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Effect of Pressure and Fat Content on Particle Sizes in Microfluidized Milk*

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ABSTRACT

Average diameters and particle size distributions in fluid milks with different fat contents and subjected to various homogenization pressures with a "microfluidizer" were evaluated. Skim, 2%, and whole milks were microfluidized at 50, 100, 150, and 200 MPa. Cream containing 41% milk fat was microfluidized at 50, 100, and 150 MPa. Particle sizes were determined by laser light scattering. As microfluidization pressure was increased from 50 to 100 MPa, particle sizes in skim, 2%, and whole milks decreased. Microfluidization at pressures greater than 100 MPa had little additional effect on reducing the particle sizes in skim and 2% milks compared with microfluidization at 100 MPa, but the particle sizes in whole milk increased as the microfluidization pressure was increased from 100 to 200 MPa due to formation of homogenization clusters. The particle sizes in cream increased as the microfluidization pressure was increased from 50 to 150 MPa. When the microfluidization pressure was held constant, the particle sizes increased as the milk fat concentration was increased. The coefficients of variations of the volume-weighted particle size distributions for cream were higher than for skim, 2%, and whole milks. Larger "big" particles and smaller "small" particles were formed in whole milk after microfluidization at 200 MPa than at 100 MPa. Although microfluidization can be used to produce small particles in skim, 2%, and whole milks, a higher than optimum pressure (above 100 MPa) applied to whole milk will not lead to the minimum d_{43} (volume-weighted average diameter) due to formation of clusters.
(**Key words:** particle sizing, microfluidization, homogenization, milk)

Abbreviation key: $\mathbf{d_{43}}$ = volume-weighted average diameter, $\mathbf{d_{32}}$ = volume-surface average diameter, **CV** = coefficient of variation.

INTRODUCTION

Microfluidizers operate by a different mechanism and at different pressures than conventional valve homogenizers. Microfluidizers contain a double-acting intensifier pump and an interaction chamber (Anonymous, 2003). The intensifier pump may be air-driven or electric-hydraulic driven and provides high pressure to force the product through the interaction chamber. The interaction chamber contains fixed-geometry microchannels. Product divides into streams as it enters the interaction chamber and accelerates to a very high velocity as it flows through the interaction chamber. These streams collide with each other. Shear and impact occur to form emulsions with very small particles. A cooling coil after the interaction chamber may or may not be present. Homogenization with a microfluidizer (microfluidization) is usually performed at higher pressures than conventional valve homogenization. Some models of a microfluidizer can generate pressures up to 276 MPa. Therefore, like conventional valve homogenization, microfluidization leads to significant changes to the fat and protein in milk.

Microfluidization and conventional valve homogenization alter the milk fat globule membrane as well as disrupt fat globules. Henstra and Schmidt (1970) used transmission electron microscopy to show that casein particles break down and adsorb to fat globule surfaces in conventionally valve homogenized milk. Michalski et al. (2002) also showed that conventional valve homogenization formed fat-protein complexes with a new membrane. Dalgleish et al. (1996) reported that fewer intact or semi-intact micelles formed the membrane surrounding fat globules in microfluidized milk than in

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conventionally valve homogenized milk. Also, Dalgleish et al. (1996) observed new types of particles by transmission electron microscopy characterized by small fat globules embedded in casein micelles. These changes alter particle sizes.

Particle size is important for many properties of milk and dairy products. Beneficial examples of decreased particle size include decreased creaming rate (Walstra et al., 1999), less susceptibility to cold agglutination (Walstra et al., 1999), potential increased accuracy of fat content determination by calibration of infrared analyzers with microfluidized milk samples and microfluidization of milk prior to milk analysis (Remillard et al., 1993), increased heat stability of concentrated milk (Whiteley and Muir, 1996), production of protein-based fat replacers (Paquin et al., 1993), and improved whiteness of Cheddar cheese (Lemay et al., 1994). Fat globule size also affects the tendency for milk fat cluster formation (Walstra et al., 1999). Particle sizes in milk and cream are altered by conventional valve homogenization and microfluidization, and the mechanism and thermodynamics of fat globule disruption have been discussed by Walstra (1983) and Walstra et al. (1999).

