Investigation of Factors Affecting Frothing Capacity of Pasteurised Whole Milk for Cappuccino Coffee

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Abstract: **The present investigation was carried out to study factors which affect frothing capacity of pasteurised whole milk produced by a local dairy plant so as to find a way of improving its frothing potential. The effects of homogenising the milk at three different pressures (125, 160 and 200 bars); fresh milk storage time (day 1 and day 10) addition of skimmed milk powder (SMP) (0, 1, 3 and 5%) and lastly varying the milk temperature prior to frothing (4±1°C and 7±1°C) were evaluated based on three variables; foam volume (FV), steam froth value (SFV) and % dissipation. Each sample was frothed five times with three replications. The highest average steam frothing value (SFV) was obtained at the highest homogenisation pressure (200 bars) and the lowest frothing was obtained at 125 bars; 129.99 and 81.78 respectively. However, foam stability decreased with an increase in homogenisation pressure as evidenced by a low percentage dissipation at 125 bars and higher one at 200 bars of 7.20% and 13.75% respectively. Generally, fresh milk had an enhanced frothing capacity at 4±1°C prior to frothing as compared to 7±1°C. Addition of 5% SMP to fresh milk resulted in an increase frothing capacity. There was no significant difference (p>0.05) found between day1 and day 10 for FV, SFV and percentage dissipation. Good foamability behaviour correlated well with an increased homogenisation pressure, SMP and low initial milk temperature prior to frothing. Thus the optimal conditions of foam volume, steam frothing value and percentage dissipation are obtained at 4±1°C initial milk temperature prior to frothing which is homogenised at 200 bars and with 5% SMP added prior to frothing. The optimal foam volume, steam frothing value and percentage dissipation are 3.78, 151.23 and 6.29 respectively at these conditions.**

Key words: **Steam frothing values, foam volume, percentage dissipation, frothing capacity, foamability, foam stability**

I. INTRODUCTION

A new market emerged during the beginning of the year (2016) for a local dairy plant to supply pasteurised whole milk to coffee shops. This growing market now demands more than 40% of the whole milk produced per week. However the coffee shops reported that foaming and sustaining the foam was poor. This led to the research to investigate the factors affecting the frothing capacity of whole milk with the aim of improving the frothing capacity of milk from the local dairy plant.

Requirements for the formation of foam include a gas, water, a surfactant and energy. The surfactant lowers the surface tension between the gas and water thereby facilitating the formation of small gas bubbles [1]. For milk foams, the surfactant constitutes the proteins present in the system (whey and casein proteins). Energy is required to overcome the interfacial free energy of the system, which is increased on foaming because of enlargement of the surface area [2]. During the formation of gas bubbles in the liquid, the gas bubbles should have sufficient time for the formation of an interfacial film to prevent the collapse or coalescence of these bubbles [3]. The foaming capacity of milk is largely due to the whey proteins, especially lactoglobulin. Due to the flexible open chain of caseins they show a high heat stability and Casein – whey protein aggregates are formed when milk is heated. Such effects are limited by commercial pasteurisation (72°C/15 sec) but UHT (135°C/2 sec) and sterilisation (121°C/15mins) cause extensive aggregation [2]. Thus one way of improving the frothing capacity of milk is to heat and cool the milk before trying to froth it [4].

The foaming of milk is an important quality attribute in the manufacture of dairy based espresso drinks. The quality of these products depends on the ability of the milk to form a stable foam thus milk's ability to produce the desired foam for gourmet coffees is of great importance [3][4]. Complains about the failure of a local dairy`s pasteurised whole milk to froth to the coffee shops` expectations during the year 2016 led to this study on foaming properties of milk. The inability of whole milk to form a stable foam when injected with steam has been previously reported [3], [4]. Specific aspects of composition and processing may affect the foaming properties of milk. Identifying the source of this failure and improving the frothing capacity could enable the milk industry to provide higher foam quality milk to meet the growing needs of coffee houses. The aim of this study was to investigate ways to improve foamability and foam stability of whole pasteurised whole milk for cappuccino coffee as a case study for a local dairy plant in Harare Zimbabwe.

