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Thermohygrometric sensor: A tool for optimizing the spray drying process

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Abstract

The introduction of a thermohygrometer into the outlet air of a spray-drying chamber allows measurement and observation of absolute and relative humidities. As an example, there is no powder stuck in a spray-drying chamber of a three-stage pilot plant when the difference between calculated and measured absolute humidity of the outlet air is below 2 g of water kg^{-1} dry air. To obtain a whole milk, skim milk or whey powder at 0.20±0.02 of water activity (at 25 °C), the relative humidity of the outlet air must be equal to 11%±1 for whole milk powder and 7%±1 for whey and skim milk powders.

Keywords: Spray drying, Thermohygrometer; Water activity; Mass balances; Dairy powder

Industrial Relevance: Conventional spray drying processes have been developed mainly through empirical approaches. Consequently this study aims–based on the complexity of milk products–towards the development of a method based on physicochemical and thermodynamic properties. The thermohygrometer used allows to avoid sticking and to optimize water content and water activity in dairy powders. The operator can follow and monitor the relative humidity in the outlet air and thus control powder composition and properties.

1. Introduction

Drying, consisting of lowering water activity by water elimination, is an effective method in preserving biological products since it does not involve severe heat treatment and allows storage at an ambient temperature. Large quantities of liquid dairy products (skim and whole milk, whey, various fractions resulting from membrane filtration and chromatographic separation) are dried in order to produce feed, food and ingredients. Most of these powders are spray dried. This process consists in spraying the concentrated liquid in droplets of about 50 μm into a large drying chamber containing air heated at around 200 °C. The temperature of the product itself lies between the wet bulb temperature and the temperature of the outlet air, i.e., remains under 100 °C. Since drying occurs rapidly within a few seconds, the thermal damage is limited. Classical spray dryers are combined with a fluid bed, which usually agglomerates in the wet zone, the fine powder coming from the drying chamber, completes the drying process and cools the powder. In recent three-stage installations, another fluid bed is included at the bottom of the drying chamber with agglomeration and additional drying functions (Masters, 1991; Sougnez, 1983).

There have been few scientific or technical studies on the powder quality obtained from spray drying in relation to the process parameters, the physicochemical composition and the microbiology of the concentrates. Manufacturers have acquired expertise in milk drying and eventually in whey-drying processes through an empirical approach. Nevertheless, due to the variety and complexity of the mix to be dried, a more rigorous method based on physicochemical (properties of milk products before drying and of powders obtained) and thermodynamic properties (water transfer during spray drying) has now become necessary. Indeed, a lack of technical, thermodynamic and economic data and of scientific methods has prevented manufacturers from optimizing equipment in terms of energy costs and powder quality (Schuck, 2002).

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The aim of this paper is to show the use of a thermohygrometric sensor with some examples of such measurements (temperature, absolute and relative humidity, dry air flow rate, water activity) through the calculation of mass and absolute humidity to prevent sticking in the dry chamber and to optimize powder moisture and water activity in relation to the relative humidity of the outlet air.

2. Materials and methods

2.1. Skim milk, whole milk and whey powders

Skim milk, whole milk and whey used in this study were obtained from a local dairy plant (Préval, Montauban, France) and spray dried at Bionov (Rennes, France) in a three-stage pilot-plant spray dryer (Fig. 1; GEA, Niro Atomizer, St Quentin en Yvelines, France), according to Schuck, Roignant, Brulé, Méjean, & Bimbenet (1998). The temperature of the concentrate before drying was lying between 20 °C for the crystallized whey concentrate and up to 40±2 °C for the other dairy products. The atomizer was equipped with a pressure nozzle (0.73-mm diameter orifice) and a four-slot core (0.51 mm nominal width), providing a 60° spray angle. Evaporation capacity was 70 to 120 kg h^{-1} (depending on inlet and outlet air temperature and air flow). Inlet air humidity was controlled and adjusted by a dehumidifier (Munters, Sollentuna, Sweden).

2.2. Chemical and physical analysis

Solid concentration and free moisture content were calculated by weight loss after drying 1.5 g of the sample mixed with sand in a forced air oven at 105 °C for 5 h (powder). Total moisture content and crystallization rate were determined according to Schuck and Dolivet (2002) by calculating the difference between total moisture and free moisture. Water activity (a_w) was measured in a water activity meter (a_w meter; Novasina RTD 200/0 and RTD 33, Pfäffikon, Switzerland) at 25 °C. Sticking was noted by the presence or absence of powder stuck to the walls of the equipment and photographed.

