Lait 82 (2002) 401–412

DOI: 10.1051/lait:2002019

Original article

Influence of processing variables on the physicochemical properties of spray dried fat-based milk powders

James KELLY[a], Philip M. KELLY[a]*, Dermot HARRINGTON[b]

[a] Dairy Products Research Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland
[b] Data Systems Department, Teagasc, 19 Sandymount Avenue, Dublin 4, Ireland

Abstract – An experimental programme based on the production of fat-containing milk powders was designed around a newly-commissioned pilot-scale Tall-form drier. The 2-stage drier was equipped with two external fluidised beds and had a nominal water evaporation capacity of 70–100 kg·h^{-1}, depending on product and process conditions. The objective was to determine the influence of process variables on the physico-chemical properties of powders containing wide ranging fat levels. Regression equations were obtained in the course of correlating powder characteristics (bulk density, free fat, moisture) to input process parameters (concentrate total solids, drier inlet temperature, fat content and stage of feed homogenisation). The interactions for cream-filled and fat-filled powders in the fat range 260–700 g·kg^{-1} are outlined. A complex series of linear, quadratic and interactive relationships were established to describe the influence of processing conditions on powder quality. In addition, the processing conditions required to produce a high free fat powder as an ingredient suitable for chocolate manufacture are briefly described.

Milk / powder / fat / free fat / spray drying

Résumé – **Influence des variables opératoires sur les propriétés physicochimiques de poudres de lait grasses séchées par atomisation**. Un programme expérimental basé sur la production de poudres de lait grasses a été mis en place autour d'un nouvel équipement de séchage pilote « Tall form ». Cet équipement de séchage à deux étages était équipé de deux lits fluidisés externes et avait une capacité nominale d'évaporation d'eau de 70–100 kg·h^{-1}, dépendant du produit et des conditions de séchage. L'objectif était de déterminer l'influence des variables opératoires sur les propriétés physicochimiques des poudres contenant une large gamme de taux de matière grasse. Les équations de régression ont été obtenues en corrélant les caractéristiques des poudres (masse volumique apparente, matière grasse libre, humidité) aux paramètres de procédé mis en œuvre (matière sèche totale du concentré, température air d'entrée dans la tour, teneur en matière grasse et stade d'homogénéisation du produit à sécher). Les interactions pour des poudres réengraissées à partir de crème ou de matière grasse à des teneurs en matière grasse comprises entre 260 et 700 g·kg^{-1} sont présentées. Une série

---

Communication at the 1st International Symposium on Spray Drying of Milk Products, Rennes, France, October 16–18, 2001.
* Correspondence and reprints
Tel.: 353 25 42222; fax: 353 25 42340; e-mail: pkelly@moorepark.teagasc.ie

complexe de relations linéaires, quadratiques et interactives ont été établies pour décrire l'influence des conditions opératoires sur la qualité de la poudre. De plus, les conditions de séchage nécessaires pour obtenir une poudre à teneur élevée en matière grasse libre pouvant servir comme ingrédient dans la fabrication de chocolat sont brièvement décrites.

Lait / poudre / matière grasse / matière grasse libre / séchage par atomisation

1. INTRODUCTION

The conversion of milk into commodity products such as butter, skim milk powder, whole milk powder and casein is a significant factor in major dairy producing countries worldwide. In Ireland, it is all the more significant given the highly seasonal nature of milk production associated with pasture-based feeding systems. The intensive flow of milk during peak production periods demands the selection of a dairy product portfolio that suits high capacity milk processing situations. Because of the versatility of spray drying as a means of producing milk powders with a wide range of physico-chemical characteristics, there is increasing interest in expanding the range of dairy ingredients with enhanced functionality in order to create new market opportunities in food formulation and food service sectors. Powders with fat contents of 360–720 $g \cdot kg^{-1}$ are used for soups, sauces, bakery coatings, toppings and fillings [6]. Furthermore, declining butter consumption arising from consumer health concerns and lifestyle changes is demanding alternative product outlets for milkfat. While whole milk powder (WMP) containing ~ 260 $g \cdot kg^{-1}$ fat is readily produced by spray drying, there is relatively little technological information on the drying of powders containing substantially higher fat contents.