II. MATERIALS AND METHODS

2.1 Sample collection

All the milk for this study was obtained from the local dairy plant in Harare and two sampling techniques were used; convenience and simple random sampling.

2.1.1 Convenient sampling technique

The first sampling technique used was convenient sampling. Several factors like closeness/easy accessibility of the company and also willingness of company's participation allowed selection during sampling.

2.1.2 Systematic sampling technique

The samples were collected four times a week at different days over a period of four months. Selection of days was based on the dairy plant`s whole milk production plan. At the time of the study, whole milk was only processed on Sundays, Mondays, Tuesdays and Thursdays at the plant.

2.2 Sample Preparation

2.2.1 Milk Preparation and Standardisation

After the milk is received, it is stored in bulk tanks (4°C ± 1°).

The milk was separated into raw skim milk and raw cream using a Verocream 3.4 (GEA West Falia separator Group) centrifugal separator/cold milk separator. After all the milk was separated and the fat removed, a C4–20, (Delta instruments) Lactoscope was used on the skim milk and Gerber method on cream to obtain accurate fat levels. The cream was recombined with the skim milk, using the Pearson Square method, to obtain the desired fat levels. These included fat contents of skim (0.08%) and whole milk (3.5%).

2.2.2 Pasteurisation

All the milk was pasteurized using a plate heat exchanger system with homogenizer at 125bars pressure. The whole milk was pasteurized at 72°C for 15 seconds. After pasteurization, milk temperature was checked and the milk was immediately cooled to ensure that the milk was maintained at 4 ±1°C.

2.2.3 Frothing procedure

For each milk sample, 100ml (4°C ± 1) was placed into a Cafféluxe milk frother (RSH-24080-119, Caffelux Distributors), which heated the milk to 65 ± 5°C for 65 to 80 seconds. The machine was switched off as soon as frothing was over. The froth was allowed to settle for 10 minutes. Froth characteristics were observed, that is the initial froth height (IF) after 5 seconds and 10 minutes and recoded. The liquid height of milk (LV) after 5 seconds, 10 minutes (LV_5 and LV_{10}) were also recorded. The total height of milk and froth after 5 seconds and 10 minutes (TV_5 and TV_{10} respectively) and the milk foam interface (FMI) were recorded. Foamability or steam frothing value (SFV) after 5 seconds and foam stability (% dissipation) after 10 minutes was calculated. Each treatment was frothed 5 times (with three replicates) and means for all values were determined. If the foam was not evenly distributed across the container, an average height was determined [4].

2.3 Effect of homogenisation pressure

Pasteurised whole milk was homogenised at three different pressures, i.e. 125, 160 and 200 bars. The temperature of the milk was stored at 4 ± 1°C. The froth characteristics (SFV, FV and % dissipation) were calculated.

2.4 Effect of storage time

After the homogenisation pressure treatments were applied to the milk samples were stored at 4°C ± 1°C for 1 day (24 hours) and 10 days (240 hours) from the time of pasteurization. The samples were then frothed as described in 2.2.3

2.5 Effect of initial milk temperature prior to frothing

The initial milk temperature for samples homogenised at 125, 160 and 200 bars was maintained at 4 ± 1°C and another batch at 7 ± 1°C. These samples were frothed and froth characteristics (SFV, FV and % dissipation) were calculated [4].

2.6 Effect of addition of milk solids (Skimmed Milk Powder)

0, 1, 3, 5% of skimmed milk powder (SMP) was added to each milk sample homogenised at 125, 160 and 200 bars and frothed. The samples were in two batches, one batch kept at 4 ± 1°C whilst the other batch was kept at 7 ± 1°C prior to frothing. The froth characteristics (SFV, FV and % dissipation) were calculated.

