Homogenisation in the dairy process - conventional processes and novel techniques

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Abstract

Milk and dairy products are typical examples of high pressure homogenized commodities. High pressure homogenization is therefore a well established process and realized at around 10 Mio tons per year in the dairy industry. Milk and dairy products are homogenized to improve product properties such as color, consistency, taste, creaming stability, creaminess and mouthfeel [1]. The basic idea of high pressure homogenization is to pressurize an emulsion premix up to several hundred bars and then pump it through a disruption system (full stream homogenisation). State of the art as disruption systems are flat valves. Besides conventional flat valves a simple or complex orifice type of valves like the interaction chamber of Microfluidics® may also serve as disruption system [2]. Within the talk, different disruption systems will be compared with regard to disruption effectiveness and power efficiency. As high pressure is required for droplet disruption into the submicron range high investment, energy and maintenance costs result from high pressure homogenization processes. The product active ingredients are subjected to intense mechanical and thermal stresses. Problems in term of costs, maintenance and ingredient degradation may be overcome by a novel micro-structured orifice called “Simultaneous Emulsification and Mixing” (SEM) [3], which will be presented in the second part of the talk. It combines the two unit operations ‘mixing’ and ‘emulsification’ in one single process unit, which results in significant energy and cost reduction, product quality improvement and process intensification. For this, an additional stream (e.g skim milk for dairy processes) is injected directly into the droplet disruption zone of a high-pressure disruption system. The design of these SEM-valves is based on CFD simulations of local flow conditions. The fabrication of the valve is realized with micro process engineering tools. The influences of product and process parameters on energy efficiency and product quality are discussed for the dairy process.

Keywords: High pressure homogenisation; Process intensification; Dairy Process; Energy saving; SEM technology

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1. Introduction

High pressure homogenizers were developed approximately 100 years ago [4] during the industrialization. The basic idea of combining a high pressure pump and a disruption system, like a valve, was presented on the universal exposition in Paris and endures to this day. Though, we see ongoing developments of the pumps and valves motivated either by daily application problems or new product challenges.

Current technique permits volume streams of up to 50,000 L/h and pressures of up to 10,000 bar, however, homogenization pressures in industrial applications today are in the range of 50 to 2000 bar. Mainly piston pumps serve as high pressure pumps. In bench-scale, commonly a single piston pump delivers the volume stream or rather the pressure, but in production plants up to eight piston pumps are found. The single piston pump has the disadvantage that the pressure and the volume stream vary extremely over time scale, which results in a pulsation of the stresses on the product. Inhomogeneous stresses act on the droplets and thus product properties are difficult to control. To reduce the pulsation, several pistons are combined phase-shifted. Valves are used to control the different pistons usually not influencing the quality of the emulsion.

2. Disruption systems for high pressure homogenization

The main part of a high pressure homogenizer is the disruption system. Here, the pressure built up by the pump is expanded resulting in specific flow conditions used for droplet disruption. The disruption systems which are available on the market can be divided in valves and nozzles.

2.1. Valves

Valves, also known as radial diffusors, are common high pressure disruption systems. The fundamental idea is to reduce the flow diameter with a valve plunger which is pushed to a valve seat forming a small gap. The fluid enters the valve via a central hole in the valve seat pumped by the high pressure pump. It is then deflected by 90° and flows through a radial gap between the valve plunger and the valve seat. Often flat valves are fitted with an impingement ring to deflect the fluid a second time before it leaves through a drain hole. The impingement ring forms a defined outlet cross section and protects the valve housing against damaging fluid mechanics, like cavitation.

![Disruption systems: Flat valve (left hand) [5] and schematic drawing of a simple orifice (1) and modified types (2, 3, 4) as published by [2,6,7] (right hand)](image)
The advantage of using valve systems is that the pressure can be easily adjusted independently from the volume stream. This can be realized by varying the plunger’s position and thus the gap size between valve seat and plunger. Further on, the pressure can be adjusted automatically to the volume stream by using a spring to pressure the plunger. Flow conditions within flat valves were intensely investigated and published by [7-11].

