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Effect of ultra-high pressure homogenization on viscosity and shear stress of fermented dairy beverage

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A B S T R A C T

In this study, dairy base consisting of raw skim milk and reconstituted whey powder were pressurized. The process used ultra-high pressure homogenization (UHPH) at levels of 150, 200 and 250 MPa and inlet temperatures of 15, 20 and 25 °C, following experimental design. Dairy base was inoculated with probiotic lactic culture, incubated, and allowed to ferment. Pineapple juice, previously sweetened with sugar or aspartame, was added, following an experimental design, resulting in dairy beverages. Appropriate formulation, considering the sensory attributes, was identified by Quantitative Descriptive Analysis (QDA) and used for studying rheological parameters. Results disclosed that formulations with higher whey levels had higher average scores for characteristic sensory attributes of products. The aim was to evaluate rheological properties (viscosity and shear stress) of fermented dairy beverages according to inlet temperature and pressure, comparing them to thermally processed samples (90 °C/60s). This evaluation showed that pressurized beverages at 150 MPa/15 °C were similar to controls. These preliminary results obtained in this study suggest that UHPH has the potential to be used to modeling some rheological characteristics of fermented dairy beverages, for example, to favorably modify their consistency. All samples exhibited viscoelastic and thixotropic behaviors.

1. Introduction

Products derived from fermented milk are widely consumed as healthy food. Increased consumer demand for natural and healthy foods (Sloan, 2005) contributes to the interest of the food industry in the production of acid gels without addition of stabilizers. Besides, they usually present some syneresis during storage (Lucey, 2004). Much effort has been devoted to new technologies such as ultra-high pressure homogenization (UHPH) in the treatment of dairy bases for the production of yoghurt, as an alternative to usual thermal processes. The potential benefit of UHPH relates to favorable modification of the texture, fermentation time, water holding capacity and acidification, among other characteristics (Grácia-Juliá et al., 2008; Harte, Clark, & Barbosa-Cánovas, 2007; Lopez-Fandiño, 2006; Sandra & Dalgleish, 2005). UHPH has been investigated in the production of yoghurt employing pressure levels up to 350 MPa (Serra, Trujillo, Quevedo, Guamis, & Ferragut, 2007). During UHPH, fluid under pressure is forced to pass through a gap on the valve and the high gradient of resulting pressure generates intense forces of shear, cavitation, impact and increase of temperature for a short period of time (Floury, Legrand, & Desrumaux, 2004). Level of denaturing and aggregation of proteins are dependent on the intensity of mechanical forces and/or temperature. Therefore, UHPH can induce several changes in protein functionality. In this sense, the presence of thermocouples for recording temperature changes during process is justified and appropriate, especially for monitoring temperature of the generated fluid after its passage through the valve (Grácia-Juliá et al., 2008).

To obtain liquid yoghurt, clot is mechanically broken before being cooled and bottled, inducing considerable changes in rheological properties, which are also affected by characteristics of the original gel (Thamer & Penna, 2006). Dairy beverage has a broad meaning and encompasses a range of products as specified in the Technical Regulation on Identity and Quality (Brasil, 2005). These products are made from milk and whey, fermented or not, with or without the addition of other ingredients. The proportion milk:whey varies considerably. There is no knowledge regarding product functionality when proportion is changed (Almeida, Bonassi, & Roça, 2001).

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Understanding rheological properties of food products is essential for the product development, quality control, sensory evaluation, equipment design and equipment evaluation process (Steffe, 1996, p. 428). Fluid flow behavior can vary from Newtonian to time dependent non-Newtonian and viscoelastic, and a given food may exhibit these behaviors depending on its origin, concentration, and previous history (Rao, 2007, p. 471). The role of protein structure in the rheological study of emulsion and gel is complex and fundamental rheological tests provide critical information on the viscoelastic behavior, depending on time and on molecular mechanisms involved in structure changes during the protein gelatinization process (Phillip, Whitehead, & Kinsella, 1994).

Proteins of foods, and especially of dairy products, are complex in their composition and structure, and can show wide variation of rheological properties in different conditions. The rheological properties of these products are strongly influenced by temperature, concentration and physical state of the dispersion (van Vliet & Walstra, 1980). Therefore, it is important to investigate the rheological properties of dairy products in relation to temperature and high pressure.

In this study, in order to obtain the set of different fermented dairy beverages, the fermented dairy base (MB) plus the beverages added with pineapple juice (chosen among tropical fruits) sweetened with sugar (MBA) or aspartame (MBL) were treated with different levels of UHPH and inlet temperature, and were compared with the heat treated product. The reason to use two types of sweeteners was to sensory evaluate and compare alternative formulations for fermented dairy beverages, mainly considering that in Brazil those kind of products are preferably sweetened with aspartame instead of sugar. The aim was to evaluate the effect of pressure levels and inlet temperature on the viscosity and shear stress of dairy based products pressurized, formulated with the two different sweeteners evaluated.