Since spray drying technology in combination with other unit processes has an important role to play in responding to market demands for powders with a wide range of functional properties, a research project investigating the influence of spray drying conditions on the physico-chemical characteristics of fat-based powders was undertaken. This paper presents the results of studies conducted during the processing and drying of cream- and fat-filled milk powders with fat contents ranging from 260 to 700 $g \cdot kg^{-1}$ fat.

2. MATERIALS AND METHODS

2.1. Experimental matrix

After undertaking exploratory trials to identify the operational limits for certain key parameters, a range of process input and product output variables were selected for detailed study according to Table I, which includes also abbreviations for the variables outlined. ECHIP® experimental design software was used to assist with the selection of values for each variable investigated (Tab. II). Statistical analysis was carried out using SAS® statistical software. A backward elimination method was used to select the final model. All variables remaining in the model were significant at the 5% level.

2.2. Fat standardisation by cream filling

Whole milk was obtained from a local dairy processor. When producing powders at the lower end of the fat range, milk was standardised on reception at the pilot plant by separating sufficient cream to give a bulk composition equivalent to 260 $g \cdot kg^{-1}$ FDM (fat-in-dry matter) as in the case of whole milk powder (WMP). Milk standardisation in order to produce higher fat powders was achieved by taking cream of known fat percentage (typically ~ 400 $g \cdot kg^{-1}$ fat) and standardising it to the desired fat content

Table I. Outline of process input and product output variables utilised in the experimental design matrix.

Experimental design matrix	
Input parameters	**Output variables**
Fat content (F) g·kg^{-1}	Moisture (g·kg^{-1})
Total solids content (TS) g·kg^{-1}	Bulk density (g·mL^{-1})
Drier inlet temperature °C (IT)	Free fat (g·kg^{-1} fat)
Drier outlet temperature °C (OT)	ADMI solubility index*
Atomisation pressure (AP)	Coffee test sediment volume*
Nozzle size	

* Results not included in statistical correlations.

Table II. Sequence of process steps involved in the preparation of cream-filled, and fat-filled powders with fat content greater or less than 350 g·kg^{-1}.

(**a**) Cream-filled.

Fat range: 260–350 g·kg^{-1}	**Fat range: 360–700 g·kg^{-1}**
Standardise fat content of whole milk	Standardise fat content of cream
Preheat: 97.5 °C × 2 min	Preheat: 97.5 °C × 2 min
Concentration (46; 50; 54 g·kg^{-1} TS)	**Concentrate homogenisation 15/5 MPa**
Concentrate heating: 65 °C	Concentration (46; 50; 54 g·kg^{-1} TS)
Concentrate homogenisation 15/5 MPa	Concentrate heating: 65 °C
Nozzle atomisation (25 MPa)	Nozzle atomisation (25 MPa)
Primary spray drying conditions Inlet air temp. (154; 166, 170, 175 °C) Outlet air temp (71–80 °C)	Primary spray drying conditions Inlet air temp. (154; 166, 170, 175 °C) Outlet air temp (71–80 ° C)
Secondary (fluidised beds) drying	Secondary (fluidised beds) drying

(**b**) Fat-filled.

Fat range: 260–650 g·kg^{-1}
Skim milk concentrate
Add coconut oil
Adjust total solids (46; 50; 54 g·kg^{-1} TS)
Concentrate heating: 65 °C
Concentrate homogenisation 15/5 MPa
Nozzle atomisation (18.8–27.8 MPa)*
Primary spray drying conditions Inlet air temp. (154; 166, 170, 175 °C) Outlet air temp (75 °C)*
Secondary (fluidised beds) drying

* Nozzle atomisation pressure was adjusted to maintain near constant air outlet temperature (75 °C).

using the skim milk fraction. As the viscosity of concentrates containing > 350 g·kg^{-1} FDM was considered too high after thermal evaporation, it was necessary to carry out homogenisation in the unconcentrated form i.e. at the standardisation stage.

2.3. Preheating and evaporation

Preheating conditions (97.5 °C × 2 min) were achieved using a combination of indirect preheating, steam infusion and direct steam injection in a pilot scale Niro 3-effect falling film evaporator (water evaporation capacity: 800 kg·h^{-1}). Concentrate (460–540 g·kg^{-1} total solids) from the evaporator was pumped by a positive displacement pump through a scraped-surface heat exchanger (heating temperature 65 °C) and delivered at ~ 0.2 MPa to the high pressure pump feeding the atomiser.

