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Original article

Pump amperage: a new method for monitoring viscosity of dairy concentrates before spray drying

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Abstract – The atomization stage in spray drying of a liquid requires a spray of droplets with a high surface-to-mass ratio. Dried products that result from moisture evaporation of atomized spray can be prepared to reach the desired particle size distribution through control of atomization variables. To meet these requirements, many atomization techniques such as pressure nozzles, two-fluid nozzles and rotary atomizers have been used in spray dryers. Many authors have proposed various relationships between droplet size, physical properties (e.g. viscosity of concentrate) and technological parameters (e.g. nozzle pressure). To optimize the moisture content in milk powder, it is necessary to control the thermodynamic parameters of the drying air, the conditions of the atomization and the properties of the concentrate. Droplet size varies in direct relationship with viscosity to the power of 0.17–0.25. There are, in fact, two possible solutions for measuring online viscosity: either an online viscometer (direct measurement) or measurement of the amperage of the concentrate extraction pump (indirect measurement). The aim of this study was therefore to develop an indirect method to estimate the viscosity of a concentrate after concentration by filtration or vacuum evaporation and before spray drying. For example, while varying the viscosity of different dairy products (concentrated whey, and whole and skim milk) by changing the parameters of concentration by vacuum evaporation, we obtained a very good correlation between concentrate viscosity and the extraction pump amperage, whatever the product. Concentration parameters can be modified during evaporation to obtain a concentrate of the same viscosity, whatever its temperature or total solid content, just by following the extraction pump amperage.

concentrated milk / vacuum evaporation / viscosity / pump

Résumé – Suivi de la viscosité des concentrés en fonction de l'ampérage. L'étape de pulvérisation de liquide dans le séchage par atomisation exige la formation de gouttelettes ayant un rapport surface / masse élevé. Pour obtenir une taille de poudres maîtrisée, on fait varier les paramètres de séchage des poudres laitières résultant de l'évaporation de l'eau des gouttelettes créées lors de l'atomisation. Plusieurs techniques de pulvérisation peuvent être utilisés pour la création de gouttelettes, tels que l'atomisation par buses haute pression, par buses bi-fluide ou par turbine. De nombreux auteurs ont proposé des relations entre la taille des gouttelettes, les propriétés physiques (telles que la viscosité) et les paramètres technologiques (tels que la pression de pulvérisation). Pour optimiser la teneur en eau dans les poudres, il est nécessaire de contrôler les conditions d'atomisation, les paramètres thermodynamiques de l'air de séchage ainsi que les propriétés du concentré. La taille des gouttelettes varie directement avec la viscosité à la puissance 0,17–0,25. En fait, il existe deux

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possibilités pour mesurer la viscosité en ligne, soit à l'aide d'un viscosimètre (méthode directe) ou soit par la mesure de l'intensité de la pompe d'extraction (méthode indirecte). L'objectif de ce travail est de développer une méthode indirecte pour estimer la viscosité du concentré après concentration par filtration ou par évaporation sous vide et avant séchage. Par exemple, en faisant varier la viscosité de trois produits laitiers (lactosérum, lait entier et lait écrémé) par variation des paramètres de concentration par évaporation sous vide, nous obtenons une bonne corrélation entre la viscosité du concentré et l'ampérage de la pompe d'extraction quel que soit le produit. Ainsi, les paramètres de concentration pourront être modifiés au cours de l'évaporation afin d'obtenir un concentré à même viscosité quelle que soit sa température ou sa teneur en matière sèche, en suivant uniquement l'ampérage de la pompe d'extraction.

lait concentré / évaporation sous vide / viscosité / pompe

1. INTRODUCTION

The atomization stage in spray drying of liquid bulk produces a spray of droplets with a high surface-to-mass ratio. Evaporation of moisture from the atomized spray creates particles which are subsequently discharged as powder from the spray dryer. The most suitable spray for a spray drying operation is one of individual droplets of more or less equal size [7]. The most commonly used spray drying equipment in the dairy industry is rotary atomizer or nozzle atomizer. Droplet size distribution depends upon atomizer design. For rotary atomization, the factors affecting size distribution are wheel periphery speed, wheel diameter and number and height of vanes, etc. For nozzle atomization they are spray angle, feed pressure, orifice size, operational conditions (e.g. feed rate) and concentrate properties (e.g. surface tension, density and viscosity of the concentrate) [7, 12]. For the dairy industry, droplet size is an important parameter because it directly influences the sizes of powder particles. The same size of droplet will give the same size of powder and will optimize the quality of the powder (and vice versa). A considerable reduction in weight, volume and diameter of the particle takes place during the removal of water from the droplets. Under ideal drying conditions, weight will decrease to about 50%, volume to about 40%, and diameter to about 75% of the droplet created by the atomization process [12].