Although particle sizes have been commonly measured in whole milk subjected to microfluidization pressures not exceeding 103 MPa (Pouliot et al., 1991; McCrae, 1994; Strawbridge et al., 1995; Dalgleish et al., 1996; Hardham et al., 2000), data on particle sizes in milks with varying fat contents or subjected to higher microfluidization pressure are limited. The objective of this study was to use laser light scattering to compare average sizes and particle size distributions in milks with various fat contents and in cream subjected to a wide range of microfluidization pressures up to 200 MPa.

MATERIALS AND METHODS

Sample Preparation

Pasteurized unhomogenized whole milk, pasteurized unhomogenized skim milk containing 0.14% fat, and raw cream containing 41% fat were obtained from the Mississippi State University dairy plant. Milks with 3.5 and 2.0% milk fat were prepared by mixing whole milk and skim milk. Whole milk containing 3.5% fat, 2% milk, and skim milk were heated from 4 to 39°C before one-pass homogenization in a Microfluidics M-210-EH "Microfluidizer" (Microfluidics International Corporation, Newton, MA) at 50, 100, 150, or 200 MPa for each of 3 replicates. Cream was heated from 4 to 39°C and subjected to one-pass microfluidization at 50, 100, or 150 MPa in one replicate. Additional replicates were not performed due to difficulty in microfluidizing 41% fat cream because of the high viscosities that developed, especially at the higher pressures. The samples were cooled and transported on ice in coolers to Texas A&M University for particle size analysis.

Fat Content Determination

The Mojonnier method according to the Mojonnier Instruction Manual (Anonymous, 1922) was used to determine fat content of the milks and cream. This method is based on extracting fat from a weighed amount of milk (or other types of dairy products) with ethyl ether and petroleum ether in specially designed flasks, decanting this ether phase into a preweighed weighing dish, evaporating the ether phase, and reweighing the weighing dish containing the extracted fat.

Particle Size Determination

Average particle sizes (d_{43} and d_{32} [arithmetic means]) and size distributions (coefficient of variations, standard deviations, and particle sizes that define the upper size limit for 10, 25, 50, 75, and 90% of colloidal material in the volume-weighted size distributions) were determined using a Coulter LS 130 Small Volume Module particle size analyzer (Coulter Corporation, Miami, FL). This instrument measures particle sizes by analyzing the diffraction of laser light and the polarization intensity differential scattering (Anonymous, 1994). Samples were heated to approximately 37°C in a water bath before analysis. A sufficient amount of milk or cream was added to distilled water in the sample cell of the particle size analyzer until a polarization intensity differential scattering obscuration of 40 to 60% was obtained (Anonymous, 1994). An optical model based on Mie theory of light scattering by spherical particles was made using values for the real refractive index of 1.503 for skim milk, 1.471 for 2% milk and whole milk, and 1.460 for cream, and a value of 0 for skim milk, 2% milk, whole milk, and cream for the imaginary refractive index. The refractive index used for skim milk and cream was based on the refractive index of 1.503 measured for bovine casein micelles (Attaie and Richter, 2000) and 1.46 reported for milk fat globules (Michalski et al., 2001), respectively. Unless specified otherwise, average particle sizes in this manuscript refer to d_{43} instead of d_{32}.

Statistical Analysis

The d_{43} and CV of the volume-weighted particle size distribution in microfluidized skim milk, 2% milk, and whole milk were analyzed with SAS System for Windows version 8 (SAS/STAT User's Guide, 1999) using

Table 1. The d_{43} of particles in unhomogenized and microfluidized (50, 100, 150, and 200 MPa) fluid milks with various fat contents versus the corresponding d_{32}. The d_{32} are in parentheses. All diameters are in nm.