2.4. Spray drying conditions

Fat-containing concentrates were spray dried on a 2-stage Tall-form drier, model TFD-20 (Niro A/S, Copenhagen, Denmark) fitted with 2 external fluidised beds (vibrofluidiser Nos.1 and 2) with a nominal water evaporation capacity of 70–100 kg·h^{-1} (Fig. 1). The concentrate was spray atomised using 3 nozzles, reference 67 × 20 (orifice insert size × core size No.) (Spraying Systems Limited, Farnham, Surrey, UK). Inlet air (IT) was heated by indirect means and maintained within the range 150–170 °C. The air outlet temperature (OT) from the drying chamber was influenced indirectly by

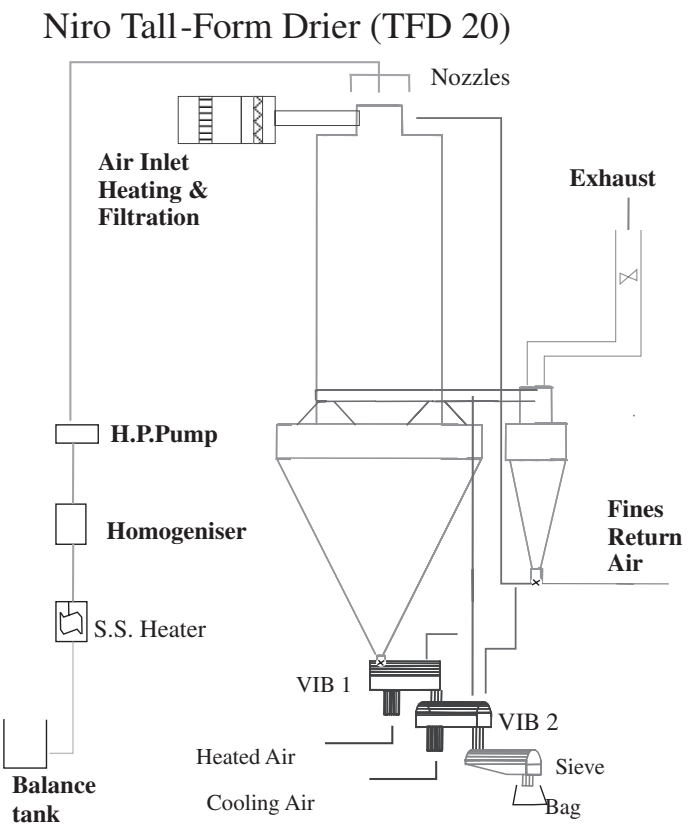

Figure 1. Outline diagram of pilot scale Tall-form spray drier.

nozzle selection, atomisation pressure (AP) and concentrate mass flowrates, but was generally in the range 72–74 °C for all trials.

2.5. Processing of fat-containing powders

A total of 34 cream-filled milk powder trials (including repeats) were undertaken. The original experimental design was revised after initial trials identified viscosity limitations associated with the homogenisation of concentrates > 350 g·kg^{-1} FDM. The high viscosity resulting from the homogenisation of these concentrates (total solids: 460–540 g·kg^{-1}) was overcome by introducing this unit operation in the early stages after standardisation (Tab. II).

Batch rather than in-line homogenisation was then used. It was also necessary to change atomiser nozzle sizes when the initial selection did not allow sufficient flexibility to control the drying process. Thus, the combined process parameters investigated included feed 2-stage homogenisation (15/5 MPa, 1st/2nd stage pressures, respectively); concentrate 2-stage homogenisation (15/5 MPa); drier inlet temperature (150; 155; 160; 165; 170 °C); atomiser pressure (25 MPa); vibrofluidiser No.1 temperature 65 °C and vibrofluidiser No. 2 temperature 30 °C.

A further study was undertaken where medium-heat, fat-filled powders using coconut oil were produced in order to compare the effects on powder properties of "filling" skim milk with either cream (natural milk emulsion) or free oil (non-emulsified fat). A total of 21 trials were accomplished using a similar experimental design as that applied to the cream-filled powders.

2.6. Production of high free fat whole milk powder

Following the outcome of the experimental drying trials, two approaches were evaluated for the preparation of high fat whole milk powder. In the first case, a skim milk concentrate base was prepared by evaporation of skim milk (preheat-treated as per medium-heat powders). Anhydrous milk fat was added to the concentrate using gentle agitation, after which it was heated to 80 °C and homogenised at low pressures before spray drying. In the second case, high fat, high free fat cream-filled powder was prepared (as per optimal conditions outlined in Fig. 2) before dry-blending with skim milk powder in order to standardise the final fat content to 260 g·kg^{-1}.