2. Material and methods

2.1. Dairy base (raw skim milk and reconstituted whey)

Raw skim milk (fat content < 0.5 mL/100 mL) was directly obtained from the milk producers (Cooperativa de Laticínios de Macuco, RJ), and stored for 24 h at (4 ± 1)°C. The dairy base was prepared adding up reconstituted whey powder (Laticínios Porto Alegre Ind. e Com. Ltda., MG) to the raw skim milk in proportions that ensured a total solid content of about 9 g/100 mL.

2.2. Preparation of the thermally pasteurized control dairy beverage

In order to obtain the fermented dairy beverages, several volumes of raw skim milk (70, 60 and 50 mL/100 mL) and whey powder reconstituted (30, 40 and 50 mL/100 mL) were mixed and thereby obtained different dairy base formulations, according to flowchart in Fig. 1(a). The resulting dairy base was pasteurized in Ultra-High Temperature (UHT) equipment (model ARMFIELD FT 25 d S S H.E, scraped surface exchanger at Embrapa Food Technology Rio de Janeiro – RJ, Brazil), heated at 90 °C during 60 s and cooled to (43 ± 1)°C. The pasteurized mixture was packaged in glass bottles with screw caps previously sterilized, in which the probiotic lactic culture (Bio Rich of Christian Hansen Ind. and Com. Ltda. consisting of *Lactobacillus acidophilus*, *Bifidobacterium bifidum* and *Streptococcus thermophilus*) had been added at a concentration of 1 g/L. All dairy base formulations were homogenized and incubated at (43 ± 1)°C being allowed to ferment until the pH reached 4.4. At that point, after cooling to 10 °C, fermented dairy beverage was prepared: F raw skim milk: reconstituted whey powder (mL:mL/100 mL)/juice (mL/100 mL) + sugar (7 g/100 mL) = F50:50/30; F50:50/20; F50:50/10; F60:40/20; F70:30/30; F70:30/20, F70:30/10 and maintained under refrigeration at (4 ± 1)°C until to be analyzed.

2.3. Methodology

Herein two methodologies were used: one for selecting the most appropriate formulation (F raw skim milk: reconstituted whey powder/pineapple juice + sugar) based on sensory analysis, and the other for studying the influence of high pressure and inlet temperature on the rheological behavior. The first methodology used dairy base only thermally treated (TT), whereas the second used the dairy base treated with pressure and inlet temperature (UHPH), according to flowchart in Fig. 1(b).

2.4. Sensory analysis

A completely randomized 2^2 factorial design, with one central point and two extra points, was proposed to study the influence of fermented dairy base and pineapple juice (Icefruit-Maisa, SP) on sensory attributes. This design was used with two types of beverages: one with sugar (Cosan-Açúcar União, RJ) (7 g/100 mL) and other with aspartame (Nutrasweet do Brasil Ltda., SP) (0.0388 g/100 mL). By varying the amount of pasteurized pineapple juice (10, 20 and 30 mL/100 mL) and fermented dairy base (raw skim milk: reconstituted whey powder = 70:30, 60:40 and 50:50 mL/100 mL) according to Table 1 14 samples were formulated following this design. After filling up the bottles, the samples were stored under refrigeration (4 ± 1)°C until the time to carry out the analyses.

The dairy beverages were evaluated using the Quantitative Descriptive Analysis (QDA) (Meilgaard, Civille, & Carr, 1999, p. 354) to characterize samples and identify the most appropriate thermally processed formulation in terms of sensory characteristics (such as appearance, consistency, taste and aroma). The selected formulated beverage was used in the subsequent studies focusing on UHPH processing. A sensory panel, of eight previously selected assessors (three men and five women, respectively, with 35–55 and 30–50 years old), elicited and defined sensory attributes using all developed formulations, and three commercial products available in the market. The list of attributes was defined by considering the best ones to describe samples. In addition, their definitions and reference terms were prepared by the sensory panel. Synonyms and related terms were reduced by the team and training sessions were conducted using a sheet with descriptive terms, consensually obtained. The sensory attributes were evaluated in a non structured 9 cm scale, varying from the score zero or one on the left side, to nine on the right side. In accordance with QDA standard procedure (Stone & Sidel, 2004, p. 365), samples were served monadically and evaluated in sensory booths under white light at the Sensory and Instrumental Evaluation Lab., Embrapa Food Technology, Rio de Janeiro – RJ, Brazil.

Data were collected in duplicate using the FIZZ software (BIOSYSTEMS, version 2.10) and analyzed by using analysis of variance (ANOVA) and principal component analysis (PCA).