Droplet size can vary with viscosity to the power of 0.17–0.25 [7]. It varies directly with feed concentrate viscosity at constant feed rate and atomization design. The situation is complicated by different viscosity characteristics with pseudoplastic, thixotropic, dilatant and rheopectic feeds and with the simultaneous change in feed density and surface tension values with change in viscosity [7]. However, if, for example, the apparent viscosity increases from 10 to 200 mPa·s, the size of either droplets or powder can double. The viscosity of a concentrate fed into a spray drier also affects powder properties such us bulk density and solubility [1].

The apparent viscosity of dairy concentrates is a function of the total solid content [5, 11] and other factors including protein concentration, pre-heat treatment, homogenization and temperature [2, 5, 11]. The total solid content is often measured directly by using the refractive index but these measurements need to be correctly related to the total solid content [12]. The apparent viscosity of whole and skim milk varies with the concentration of protein reached by ultrafiltration. At concentration factors from 1 to 3, viscosity is independent of shear rate between 10 and 1000 s^{-1}, for both whole and skim milk, while samples follow a shear-thinning behavior at higher concentrations. The apparent viscosity of whole and skim milk increases with the casein concentration to the power of ≈6 [10]. The viscosity of whey concentrates is lower than that of casein solutions, because of the compact globular shape of whey proteins. For whey concentrates, apparent viscosity increases with protein concentrations to the power of 5 [8]. The apparent viscosity of a β-lactoglobulin solution in a phosphate buffer increases with the protein concentration (C) up to 100 $g \cdot kg^{-1}$ at 0.8 C, and

Table I. Whey concentrate: technical parameters, total solid content, apparent viscosity and extraction pump amperage. CF: concentration factor.

Sample	Inlet flow rate ($kg \cdot h^{-1}$)	Outlet flow rate ($kg \cdot h^{-1}$)	Vapour pressure (kPa)	Inlet temperature (°C)	Outlet temperature (°C)	Concentrate total solid ($g \cdot kg^{-1}$)	Refraction index (%)	CF	Apparent viscosity (mPa·s)	Pump amperage (A)
1	310	56	190	69	50	400.5 ± 1.2	41.0 ± 0.2	6.1	6.1 ± 0.5	1.56 ± 0.02
2	310	47	190	67	45	523.9 ± 1.3	53.0 ± 0.1	8.0	17.4 ± 1.3	1.68 ± 0.01
3	310	42	190	65	40	647.5 ± 1.1	67.0 ± 0.3	9.9	520.0 ± 90.0	2.28 ± 0.01
4	310	48	180	63	40	516.6 ± 0.8	52.0 ± 0.2	7.9	24.9 ± 2.0	1.68 ± 0.02
5	310	54	170	61	40	415.5 ± 1.5	41.0 ± 0.1	6.4	7.5 ± 0.5	1.58 ± 0.01
6	325	51	190	65	40	505.2 ± 0.9	53.0 ± 0.3	7.7	19.2 ± 1.2	1.65 ± 0.02
7	340	61	190	65	40	397.7 ± 0.8	41.5 ± 0.1	6.1	7.1 ± 0.4	1.64 ± 0.01
8	310	42	200	70	45	647.5 ± 1.2	62.0 ± 0.2	9.9	60.6 ± 1.2	1.92 ± 0.01
9	300	40	200	70	45	679.3 ± 1.1	67.0 ± 0.2	10.4	292.3 ± 15.8	2.15 ± 0.01
10	300	44	180	66	45	563.7 ± 1.3	55.0 ± 0.1	8.6	24.1 ± 0.5	1.71 ± 0.01
11	300	42	190	68	45	611.4 ± 1.2	61.0 ± 0.2	9.4	61.6 ± 0.8	1.93 ± 0.02
12	325	44	210	72	45	643.7 ± 1.1	63.0 ± 0.1	9.9	124.7 ± 2.6	1.95 ± 0.01
13	310	47	190	68	45	537.9 ± 0.6	50.0 ± 0.3	8.2	16.7 ± 0.2	1.66 ± 0.02
14	300	41	190	68	45	638.4 ± 1.3	61.0 ± 0.2	9.8	215.2 ± 11.8	1.96 ± 0.01

increases more rapidly at higher concentrations [9].