2.3. Thermodynamic measurement

Air flow rate $\dot{m}_{\mathrm{dry\ air}}$ was measured with an anemometer TA 10ZG1b (Höntzsch GmbH, Waiblingen, Germany) at five positions of the straight cylindrical duct section, according to Masters (1991). The weighted average of velocities multiplied by the total cross-section gave the volume flow rate. Three replications of air flow rate measurement were performed before the air heater, with a standard deviation of 2%, according to Schuck et al. (1998) and Bimbenet, Schuck, Roignant, Brulé, & Méjean (2002). Concentrate mass flow rate $\dot{m}_c$ was measured with a flowmeter (Danfoss, Nordborg, Denmark). The temperature (°C), absolute humidity (AH; kg water kg^{-1} dry air) and relative humidity (RH; %) were measured using a thermo-hygrometer HM 138 (Vaisala SA, Guyancourt, France). On

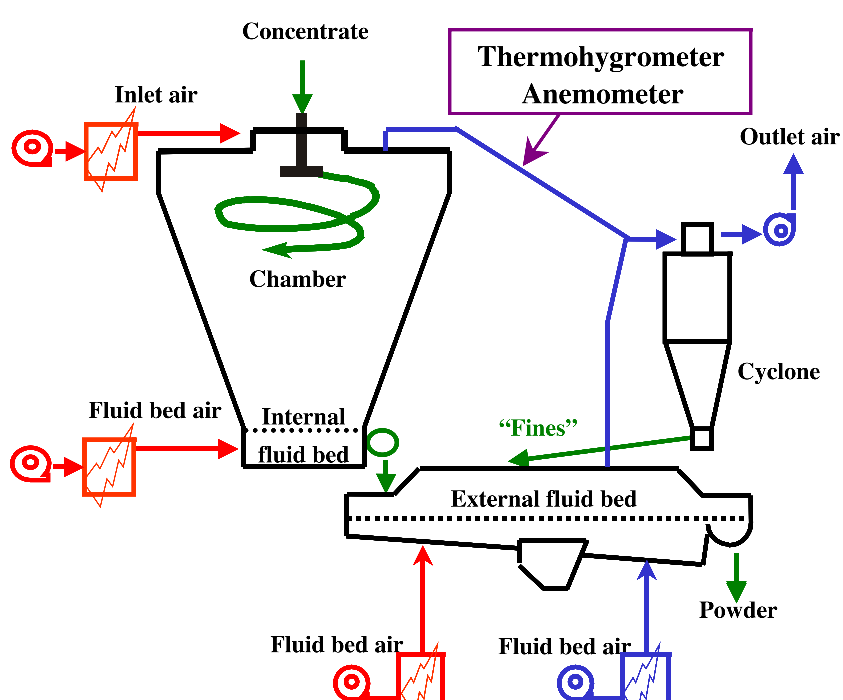

Fig. 1. Three-stage spray dryer pilot. The thermohygrometer and anemometer positions are indicated.

Table 1
Results of experiments performed on whey, whole milk and skim milk powders

