emulsions (see Section 2.2) were pre-emulsified running the rotor at a low tip-speed (8 m/s) in the mixer and then emulsified at the desired tip-speed by running, stopping and sampling the emulsion after 0, 20, 40, 60, 360 and 540 s of processing time.

The continuous mixer pre-emulsions (200 L) were produced with gentle shearing using a high speed mixer. A flow-loop was constructed with two tanks, the continuous RSM and piping allowing the content of one tank to be transferred, over the mixer, to the other tank, or to be recirculate over the mixer and one of the tanks. Five to eight single passage experiments were carried out for each operating condition; the entire emulsion volume was passed from one tank to the other and samples were taken after each passage. After this, the emulsion was recirculated over the RSM and one tank for up to 36 min and samples were withdrawn regularly.

Both systems were equipped with a water-cooling jacket to ensure constant temperatures (20 °C).

2.2. *Model emulsion*

The model emulsion was formulated by dispersing rapeseed oil (AAK Sweden AB, Karlshamn, Sweden) in a 65% (w/w) aqueous sugar solution (Nordic Sugar A/S, Copenhagen, Denmark). The sugar concentration was chosen in order to obtain a Newtonian continuous phase viscosity similar to the non-Newtonian apparent viscosity at the shear rates experienced in the rotor–stator region. With a rotor tip-speed of