2.5. Rheological behavior

The dairy base, chosen by the methodology explained in 2.3, was pressurized using an ultra-high pressure homogenizer model FPG7400H: 350 (STANSTED Fluid Power Ltd., Essex – UK) with a flow rate of 250 mL min−1. Thermocouples were installed in different positions of the equipment in order to monitor the inlet temperature (T_1) of the dairy base, the previous temperature (T_2) of

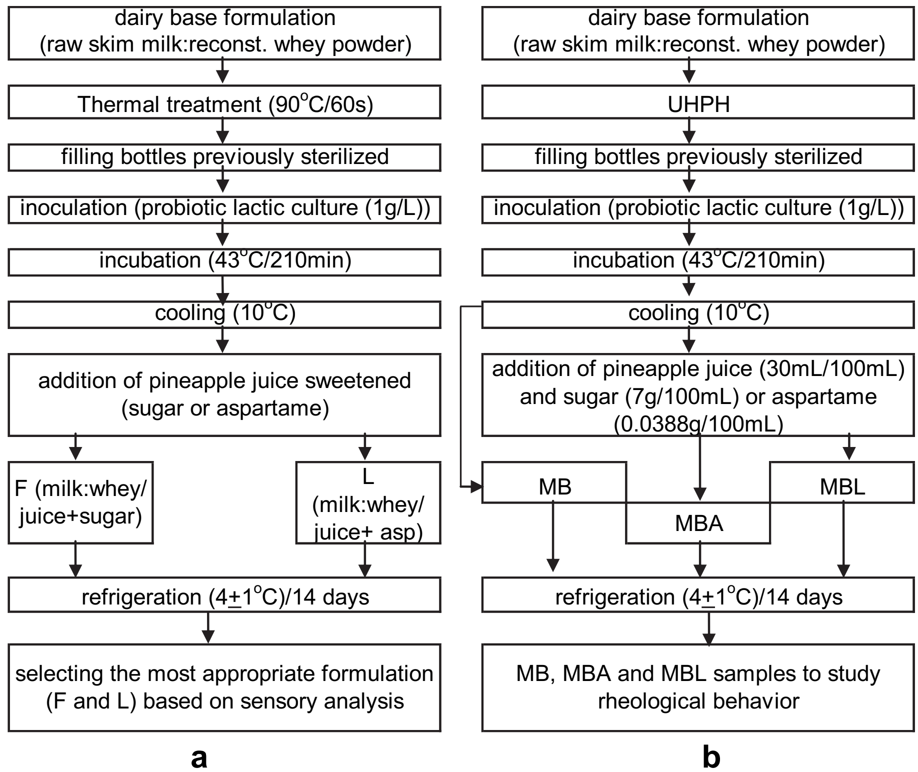

Fig. 1. Production flowcharts of: (a) Thermal treatment of dairy base formulations to produce $F_{milk:whey/juice+sugar}$ and $L_{milk:whey/juice+aspartame}$ beverages, according to Table 1, for sensory analysis and (b) UHPH process, according to Table 2, to obtain fermented dairy beverages (MB), fermented dairy beverages with pineapple juice and sugar (MBA) and fermented dairy beverages with pineapple juice and aspartame (MBL) for studying the rheological behavior.

the first homogenization valve, the temperature (T_{11}) after the second homogenization valve, and the temperature (T_{12}) after the heat exchanger to cool the dairy base. All of them were connected to the data logger Model 692-8010 (Barnant Co., Barrington IL, USA) used to record data. To the UHPH processing, pressure levels of 150, 200 and 250 MPa with inlet temperatures of the dairy base of 15, 20 and 25 °C were used, according to the 2^2, with central points, a factorial design proposed for processing the samples (Table 2). The dairy base pressurized was collected in glass bottles with screw caps previously sterilized, in which the probiotic lactic culture, the same cited on item 2.2, had been added at a concentration of 1 g/L, in order to inoculation the samples. The samples were homogenized and incubated at (43 ± 1)°C, allowing fermentation up to pH 4.4. To the ready and cooled (10 °C) fermented dairy beverage, it was added commercial pasteurized pineapple juice sweetened with sugar or with aspartame. The samples obtained were: MB = fermented dairy beverage (50 mL raw skim milk + 50 mL reconstituted whey powder); MBA = MB with pineapple juice (30 mL/100 mL) and sugar (7 g/100 mL) and MBL = MB with pineapple juice (30 mL/100 mL) and aspartame (0.0388 g/100 mL). The products were kept at (4 ± 1)°C for being used in subsequent rheological characterization (shear stress and apparent viscosity as dependent variables).

Table 1
Experimental design for dairy beverage formulation.