2.7. Analytical

Fat content (F) was measured by the Röse Gottlieb principle according to the FIL-IDF standard method 22B: 1987 [7]. Free fat was measured by the method described in Niro Atomiser [10]; moisture by oven method [9]; bulk density by FIL-IDF [8], solubility index by ADMI [1] and coffee sediment by [14].

3. RESULTS

3.1. Cream-filled powders

It is desirable normally to produce whole milk and fat-filled milk powders with low levels of free fat. Too high a free fat pre-disposes powder to greater levels of oxidation and contributes to poor rewetting properties during reconstitution later. Homogenisation and spray atomisation assist in reducing free fat, and in this respect, nozzles are generally better than disc atomisers. In contrast, operating at relatively high outlet air temperatures tends to promote higher free fat levels. During the course of exploratory trials (Tab. III), a comparison between two types of nozzles (Tab. III) suggested that reducing nozzle No. resulted in lower free fat (59 g·kg^{-1} fat for nozzle size 69 compared with 75 g·kg^{-1} fat for size 74) when drying a fat-containing concentrate (260 g·kg^{-1} fat WMP) at

460 g·kg^{-1} total solids and with a common drier air outlet temperature of 90 ºC.

Reducing the nozzle size further to No. 67 when drying a whole milk (260 g·kg^{-1} fat in powder) concentrate containing 540 g·kg^{-1} total solids enabled the drier to operate at a much lower outlet temperature of 69 ºC and not "over dry" the powder by going below the moisture specification (Tab. IV). A very satisfactory free fat content of 11.6 g·kg^{-1} fat was obtained under these conditions. The near-optimum process parameter settings for the production of 260 g·kg^{-1} fat-containing whole milk

Table III. Influence of nozzle size on free fat and moisture content of cream-filled powder (260 g·kg^{-1}) (**a**) at low total solids (460 g·kg^{-1}) and constant air outlet temperature; (**b**) at high total solids (540 g·kg^{-1}) and variable air outlet temperatures, and (**c**) at variable total solids and spray drier air inlet and outlet temperatures of 165 ºC and 74 ºC, respectively.

Nozzle size	Total solids g·kg^{-1}	Outlet temp. °C	Moisture g·kg^{-1}	Free fat g·kg^{-1} fat
(**a**)				
74	460	90	15.2	75
69	460	90	12.1	59
(**b**)				
74	540	98	17.1	34.7
69	540	90	10.0	31.2
67	540	69	31.0	11.6
(**c**)				
67	460	74	23.6	23.7
"	500	"	30.2	9.6
"	540	"	23.0	9.7

Table IV. ADMI Solubility Index and Coffee Test Sediment Values for fat-filled milk powders.

Powder fat %	Inlet temp. ºC	Outlet temp. ºC	ADMI solubility index	Coffee sediment Vol (mL)
26	175	75	< 0.1	< 0.8
26	175	75	< 0.1	0.5
26	170	72	< 0.1	0.6
26	174	75	< 0.1	0.6
26	174	75	< 0.1	< 0.5
28	174	74	< 0.1	< 0.2
28	170	74	< 0.1	< 0.1
32	170	72	< 0.1	< 0.1
32	171	72	< 0.1	< 0.1
35	168	72	< 0.1	< 0.5
35	169	73	< 0.1	0.7
35	170	73	< 0.1	< 0.2
35	170	72	< 0.1	0.4
45	175	73	n.a.	< 0.1
45	175	74	n.a.	< 0.1
45	175	74	n.a.	< 0.1
55	170	72.5	n.a.	< 0.3
55	169	74	n.a.	0.3
65	154	72	n.a.	0.2
65	164	73	n.a.	0.2
65	166	73	n.a.	0.2

powders with free fats < 10 g·kg^{-1} fat and powder moisture approaching typical specification level (Tab. V) were achieved using nozzle 67 to spray atomise concentrates with total solids content varying from 500 to 540 g·kg^{-1}, and at drier air inlet and outlet temperatures of 165 and 74 °C, respectively. Nozzle 67 was, therefore, used during subsequent processing of high fat powders.