Experiment	Whey powder				Whole milk powder			Skim milk powder				
	1	2	3	4	5	6	7	8	9	10	11	12
Crystallization rate (%)	75	20	72	72		–	–	–	–	–	–	–
Concentrate mass flow rate (kg h^{-1})	146.2	146.2	162.5	162.5	143.8	143.8	143.8	147.5	147.5	149.5	149.5	172.5
Total solid content (g kg^{-1})	525.0	525.0	568.0	568.0	471.7	471.7	471.7	472.9	472.9	464.5	464.5	464.5
Water mass flow rate (kg h^{-1})	69.5	69.5	70.2	70.2	76.0	76.0	76.0	77.7	77.7	79.7	79.7	92.4
Air flow rate (kg h^{-1})	3106	3106	4843	4843	3106	3106	3106	3106	3106	4316	4316	4316
Measured AH in inlet air (kg water kg^{-1} DA)	0.006	0.006	0.002	0.014	0.006	0.006	0.006	0.006	0.006	0.002	0.008	0.008
Dry air flow rate (kg h^{-1})	3087	3087	4833	4776	3087	3087	3087	3087	3087	4307	4281	4281
Inlet temperature (ºC)	220	220	220	220	210	190	140	240	150	190	190	190
Outlet temperature (ºC)	88	88	85	81	86	80	52	90	60	76	74	70
Calculated AH in outlet air (kg water kg^{-1} DA)	0.0285	**0.0285**	0.0165	**0.0287**	0.0306	0.0306	**0.0306**	0.0312	**0.0312**	0.0205	0.0266	0.0296
Measured AH in outlet air (kg water kg^{-1} DA)	0.0280	**0.0240**	0.0158	**0.0250**	0.0312	0.0300	**0.0209**	0.0300	**0.0180**	0.0187	0.0260	0.0280
Sticking	No	**Yes**	No	**Yes**	No	No	**Yes**	No	**Yes**	No	No	No
Measured RH in outlet air (%)	6.7	5.8	4.3	7.9	8.0	9.8	24.2	6.7	14.3	7.4	11.0	14.0
Water activity at 25 ºC	0.19	0.17	0.13	0.22	0.16	0.20	0.32	0.20	0.26	0.20	0.24	0.26
Powder-free moisture (g kg^{-1})	19.1	nm	15.6	22.5	22.1	26.7	nm	40.7	nm	39.6	42.4	45.2

DA—dry air; AH—absolute humidity; RH—relative humidity; nm—not measured.

the other hand, the absolute humidity in the outlet air (AH_O) was also calculated by means of a mass balance:

$$AH_O = AH_I + \frac{\dot{m}_{water}}{\dot{m}_{dry\ air}} \quad (1)$$

where AH_I is the measured inlet air absolute humidity (kg water kg^{-1} dry air), $\dot{m}_{dry\ air}$ is the dry air flow rate (kg h^{-1}) and $\dot{m}_{water}$ the water mass flow rate (kg h^{-1}), as given by

$$\dot{m}_{water} = \dot{m}_c(1000 - TS_c) \quad (2)$$

where $\dot{m}_c$ is the measured concentrate mass flow rate (kg h^{-1}), and TS_c is the total solid content of the concentrate (g kg^{-1}).

3. Results and discussion

All measurements and calculations are reported in Table 1, categorized according to the type of dairy powders and experimental conditions.

3.1. Relationship between sticking and absolute humidity in a spray dryer

3.1.1. Whey powders

Compared to experiment 1, experiment 2 showed that the decrease in the crystallization rate from 75% to 20% was accompanied by a reduction of the AH measured in outlet air from 28 to 24 g water kg^{-1} dry air for the same spray drying conditions and with the same calculated AH in outlet air. In experiment 2, we also noted the presence of powder stuck in the spray dryer chamber (Fig. 2c), which corresponds to a significant difference between the measured and calculated AH in outlet air (4.5 g water kg^{-1} dry air). In the experiment 1, there was no significant difference between the measured and the calculated AH in outlet air (0.5 g water kg^{-1} dry air), and no powder was stuck (Fig. 2b). These results can be understood according to the fact that noncrystallized lactose is an amorphous and hygroscopic form, which binds several water molecules; the lower the crystallization rate, the more difficult the water removal for the same energy balance in the spray dryer and, in consequence, the higher the powder free moisture and sticking behavior with regards to glass transition.

The increase in AH of the inlet air in experiment 4 caused an increase in the AH measured in outlet air compared to experiment 3 without modification of the spray drying conditions. At the same time, powder stuck was only observed in experiment 4 (Fig. 2c). This sticking can be related to an increase in the difference between the measured and calculated AH in outlet air from 0.7 g water kg^{-1} dry air for experiment 3 to 3.7 g water kg^{-1} dry air for experiment 4. As far as inlet and outlet air temperatures were the same for experiments 3 and 4, an increase in AH of the inlet air limits the evaporating capacity of the spray dryer, leading to higher powder moisture and sticking behavior.