Experiment	Coded variables		Original variables	
	X_1	X_2	Dairy base (milk:whey) (mL/100 mL)	Pineapple juice (mL/100 mL)
1	−1	−1	70:30	10
2	1	−1	50:50	10
3	−1	1	70:30	30
4	1	1	50:50	30
5	0	0	60:40	20
6	−1	0	70:30	20
7	1	0	50:50	20

2.6. Rheological characterization

Rheology is the science of the deformation and flow of matter. There are three ways to deform a substance: shear, extension and bulk compression. It is possible to conduct tests, in all three modes of deformation, under steady state, transient and dynamic conditions (Steffe, 1996, p. 428). The tests of the current study were performed under a steady state condition to assess the flow behavior of the samples. The shear stress and apparent viscosity were measured in a strain-controlled rheometer (ARES, TA Instruments, New Castle, DE, USA) coupled to the TA Orquestrator software. A concentric cylinder geometry was used (rotor diameter (bob): 32 mm; diameter cup: 34 mm; rotor length (bob): 33.2 mm) and the sample volume in each test was 20 mL. The following experimental conditions were used for all fermented dairy samples processed by UHPH and by thermal treatment: temperature (10 ± 1)°C with a stabilization time of 10 min; after that, two cycles were performed, varying the shear rate, i.e., one ranging from 0 to 300 s^{-1} in 600 s (rise cycle), followed by the return to 0 s^{-1} in 300 s

Table 2
Variables and variable levels for an experimental design used in UHPH processing of dairy base formulation.

Variable	Variable level		
	Low	Central	High
Pressure (MPa)	150	200	250
Inlet temperature (°C)	15	20	25

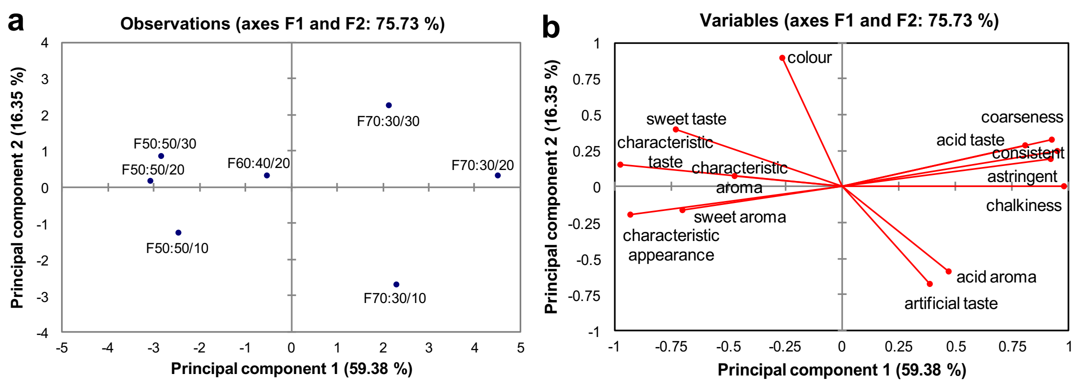

Fig. 2. Principal Component Analysis – PCA – showing (a) the position of samples: fermented dairy beverages with pineapple juice and sugar (F milk:whey (mL:mL/100 mL)/juice (mL/100 mL) + sugar (g/100 mL)) and (b) the position of the respective sensory attributes.

(descendent cycle). The changes were observed in the apparent viscosity (loss of structure) and in shear stress (Steffe, 1996, p. 428).

2.7. Statistical analysis

Analysis of variance (ANOVA), principal component analysis (PCA) and design of experiments were used to investigate the influence of different beverage formulations on the rheological behavior and sensory attributes. For all statistical analyses, a significance level of 5% was considered. Principal Component Analysis (PCA) is a valuable statistical tool widely used in sensory data analysis (Borgognone, Bussi, & Hough, 2001).

3. Results and discussion

3.1. Identification of the dairy beverage formulation

For shortness, only the seven samples sweetened with sugar are shown in Fig. 2(a). The distribution of sensory attributes defined in the space by first and second dimensions are shown in Fig. 2(b). The sum of the principal components 1 and 2 (PC1 and PC2) accounted for by 76% of variation among samples with sugar, and for 80% of variation among samples with aspartame (data not shown). The sensory results for aspartame were presented elsewhere (Masson, Deliza, Calado, & Rosenthal, 2009).

Comparing Fig. 3 (a) and (b), we can see that the formulations with higher levels of whey, formulation F_{50} – sugar – (and formulation L_{50} – aspartame, not shown) were characterized as having much higher intensity of sensory attributes, such as characteristic aroma, appearance and taste. However, the attributes considered as having negatively contributed to the product unwanted profile (acid taste, astringency, coarseness consistency and chalkines s consistency) were perceived with much higher intensity in formulations containing lower levels of whey (F_{30} and L_{30}), practically independent of pineapple juice concentrations. These results revealed that the formulations with higher levels of whey (F_{50} and L_{50}) were selected and considered as the most appropriate in terms of sensory properties, based on the expected attributes for fermented dairy beverage. We also noticed that PC1 represents very well the following attributes: characteristic appearance, consistency, coarseness consistency, chalkiness consistency, characteristic taste and astringency. PC2 represents color reasonably well.