2.7 Milk foam evaluation parameters

For this study foamability, foam stability and overrun were investigated

2.7.1 Foamability

Foamability refers to the propensity of milk to foam and is most easily determined as the volume of foam formed from a given quantity of milk [5]. Foamability measurements may be carried out in graduated cylinders, whereby the volume of foam (FV) is determined as the total volume (TV) of the sample column minus the volume of liquid underneath the foam (LV).

$$FV = TV - LV$$

(EQUATION 1)

2.7.2 Foam Stability

Foam stability refers to the ability of the foam to retain its volume as a function of storage time and conditions [6]. Kamath et al [8] reported that foam stability is most readily measured by determining foam volume as a function of storage time under defined storage conditions. A commonly used measure to express the foam to reduce to half of its original volume. Decreases in foam volume occur as a result of drainage of liquid from the foam, as well as due to coalescence and disproportionation of gas bubbles [7].

$$\%Dissipation = \frac{IF - FF5}{IF - FMI} \times 100$$

(EQUATION 2)

Where:
IF = Foam height after 5 seconds of frothing
FF_{10} = Final foam height after 10 minutes
FMI = Final milk/ foam interface

$$FV10 = TV10 - LV10$$

(EQUATION 3)

Where:
FV_{10} = Foam volume after 10 minutes
TV_{10} = Total volume after 10 minutes
LV_{10} = Liquid volume after 10 minutes

2.7.3 Overrun

Overrun refers to the volume of air incorporated in the foam and is closely related to the density of the foam [7]. Foam overrun increases with decreasing density of the foam, which is commonly associated with more voluminous foams. Overrun is generally calculated as the difference in density between the milk and the foam, divided by the density of the foam [8]. In practice, densities are generally replaced by the weight of a given volume of liquid and foam. Drainage of liquid from the foam also increases overrun, as a result of which foam overrun can increase during storage of milk foams. This is usually determined using Steam Frothing Values (SFV).

$$SFV = \frac{TV - LV}{LV} \times 100$$

(EQUATION 4)

Where:

TV = Total volume milk and froth after 5 seconds of frothing

LV = Volume of milk at liquid froth interface after 5 seconds of froth

2.8 Data analysis

A one-way ANOVA (95% confidence level) was used to analyse the effect of homogenisation pressure whilst a two-way ANOVA (95% confidence level) with replicates (each trial was done five times) was used to analyse for significant difference between the averages of the response variables, SFV, foam value and percent dissipation, due to the different control factors (SMP and initial milk temperature prior to frothing). The optimum levels for the control factors was determined and the performance under these levels was predicted using response surface modelling.

III. RESULTS AND DISCUSSION

3.1 Effect of homogenisation pressure

From Table 1 an increase in homogenisation pressure resulted in an increase in frothing capacity. In addition Figures 1, 2 and 3 showed a significant difference in FV, SFV and % Dissipation at 95% confidence level with an increase in homogenisation pressure (125, 160 and 200 bars ($p<0.05$)).These results agree with observations made by Kinsella [11] who noted that a homogenisation pressure of the magnitude of 125 and above can have an influence on frothing capacity. The increased frothing capacity is attributable to fat globule size reduction and the associated partial denaturation of globular proteins in milk [9], [10] and [11]. In addition the whipping action during agitation stretches the polypeptide chains resulting in breaking up of stabilising forces in the globular proteins thereby increasing adsorption capacity of protein molecules.

TABLE 1: EFFECT OF HOMOGENISATION PRESSURE ON FROTHING CAPACITY

Homogenisation pressure (bars)	AVERAGE OF FIVE REPLICATES		
	FV (cm)	SFV	% Dissipation
125	2.78	81.78	7.20
160	3.06	91.64	9.81
200	3.64	129.99	13.75

