Journal of Food Engineering 195 (2017) 31–39

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Scale-down failed – Dissimilarities between high-pressure homogenizers of different scales due to failed mechanistic matching

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ARTICLE INFO

Article history:
Received 22 March 2016
Received in revised form
22 July 2016
Accepted 19 September 2016
Available online 22 September 2016

Keywords:
High-pressure homogenization
Scale-up
Emulsification
Fluid dynamics
Fragmentation

ABSTRACT

The high-pressure homogenizer (HPH) is used extensively in the processing of non-solid foods. Food researchers and producers use HPHs of different scales, from laboratory-scale (~10 L/h) to the largest production-scale machines (~50 000 L/h). Hence, the process design and interpretation of academic findings regarding industrial condition requires an understanding of differences between scales. This contribution uses theoretical calculations to compare the hydrodynamics of the different scales and interpret differences in the mechanism of drop-breakup.

Results indicate substantial differences between HPHs of different scales. The laboratory-scale HPH operates in the laminar regime whereas the production-scale is in the fully turbulent regime. The smaller scale machines are also less prone to cavitation and differ in their pressure profiles. This suggest that the HPHs of different scales should be seen as principally different emulsification processes. Conclusions on the effect or functionality of a HPH can therefore not readily be translate between scales.

1. Introduction

The high-pressure homogenizer (HPH) is used extensively for emulsification, dispersion and particle disruption in low to intermediate viscosity food processing. Applications include volumetrically large products such as milk, as well as smaller or specialized emulsion foods.

HPHs are available in different scales. Small-scale laboratory HPHs are used in academic research and in the early phases of industrial product development. These are typically run at ~10 L/h. Large production-scale HPHs used in high-volume processing (i.e. milk and fruit juices) range up to ~50 000 L/h. Meanwhile, intermediary pilot-scale HPHs (~100 L/h) are used as a stage in scale-up and for processing of specialty products (cf. Phipps, 1982a; Walstra, 1975).

From an industrial viewpoint, it is important to understand any difference between HPHs of different scales. Product development often starts from experiments on laboratory-scale machines, and efficient process development requires similarity, or at least a fundamental understanding of differences when scaling up to production-scale in later stages. Understanding differences between scales also becomes important when interpreting the relevance of academic research findings on technical high-pressure homogenization since academic studies, e.g. on the effect of new emulsifiers, improved designs, modelling frameworks or functional formulations, are often conducted in laboratory-scale HPHs.

Significant advances have been made in the last decade in clarifying the mechanism of emulsification in HPHs, for example, through single-drop visualizations (Budde et al., 2002; Innings and Trägårdh, 2005; Innings et al., 2011a; Kelemen et al., 2015b), velocity field-measurements (Gothsch et al., 2016; Håkansson et al., 2011; Innings and Trägårdh, 2007; Kelemen et al., 2015a), CFD-calculations of velocity fields (Håkansson et al., 2012; Steiner et al., 2006; Taghinia et al., 2015) and emulsification modelling (Håkansson et al., 2009; Janssen and Hoogland, 2014; Raikar et al., 2009). However, none of these studies have elaborated on potential differences between HPH scales, and often, a single geometrical setting or flow condition is considered to be representable of the general HPH. Due to the substantial differences in volumetric flowrate (10–10 000 L/h), mechanistic differences could be expected and need to be better understood in order to ensure the efficient food-emulsification scale-up in industrial production. Moreover, some academic disagreement remains as to the mechanism of emulsification in HPH (see discussion in Håkansson, 2015). It could be hypothesized that the presence of significant differences between scales could help explain these remaining controversies.

The objective of this contribution is, first, to investigate how

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http://dx.doi.org/10.1016/j.jfoodeng.2016.09.019
0260-8774/

HPHs of different scales differ in terms of hydrodynamic parameters of relevance for food emulsification using previously established and experimentally verified hydrodynamic models. Secondly, by comparing these primary findings to existing velocity-field and breakup-visualization literature, the aim is to discuss differences in emulsification mechanism between HPHs of different scales. This will be done in order to improve our understanding of both food emulsification equipment design and improve our ability to interpret scale-up experiments.

1.1. The valve HPH

The design and operation of the valve-HPH has been comprehensively described elsewhere (e.g. Håkansson, 2015; Innings, 2015; McClements, 2004; Phipps, 1985). In summary, a pre-emulsion is forced radially through a narrow gap under high pressure (see Fig. 1). The fluid accelerates into the inlet chamber, enters the gap at high velocity and exits as a jet discharging into the outlet chamber. A displacement pump (often in the form of one to five piston pumps) is responsible for creating the high inlet pressures required to overcome friction losses in the valve and ensure a high gap velocity. HPHs often consist of two serially mounted valves, where the second valve is used for creating a back-pressure for the first. Cavitation is known to take place in and downstream of the gap but is suppressed by applying back-pressure (Gothsch et al., 2016; Håkansson et al., 2010; Innings et al., 2011b). Different suggestions on what causes fragmentation have been given, for instance, a laminar deformation-driven breakup (Phipps, 1975), turbulent interactions (Walstra, 1969) or cavitation (Kurzhals, 1977). Break-up visualizations indicate a breakup taking place downstream of the gap exit, from either turbulent or laminar mechanisms (Budde et al., 2002; Innings and Trägårdh, 2005; Innings et al., 2011a; Kelemen et al., 2014, 2015a, 2015b).