3.2. Increase in temperature during UHPH processing

For each level of pressure applied to the UHPH processing of the dairy base (150, 200 and 250 MPa), the thermocouples recorded temperatures along the operation, as shown in Table 3. An increase in temperature was observed for all pressure conditions along the processing. As the inlet temperature T_1 increased from 15 to 25 °C and the pressure level from 150 to 250 MPa, the highest value in T_{11}, and consequently in T_{12}, was observed. After T_{11} stabilization, the dairy base passed through the heat exchanger and was rapidly cooled to T_{12} in a fraction of seconds. The lower heating time observed for the UHPH process compared to the heating time

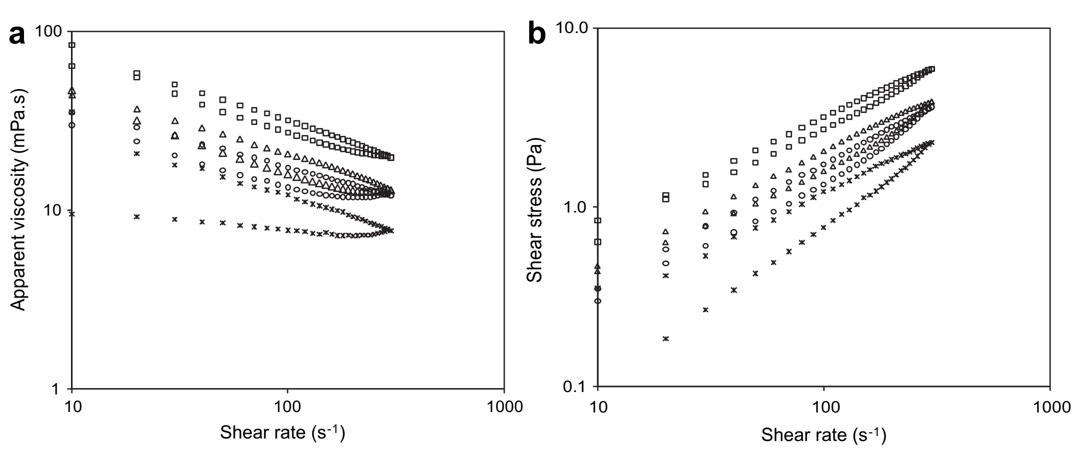

Fig. 3. (a) Apparent viscosity and (b) Shear stress curves for MBA beverages = fermented dairy beverage (50 mL raw skim milk: 50 mL reconstituted whey powder/100 mL) with pineapple juice (30 mL/100 mL) and sugar (7 g/100 mL) processed by UHPH: △ 150 MPa-15 °C; ⋇ 250 MPa-25 °C; ○ 200 MPa-20 °C and thermal treatment: □ 90 °C/60s.

Table 3
Average and standard deviation[a] of the temperature values[b] used during UHPH process to the dairy base formulation (raw skim milk + reconstituted whey powder).

Pressure (MPa)	T_1 (°C)	T_2 (°C)	T_{11} (°C)	T_{12} (°C)
150	14.50 ± 0.47	21.36 ± 0.31	51.63 ± 1.22	34.09 ± 1.19
150	24.88 ± 0.23	28.79 ± 0.75	58.57 ± 1.06	38.17 ± 0.95
250	16.73 ± 0.29	26.17 ± 0.75	74.84 ± 0.61	46.21 ± 1.07
250	24.56 ± 0.18	34.04 ± 0.70	80.90 ± 1.43	51.78 ± 1.15
200	19.82 ± 0.17	28.70 ± 0.17	68.30 ± 1.49	44.03 ± 1.86
200	19.92 ± 0.08	28.80 ± 0.32	69.56 ± 0.53	45.01 ± 0.43
200	20.06 ± 0.05	29.15 ± 0.18	69.57 ± 0.64	45.51 ± 0.47

[a] Average and standard deviation of 10 replicates of each temperature value.
[b] Temperatures: T_1 = inlet, T_2 = before the first homogenization valve, T_{11} = after the second homogenization valve and T_{12} = after the heat exchanger.

necessary to the thermal pasteurization is an advantage, as it allows to obtain products with less damage caused by heat, avoiding adverse effects on the flavor and nutrient content (Pereda, Ferragut, Quevedo, Guamis, & Trujillo, 2007).