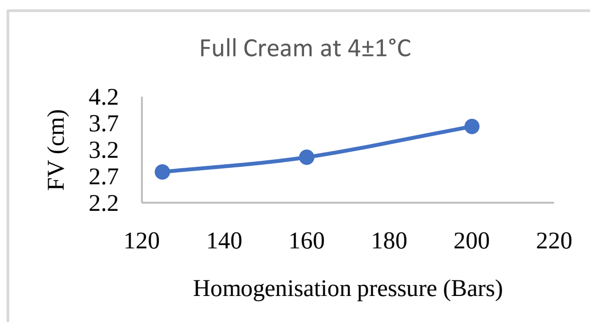

FIGURE 1: EFFECT OF HOMOGENISATION PRESSURE ON FOAM VOLUME

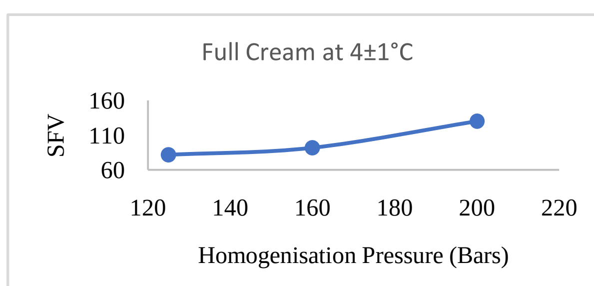

FIGURE 2: EFFECT OF HOMOGENISATION PRESSURE ON FOAMABILITY

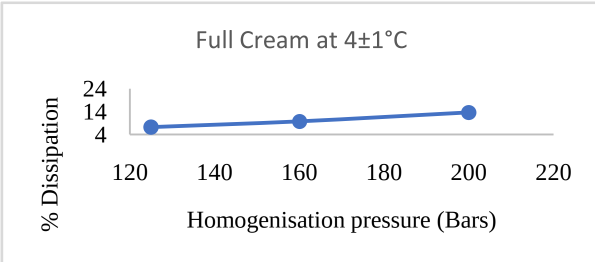

FIGURE 3: EFFECT OF HOMOGENISATION PRESSURE ON FOAM STABILITY

3.2 Effect of storage time

Table 2 relates the effect of storage time of the milk on frothing capacity. There was no significant differences ($p>0.1$) observed in the SFV, FV and % dissipation of the pasteurised whole milks of day 1 and day 10. The average SFVs were 81.78, 91.64, 129.99 (day 1) and 81.67, 91.09, 130.48 (day 10) at 125, 160 and 200 bars homogenisation pressures respectively.

TABLE 2: EFFECT OF STORAGE TIME ON FROTHING CAPACITY

DAY	AVERAGE OF FIVE REPLICATES								
	FV (cm)			SFV			% Dissipation		
	125 bars	160 bars	200 bars	125 bars	160 bars	200 bars	125 bars	160 bars	200 bars
1	2.78	3.06	3.64	81.78	91.64	129.99	7.20	9.81	13.75
10	2.74	3.04	3.68	81.67	91.09	130.48	7.25	9.74	13.61

3.3 Effect of skimmed milk powder

TABLE 3: EFFECT OF SKIMMED MILK POWDER ON FROTHING CAPACITY AT 4±1°C

SMP %	AVERAGE OF FIVE REPLICATES								
	FV (cm)			SFV			% Dissipation		
	125 bars	160 bars	200 bars	125 bars	160 bars	200 bars	125 bars	160 bars	200 bars
0	2.78	3.06	3.32	81.78	91.64	129.99	7.20	9.81	13.75
1	2.96	3.26	3.64	96.73	110.14	135.90	6.76	9.20	13.04
3	3.18	3.38	3.70	106.71	117.36	141.93	4.72	5.92	8.53
5	3.36	3.56	3.78	113.52	126.26	151.23	2.98	4.21	6.29

TABLE 4: EFFECT OF SKIMMED MILK POWDER ON FROTHING CAPACITY AT 7±1°C

SMP %	AVERAGE OF FIVE REPLICATES								
	FV (cm)			SFV			% Dissipation		
	125 bars	160 bars	200 bars	125 bars	160 bars	200 bars	125 bars	160 bars	200 bars
0	2.36	2.61	3.00	50.71	61.78	97.66	9.15	12.76	16.65
1	2.55	2.88	3.24	63.64	80.87	106.44	8.01	11.01	15.04
3	2.80	3.12	3.46	80.21	94.73	116.36	6.65	8.89	11.51
5	3.02	3.27	3.63	95.15	102.14	125.51	4.91	6.86	8.94