Pressure (MPa)	Type of fluid milk			
	Skim	2%	Whole	41% Cream
0	383.7 (212.3)	3652 (2719)	4489 (3278)	11090 (3721)
50	$230.3^{c, x}$ (191.3)	$392.7^{b, x}$ (262.7)	$460.0^{a, x}$ (300.7)	5375 (1784)
100	$208.0^{c, y}$ (178.0)	$275.3^{b, y}$ (219.7)	$304.3^{a, z}$ (239.0)	11920 (1977)
150	$204.7^{c, y}$ (176.0)	$270.0^{b, y}$ (215.3)	$361.0^{a, y}$ (238.3)	26440 (2521)
200	$205.7^{c, y}$ (177.3)	$268.0^{b, y}$ (213.3)	$383.3^{a, y}$ (236.7)	

^{a,b,c}Means of d_{43} not containing a common letter (a, b, or c) in a given row (different type of fluid milk subjected to a given microfluidization pressure) are significantly ($P < 0.05$) different from each other by the Bonferroni *t*-test.

^{x,y,z}Means of d_{43} not containing a common letter (x, y, or z) in a given column (the same type of fluid milk subjected to different microfluidization pressures) are significantly ($P < 0.05$) different from each other by the Bonferroni *t*-test.

the general linear models procedure. The effect of each microfluidization pressure on the d_{43} and CV for milks with a given fat content and the effect of each fat content on the d_{43} and CV for milks subjected to a given microfluidization pressure were analyzed as separate randomized complete block designs. Mean separations at $P = 0.05$ were performed by the Bonferroni *t*-test, and *P* values for differences between each pair of treatments were determined according to the *t*-test. The unhomogenized samples were not included in the statistical analyses because of the high variance among different replicates of the unhomogenized samples compared with the microfluidized samples.

RESULTS AND DISCUSSION

Mean Particle Sizes

The effects of fat content and microfluidization pressure on the d_{43} and the corresponding d_{32} of particles can be determined from Table 1. Microfluidization pressure significantly ($P < 0.001$) affected particle sizes in skim milk, 2% milk, and whole milk. The d_{43} of particles in unhomogenized whole milk and 2% milk was reduced almost 10-fold after microfluidization at 50 MPa, but this reduction of d_{43} for skim milk was less than 2-fold. For skim milk, 2% milk, and whole milk, the d_{43} of particles significantly ($P < 0.001$) decreased as the microfluidization pressure was increased from 50 to 100 MPa. Additional increases in microfluidization pressure did not cause further reductions in the d_{43} of particles in skim milk and 2% milk compared with microfluidization at 100 MPa ($P > 0.05$). However, the d_{43} of particles in whole milk significantly ($P < 0.001$) increased from 304 to 383 nm as the microfluidization pressure was increased from 100 to 200 MPa. The particle size distributions in whole milk microfluidized at 100 and 200 MPa are shown in Figure 1. Particles less than 100 nm could not be detected by the particle size analyzer, but these particles are thought to only have a minor effect on the d_{43} and d_{32}. Although the d_{43} of particles in cream containing 41% milk fat decreased by approximately one-half during microfluidization at 50 MPa, the d_{43} increased when the microfluidization pressure was increased from 50 to 150 MPa. The fat content had a significant ($P < 0.001$) effect on particle size at each microfluidization pressure. When holding microfluidization pressure constant, the d_{43} of particles in whole milk was significantly ($P < 0.005$) greater than d_{43} of particles in 2% milk, and d_{43} of particles in 2% milk was significantly ($P < 0.005$) greater than d_{43} of particles in skim milk. The d_{43} of particles in the 41%