2.2. Orifices and nozzles

An orifice presents the technically simplest possibility to increase the pressure and transfer this energy into high flow velocities (see Fig. 1, 1) [12]. In contrast to valves, simple orifices are constructed without any movable part. This has the advantage that orifices are easy in manufacturing. At constant viscosity of the emulsion the homogenizing pressure is adjusted by the volume stream or the orifice hole diameter respectively the cross section area. Increasing the volume stream at target pressure loss requires a numbering up of the orifices as realized e.g. in [13,14]. Numbering up is only limited by a minimum distance between the holes being in the order of 10 [6]. To ensure a constant homogenizing pressure even for fluctuating volume flow rates, the number of orifices has to be automatically adapted, as well.

Bayer (now BTS) was under the first to patent and commercialize orifices for high pressure homogenization applications [15]. Basic research on the flow conditions in orifices of circular cross-section and their effect on droplet disruption was first published by Stang and Schubert in Karlsruhe [2]. This was followed by intense research in several groups also resulting in several patents [2,6,7,16-25]. Typical dimensions of the orifice are hole diameters of \( d = 0.1 \) to 1 mm and a thickness of \( l = 0.4 \) to several mm. By modification of the orifice, so called nozzles were developed. In Fig. 1, (2) a trench is used instead of a hole. The trench has the advantage that just the smaller edge has an impact on the homogenization result and thus, the larger one can be used for an increase of the cross section area and thus the volume flow rate [6]. This is just limited by the production accuracy of the smaller edge. Impinging the free jet which develops in the orifice’s outlet section on a plate or a second liquid jet (see Fig. 1, 3) improves droplet break-up by inducing turbulent disturbances [6]. Similar effects are found for orifices with internal steps deflecting the flow (Fig. 1, 4) [6,16]. A deflecting orifice was developed by Microfluidics and called Z-Chamber. They further on developed a Y-Chamber were to streams impingement [26,27].

3. Flow conditions

Generally, a laminar flow is found after the high pressure pump. Due to the reduction of the area cross-section in front of a disruption system, the stream is accelerated and elongated, which results in elongational and shear stresses. From a critical homogenization pressure the stream detaches on the inlet edge and thus produces the first depression area. In this depression area cavitation may occur. Furthermore the detaching of the flow depicts an instability in the stream and may also induce a turbulent transition or a back flow area. Inside the hole, the core of the stream stays laminar but on the boundaries first eddies can rise.

Within a short orifice type valve, elongational and later shear stresses dominate the flow. On the outlet edge of the hole, the flow detaches. This detaching results again in a depression area and cavitation. Depending on the outlet geometry, a free jet develops. At the boundaries of the free jet transitional or turbulent flow regions may develop and induce shear, elongational and rotational stresses. Boundary effects in smaller outlet channels also influence the turbulence and cavitation behavior [28].

Geometric parameters influence local flow conditions. In flat valves, as designed to date, the inlet edge has no 90° but rather around 45°. This extends the time of the elongational flow in the inlet and reduces the effects of the detaching on the hole’s inlet. Thus, a reduction of the abrasion can be achieved and
elongation acts for a longer period on droplets. An additional deflection of the fluid inside the hole (see Fig. 1, 4) results in an additional detaching point and therefore higher turbulences and cavitation around the valve [11,29,30].

4. Homogenisation of Milk

Milk is commonly homogenized by flat valves. To investigated, if milk can be produced more efficient, we homogenized common full cream milk with a fat content of $\varphi = 3.5 \text{ vol.-}\%$ with the different disruption system by homogenization pressures up to 1000 bar.

In all disruption systems the droplet size decreases with increasing homogenization pressure, which indicates that the process is dominated by disruption process. The simple nozzle (○) is able to produce droplets in the range of the flat valve (▼). Thus the nozzle is as efficient as the flat valve. An increase of the efficiency can be achieved by using the Interaction Chambers of Microfluidics. Here the Z-Chamber (▲) is at low pressures a little bit then the Y-Chamber (■). In conclusion the homogenization von milk can be influenced by the disruption geometry and deflection systems are most efficient. But up to day these systems have not been realized in production due to the limited scale up, the missing adaption of the volume stream and the homogenization pressure and the missing cleaning routines.