There are two possible methods of measuring on-line viscosity: either by viscometer (direct measurement) [4, 6] or by the amperage of the concentrate extraction pump (indirect measurement). The aim of this study was therefore to develop and propose indirect methods to estimate the total solid content by refractive index and to estimate the viscosity of the different dairy concentrates by following the amperage of the extraction pump.

2. MATERIALS AND METHODS

2.1. Concentration

The experiments on skim milk, whole milk and whey concentrates were performed at Bionov (Rennes, France) in a 2-stage pilot plant falling film vacuum evaporator (GEA, Niro Atomizer, St Quentin en Yvelines, France). Evaporation capacity was close to 300 $kg \cdot h^{-1}$. Dairy liquids were concentrated by modification of certain parameters such as inlet and outlet flow rate, vapor pressure, and 1st and 2nd stage temperature of boiling. The inlet flow rate was modified by variation of the speed of the positive inlet pump. The outlet flow rate was modified by variation of the inlet flow rate or by variation of the total solid content of the concentrate. The intensity (amperage) of the concentrate extraction pump (centrifugal pump FP 731 KF n° 423-33-058, Fristam, Noisy le sec, France) after the second stage was measured during each experiment, after 30 min of stabilization. All the parameters are reported in Tables I, II and III for whey, whole milk and skim milk, respectively.

2.2. Chemical analysis

Total solid contents (TS) were calculated by weight loss after drying 5 g of each sample (liquid and concentrate) with sand in a forced air oven at 105 °C for 7 h. The TS contents of skim milk, whole milk and whey before concentration were 91.4, 131.6 and 65.2 $g \cdot kg^{-1}$, respectively. The TS content of the concentrates was also determined by the refractive index (RI) by using a refractometer (Altago Co Ltd, Tokyo, Japan). The concentrate TS content measured by oven and by refractometry methods is summarized in Tables I, II and III for the whey, whole milk and skim milk, respectively.

Table II. Whole milk concentrate: technical parameters, total solid content, apparent viscosity and extraction pump amperage. CF: concentration factor.

Sample	Inlet flow rate ($kg \cdot h^{-1}$)	Outlet flow rate ($kg \cdot h^{-1}$)	Vapour pressure (kPa)	Inlet temperature (°C)	Outlet temperature (°C)	Concentrate total solid ($g \cdot kg^{-1}$)	Refraction index (%)	CF	Apparent viscosity (mPa·s)	Pump amperage (A)
1	310	98	200	70	50	401.6 ± 0.7	36.0 ± 0.3	3.1	9.2 ± 0.5	1.56 ± 0.02
2	310	87	200	68	45	452.3 ± 0.6	41.0 ± 0.2	3.4	16.7 ± 0.3	1.63 ± 0.01
3	310	79	200	66	40	497.7 ± 0.8	46.0 ± 0.1	3.8	38.8 ± 0.7	1.72 ± 0.01
4	310	64	220	70	40	621.2 ± 1.1	55.0 ± 0.1	4.7	430.0 ± 40.0	2.15 ± 0.02
5	310	84	200	66	40	468.0 ± 1.0	42.0 ± 0.1	3.6	22.5 ± 0.3	1.65 ± 0.01
6	310	93	190	64	40	423.7 ± 1.0	39.0 ± 0.1	3.2	13.7 ± 0.4	1.59 ± 0.02
7	325	90	200	66	40	458.5 ± 0.9	42.0 ± 0.2	3.5	19.9 ± 0.4	1.66 ± 0.01
8	340	105	200	66	40	414.1 ± 0.8	36.0 ± 0.2	3.1	11.9 ± 0.4	1.60 ± 0.01

Table III. Skim milk concentrate: technical parameters, total solid content, apparent viscosity and extraction pump amperage. CF: concentration factor.