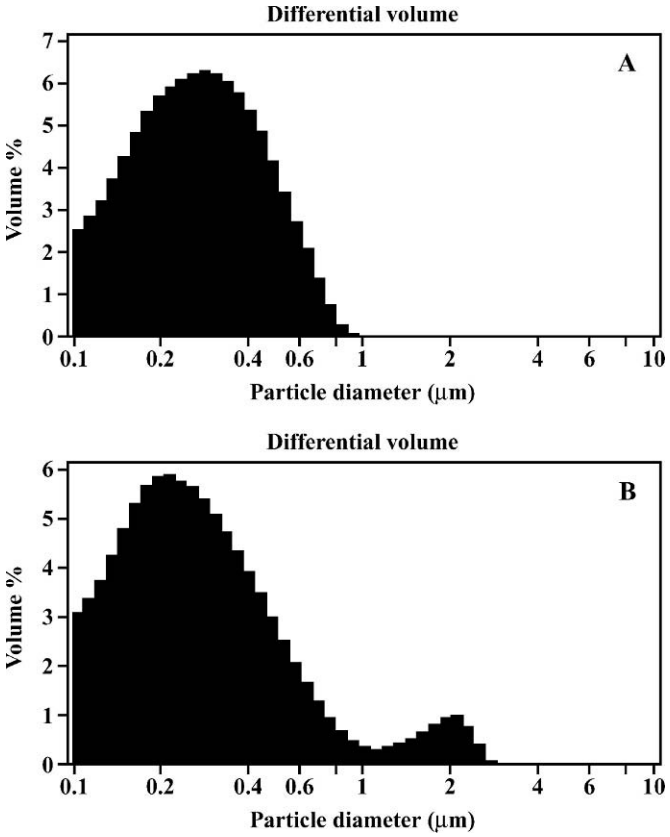

Figure 1. Particle size distribution in whole milk microfluidized at a) 100 MPa and b) 200 MPa.

Table 2. The average CV (in %) for volume-weighted particle size distributions for unhomogenized and microfluidized (50, 100, 150, and 200 MPa) skim milk, 2% milk, whole milk, and 41% cream.

Pressure (MPa)	Type of fluid milk			
	Skim	2%	Whole	41% Cream
0	113	41.9	101	209
50	48.1$^{b, x}$	86.4$^{a, x}$	83.6$^{a, y}$	212
100	44.1$^{b, y}$	50.0$^{a, y}$	50.0$^{a, z}$	254
150	43.3$^{c, yz}$	50.6$^{b, y}$	100$^{a, xy}$	148
200	42.6$^{b, z}$	51.6$^{b, y}$	112$^{a, x}$	

^{a,b,c}Means of CV not containing a common letter (a, b, or c) in a given row (different type of fluid milk subjected to a given microfluidization pressure) are significantly ($P < 0.05$) different from each other by the Bonferroni *t*-test.

^{x,y,z}Means of CV not containing a common letter (x, y, or z) in a given column (the same type of fluid milk subjected to different microfluidization pressures) are significantly ($P < 0.05$) different from each other by the Bonferroni *t*-test.

cream samples were approximately 3 to 10 times higher than the corresponding d_{32}. The particle size distribution for each of these cream samples contained multiple peaks as indicated by the large CV of the particle sizes for these samples (Table 2).

Although no attempt was made to identify types of particles in the samples during the particle size analysis in this study, casein micelles and fat globules constitute nearly all of the particles that have sizes in the range that can be detected by the particle size analyzer used in this study. Casein micelles typically have diameters between 30 and 300 nm (Swaisgood, 1996), so the larger micelles could have been detected by the particle size analyzer and should have had an influence on the particle size distributions of all of the unhomogenized samples. These effects of casein micelles on the particle size distributions of the unhomogenized samples should be more apparent in skim milk than in products that contain milk fat because the fat globules may overshadow the casein micelles in the products that contain fat. Because relatively few fat globules are present in skim milk, the larger particles in 2% and whole milks and 41% fat cream compared to skim milk were due to more and larger fat globules in products containing fat. Since almost all of the larger particles detected in unhomogenized skim milk were smaller than the majority of particles detected in unhomogenized 2% and whole milks and cream, these few fat globules in skim milk not effectively removed by separation were predominantly small fat globules.