3.3 Effect Of Storage Temperature and Addition Of Skimmed Milk Powder (SMP) on Frothing Capacity

As shown in Table 3 and Table 4, initial temperature of milk had an effect on frothing capacity, in particular the SFV, FV and % dissipation. There were significant differences for SFV, FV and % dissipation between milk stored at 4 ± 1°C and 7 ± 1°C ($p<0.05$). Pasteurised whole milk stored at 4°C showed a better frothing capacity than milk stored at 7°C as shown in Table 3 and 4 respectively. The initial milk temperature significantly affected foam formation and stability in foams generated by mechanical agitation. This can be attributable to the fact that more energy is required to raise a lower milk temperature of 4 ± 1°C to 65 ± 5°C and hence more air is incorporated in so doing than in the case of a higher milk temperature of 7 ± 1°C. Increasing initial temperature of milk from 7 ± 1°C to the typical consumption temperature of 65 ± 5°C decreased the volume of air incorporated into the milk and resulted in a faster decrease in foam-to-liquid ratio over time [8].

On addition of skimmed milk powder, there were significant differences with increases in % SMP added (0, 1, 3 and 5%) ($p<0.05$) for SFV, FV and % dissipation. As illustrated in Figs 7 – 9. Addition of SMP prior to frothing enhanced the whole milk's steam frothing capacity with 5% SMP giving optimal results. Whole milk without SMP had a lower frothing capacity compared to samples with SMP added. The enhanced frothing capacity is attributable to the denaturation of globular proteins, which enhances surface activity of the proteins. This was supported by Marinova et al [10], who noted that, heat and mechanical agitation stretch the polypeptide chains until the stability forces of the proteins break thereby unravelling previously entangled hydrophobic residues. In addition, steam temperature determines the physical phenomena such as foamability of milk and stability of milk foam by altering the protein composition and protein-protein interactions at the air-liquid interface of milk foams. This is important because the extent of whey protein denaturation has important consequences on the functional properties of many milk products [10].

Foam is forced in milk on introduction of forced air and heat. This is due to β-lactoglobulin which, entraps the air bubbles and create the foam matrix [5]. This is evident from the increased foamability and foam volume with addition of skimmed milk powder as shown in Figs 4-5. Skimmed milk powder (SMP) contains the globular whey protein β-lactoglobulin, thus an increase in percentage of SMP resulted in an increased concentration of these proteins.

The degree to which whey proteins are denatured in milk depends on the heating procedures. In the native state, whey proteins have a definite conformation, which when exposed to heat above certain critical levels, is disrupted, and characteristic properties of the protein are altered. This is important because the extent of whey protein denaturation has important consequences on the functional properties of many milk products [10]. Casein proteins do not undergo any detectable changes at temperatures below 100°C, but any temperatures above 65°C affect the casein micelles.

Proteins in milk allow milk to create foam when introduced to forced air and heat. Specifically, the globular whey protein β-lactoglobulin, is mainly responsible for milk's ability to entrap the air bubbles and create the foam matrix [5]. This is evident by the increased foamability and foam volume with addition of skimmed milk powder. Skimmed milk powder (SMP) contains the globular whey protein β-lactoglobulin, thus an increase in percentage of SMP in the milk results in an increased concentration of these proteins. As heat and mechanical agitation are introduced into the milk, these proteins unravels exposing their previously entangled hydrophobic end to the introduced air bubbles causing an increase in strength of the of the air bubble. The temperature determines the physical phenomena such as foamability of milk and stability of milk foam by altering the protein composition and protein-protein interactions at the air-liquid interface of milk foams.