1.2. HPH-experiments on differences between scales

Many empirical studies on emulsification are available in the literature. However, few of these discuss differences between HPH scales. Independent of scale, studies generally reveal a constant scaling of applied homogenizing pressure to the resulting drop size (Phipps, 1985; Walstra, 1975; Walstra and Smulders, 1998),

$$d_{32} \propto \Delta P^{-q}, \tag{1}$$

for low to intermediate volume fractions of the disperse phase (<10–12% for milk, Phipps, 1985). A common claim in HPH-literature is that smaller machines have higher q-values (Walstra, 1975). This has been interpreted as a shift between regimes of turbulent fragmentation, from turbulent inertial (TI) to turbulent viscous (TV) (Walstra and Smulders, 1998). However, the empirical base for this interpretation is limited (see Walstra and Smulders, 1998, p. 74) and sometimes lacking (Phipps, 1982a, 1982b). Systematic empirical emulsification studies compared from a laboratory scale-up to true modern production-scale are still lacking, most likely due to the large cost of performing production-scale experiments. Theoretical comparisons could therefore offer a promising starting point in understanding differences between HPHs of different scales.

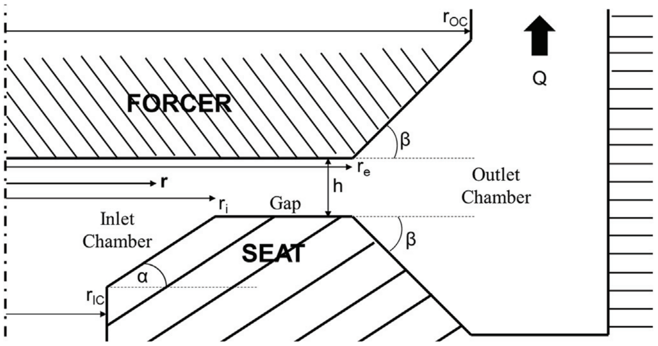

Fig. 1. Not to scale schematic drawing of the narrow-gap HPH valve geometry. Table 1 gives relevant dimensions for the different HPH scales.

2. Calculations

Hydrodynamic calculations were carried out for three representative HPH scales; a laboratory-scale, a pilot-scale and a production-scale HPH (see Table 1). The laboratory-scale is comparable to the bench-top HPHs used in academic research, for example the SPX APV Model 2000 (SPX, Charlotte, NC). The pilot-scale corresponds to the smaller industrial HPH (~100 L/h) (Innings and Trägårdh, 2007; Phipps, 1982a) and the production-scale corresponds to the largest production scale with flowrates ~10 000 L/h, cf. SPX Gaulin 185Q (SPX, Charlotte, NC), GEA Ariete NS5355 (GEA Niro Soavi, Parma, Italy) or Tetra Alex 400 (Tetra Pak Processing Systems, Sweden, Lund). Homogenizing pressures between 5 MPa and 45 MPa (first stage homogenizing pressures) were considered.

Gap heights are set implicitly in the HPH operation by adjusting the homogenizing pressure and volumetric flowrate. In the calculations, gap-height was obtained by solving for h (given r_i, r_e, Q and ΔP) in (Phipps, 1975)

$$\Delta P = \Delta P_{IC} + \Delta P_{gap} + \Delta P_{OC} = \frac{\rho}{4}\left(\frac{Q}{2\pi \cdot r_i \cdot h}\right)^2 + \Delta P_{gap} + \frac{\rho}{2}\left(\frac{Q}{2\pi \cdot r_e \cdot h}\right)^2, \tag{2}$$

where

$$\Delta P_{gap} = \begin{cases} \dfrac{6\rho\upsilon Q}{\pi h^3}\ln\dfrac{\mathrm{r_e}}{r_i} & \mathrm{Re}_i < 500 \\ \dfrac{5\rho\upsilon^{3/5}}{h^3}\left(\dfrac{Q}{2\pi}\right)^{7/5}\left(\dfrac{1}{r_i^{2/5}} - \dfrac{1}{r_e^{2/5}}\right) & \mathrm{Re}_i > 500 \end{cases}, \tag{3a}$$

$$\mathrm{Re}_i = \mathrm{Re}\frac{r_e}{r_i}, \tag{3b}$$

using a numerical trust-region non-linear equation solver (fsolve) used as implemented in MATLAB 2015a (MathWorks, Natick, MA) with a tolerance of 10^{-6}.

The average velocity in the valve at radial position, r, is obtained from

Table 1
Three HPH scales.

	Notes	Laboratory-scale	Pilot-scale	Production-scale
Q [L/h]		10	100	10 000
r_i [mm]	1	2.0	3.0	14
r_e [mm]	1	2.5	4.0	15
L_g [mm] (=r_e−r_i)		0.5	1.0	1.0
α [°]	2	30	30	30
β[°]	2	45	45	45

1) Pilot-scale and production-scale dimensions obtained from Innings and Trägårdh (2007). Laboratory-scale dimensions are assumed from measurement of a SPX APV Model 2000.
2) Assumptions based on Phipps (1985). This only influences the acceleration and deceleration rate in inlet and outlet chamber of Fig. 3.