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Applications of hydrodynamic cavitation for instant rehydration of high protein milk powders

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ABSTRACT

The aim of this study was to evaluate the effectiveness of an in-line hydrodynamic cavitation (HC) system, for rehydration of milk protein concentrate powders (MPC) at semi-industrial pilot scale. MPC powder was dispersed in water at 50 °C at 20% (w/w) dry matter (DM) with two commonly used high-shear powder inductors/mixers. The MPC dispersions created were then passed through the HC system to assess subsequent hydration behaviour of the MPC powders. Particle size distribution (PSD) of MPC dispersions prepared using conventional high-shear mixing indicated that complete rehydration of MPC powders was not achieved, with an average D_{90} and $D_{[4,3]}$ values of 21.17 μm and 5.62 μm respectively, observed in MPC dispersions. In contrast MPC dispersions subjected to HC had a PSD indicative of complete rehydration, with an average D_{90} and $D_{[4,3]}$ values of 0.45 μm and 0.19 μm, respectively. Apparent viscosity decreased significantly ($p \leq .05$) post HC compared to dispersions subjected to conventional high shear mixing. Phase separation profiles showed that HC treated MPC dispersions had increased stability to sedimentation compared to high-shear treated samples. Wetting, immersion, dissolution and solubilisation of high protein powders occurred instantaneously (and simultaneously) during HC. This emerging technology has the potential to achieve complete rehydration of powders in significantly less time than conventional rehydration processes employed by dairy and other industries.

1. Introduction

Rehydration characteristics are often considered a critical attribute in the overall determination of quality in dairy powders. Complete powder rehydration is usually a pre-requisite for effective expression of a dried protein ingredient's underlying functionality (Crowley et al., 2015). MPC powders provide casein and whey proteins in the same ratio as milk and are used in a wide variety of nutritional formulations such as infant milk formula, non-fat yogurts, dairy based beverages, sports and nutritional products (Baldwin and Pearce, 2005; McCarthy et al., 2014; Mistry, 2002; Sharma et al., 2012). MPC powders are produced from skim milk by a combination of filtration, evaporation and spray drying (Anema et al., 2006; Baldwin and Truong, 2007; Crowley et al., 2015; Udabage et al., 2012). Typically MPC powders exhibit poor wettability, dispersibility and cold water solubility, with rehydration properties that deteriorate during storage (Bouvier et al., 2013; Ji et al., 2016; McCarthy et al., 2014).

Several authors have indicated that during rehydration of high protein powders a substantial fraction of the powder remains undissolved, with flotation, sedimentation and aggregation (lumps/clumping) phenomena rife when subjected to normal conditions of rehydration (room temperature, moderate agitation, < 1 h) (Bouvier et al., 2013; Havea, 2006; Ji et al., 2016). It has been reported in the literature that high protein milk powders can take >9 h or longer at ~5% (w/w) dry matter to fully rehydrate, as confirmed by light scattering measurements (Gaiani et al., 2007; Jeantet et al., 2010). Insolubility in powders is driven by a number of physico-chemical changes, which occur during the spray drying of high protein dairy concentrates like MPC. Structural changes such as protein reorientation (during spray drying) alter rehydration dynamics and retard the recovery of the native protein form, a phenomena which is compounded by low levels of (soluble) lactose in MPC, which acts to stabilise protein structure during drying. Additionally, concentration processes like spray drying alter the ionic environment of the casein micelle, modify protein charge distribution and reactivity of ionic species, and thereby influence

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rehydration kinetics (Baldwin and Truong, 2007). Rehydration behaviour can continue to evolve post drying, particularly in casein dominant powders where loss of solubility during storage has been attributed to the formation of a surface skin comprised of closely packed and cross-linked micelles (Baldwin, 2010; Baldwin and Truong, 2007; Mimouni et al., 2010a, 2010b).

Improvement in solubility can be achieved by a combination of dissolving at high temperatures, applying mechanical energy in the form of high shear and/or increasing rehydration time (to several hours), which may not be practical or economically feasible for many food processors. Many studies have investigated ways to modulate rehydration behaviour through exploitation of the chemistry and behaviour of milk components, through alteration of the ionic environment pre- and post-drying (Bhaskar et al., 2001; Mao et al., 2012; Marella et al., 2015; Schuck et al., 2002) or through addition of whey proteins (Gaiani et al., 2007). Technological solutions also improve cold solubility of MPC powders and include static high pressure treatment (Udabage et al., 2012), high intensity ultrasonication (Augustin et al., 2012; McCarthy et al., 2014; Richard et al., 2013), homogenisation and microfluidisation (Augustin et al., 2012) and extrusion porosification (Bouvier et al., 2013).

Increasing mechanical agitation during powder dissolution helps decrease rehydration time by promoting turbulence and facilitating solubilisation of powder particles in the liquid media (Richard et al., 2013). Hydrodynamic cavitation, which generates similar effects as well-established, acoustic cavitation methods, can be used for intensification of different chemical and physical processing applications across different industries (Gogate, 2011; Iskalieva et al., 2012). Cavitation is the formation, growth and violent collapse of bubbles in a liquid medium and occurs at millions of locations in the reaction zone, simultaneously generating localised high temperature and pressure. In a heterogeneous solid/liquid system (water/powder), such as an MPC dispersion, collapse of cavitation bubbles at or near the powder surface results in significant structural and mechanical disruption of powder particles. This provides sufficient energy for particle erosion and fragmentation, allowing access to additional powder substrate by the aqueous media, which promotes solubilisation through efficient mixing and enhanced mass transfer (Iskalieva et al., 2012).