3.3. Processing UHPH effect on rheological characteristics of dairy beverages (MB, MBA and MBL)

Table 4 shows that the data of apparent viscosity for shear rate equal 50 s^{-1} (rise cycle) of MB, MBL and MBA samples from the processes of the UHPH and the control samples. This value of shear rate was chosen because it represents approximately the sensation perceived in the mouth (Bourne, 2002, p. 427). At this condition, the apparent viscosity showed the lowest values for all samples processed by UHPH at 250 MPa and inlet temperature (T_1) of 25 °C, probably because of a modification in the protein structure. The highest values were obtained for the samples in which dairy bases were submitted to a milder process (UHPH: 150 MPa and T_1 = 15 °C) and to the thermal process (TT: 90 °C/60 s), since milk proteins suffered less destruction in such conditions.

Table 4
Apparent viscosity values at 50 s^{-1} shear rate (rise cycle) for UHPH samples and Thermal treatment control samples.

UHPH process		Apparent viscosity (mPa s)		
		Sample[b] type		
Pressure (MPa)	Inlet temperature (°C)	MB	MBA	MBL
150	15	41.65	26.67	35.52
150	25	24.22	18.42	19.00
250	15	23.98	26.75	26.28
250	25	21.46	15.37	13.35
200[a]	20[a]			
200[a]	20[a]			
200[a]	20[a]	25.55 ± 1.20[c]	24.15 ± 1.81[c]	24.99 ± 2.41[c]

Thermal treatment		Control sample[b]		
Temperature (°C)	Time (s)	MB	MBA	MBL
90	60	37.63 ± 0.99[c]	41.50 ± 0.24[c]	35.41 ± 0.44[c]

[a] Central point level.
[b] Samples: MB = fermented dairy beverage (50 mL raw skim milk + 50 mL reconstituted whey), MBA = fermented dairy beverage (50 mL raw skim milk + 50 mL reconstituted whey) with pineapple juice (30 mL/100 mL) and sugar (7 g/100 mL), MBL = fermented dairy beverage (50 mL raw skim milk + 50 mL reconstituted whey) with pineapple juice (30 mL/100 mL) and aspartame (0.0388 g/100 mL).
[c] Apparent viscosity triplicates average and standard deviation.

Considering the results, it is clear that the rheological behavior may be primarily related to the type of interactions among the particles and the molecules responsible for the gel formation.

The degree of whey protein denaturation is a very important factor that affects the rheological behavior of the gel, and can be related to the intensity of the temperature and the pressure applied. It is also responsible for the protein–protein interactions, and the retention of whey proteins in the network gel (Serra, Trujillo, Guamis, & Ferragut, 2009). The homogenization pressure from 140 to 200 MPa without fluid pre-heating does not seem to induce the protein denaturation in whey (Hayes & Kelly, 2003; Paquin, Lacasse, Subirade, & Turgeon, 2003; Sandra & Dalgleish, 2005), as demonstrated by the results obtained in the present study.

Previous studies have reported that during the process of UHPH, in which pressure exceeding 200 MPa was applied, there was a partial disintegration of casein micelles (Sandra & Dalgleish, 2005; Serra et al., 2007), which resulted in an increased number of fragments of casein solution and then in greater solvation of the protein (Serra et al., 2009). Moreover, the disintegration of casein micelles is accompanied by the solubilization of colloidal calcium phosphate (Serra et al., 2007). These facts suggest that the structure of the gels obtained by UHPH is dominated by casein–casein interactions instead of the interactions of whey protein–casein. On the other hand, this structure seems to be composed, primarily, by the casein–casein unions combined with electrostatic and hydrophobic interactions, known as aggregation of casein particles (Mellema, 2000).

3.4. Viscosity and shear stress time dependence and thixotropy

Samples of MB, MBA, MBL (control and pressurized) were stored for 14 days under refrigeration temperature (4 ± 1)°C; after that, they were analyzed. Fig. 3 shows (a) apparent viscosity (mPa s) and (b) shear stress (Pa) curves *versus* shear rate ranging from 0 to 300 s^{-1} in 600 s (rise cycle), followed by return to 0 s^{-1} in 300 s (descent cycle) of the MBA samples studied. It can be observed a thixotropy behavior for all samples, including MB and MBL ones, although data were not shown here. The protein destruction of the pressurized samples in the most severe pressure and inlet temperature (UHPH 250 MPa/25 °C) was significant, as evident from the hysteresis loop and the lack of full recovery of the shear stress and apparent viscosity values.

3.5. Effect of pressure and temperature on the apparent viscosity and shear stress

Fig. 4 shows the decreasing tendency of the apparent viscosity of UHPH processed samples (MB, MBL and MBA) with pressure (a) and temperature (b), respectively, at specific shear rates – 10, 150 and 300 s^{-1}, a range usually studied. By Anova analysis, it was observed that for all samples, for 150 and 300 s^{-1}, there was no statistical significant difference ($p < 0.05$) on the average apparent viscosity related to pressure and temperature.