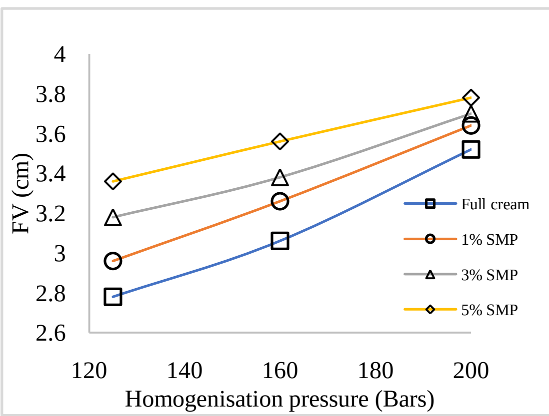

FIGURE 4A: EFFECT OF SKIMMED MILK POWDER ON FOAM VOLUME AT 4±1°C

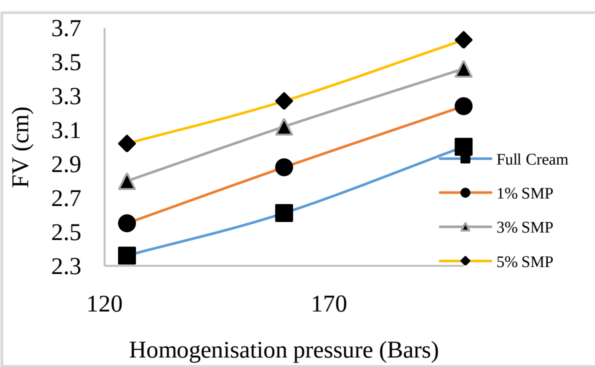

FIGURE 4B: EFFECT OF SKIMMED MILK POWDER ON FOAM VOLUME AT 7±1°C

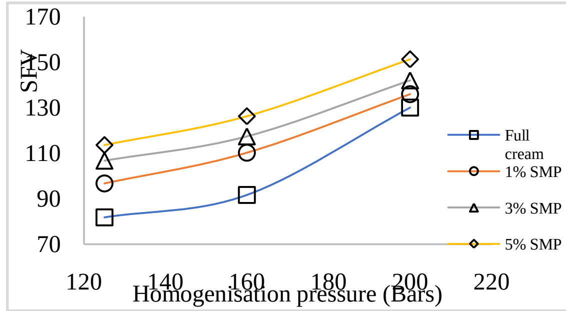

FIGURE 5A: EFFECT OF SKIMMED MILK POWDER ON FOAMABILITY AT 4±1°C

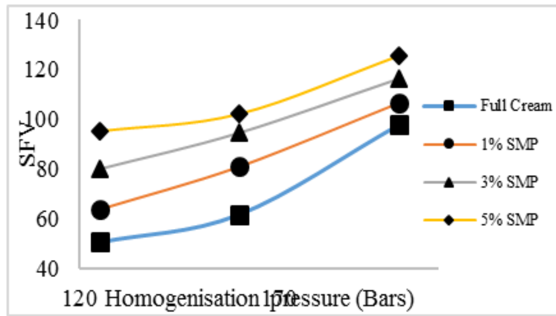

FIGURE 5B: EFFECT OF SKIMMED MILK POWDER ON FOAMABILITY AT 7±1°C

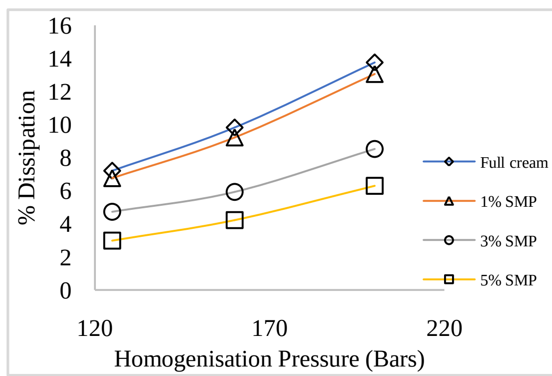

FIGURE 6A: EFFECT OF SKIMMED MILK POWDER ON FOAM STABILITY AT 4±1°C

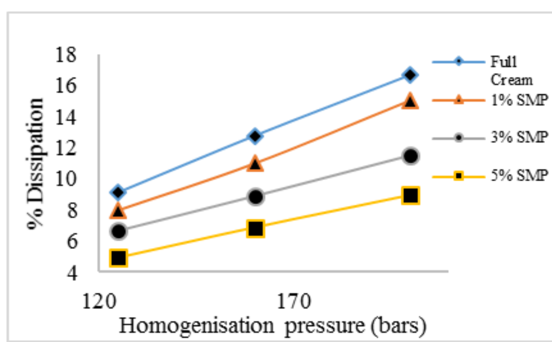

FIGURE 6B: EFFECT OF SKIMMED MILK POWDER ON FOAM STABILITY AT 7±1°C

Generally, results from this study demonstrate that foamability increase with pressure of homogenisation, milk proteins and at a milk temperature of 4 ± 1°C prior to frothing in whole milk. On the other hand, the foam is more stable at lower pressure of homogenisation, higher milk proteins and at a milk temperature of 4 ± 1°C prior to frothing in whole milk. Foams are metastable and with time the liquid between the lamellae drain; gas diffuses from the small to large bubbles (disproportionation), the film tends to thin and become fragile, causing rearrangement, and ultimately stresses and shocks may cause localized rupture [11]. This explains why dissipation of the foam occurs after 10 minutes in all the treatments