As the total fat content of the powders increased from 260 g·kg^{-1} to 700 g·kg^{-1}, there was a clear indication of free fat levels increasing. The slight curvilinear relationship between percentage free fat and total fat content in the powders (Fig. 2) corresponded with the statistical evidence that fat level alone accounted for 960 g·kg^{-1} of the free fat variation. Thus, at the highest fat level (700 g·kg^{-1}) fifty five per cent of its content in powder is in a "free" form i.e. extractable by solvent and, by definition, to be substantially de-emulsified by the prevailing conditions of droplet/particle dehydration.

Table V. Interrelationships between input variables (fat content = F; total solids = TS; inlet temperature = IT; outlet temperature = OT) on powder free fat, bulk density and moisture of cream-filled powders (260–700 g·kg^{-1}).

Variable	Free fat g·kg^{-1} fat	Bulk density g·mL^{-1}	Moisture g·kg^{-1}
Constant	–10.77	3.46	3.42
F			
TS			–0.13
IT			
OT			
F^2	0.013*** ($p < 0.001$)		
TS^2			
IT^2		–0.00025** ($p = 0.0049$)	
OT^2		–0.00066** ($p = 0.0049$)	
F × TS		0.00030** ($p = 0.0016$)	
F × IT		–0.00011*** ($p = 0.0004$)	–0.0002*** ($p < 0.001$)
F × OT			
TS × IT		0.00071* ($p = 0.0170$)	
TS × OT			
IT × OT		0.00066** ($p = 0.0036$)	
Adjusted R^2	0.96	0.94	0.91

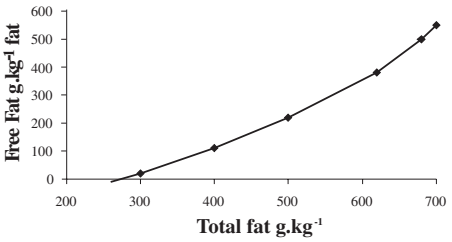

Figure 2. Effect of total fat content on free fat levels of spray dried cream-filled powders.

Statistical analyses of all fat-containing powders (260–700 g·kg^{-1} fat) produced by standardisation using cream established a number of relationships between input process conditions and powder physico-chemical characteristics. Bulk density was not affected linearly, but was affected quadratically and interactively by a number of variables. The adjusted correlation coefficient (R^2) indicates that 94 per cent of the variability was due to six of the variables F^2, IT^2, OT^2, F ×, TS IT × and IT × OT (Tab. VI). The interactive effect of fat level and inlet temperature was highly correlated ($R^2 = 0.91$) with moisture content, while other variables had a negligible effect (Tab. VI).

Linear inverse relationships which intersected more or less at mid-axis were established between fat content and bulk density for different drier air inlet temperatures (150–170 °C) when drying cream-filled concentrate containing 500 g·kg^{-1} total solids (Fig. 3). The influence of drier outlet temperature on the relationship between fat content and bulk density was inversely linear in the temperature range 70–78 °C (Fig. 4). Unlike the influence of inlet air temperature where all lines were in close proximity and the inverse slopes were of a gradual nature, operating at different outlet temperatures (Fig. 4) revealed greater sensitivity in the relationship between bulk density and fat content.

3.2. Fat-filled powders

There were linear, quadratic and interactive effects between IT, AP, F, IT^2, AP^2, F^2 IT × AP, and IT × F with free fat content ($R^2 = 0.99$) (Tab. VI). Moisture was influenced by a number of factors that also affected free fat e.g. atomisation pressure, fat content and inlet temperature (linear); and inlet temperature × fat content, atomisation pressure x total solids (interactively). Bulk density was affected mostly by an interaction between atomisation pressure and total fat ($R^2 = 0.78$).

Free fat levels were similar irrespective of whether homogenisation was carried out before or after concentration. The interactions of input variables had a greater influence on the free fat content of fat-filled

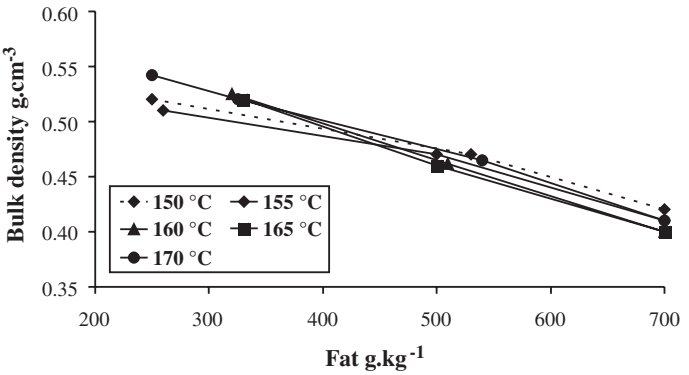

Figure 3. Effect of drier air inlet temperature on the interrelationship between fat content and powder bulk density of cream-filled powders based on concentrate containing 500 g·kg^{-1} solids.