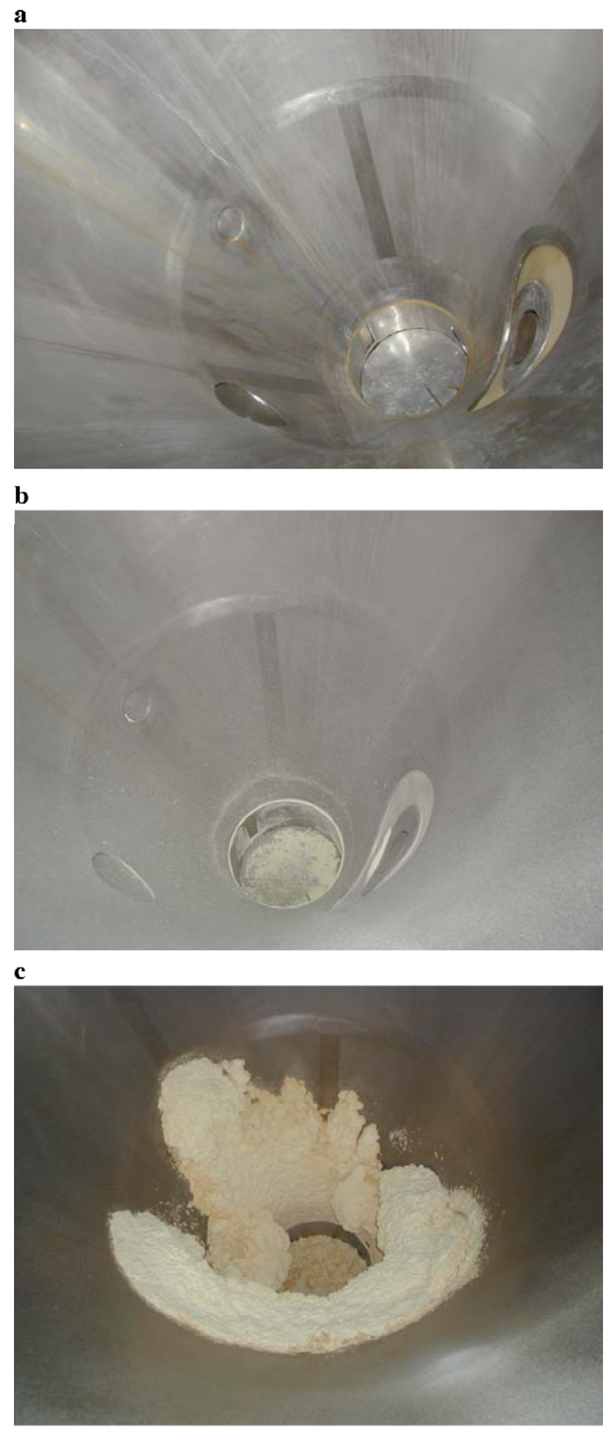

Fig. 2. Spray-drying chamber. (a) Clean installation; (b) no powder stuck to surface; and (c) powder stuck to surface.

3.1.2. Whole milk powders

The decrease in the outlet temperature from 86 °C (experiment 5) to 80 °C (experiment 6) and 52 °C (experiment 7) obtained by decreasing the inlet temperature (Table 1) resulted in an increase in the difference between calculated and measured outlet air AH up to 9.7 g water kg^{-1} dry air. Powder was stuck in experiment 7 (Fig. 2c) that can be explained by a decrease in the drying rate, followed by sticking of the powder; the higher the powder moisture, the higher the susceptibility to sticking.

3.1.3. Skim milk powders

The decrease in the outlet temperature from 90 °C (experiment 8) to 60 °C (experiment 9) due to the decrease in the inlet temperature resulted in an increase in the difference between calculated and measured AH in outlet air to 13.2 g water kg^{-1} dry air (experiment 9), which correlated with the occurrence of powder sticking. The decrease in the outlet temperature obtained by the increase in the inlet air AH (experiment 11 compared to experiment 10) and/or the increase in concentrate mass flow rate (experiment 12 compared to experiment 11) increased both the calculated and measured AH in outlet air. Thus, the difference between calculated and measured AH remains at low values, in the 0.6 to 1.8 g water kg^{-1} dry air range. As a consequence, no powder was stuck in the spray dryer chamber during these experiments (Fig. 2b).