Sample	Inlet flow rate ($kg \cdot h^{-1}$)	Outlet flow rate ($kg \cdot h^{-1}$)	Vapour pressure (kPa)	Inlet temperature (°C)	Outlet temperature (°C)	Concentrate total solid ($g \cdot kg^{-1}$)	Refraction index (%)	CF	Apparent viscosity (mPa·s)	Pump amperage (A)
1	310	78	190	69	50	400.9 ± 0.8	43.0 ± 0.1	4.4	13.2 ± 0.3	1.63 ± 0.01
2	310	64	190	65	40	553.0 ± 0.9	58.0 ± 0.1	6.1	1538.0 ± 114.0	2.45 ± 0.01
3	310	69	180	64	40	490.1 ± 1.1	52.0 ± 0.2	5.4	110.6 ± 0.5	1.83 ± 0.02
4	310	76	170	63	40	419.5 ± 0.9	45.0 ± 0.1	4.6	24.8 ± 0.4	1.66 ± 0.01
5	325	76	200	65	40	444.2 ± 1.4	50.0 ± 0.3	4.9	40.6 ± 0.5	1.68 ± 0.01
6	340	88	200	65	40	380.2 ± 0.8	41.0 ± 0.2	4.2	13.1 ± 0.2	1.63 ± 0.01
7	310	69	200	69	45	493.2 ± 1.5	53.0 ± 0.1	5.4	47.4 ± 0.1	1.77 ± 0.01
8	310	63	210	71	45	567.6 ± 0.6	59.0 ± 0.1	6.2	357.0 ± 9.5	2.15 ± 0.01
9	310	66	205	70	45	525.4 ± 0.9	56.0 ± 0.1	5.7	102.6 ± 0.4	1.92 ± 0.02
10	325	77	205	70	45	443.2 ± 1.5	48.0 ± 0.1	4.9	22.3 ± 0.1	1.63 ± 0.02
11	340	75	220	72	45	493.7 ± 1.4	50.0 ± 0.2	5.4	48.3 ± 0.2	1.77 ± 0.01
12	340	68	230	74	45	587.1 ± 0.9	58.0 ± 0.1	6.4	952.8 ± 53.7	2.35 ± 0.01
13	325	68	225	73	45	547.2 ± 1.3	56.0 ± 0.3	6.0	534.0 ± 23.1	2.05 ± 0.01
14	325	71	210	71	45	503.0 ± 1.1	53.0 ± 0.2	5.5	67.8 ± 0.2	1.75 ± 0.02
15	325	67	220	72	45	551.7 ± 1.2	58.0 ± 0.3	6.0	382.9 ± 11.7	2.05 ± 0.01
16	300	65	190	66	45	515.7 ± 1.2	54.0 ± 0.1	5.6	78.7 ± 0.7	1.88 ± 0.01
17	300	63	195	67	45	544.4 ± 0.7	59.0 ± 0.2	6.0	269.7 ± 2.3	2.10 ± 0.01
18	300	68	185	65	45	471.3 ± 0.6	50.0 ± 0.1	5.2	32.5 ± 0.1	1.72 ± 0.01
19	340	72	225	73	45	535.2 ± 0.9	55.0 ± 0.2	5.9	101.4 ± 0.6	1.88 ± 0.01

2.3. Rheological properties

Flow curves were obtained at 40 to 50 °C with the AR1000 rheometer (TA Instruments France, Guyancourt, France) in a coaxial cylinder geometry (internal radius: 23.05 mm; external radius: 25 mm; aluminum rotor height: 30 mm; bottom gap: 4 mm). Samples were equilibrated at the measurement temperature for 2 min, then sheared for 8 min at increasing rates from 1 to 300 s^{-1}, and sheared for 8 min at decreasing rates from 300 to 1 s^{-1}. Samples were either Newtonian, or shear-thinning. Apparent viscosity (AV) was obtained separately from the two steps as the mean of the

apparent viscosity at high strain rates (from 200 to 300 s^{-1}). Standard deviation was deduced from these two measurements. Apparent viscosity values are summarized in Tables I, II and III for whey, whole milk and skim milk, respectively.