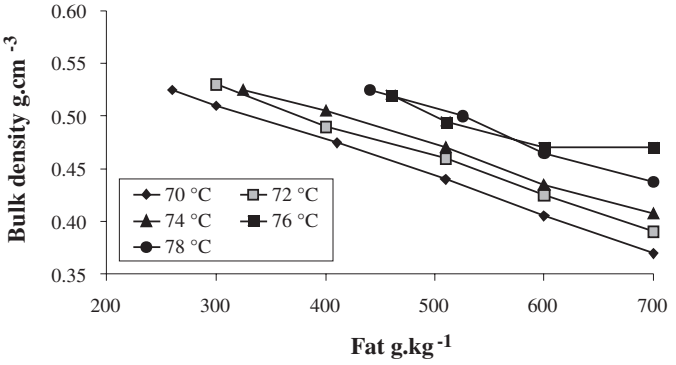

Figure 4. Effect of drier air outlet temperature on the interrelationship between fat content and powder bulk density based on concentrate containing 500 g·kg^{-1} solids.

Table VI. Interrelationships between input variables (fat content = F; total solids = TS; inlet temp = IT; outlet temp = OT; atomisation pressure = AP) on powder free fat, bulk density and moisture of fat-filled powders (260–650 g·kg^{-1}).

Variable	Moisture g·kg^{-1}	Free fat g·kg^{-1} fat	Bulk density g·mL^{-1}
Constant	–72.85	1178.95	0.65
IT	0.30*** ($p < 0.001$)	–11.37*** ($p < 0.001$)	
AP	0.17*** ($p < 0.001$)	–1.32** ($p = 0.0079$)	
TS			
F	1.07*** ($p < 0.001$)		
IT^2		0.024*** ($p < 0.001$)	
AP^2		–0.0018*** ($p < 0.001$)	
TS^2	0.0063** ($p = 0.0039$)		
F^2		0.038*** ($p < 0.001$)	
IT × AP		0.0013*** ($p < 0.001$)	
IT × TS			
IT × F	–0.0054*** ($p < 0.001$)	–0.015*** ($p < 0.001$)	
AP × TS	–0.0026** ($p = 0.0055$)		
AP × F	–0.00081** ($p = 0.0028$)		–0.000013*** ($p < 0.001$)
TS × F			
Adjusted R^2	0.96	0.99	0.78

rather than the cream-filled powders. By contrast, free fat levels in cream powders were solely dependent on total fat. Although the experimental matrix was similar, a slight difference was introduced to the operating protocol during drying of fat-filled powders. In this instance, outlet temperature was maintained at 72–74 °C and atomisation pressure was adjusted as a major input variable in order to attain this target value. As a consequence, atomisation pressures varied and these values were utilised during statistical analyses (Tab. VI). It seems likely that this process modification gave rise to a wider set of relationships (linear, curvilinear and interactive) involving several other input variables.

ADMI solubility index (SI) values were < 0.1 mL sediment for all cream- and fat-filled powders measured in the range 240–350 g·kg^{-1} fat (Tab. IV). Similar data for fat-filled powders > 350 g·kg^{-1} fat is not available, however it is to be expected that such values should be similar since the proportion of protein exposed to heat-induced changes during processing decreases with increasing fat content. Sediment volumes measured during coffee stability tests of fat-filled powders were higher compared to their corresponding ADMI SI values. Coffee sediment values declined moderately with increasing fat content i.e. were consistently ≤ 0.3 mL for fat-filled powders in the fat range 450–650 g·kg^{-1}, while those in the lower fat range (260–350 g·kg^{-1}) had frequent occurrences of sediment values corresponding to 0.5–0.8 mL.