At shear rate of 10 s^{-1} in Fig. 4, average values of apparent viscosity were statistically different among samples. Moreover, the average apparent viscosity for MB sample decreased around 32% when pressure (a) and temperature (b) ranged from 150 to 250 MPa and 15–25 °C, respectively. A different behavior was observed for MBA and MBL curves, at the same shear rate; the average apparent viscosities reached the lowest values at 20 °C and 200 MPa. These facts are probably because of differences in the sample formulation composition; MB samples have higher protein content and neither sweetener nor juice was added to them. As a consequence, the protein denaturing might have occurred in higher intensity in these samples. Several authors have reached similar conclusions in their studies (Hayes & Kelly, 2003; Paquin et al., 2003, Sandra &

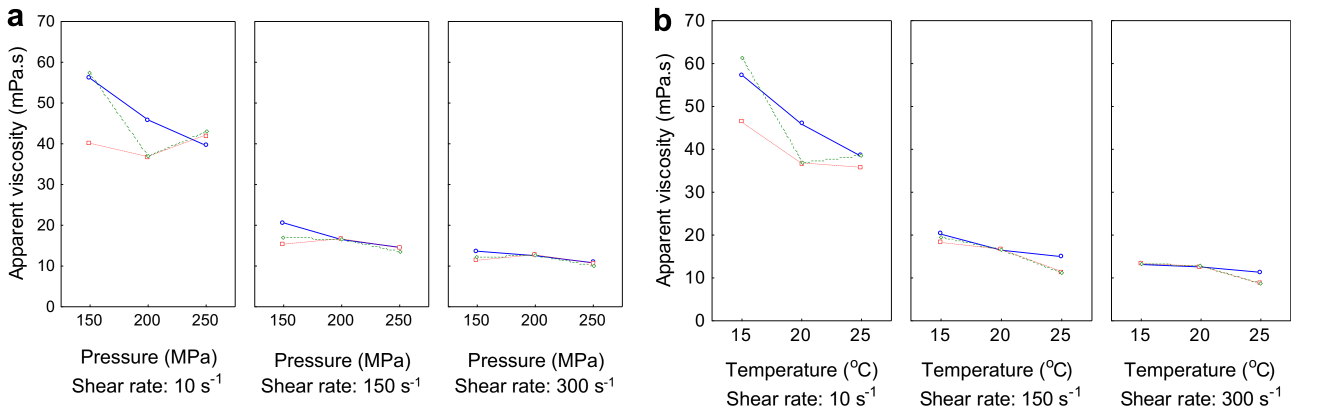

Fig. 4. Average apparent viscosity *versus* shear rate and varying (a) pressure and (b) inlet temperature of samples: -o-MB = dairy beverage (50 mL raw skim milk + 50 mL reconstituted whey powder); -□- MBA = dairy beverage (50 mL raw skim milk + 50 mL reconstituted whey powder) with pineapple juice (30 mL/100 mL) and sugar (7 g/100 mL); -◇-MBL = dairy beverage (50 mL raw skim milk + 50 mL reconstituted whey powder) with pineapple juice (30 mL/100 mL) and aspartame (0.0388 g/100 mL). ANOVA: R-sqr = 0.96708; R-adj = 0.94629; 63 Runs; MS Pure Error = 0.0000062. ($P < 0.05$).

Dalgleish, 2005; Serra et al., 2007; Serra et al., 2009). The higher sweetener and juice contents of MBA and MBL samples probably are responsible for the structure recovery at 250 MPa.

Despite no measurement of particle size was taken, the results suggest that the viscosity could have been influenced by the size of these particles, aggregates of casein and whey proteins from denaturing caused by pressure. At pressures above 200 MPa, the average apparent viscosity was similar regardless the shear rate used in the UHPH process, probably due to the increasing denaturing of milk proteins and whey caused by these higher pressures. Similar results were reported by Walstra and Jenness (1984), Floury, Desrumaux, and Lardieres (2000), Clare et al. (2005). Pereda et al., 2007, found that the UHPH processes decreased the particle size of milk processed in the pressure level from 200 to 300 MPa, directly affecting the viscosity.

Although not shown here, the same analysis was performed for shear stress. Differently from the apparent viscosity, as the shear rate increased, a tendency to increase the shear stress for all investigated samples was observed. For shear rate of 10 s^{-1}, there was no significant decrease in the shear stress for all samples when pressure and temperature ranged from 150 to 250 MPa and from 15 to 25 °C, respectively. For 150 and 300 s^{-1}, there was a statistical significant difference ($p < 0.05$) on shear stress related to pressure and temperature. With respect to protein denaturing, the same comments mentioned earlier for apparent viscosity apply to shear stress.