3.2. Relationship between a_w and relative humidity in spray dryer

The spray-drying parameters (absolute humidity of inlet air, inlet and outlet air temperature, concentrate mass flow rate, etc.) were changed to vary the relative humidity of the outlet air, as well as the water activity and moisture content of the different dairy powders over 12 experiments. Water activity and relative humidity values are reported in Table 1. The correlation between water activity and relative humidity showed r^2 coefficients close to 0.98 for whey, whole and skim milk powders. Eqs. (3), (4) and (5) give the relative humidity of the outlet air as a function of the water activity of the crystallized whey, skim milk and whole milk powders, respectively,

$$RH = 40.2 \times a_w - 0.95 \quad (3)$$

$$RH = 116.6 \times a_w - 16.38 \quad (4)$$

$$RH = 105.6 \times a_w - 9.93 \quad (5)$$

For example, to obtain a dairy powder at 0.2 of a_w at 25 °C using our three-stage pilot-plant spray dryer, the RH of the outlet air must be close to 7% for crystallized whey and skim milk powders and close to 11% for whole milk powders.

4. Conclusions

It was demonstrated in this study that a thermohygrometer can be used to avoid sticking and to optimize water content and water activity in dairy powders. From these results, one can observe that the calculated AH is systematically higher than the measured one because calculated AH corresponds to the maximal theoretical value that can be reached. Indeed, the calculation of AH by the means of the mass balance is based on the hypothesis that the air circulating in the spray drier removes all the water from the concentrate. Thus, if the difference between calculated and measured absolute humidity of the outlet air was below 2 g of water kg^{-1} dry air (depending on the spray drier with regards to measurements accuracy), there was no problem of sticking in the spray dryer chambers whatever the dairy concentrate used in this study. On the other hand, sticking was observed for differential AH above 2 g water kg^{-1} dry air (Fig. 3), corresponding to lower water removal and

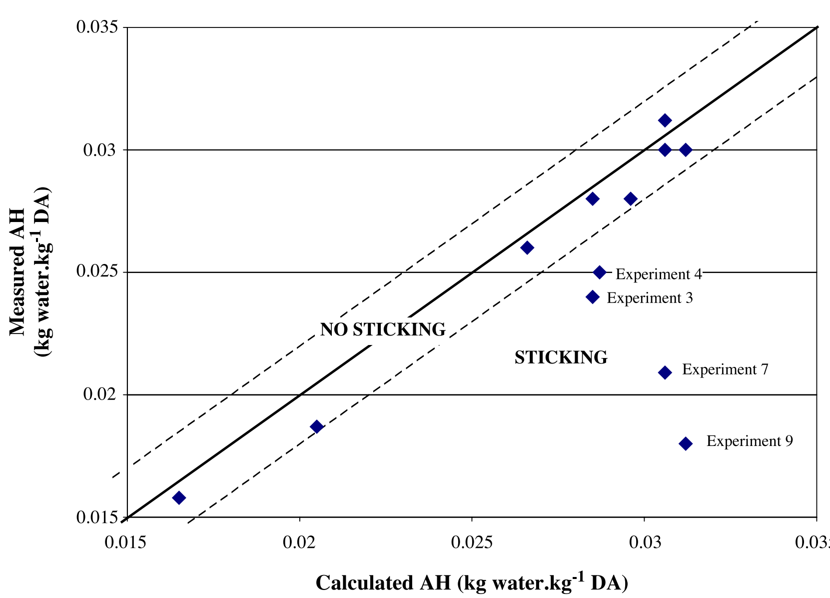

Fig. 3. Measured AH (kg water kg^{-1} dry air) as a function of calculated AH (kg water kg^{-1} dry air). The solid line represents the first bisecting line, and broken lines correspond to bisecting line more or less 0.002 kg water kg^{-1} dry air.

consequently to favorable sticking conditions. The operator can follow the absolute humidity and anticipate a variation in drying parameters according to the differences between calculated and measured absolute humidity.

The operator can also follow the relative humidity in outlet air. To achieve a dairy powder with the same water activity and moisture content, he or she must always obtain the same relative humidity in outlet air by using the preceding equations according to the dairy products whatever are the spray-drying conditions (inlet air temperature, relative and absolute humidity).

The changes in relative and absolute humidity (resulting from variations in absolute humidity of inlet air, total solid content of concentrate, crystallization rate, outlet air temperature, etc.) can be rapidly observed in the outlet air using a thermohygrometer before such changes significantly affect powder moisture, water activity and powder behavior with regard to sticking.

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