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Process development for continuous crystallization of fat under laminar shear

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ABSTRACT

A novel continuous laminar shear structuring crystallizer with a suitable cooling system was designed and built. This is a new method to continuously crystallize edible fat in the desirable polymorphic form from the melt while being uniformly sheared.

The machine consists of four main sections: Feed unit, shearing mechanism, cooling system and power unit. In each of these sections specific design considerations are taken into account which makes the process controllable and continuous. The shearing unit is made of two concentric cylinders. The internal cylinder is stationary and has a cooling system inside for temperature control. The outer cylinder rotates to produce a uniform shear in the sample fluid placed in the 1.5 mm gap between the cylinders. The sample's feed rate is controlled while it is pumped to the gap. The cooling system has three segments and provides an individual temperature gradient for each region.

Cocoa butter and a binary mixture of cocoa butter and milk fat were crystallized from the melt under shear and different cooling regimes. A major modification in the samples phase transition behavior was observed; laminar shear induces acceleration of phase transition from less stable polymorphic form to the more stable form, $\beta_{V.}$ Moreover, X-ray diffraction patterns clearly showed crystalline orientation of the samples. This machine may open up new avenues for processing and manufacturing chocolate, shortenings and margarine.

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1. Introduction

The crystallization of fats plays an essential role in controlling the physical properties of fat containing products since fats have the ability to exist in different crystalline forms (with different types of crystal packing and thermodynamic stabilities) (Chapman, 1962). The confectionary industry uses only one form, βV, as the optimal polymorph in chocolate manufacturing, since this form is the stable polymorphic phase with a melting point that is high enough to allow chocolate to be stored at room temperature and low enough for chocolate to become a smooth liquid when it is heated in the mouth. This form is also known for giving a clean snap, a glossy appearance and optimal color to chocolate (Nelson, 1994). Unfortunately, the form βV is not obtained by simple cooling. Therefore, in industrial manufacturing, a shear field is added to the crystallization process of the fat system because application of a uniform shear alongside controlled cooling can help in attaining of the desirable polymorphic phase. Several studies showed two major effects of shear on the fat crystallization when it enhances the rate of heat transfer and helps produce a homogeneous product:

(i) Shear accelerates solid-state phase transformation (Stapley et al., 1999; MacMillan et al., 2003; Ziegleder (cited in Becket, 2000); Becket, 2000; Mazzanti et al., 2003; Bolliger et al., 1998; Sonwai and Mackley, 2006, Breitschuh et al., 1999, Windhab, 1999). Shear improves overall mixing and breaks newly formed crystallites around the seed crystals, which creates a greater number of seed crystals (Becket, 2000; Stapley et al., 1999). Windhab (1999) believes shear influences the crystallization kinetics and the crystal structure of polymorphic fat systems. Bolliger et al. (1998) suggested that shear has a direct effect on the kinetics of nucleation because the induction time is lowered if higher shear rates are used. MacMillan et al. (2003) and Ziegleder reported the transformation to more stable polymorphs as a result of applying shear. In addition, Mazzanti et al. (2003) reported the phase transition of less stable form II to stable form V in crystallization under shear, which is in agreement with Sonwai and Mackley's (2006) work. In studying the effect of shear on crystallization another factor that needs to be considered is the rate of shear. There is a critical shear rate that must be exceeded in order to produce the proper seed crystals (Stapley et al., 1999). High shear has the effect of breaking the solid fat crystals and uniformly distributing them throughout the melt. The phenomenon of a rapid increase in the number of crystal fragments with a quick transformation into the solid phase occurs sooner in crystallization under high shear rate (for shear rates of 300 and 500 s^{-1} compared to 100 s^{-1} in CB crystallization) (Sonwai and Mackley, 2006). The degree of shearing is responsible for enhancing crystalline growth

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(Briggs, 2004). As the shear rate increases, the formation time of form III remains constant, while the formation time of form V decreases (MacMillan et al., 2003; Sonwai and Mackley, 2006). Mazzanti et al. (2003) found that a high shear rate provides enough energy to either induce the solid-state transformation, or to melt most of the crystals, leaving behind a nucleus for the growth of form V crystal. Based on their study, when cocoa butter was crystallized under a shear rate of 1440 s^{-1}, the formation of form IV was not observed, while βV formed in less than 20 min. This result was also observed by Becket (2000), MacMillan et al. (2003), and Mazzanti et al. (2005). Interestingly, the same authors (Mazzanti et al., 2004) reported that the induction time of form V was higher at a shear rate of 720 s^{-1} compared with the shear rate of 90 s^{-1}. This observation contradicted the previous report by MacMillan et al. (2003). Sonwai and Mackley (2006) explained the discrepancy between these works in usage of cocoa butter from different origins with different TAG compositions when their work was in disagreement with MacMillan's.