3.3. Production of high free fat whole milk powder

An alternative approach to whole milk powder manufacture afforded the use of gentle blending of anhydrous milk fat with skim milk concentrate and the application of moderate homogenisation pressures. The free fat levels obtained were unacceptably low: in fact, contrary to expectations, two-stage homogenisation at pressures of 3 MPa and 1 MPa, (1st stage/2nd stage, respectively) resulted in higher free fat levels (140 g·kg^{-1} fat) compared with 98 g·kg^{-1} fat for the non-homogenised sample.

An alternative process, which exploited the outcome of experiments described earlier, involved the production of high free fat powders. The process steps involved the preparation of high fat base (concentrate) using cream; standardising with skim milk in order to adjust FDM to 700 g·kg^{-1} before concentration (460–480 g·kg^{-1} total solids) and spray drying. The resulting high fat-high free fat powder was dry-blended with skim milk powder in order to standardise downward the fat content to that of whole milk powder i.e. 260 g·kg^{-1} fat. A free-fat level of 820 g·kg^{-1} fat was obtained. A suggested alternative arrangement based on co-drying is also proposed i.e. spray drying a high fat base while simultaneously dry feeding skim milk powder into the drying chamber.

4. DISCUSSION

The process conditions affecting free fat levels in whole milk powder (260 g·kg^{-1} fat) observed in this case and by others [2, 4, 5] were overtaken by the dominant effect of total fat alone according as its content in powders increased. This was especially the case with cream-filled powders. On the other hand, when the spray drying of fat-filled powders was regulated (based on outlet temperature set-point) by the high pressure pump feeding the atomiser, atomisation pressure and its interactions with other parameters also became significant. In any case, it is evident that the application of homogenisation conditions typically associated with whole milk powder manufacture is insufficient to provide “durable” coverage of a high fat emulsion formed from a skim milk base (aqueous phase) during the dehydration phase. This physical characteristic

is of benefit to some food applications where immediate flavour and fat release is desired in the case of soup preparation and chocolate conching, respectively. However, if less free fat is desired in high fat powders, then more severe homogenisation conditions of emulsions prepared using optimal aqueous ingredients such as those applied during microencapsulation are necessary [13, 15]. Young et al. [15] increased microencapsulation efficiency i.e. reduced the amount of extractable fat – "free fat" by firstly emulsifying anhydrous milk fat in solutions prepared with whey protein isolate and carbohydrate, and homogenising the resulting emulsions at 50 MPa in 4 successive passes before spray drying.

Solubility index variation [6] in whole milk powder is also sensitive to process variation as well as compositional changes especially in the case of protein content. However, it appears to become less important as total fat content increases. This is understandable given that the commensurate reduction in protein content lessens its exposure to the deleterious effects of heat and concentration during processing.

Coffee sediment volumes, on the other hand, are expected to be higher than the ADMI SI equivalents for each powder given the severity of the test conditions e.g. low pH and relatively high temperature (80 ^{o}C). Commercial whole milk powders have been assessed on an arbitrary basis as "coffee stable" or "coffee unstable" depending on whether their sediment values were less than or greater than 1 mL, respectively [14]. However, under optimised conditions coffee sediment values < 1 mL were achievable for 260 g·kg^{-1} fat-containing whole milk powders [11] when produced on the same drier.

Atomiser nozzle size selection is critical when producing powders to specification, not alone because of the need to control feed rate within the water evaporation rates dictated by the limits of milk drying parameters, but also because of the effects on other physico-chemical parameters. It would appear that the optimisation studies undertaken at an early stage of the work with whole milk powder identified an appropriate nozzle size that suited the drying of higher fat powders subsequently. A related experience with disc atomisers shows that increasing peripheral speed of the rotating wheel intensified the homogenisation effect only if a whole milk concentrate were not already homogenised [3]. This could be loosely compared with increasing atomiser pressure on spray nozzles.

Ninety-four percent of the variation in bulk density of cream-filled powders was explained by a complex series of relationships between the process parameters: fat content, drier inlet temperature, drier outlet temperature, the interactions between fat and concentrate solids, inlet temperature and concentrate solids, inlet and outlet temperatures. Such complexity is already known for regular and agglomerated skim milk and whole milk powders [11]. However, this was simplified to a dominant interaction between atomisation pressure and total fat content in the case of fat-filled powders, presumably for the reasons already outlined surrounding the use of atomisation pressure as a process control parameter.