5. The dairy process

In the conventional dairy process, raw milk is separated prior to homogenization into a low-fat phase (0.03 to 0.3 vol.-% fat, ‘skim milk’) and a fat-enriched phase (30 to 42 vol.-% fat, ‘cream’) using a separator. In the conventional „full stream“ homogenization process, milk is then standardized to the final product fat content by mixing these two phases and then homogenized. Also conventionally applied are „partial stream“ homogenization processes, in which the cream is diluted with skim milk to a fat content of 15 to 17 vol.-%, homogenized and afterwards standardized again to the target fat concentration of, for
example, 3.5 vol.-% in full cream milk. This reduces the energy required as less continuous phase has to be compressed to homogenization pressure [1].

6. Simultaneous emulsification and mixing

This two-step re-mixing process interrupted by high pressure homogenization is required as aggregation of fat globules (casein bridging) is found in homogenized cream above 13 vol.-% of fat [1,30]. The negative impact of aggregation can be compensated by an increased homogenizing pressure up to fat contents of 17 vol.-%. At fat contents higher than that, the process is mainly controlled by coalescence and aggregation of the fat globules leading to dissatisfying homogenization results (see Fig. 3, Δ). Coalescence of newly formed fat droplets is found until adsorbing dairy proteins have stabilized the droplets. In stabilization of milk fat globules, a secondary droplet membrane is built up by adsorbing casein micelles and sub-micelles as well as lactoalbumins and lactoglobulins [31,32]. As adsorbed casein micelles tend to adsorb at more than one fat globule at the same time and also strongly interact, bridges between fat globules are formed at increased fat content resulting in high aggregation rates. These fat globule aggregates can be partially destroyed in a second homogenizing stage [33], as it is realized in conventional technical processes. However, with increasing fat globule concentration, coalescence and aggregation rates increase as well [3,34,35] limiting partial homogenization to 17 vol.-% of fat. Thus the energy reduction potential cannot be fully exploited.

Fig. 3. Influence of the fat content of homogenized cream and the homogenization pressure on the characteristic max. droplet diameter $x_{90,3}$ full stream and for partial homogenization processing. When SEM valves are used, cream of 32 and 42 vol.-% fat were mixed with skim milk ($\varphi = 0.3$ vol.-%) within the valve. In conventional full stream homogenization milk (volume fat content $\varphi = 3.5$ vol.-%) and cream ($\varphi = 32$ vol.-%) were homogenized as “full stream” [30]

In the common dairy process the standardization (which in fact is done by mixing) is located several meters behind the homogenizer. SEM valves enable us (1) to combine the homogenization and standardization step in one process unit, (2) to dilute the fat globules directly after their production, and (3) to add additionally emulsifier molecules (here: dairy proteins) in the moment of their need (droplet break-up) with high mixing intensity. For this, SEM valves are run in operational mode 3, with a premix,
here cream at a fat content of 32 to 42 vol.-%, is homogenized as main stream, and the skim milk runs as mixing stream at pressures being 0.1 to 20 % of the homogenizing pressure.

Comparing the SEM partial homogenization results at 32 and 42 vol.-% fat, respectively, to those of conventional full stream homogenization at 3.5 vol.-% fat, product quality is fully maintained (with a slight, but negligible improve at 32 vol.-% and a slight loss in 42 vol.-% fat, see Fig. 3).

However, the new SEM-process requires only 20 % of energy input compared to the full stream process, and only 60 % of the energy applied in conventional partial homogenization processing of dairy products. This results in considerable energy and cost savings in dairy processing without any loss in product quality. In addition, two mixing units can be eliminated from the process line resulting in less investment, cleaning and maintenance costs.

7. Conclusion

High pressure homogenisation is well established in the dairy industry. The main component of the homogeniser is disruption system. Different homogenisation systems are available on the market today mainly divided in valves and orifices. Compared to valves with new deflecting orifice slightly more efficient homogenisation of milk can be realized. A higher potential in more efficient processes is to use the SEM-technology.

In dairy processing, the conventional partial stream homogenization is today limited to 17 wt.-% of fat in the homogenized cream. With the SEM valve cream can be homogenized at fat contents up to 42 wt.-%, resulting in energy reduction of up to 90%.

References


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