3. RESULTS AND DISCUSSION

3.1. Refractive index

The results in Tables I, II and III indicate a strong and linear relationship between TS content and RI as a function of the dairy concentrates. The linear regression between TS content ($g \cdot kg^{-1}$) and RI (%) for these results was established as a function of the biochemical composition of the dairy ingredients so that:

$$TS = (10.7\ RI) - 32.4 \quad (R^2 = 0.98)$$
for the whey concentrate (1)

$$TS = (11.2\ RI) - 3.5 \quad (R^2 = 0.97)$$
for the whole milk concentrate (2)

$$TS = (10.6\ RI) - 56.0 \quad (R^2 = 0.95)$$
for the skim milk concentrate (3)

These results can be explained as follows. The refractive index in dairy products is determined by the refractive index of lactose, minerals, fat and even proteins, and is a function of the concentration of each component mentioned [12]. This means, however, that the sum measured is subject to change according to seasonal variations and biochemical composition of the dairy concentrates. According to Westergaard [12], the factor F ($TS = RI \times F$) is therefore not constant and frequent changes should be made to the factor based on drying oven tests in the laboratory. Thus, the different F values (Eqs. (1–3)) can be explained by the differences in biochemical composition between whey, whole milk and skim milk.

3.2. Viscometry

The results in Tables I, II and III indicate a power relationship between TS content and apparent viscosity (AV) as a function of the dairy concentrates and temperature. Power law regression between TS ($g \cdot kg^{-1}$) content and AV was established from these results as a function of the biochemical composition and temperature of the dairy ingredients as follows:

$$AV = (7 \times 10^{-29})\ TS^{10.8} \quad (R^2 = 0.86)$$
for whey concentrate at 45 °C (4)

$$AV = (3 \times 10^{-22})\ TS^{8.5} \quad (R^2 = 0.90)$$
for whey concentrate at 40 °C (5)

$$AV = (4 \times 10^{-23})\ TS^{8.9} \quad (R^2 = 0.97)$$
for whole milk concentrate at 40 °C (6)

$$AV = (5 \times 10^{-37})\ TS^{14.1} \quad (R^2 = 0.89)$$
for skim milk concentrate at 45 °C (7)

$$AV = (5 \times 10^{-32})\ TS^{12.5} \quad (R^2 = 0.93)$$
for skim milk concentrate at 40 °C. (8)

The AV decreased with the increase in temperature which naturally has a direct influence on viscosity, higher temperature leading to lower viscosity. As already reported, AV also varied as a function of biochemical composition [3, 8, 10]. Composition influenced the AV, especially the protein content in relation to the lactose content. When the protein:lactose ratio is high, the concentrate will have a high viscosity. As a general rule and as shown in our results, higher fat and lactose contents will give lower viscosity and a higher protein content will give higher viscosity [12]. The whey concentrate was less viscous than the whole milk and the skim milk concentrates at 40 °C.

3.3. Pump intensity

The results summarized in Tables I, II and III also indicate a strong relationship between the AV and pump intensity (PI) whatever the nature of the concentrate:

$$AV = 0.02\ PI^{13.1} \text{ or } PI = 1.36\ AV^{0.07} \text{ with } R^2 = 0.93 \quad (9)$$

For an outlet flow rate from 41 to 105 $kg \cdot h^{-1}$, density from 1100 to 1300 $kg \cdot m^{-3}$, viscosity from 6.1 to 1538 mPa·s and for an internal diameter of the circuit of $38 \cdot 10^{-3}$ m, the Reynolds number remained lower than 2000, showing that in all cases the experiments were performed under the laminar