3.4 Surface response models for optimisation

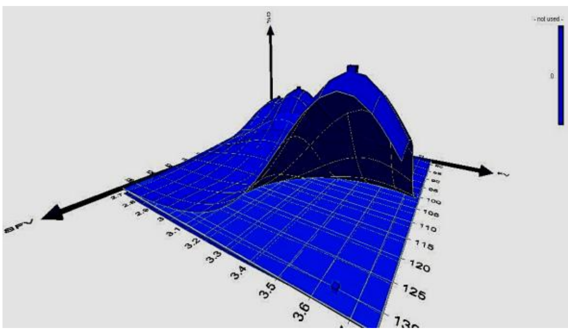

FIGURE 7: EFFECT OF HOMOGENISATION PRESSURE SURFACE RESPONSE GRAPH

TABLE 5: EFFECT OF HOMOGENISATION PRESSURE SURFACE RESPONSE TABLE

			Homogenisation pressure (bars)
FV (cm)	Minimum	2.78	125
	Maximum	3.64	200
SFV	Minimum	81.78	125
	Maximum	129.99	200
% Dissipation	Minimum	7.19	125
	Maximum	13.75	200

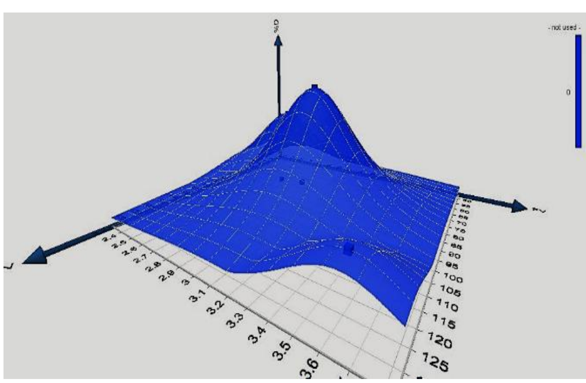

FIGURE 8: EFFECT OF TEMPERATURE SURFACE RESPONSE GRAPH

TABLE 6: THE EFFECT OF INITIAL MILK TEMPERATURE SURFACE RESPONSE MODEL

			Homogenisation pressure (bars)	Initial Milk Temperature (±1°C)
FV (cm)	Minimum	2.38	125	7
	Maximum	3.64	200	4
SFV	Minimum	51.31	125	7
	Maximum	129.99	200	4
% Dissipation	Minimum	7.19	125	4
	Maximum	24.18	200	7

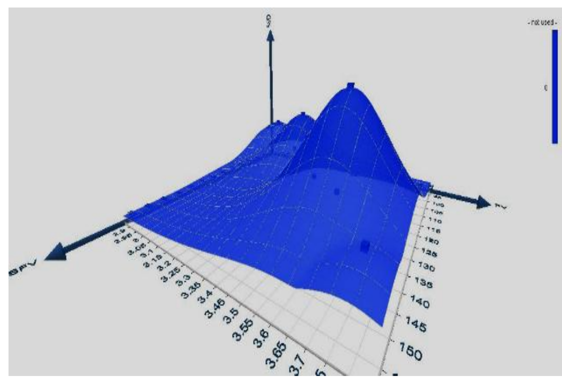

FIGURE 9: EFFECT OF SMP AT 4±1°C INITIAL MILK TEMPERATURE SURFACE RESPONSE GRAPH

TABLE 7: EFFECT OF SMP AT 4±1°C INITIAL MILK TEMPERATURE SURFACE RESPONSE TABLE

			Homogenisation pressure (bars)	SMP (%)
FV (cm)	Min	2.78	125	0
	Max	3.78	200	5
SFV	Min	81.78	125	0
	Max	151.23	200	5
% Dissipation	Min	2.98	125	5
	Max	13.75	200	0