Moisture content was independent of concentrate total solids for both cream- and fat-filled powders, but dependent on the interaction between fat content and inlet temperature (cream-filled), and interactions involving inlet air temperature and atomisation pressure in the case of fat-filled powders.

High inlet air temperatures are normally desirable from an energy efficiency perspective during drying, and may improve bulk density provided that the risk of causing case hardening on the surfaces of powder particles is avoided. Such developments may restrict moisture evaporation and disimprove bulk density by causing "ballooning" [12] of particles due to air bubble

expansion. The use of low outlet air temperatures from the primary chamber as featured in modern 2- and 3-stage drying installations circumvents such downside risks associated with use of high inlet air temperatures. Moderate air inlet temperatures have been traditionally associated with the operation of Tall-form spray driers, and the input values used during the present study (150–170 °C) are less severe than those (155–225 °C) evaluated elsewhere [3] using a more conventional spray drying tower. Low air outlet temperatures generally favour more uniform drying of droplets, controlled particle shrinkage and improved powder bulk density [3]. However, in the present study lowering the outlet temperature from 70 to 78 °C reduced bulk densities. Further investigations are necessary to explain this observation.

ACKNOWLEDGMENTS

The assistance of M.K. Keogh with the application of ECHIP® experimental design software is greatly appreciated. Financial support for this research was provided under the European Regional Development Fund (Structural Funds) of the EU.

REFERENCES

[1] ADMI (American Dry Milk Institute), Determination of solubility index standards for grades of dry milks including methods of analysis, Bull 916 (revised), Chicago IL, USA, 1971, pp. 26–27.

[2] Buma T.J., Free-fat in spray-dried whole milk. 8. The relation between free-fat and particle porosity of spray-dried whole milk, Neth. Milk Dairy J. 19 (1971) 123–140.

[3] De Vilder J., Martens R., Naudts M., Influence of process variables on some whole milk powder characteristics, Milchwissenschaft 31 (1976) 396–401.

[4] De Vilder J., Moermans R., Martens R., The free-fat content and other physical characteristics of whole milk powder, Milchwissenschaft 32 (1977) 347–350.

[5] De Vilder J., Martens R., Naudts M., The influence dry matter content, the homogenization and the heating of concentrate on physical characteristics of whole milk powder, Milchwissenschaft 34 (1979) 78–84.

[6] Early R., The use of high-fat and specialized milk powders, J. Soc. Dairy Technol. 43 (1990) 53–56.

[7] IDF, Milk, whey and buttermilk, determination of fat content, Röse Gottlieb gravimetric method, Standard 22B, Int. Dairy Fed., Brussels, Belgium, 1987.

[8] IDF, Dried milk and milk products, Determination of bulk density, Standard 134A Int. Dairy Fed., Brussels, Belgium, 1995.

[9] Niro Atomizer, Determination of moisture. Method No. A1b in: Haugaard Sørenson I., Krag J., Pisecky J., Westergaard V. (Eds.), Analytical methods for dry milk products (4th ed.), A/S Niro Atomizer, Copenhagen, Denmark, 1978, pp. 10–11.

[10] Niro Atomizer, Determination of free fat on the surface of milk powder particles. Method No. A10a in: Haugaard Sørenson I., Krag J., Pisecky J., Westergaard V. (Eds.), Analytical methods for dry milk products (4th ed.), A/S Niro Atomizer, Copenhagen, Denmark, 1978, pp. 46–47.

[11] Oldfield D.J., Teehan C.M., Kelly P.M., The effect of preheat temperature and other process parameters on the coffee stability of instant whole milk powder, Int. Dairy J. 10 (2000) 659–667.

[12] Pisecky J., Bulk density of milk powders, Dairy Ind. Int. 43 (1978) 4–7, 10–11.

[13] Rosenberg M., Young S.L.,Whey proteins as microencapsulating agents. Microencapsulation of anhydrous milkfat - structure evaluation, Food Struct. 12 (1993) 31–41.

[14] Teehan C.M., Kelly P.M., Devery R., O'Toole A., Evaluation of test conditions during the measurement of coffee stability of instant whole milk powder. Int. J. Dairy Technol. 50 (1997) 113–121.

[15] Young S.L., Sarda X., Rosenberg M., Microencapsulating properties of whey proteins. 2. Combination of whey proteins with carbohydrates, J. Dairy Sci. 76 (1993) 2878–2885.