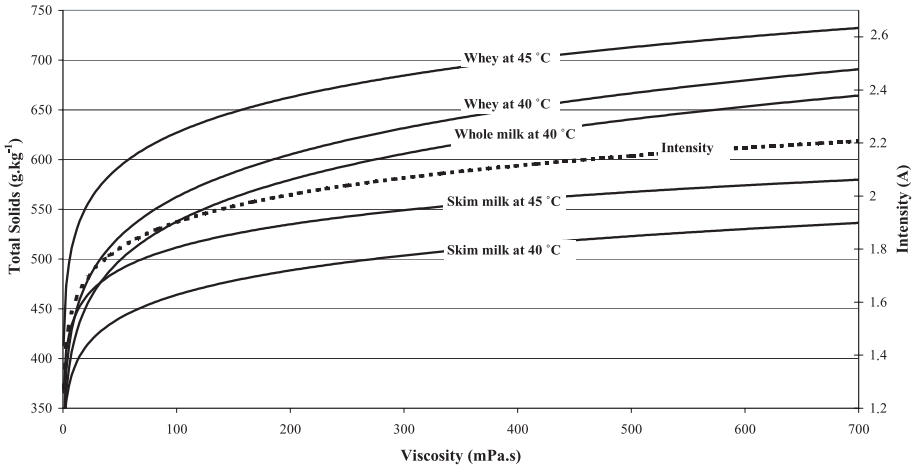

Figure 1. Relationships between apparent viscosity, extraction pump intensity and total solid content.

regime. We can therefore describe the parameters which modify pump intensity by using the electrical power (Eq. (10)) and Poiseuille equation (Eq. (11)):

$$P = \frac{UI}{\varepsilon} = \dot{V}\Delta P \qquad (10)$$

and

$$\Delta P = \frac{\dot{V}8LAV}{\pi R^4} \qquad (11)$$

with

P: Electric power supplied (W),
U: Electric tension (V),
I: Pump intensity (A),
ε: Efficiency (no unit),
$\dot{V}$: Volume flow rate ($m^3 \cdot s^{-1}$),
R: Radius (m),
ΔP: Pressure drop (Pa),
L: Length (m),
AV: Apparent viscosity (Pa·s).

With equations (10) and (11), we can describe intensity I as

$$I = \alpha\beta AV \qquad (12)$$

with

$$\alpha = \frac{8L}{\pi R^4 U} \qquad (13)$$

and

$$\beta = \dot{V}^2\varepsilon \qquad (14)$$

For a defined vacuum evaporator and a constant outlet volume flow rate, α and β are also constant and intensity I is only dependent on the viscosity, with a linear relationship. For example, volume flow rate can be classified into 4 categories (39 ± 8; 55 ± 3; 72 ± 9; $98 \pm 7 \times 10^{-3}$ $m^3 \cdot h^{-1}$) and the determination coefficients for linear regressions between I and AV are 0.84; 0.90; 0.96 and 0.94, respectively. However, it is very difficult always to concentrate at the same volume flow rate ($\dot{V}$). As $\dot{V}$ varies with time, ε and β also vary with time. With an industrial evaporator, the pump intensity (PI) depends on β and AV at the same time (α being always constant), thus explaining the power relationship between AV and PI (Eq. (9)).

Figure 1 shows a double relationship between AV, PI and TS. This figure can easily be exploited by operators. For example, to obtain a concentrate at an AV of 100 mPa·s each time, and to obtain the same size of droplet during spray drying, the PI must always be close to 1.9 and the TS of the concentrate will be close to 625 $g \cdot kg^{-1}$ for a whey concentrate at 45 °C, 560 $g \cdot kg^{-1}$ for a whey concentrate at 40 °C, 530 $g \cdot kg^{-1}$ for a whole milk concentrate at 40 °C, 510 $g \cdot kg^{-1}$ for a skim milk concentrate at

45 °C and 460 g·kg^{-1} for a skim milk concentrate at 40 °C. If the operator maintains PI at 1.9 A, AV will always be the same and the operator will be able to vary the evaporation parameters (temperature, inlet or outlet flow rate, vacuum, etc.) while maintaining amperage at 1.9 A. On the other hand, for the same intensity and thus the same viscosity, the total solid content of the concentrate will not always be the same, according to the composition and temperature.

4. CONCLUSIONS

This study showed that the amperage of the concentrate extraction pump is related to the apparent viscosity of dairy concentrates during vacuum evaporation. The AV did not change for the same PI and the sizes of droplets and powder particles were also the same during spray drying. Concentration parameters can be modified during evaporation to obtain a concentrate of the same viscosity, whatever its temperature, composition or total solid content, by monitoring only the extraction pump amperage, but only if the outlet volume flow rate does not vary too much.

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