3.6. Effect of thermal treatment compared to the UHPH on the rheological parameters

In order to verify the effect of thermal treatment and the pressure process, we compared the mean values of apparent viscosity and shear stress for samples MB, MBA, MBL processed by UHPH and controls varying with shear rate (rise cycle). It was observed that the apparent viscosity and shear stress curves of the samples processed by UHPH at 150 MPa and 15 °C were similar to thermal processed (TT: 90 °C/60s) products, as shown in Fig. 5(a) and (b), respectively. For all samples investigated, apparent viscosity decreased and shear stress increased as the shear rate increased from 10 to 300 s^{-1}. It was also observed a shear-thinning behavior for viscosity. The survey of rheological parameters of apparent viscosity and shear stress made it possible to compare the UHPH and thermal processes applied to the dairy base, not yet explored so far (Grácia-Juliá et al., 2008; Harte et al., 2007; Lopez-Fandiño, 2006; Paquin et al., 2003; Sandra & Dalgleish, 2005; Serra et al., 2009).

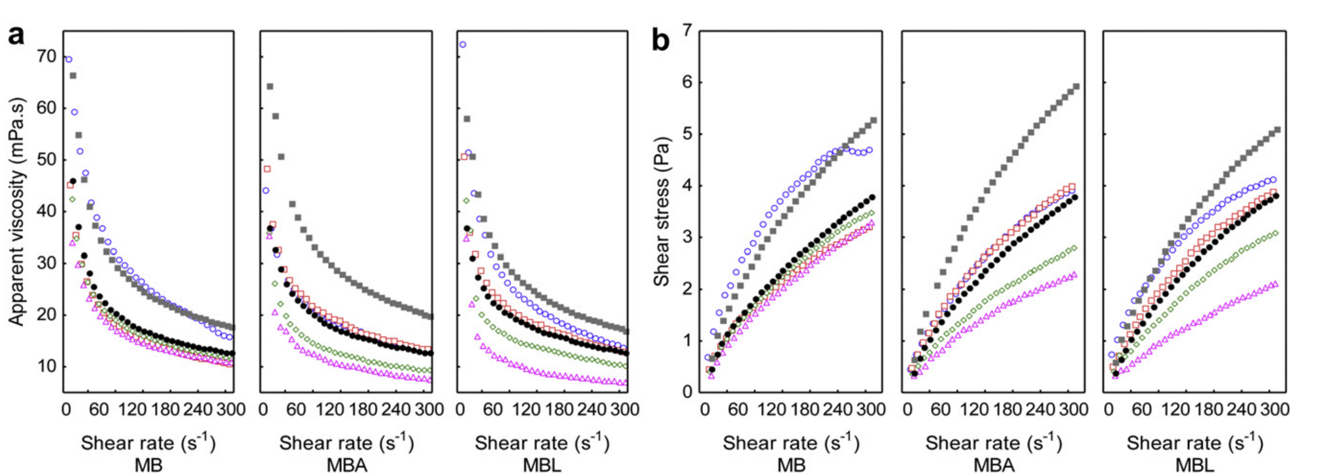

Fig. 5. (a) Apparent viscosity (mPa s) and (b) Shear stress (Pa) by varying shear rate (s^{-1}) for UHPH process: ○ 150 MPa-15 °C; □ 250 MPa-15 °C; ◇ 150 MPa-25 °C; △ 250 MPa-25 °C; ● 200 MPa-20 °C and thermal treatment: ■ 90 °C/60s for MB = fermented dairy beverage (50 mL raw skim milk + 50 mL reconstituted whey powder), MBA = fermented dairy beverage (50 mL raw skim milk + 50 mL reconstituted whey powder) with pineapple juice (30 mL/100 mL) and sugar (7 g/100 mL), MBL = fermented dairy beverage (50 mL raw skim milk + 50 mL reconstituted whey powder) with pineapple juice (30 mL/100 mL) and aspartame (0.0388 g/100 mL) samples.

4. Conclusion

The fermented dairy beverages with probiotic starter cultures showed a wide diversity on the rheological properties and sensory attributes, which were influenced by the formulation and, consequently, by the ingredients. The samples exhibited viscoelastic and thixotropic behaviors during the two cycles of shear rate. The UHPH process, at 150 MPa and $T_1 = 15$ °C, was the most similar one to the thermal process (TT: 90 °C/60s), considering the rheological parameters of viscosity and shear stress of the investigated conditions. The apparent viscosity and the shear stress showed the lowest values for all samples processed by UHPH at 250 MPa and $T_1 = 25$ °C. The protein denaturing of the pressurized samples at this most severe condition was significant, as evident from the hysteresis loop and the lack of full recovery of the shear stress and apparent viscosity values. On the other hand, the highest values were verified under milder condition (UHPH at 150 MPa and $T_1 = 15$ °C), in which milk proteins might be less affected. These results may suggest that this milder condition was suitable to yield a product with adequate rheological characteristics. Changes induced by UHPH can be used to open up new possibilities in dairy product developments. These preliminary results suggest that UHPH has a potential to model some rheological properties of dairy fermented beverages, thus decreasing the need for additives and stabilizers.

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