The present study describes previously unreported applications for hydrodynamic cavitation, as a novel technology for the instantaneous rehydration of high protein powders. Hydrodynamic cavitation is an emerging process technology and its effectiveness in applications such as waste water treatment, water disinfection, delignification, and formulation of Greek style yogurts has been reported in the literature (Chakinala et al., 2008; Loraine et al., 2012; Meletharayil et al., 2016; Saharan et al., 2013; Zupanc et al., 2013). Its application in dairy powder rehydration has not been investigated to date. Additionally it has been reported that cavitation provides more efficient conversion of electrical energy to heat and shear compared to conventional high shear processes (Badve et al., 2014). Moreover, rehydration of MPC has been studied previously but dry matter addition levels during reconstitution have been low (1.15–5.0% (w/w)). This study provides insights into the potential applications of hydrodynamic cavitation at semi-industrial pilot scale for the instantaneous rehydration of MPC80 at dry matter contents up to 20% (w/w), a level typical of many commercial process applications.

2. Materials and methods

2.1. Materials

Milk protein concentrate powder with 80% protein content (MPC80) was obtained from a local dairy supplier in Ireland. The protein, moisture, fat, lactose and ash content of the MPC were 80.63% (w/w), 4.38% (w/w), 1.38% (w/w), 4.9% (w/w) and 7.54% (w/w), respectively.

2.2. Dispersion of MPC80 powders

MPC powder was rehydrated in RO (reverse osmosis) water at 50 °C to obtain a dispersion of 20% w/w DM (dry matter) content. Two commonly used high-shear mixers were used for the dispersion of MPC powders and are discussed as follows:

High-shear mixing process 1 (HS1) – Dispersion of MPC80 was carried out by weighing 240 kg of RO water in a 600 L capacity, jacketed, stainless steel tank. The tank was attached to a continuous in line Crepaco mixer (APV Pulvermixer, SPX Flow Technology, Pasteursvej, Silkeborg, Denmark). MPC80 powder (60 kg) was inducted directly into the recirculating liquid stream as it passed through a high shear mixing head, with a “squirrel cage” deign. The dual blending action combines swirl with a deep-draw vortex that rapidly disperses milk powder into the aqueous phase with minimal foaming (Tamime and Robinson, 1999). Once dispersed, the solution was recirculated for 10 min.

High shear mixing process 2 (HS2) – Dispersion of MPC 80 (30 kg) was carried out in a 180 L capacity, jacketed, stainless steel tank, containing 120 kg of RO water. A high shear mixer (Silverson EX, Silverson Machines Ltd, UK) equipped with a dispersion head (120 mm × 55 mm) operating at 2075 rpm was lowered into the tank, below the liquid surface. MPC powder was added manually to the tank, whereby the high-shear action of the Silverson mixer rapidly dispersed agglomerates, whilst constantly exposing an increasing surface area of powder to the surrounding liquid (Tamime and Robinson, 1999). Following dispersion of the MPC80 powder, the solution was further mixed under high-shear for 10 min. Two separate batches of 150 kg were prepared to obtain an overall batch size of 300 kg for each trial.

2.3. Hydrodynamic cavitation

Rehydration of MPC dispersions was carried out using an SPX hydrodynamic cavitator (Model P286184-12” R4, SPX Flow Technology, Pasteursvej, Silkeborg, Denmark) equipped with a proprietary dispersion head (300 mm diameter), consisting of 160 discrete fluid channels which, based on rotational speed, govern the cavitational forces applied to the product. The rotor speed, which determines the extent of cavitation, was driven by a 30 kW motor, controlled by a variable frequency drive. The gap between the rotor and outer casing was 3 mm. MPC 80 dispersions from HS1 and HS2 were supplied to the cavitator *via* a centrifugal feed pump. The flow rate, and hence residence time in the cavitation zone, was controlled by a manual, back-pressure valve on the system outlet.

At high rotational speed, two counteracting forces are generated in the dispersion head. High fluid velocities created by rotation of the dispersion head, force liquid into the radial fluid channels, while opposing centrifugal forces create an impetus for expulsion of the liquid from the channels. These counteracting forces lead to compression and relaxation of the liquid and create regions of high and low pressure resulting in the formation of bubbles. Cavitation is the formation, growth and collapse of these bubbles leading to an energy interchange, which is resolved by an increase in temperature and shear in the fluid channels. Optimal operational conditions for the cavitator were determined from preliminary trials (data not shown). MPC dispersions (50 °C) were cavitated at a flow rate of 850 L/h, at a motor frequency of 48.8 Hz, (77% of nominal motor capacity), electrical current of 30.7 A and a rotor speed of 2914 rpm. System back-pressure was maintained at 2.4 bar, while average ΔT