(ii) Shear induces the orientation of formed crystallites (Mazzanti et al., 2003). It aligns triglyceride molecules parallel to each other in the shear field and then moves them past each other (Stapley et al., 1999). In a fat crystal system, crystal orientation is a consequence of the strength of the shear and the asymmetry of the platelet-like crystal (Mazzanti, 2004). At different stages of crystallization, crystals are under different conditions and forces and tend to aggregate. Therefore, the distribution of particle orientation is a consequence of interplay between ordering induced by shear forces and disordering induced by Brownian forces (Fitzgerald et al., 2001). Even though many researchers studied fat polymorphic behavior under shear, only very little work has been conducted on the effect of shear on the fat crystal orientation (MacMillan et al. 2003; Mazzanti et al., 2003, 2005; Mazzanti et al., 2004). These studies observed weak or no significant orientation at low shear rate in cocoa butter crystallization.

This research aims to develop a new method for processing and manufacturing of chocolate, shortening and margarine. In this study a new fat crystallizer that can produce sheets of crystallized fat continuously was designed and built. Fat is crystallized under the action of laminar shear while it is being cooled.

2. Materials and methods

2.1. Process

Fig. 1 schematically shows the process set up of the shear crystallizer. Its design is based on two concentric and horizontal cylinders referred to here as inner tube and outer tube. The inner tube is fixed while the outer tube rotates. The melted fat sample was continuously pumped through the gap between the two cylinders. Oil is crystallized under shear and controlled cooling conditions while traveling from one side of the tube to the other side. Due to the rotation of the outer cylinder and the resulting shear flow, mechanical energy is homogeneously dissipated throughout the system.

The laminar shear structural crystallizer has four main parts: food unit, shearing mechanism, cooling system and power unit. The feed unit is made up of an isolated reservoir, a gear pump and a controller.

In the shearing unit, the inner tube is fixed to the crystallizer base plate at one end and the outer tube, supported at both ends by two ball bearings, is rotating by a belt which transfers the rotation from the transmission unit to the outer tube. The gap between the two tubes along with the rotating velocity of the outer tube, determines the shear rate:

$$\dot{\gamma} = \frac{V_{\text{shear}}}{\delta} \quad (1)$$

where $\dot{\gamma}$ is the shear rate, V_{shear} is the shear velocity and δ is the gap between tubes.

The limit of stability for laminar flow inside the crystallizer is determined by the condition based on Eq. (2) (Swanson, 1970):

$$\text{Re}\sqrt{\frac{\delta}{r_i}} < 41.3 \quad (2)$$

where Re and r_i are Reynolds number and the radius of inner tube, respectively.

The crystallization time was determined according to the crystallizer length (L_{tube}) and the feed rate (V_{feed}), and can be increased by reducing the feed rate, if longer periods of time are required to crystallize the fat. The power unit includes an electromotor with variable rotary speed, a controller, and a power transmission unit to transfer the rotation to the shearing unit by inducing the necessary torque.

2.2. Heat transfer model

The crystallization temperature is one of the vital thermodynamic parameters in fat crystal formation and growth. It is thus necessary to design a suitable cooling system to control fat temperature during the crystallization process. In this machine, the temperature is controllable using three different water jackets. As a counter-flow heat exchanger, each water jacket is adjusted for a different cooling rate which keeps the crystallization under control and provides a uniform temperature difference between the water and the oil throughout the crystallization path. From the principle of conservation of energy, the total heat transferred from the fat is equal to the heat transfer to/from air and the heat transferred to cooling water:

$$Q_{\text{fat}} = Q_{\text{fat}\leftrightarrow\text{air}} + Q_{\text{fat}\rightarrow\text{water}} \quad (3)$$

where Q_{fat} represents heat that should be dissipated to decrease the fat's temperature based on designed cooling regime, $Q_{\text{fat}\leftrightarrow\text{air}}$ is the heat transfer between fat and air and $Q_{\text{fat}\rightarrow\text{water}}$ is the heat transferred from fat to water, as shown in Fig. 2.

Heat that needs to be dissipated from the oil, Q_{fat}, is obtained from:

$$Q_{\text{fat}} = Q_1 + Q_2 + Q_3 \quad (4)$$

where Q_1, Q_2 and Q_3 represent the heat dissipations due to the fat undercooling, friction by viscous shearing and fat phase change (latent heat), respectively. Depending on the oil properties and the degree of undercooling different amounts of heat need to be dissipated by each water jacket. Because, this heat dissipation is related to the changes in the oil temperature at each cooling step, it can be obtained from Eq. (5):

$$Q_1 = m_{\text{fat}} c_{\text{fat}} \Delta T_{\text{fat}} \quad (5)$$

where ΔT_{fat} is the temperature gradient of fat through the water jacket, c_{fat} is the specific heat of the fat and m_{fat} is the rate of fat mass inserted into the system.

Viscous friction is another source of heat that needs to be dissipated. The amount of heat is equal to the amount of work to be done to overcome viscous resistive force which theoretically is equal to the input power:

$$Q_2 = P = T\omega \quad (6)$$

where T is the resisting torque. The latent heat is also obtained from:

$$Q_3 = \phi \dot{m} L_s \quad (7)$$

Where ϕ and $\dot{m}$, are the solid fat content and the feed rate, respectively. L_s, the latent heat is determined by differential scanning calorimetry technique.

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