The fat globule sizes in unhomogenized whole milk measured in other studies were often similar to the particle sizes measured in the present study. The d_{32} for fat globules in cows' milk were 3.34 μm when measured using a Coulter counter, fluorescence microscopy, or spectroturbidimetry (Walstra, 1969), 3.5 μm when measured by spectroturbidimetry (Walstra, 1975), and 3.51 μm when measured by laser light scattering (Attaie and Richter, 2000) compared with a d_{32} of 3.278 μm obtained in the present study. Remillard et al. (1993) used photon correlation spectroscopy and reported a d_{43} of 3.04 μm for fat globules in raw cows' milk after treatment with a protein dissociating buffer compared with a d_{43} of 4.489 μm without the use of a protein dissociating buffer in the present study

Microfluidization produced smaller particles in milk at 35 MPa (McCrae, 1994) and in concentrated milk at 34 MPa (Whiteley and Muir, 1996) than conventional valve homogenization at the equivalent pressure. Microfluidization can usually be performed at higher pressures than conventional valve homogenization, often leading to even smaller particles. However, McCrae (1994) reported that the extrapolated rate at which the average fat globule size decreased with increasing pressure was greater for conventional valve homogenization than for microfluidization. McCrae (1994) predicted by extrapolation that an equivalent average size of fat globules in milk would be obtained after microfluidization at 103 MPa compared with conventional valve homogenization at 63 MPa.

Decreased average particle sizes in whole milk were found when increasing the microfluidization pressure from 14 to 42 MPa (Dalgleish et al., 1996), from 19.3 to 67.6 MPa (Pouliot et al., 1991), and from 35 to 103 MPa (McCrae, 1994). These trends for effect of microfluidization pressure up to 103 MPa on average particle sizes agree with the trend of decreasing average particle size when increasing microfluidization pressure from 50 to 100 MPa in the present study. However, microfluidization at 100 MPa produced the smallest average size particle in whole milk, and average particle sizes increased when microfluidization pressure was increased above 100 MPa.

Lemay et al. (1994) found that average sizes of fat globules in 15% fat cream decreased as microfluidization pressure was increased from 14 to 69 MPa. This trend of decreased particle size with increasing microfluidization pressure did not agree with the results from the present study. Possible explanations for the different trends include a different range of microfluidization pressures (14 to 69 MPa vs. 50 to 150 MPa) and different fat contents of the creams (15 vs. 41%).

Some of the decreases in particle sizes that occurred in skim milk, 2% milk, and whole milk in the present study were probably due to the increased microfluidization temperature that accompanied the increased microfluidization pressure. Tunick et al. (2000, 2002) found large decreases in fat globule sizes in Mozzarella

cheese after the microfluidization temperature of the cheesemilk was increased from 10 to 54°C.

CV and Standard Deviations

The average CV for the volume-weighted particle size distributions are presented in Table 2. The average CV for unhomogenized skim milk was more than twice as high as the average CV for microfluidized skim milk. Skim milk and 2% milk microfluidized at 50 MPa had significantly ($P < 0.001$) higher CV than skim milk and 2% milk, respectively, microfluidized at 100, 150, and 200 MPa. For whole milk, microfluidization at 200 MPa resulted in a significantly ($P < 0.01$) higher CV than microfluidization at 50 and 100 MPa, and microfluidization at 100 MPa resulted in significantly ($P < 0.001$) lower CV than the remaining microfluidization pressures. When holding microfluidization pressure constant, whole milk had significantly ($P = 0.001$) higher CV than skim milk at all microfluidization pressures, and 2% milk had significantly ($P < 0.05$) larger CV than skim milk after microfluidization at 50, 100, and 150 MPa. Except for cream microfluidized at 150 MPa, the CV of the cream samples were over 200%. These high CV for cream were caused by multiple peaks in their particle size distribution.

The width of particle size distribution from another study was compared to the width of particle size distributions in the present study. The standard deviation of 110 nm for the volume-weighted size distribution of fat globules in whole milk microfluidized at 69 MPa in the study of Remillard et al. (1993) was less than the standard deviations of 369 to 411 nm and 151 to 153 nm for the volume-weighted size distribution of all particles after microfluidization of whole milk at 50 and 100 MPa, respectively, in the present study (data not shown). Part of this difference in standard deviation may be due to use of a dissociating buffer in the study of Remillard et al. (1993).