TABLE 8: EFFECT OF SMP AT 7±1°C INITIAL MILK TEMPERATURE SURFACE RESPONSE TABLE

			Homogenisation pressure (bars)	SMP (%)
FV (cm)	Min	2.36	125	0
	Max	3.63	200	5
SFV	Min	50.71	125	0
	Max	125.51	200	5

% Dissipation	Min	4.91	125	5
	Max	16.65	200	0

As shown in Figs 7-9, response surface methodology was used to optimise the combinations for all the variables involved.

The effect of homogenisation pressure values of both FV and SFV (3.64 and 129.99 respectively) were obtained at 200 bars and the minimum percentage dissipation of 7.19 was obtained at 125 bars (Fig 7). Thus generally a homogenisation pressure of 200 bars is recommended for the production of a maximum foam volume and overrun. Maximum values of FV and SFV (3.64 and 129.99 respectively) were obtained at 4±1°C initial milk temperature prior to frothing and a minimum percentage dissipation of 7.19 was obtained at 4±1°C initial milk temperature prior to frothing (fig 8).

Overall, all optimal conditions of foam volume, steam frothing value and percentage dissipation were obtained at 4±1°C initial milk temperature prior to frothing. From the surface response model (Fig 7-9), maximum values of FV and SFV (3.78 and 151.23 respectively) were obtained at 5% SMP (200 bars and 4±1°C initial milk temperature prior to frothing). A minimum percentage dissipation of 2.98% was obtained at 5% SMP (125 bars and 4±1°C initial milk temperature prior to frothing). Thus all the optimal conditions of foam volume, steam frothing value and percentage dissipation are obtained at 5% SMP added to the milk prior to frothing. The same conditions were obtained of 5% SMP at 7±1°C initial milk temperature prior to frothing for FV, SFV and percentage dissipation (fig 8).

Thus overall, the optimal conditions of foam volume, steam frothing value and percentage dissipation are obtained at 4±1°C initial milk temperature prior to frothing which is homogenised at 200 bars and with 5% SMP added prior to frothing. The optimal foam volume, steam frothing value and percentage dissipation are 3.78, 151.23 and 6.29 respectively at these conditions [12].

IV. CONCLUSION

Results from this study showed that foamability increases with increase in homogenisation pressure but foam stability decreases as homogenisation pressure increases [12]. There was no significant difference (p>0.05) found between day1 and day 10 for FV, SFV and percentage dissipation, thus milk storage time has no significant effect on milk frothing capacity. Good foamability behaviour and foam stability correlated well with a low initial milk temperature of 4±1°C prior to frothing. Foamability (FV, SFV) increases with increase in percentage SMP added to milk prior to frothing but foam stability decreases. Addition of 5% SMP resulted in high frothing capacity of fresh milk [13]. Foams are metastable and with time the liquid between the lamellae drain; gas diffuses from the small to large bubbles (disproportionation), the film tends to thin and become fragile, causing rearrangement, and ultimately stresses and shocks may cause localized rupture [11][14]. This explains why dissipation of the foam occurs after 10 minutes in all the treatments. Steam frothing capacity of whole fresh milk is enhanced by a high homogenisation pressure of 200 bars, addition of 5% SMP prior to frothing, a low initial milk temperature of 4 ± 1°C prior to frothing but unaffected by storage time (day 1 or day10). Thus overall, the optimal conditions of foam volume, steam frothing value and percentage dissipation are obtained at 4±1°C initial milk temperature prior to frothing which is homogenised at 200 bars and with 5% SMP added prior to frothing. The optimal foam volume, steam frothing value and percentage dissipation are 3.78, 151.23 and 6.29 respectively at these conditions.

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