Cumulative Distribution of Particle Size

The particle sizes that defined the upper size limit for 10, 25, 50, 75, and 90% of the colloidal material are presented in Table 3. This partitioning showed that microfluidization affected the particle size distributions in several ways. First, unhomogenized skim milk had 90% of its colloidal material in particles with diameters less than 1015 nm, but after microfluidization at 200 MPa, 90% of the colloidal material was in particles that had a diameter less than 331 nm. The respective values for 10% of the colloidal material were 121 nm for unhomogenized skim milk and 116 nm for skim milk microfluidized at 200 MPa. Therefore, the decreased particle sizes in skim milk after being microfluidized were primarily due to reducing the size of larger particles such as fat globules rather than of smaller particles such as casein micelles. Second, particles that were the sizes of casein micelles were generally not observed in unhomogenized 2% and whole milks. This observation might be explained by the large fat globules preventing the observation of the smaller particles by the particle size analyzer. After microfluidization of 2% and whole milks, particles less than 160 nm were observed as shown by the particle sizes for 10% of the colloidal material for the 2% and whole milks. These small particles with sizes typically reported for casein micelles were likely homogenization clusters of protein and milk fat as will be discussed in the next section. Finally, the particle sizes in whole milk which defined 10, 25, and 50% of the colloidal material decreased as microfluidization pressure was increased from 100 to 200 MPa, but the particle sizes in whole milk that defined 75 and 90% of the colloidal material increased as microfluidization pressure was increased from 100 to 200 MPa. Therefore, there were larger "large" particles and smaller "small" particles in whole milk microfluidized at 200 MPa than in whole milk microfluidized at 100 MPa. This interpretation was supported by the d_{43} and CV because there was a 26% increase in d_{43} (Table 1) and more than a 2-fold increase in CV (Table 2) for whole milk microfluidized at 200 MPa compared with 100 MPa.

A similarity existed between the changes of variously sized particles in the present study and the study of Strawbridge et al. (1995). Smaller reductions in sizes of smaller particles than for larger particles after microfluidization of whole milk were found when microfluidization pressure was increased from 50 to 100 MPa in the present study and from 14 to 42 MPa in the study of Strawbridge et al. (1995).

The rate of instability, including creaming, is reduced by reducing the size of the larger particles (Robin et al., 1992). Microfluidization of whole milk at 100 MPa would probably prolong the shelf life in terms of delaying creaming more than the other treatments for whole milk in the present study since the particle size below which 90% of the volume of the colloidal material lie was lower for this treatment than for the other treatments. This potential to delay creaming may be beneficial for milks with a long shelf life such as sterilized milk and concentrated milk. Microfluidization at 70 MPa instead of conventional valve homogenization at 17.5 MPa first stage and 3.5 MPa second stage increased shelf life of ultra-high temperature processed milk in terms of fat separation in the study of Hardham et al. (2000).

Table 3. The diameter (in nm) of particles in which the given percentage of colloidal material was in smaller particles for the volume-weighted particle size distribution for unhomogenized and microfluidized (50, 100, 150, and 200 MPa) skim milk, 2% milk, whole milk, and 41% cream.

Pressure (MPa)	Type of fluid milk	Percentage of colloidal material				
		10	25	50	75	90
0	Skim	121	153	214	358	1015
	2%	1943	2538	3414	4552	5796
	Whole	2180	2713	3472	4410	5470
	Cream	2001	2746	4070	6652	20230
50	Skim	119	149	201	281	385
	2%	141	196	305	466	672
	Whole	158	231	357	535	802
	Cream	849	1341	2395	4152	6760
100	Skim	116	140	183	249	339
	2%	129	169	241	350	474
	Whole	136	184	270	392	524
	Cream	929	1471	2578	4894	17450
150	Skim	115	139	182	245	331
	2%	127	166	235	341	466
	Whole	133	179	263	402	594
	Cream	1029	1727	3625	48220	95830
200	Skim	116	140	183	247	331
	2%	126	164	231	337	466
	Whole	132	175	259	404	637

Homogenization Clustering

The increase in the size of the largest particles in whole milk with increasing microfluidization pressure was probably due to formation of new particles of fat and protein. Although structures resembling homogenization clusters of 2 fat globules with shared proteinaceous material in whole milk microfluidized at 100 and 200 MPa were observed in transmission electron micrographs for other samples (Olson, 2000), clustering in the form of extensive complexes (especially fat and protein connected in the form of chains and aggregates) and proteinaceous material containing embedded fat globules were much more prevalent. Walstra (1980) reported that the larger casein micelles were disrupted at high pressures and reassociated after conventional valve homogenization.

Cream samples were not observed under a transmission electron microscope, so the microstructure of this sample is unknown. The large particles in cream were most likely large homogenization clusters of fat and protein in the form of chains and aggregates. Although the high cream viscosity that developed during microfluidization, especially at the higher pressures, indicated that extensive homogenization clustering and possibly some coalecence occurred during microfluidization, the possibility that some partial coalescence could have occurred after microfluidization but before particle size analysis leading to an increased average particle size can not be ruled out.

The extent of homogenization clustering is affected by homogenization pressure, fat content, homogenization temperature, and fat globule size. Clustering becomes more prevalent with increased amount of newly created surface area relative to the amount of shareable surfactant (Ogden et al., 1976), explaining the increased clustering with increased homogenization pressure or a higher fat content (Doan, 1929). Extent of clustering as judged by the particle size distributions in the present study increased as microfluidization pressure and fat content increased. However, the extent of clustering decreased with increasing microfluidization pressure in the study of McCrae (1994). McCrae (1994) suggested that the lower than expected amount of clustering in microfluidized milk, especially at higher pressures, was due to a high protein load in microfluidized milk. Although clustering was observed in whole milk in the present study, Walstra (1983) stated that clustering does not usually occur when the fat content of fluid milk is less than 9%. This statement by Walstra (1983) probably only applies to conventional valve homogenization performed at pressures lower than the microfluidization pressures used in the present study. Also, clustering is favored by low conventional valve homogenization temperatures (Mulder and Walstra, 1974). The Deryaguin-Landau and Verwey-Overbeek (DLVO) theory predicts that the fat globule diameter influences the tendency of cluster formation (Kurzhals, 1973).

CONCLUSIONS

The effect of microfluidization pressures between 50 and 200 MPa on average particle sizes and the volume-weighted particle size distributions of skim milk, 2%

milk, whole milk, and 41% cream was evaluated in this study. The d_{43} of particles in skim, 2%, and whole milks decreased when microfluidization pressure was increased from 50 to 100 MPa. Although additional increases in microfluidization pressure above 100 MPa did not significantly change the d_{43} of particles in skim and 2% milks compared to microfluidization at 100 MPa, the d_{43} of particles in whole milk increased from 304 to 383 nm when the microfluidization pressure was increased from 100 to 200 MPa. The d_{43} of particles in microfluidized cream increased as the microfluidization pressure was increased from 50 to 150 MPa. This increased particle size was probably due to formation of homogenization clusters in the form of chains and aggregates of fat and protein in whole milk and cream and possibly also from some coalescence of fat globules in the cream. Microfluidization led to greater reductions of size of the larger particles compared with the smaller particles in skim milk. However, the cumulative particle size distribution in whole milk showed that there were larger "large" particles and smaller "small" particles after microfluidization at 150 and 200 MPa than at 100 MPa. Smaller "large" particles produced by microfluidization of whole milk at 100 MPa instead of 50, 150, or 200 MPa should prolong the time before creaming occurs, and this potential increased stability may be beneficial for products with a long shelf life such as in UHT processed whole milk or concentrated milk.

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