Effects of Humidity and Temperature on the Performance of Milk Powder Baghouses

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***Abstract*—A bench scale filtration apparatus was used to investigate the influence of powder composition, and temperature and humidity of the carrier gas on the structure of the filter cake formed in milk powder baghouses. Two types of powder, a skim milk powder (SMP) and a high fat milk protein concentrate (MPC) were filtered from air using a polyester filter, at a range of temperatures and humidity levels. The filter cake mass and pressure drop were measured and used to calculate the cake permeability, and the filter cake structure was examined using a microscope. Increased stickiness of particles resulted in the appearance of dendritic structures in the filter cake and hence an increase in porosity and reduction in cake resistance. Cake resistance in SMP was lowest at the highest relative humidity tested, indicating that cohesion in SMP was primarily due to the glass transition of amorphous lactose. The cake resistance in MPC was lowest at the highest temperatures tested, but was not affected by relative humidity, indicating that cohesion in this powder was primarily due to melted fat. In general, the MPC formed a more permeable filter cake and exhibited much higher deposition onto the filter than the SMP. The deposition rate of SMP powder decreased at higher relative humidity. The cause of this effect could not be determined, however likely explanations are increased agglomeration and gravitational settling of stickier powder prior to reaching the filter, or the breakage of fragile dendritic structures formed by sticky powder. The deposition rate of MPC was not affected by either temperature or humidity.**

***Index Terms*—baghouse, milk powder, filtration, stickiness, cake**

I. Introduction

Occasional problems are encountered during the production and handling of dairy powders due to variations in the cohesive and adhesive properties of the powder. Sticky powders cause increased fouling in spray driers and associated processing equipment, while caking in hoppers and silos causes blockages and handling difficulties. While these problems have been studied extensively, the effect of stickiness on the performance of baghouses has been largely neglected. Research on other powders has demonstrated correlations between powder cohesion and filter cake porosity [1], and between humidity and cake adhesion [2]. The powders used in these studies were very different to dairy powders, so some targeted research is needed to enable more accurate prediction of dairy baghouse performance.

Most dairy powders contain amorphous lactose, which is highly hygroscopic. In the presence of sufficient moisture and temperature, the lactose undergoes a glass transition, and behaves as a highly viscous liquid. This allows lactose bridges to form between particles, causing strong bonding. This is a major cause of caking during storage, especially in low fat powders such as skim milk powder (SMP). The temperature of the glass transition, T_g, decreases with increasing water activity [3], and so is highly dependent on changes in ambient humidity. The caking process is also time dependent, and occurs more rapidly at conditions of higher temperature and moisture [4]. In addition, some researchers have defined a sticky point, above which the adhesion of particles essentially becomes instantaneous, resulting in a marked decrease in flowability and an increase in adhesion to surfaces [5].

Stickiness due to lactose is generally described in terms of the temperature offset from the glass transition, $T-T_g$, [4], [6], [7]. The sticky point for a particular powder occurs at a critical temperature offset, $(T-T_g)_{crit}$, regardless of the specific temperature and humidity levels used [5]. The value of $(T-T_g)_{crit}$ depends on powder composition, with some high-protein powders having a critical temperature offset of up 90 ℃ [8]. Measurements of $(T-T_g)_{crit}$ also depend on the method used, due to different shearing and inertial forces produced by different methods. As an example, reported values for SMP range from 23.3 ℃ using a stirrer method [7] to 37.9 ℃ using a particle bombardment method [5].

Another major contributor to the cohesion and flowability of milk powders is the presence of fat. Milk contains a range of fats with melting temperatures ranging from -40 ℃ to +40 ℃ [9]. In spray dried dairy powders, fat tends to accumulate on the surface of the particles [10], [11], so even low levels of bulk fat can have significant effects on the particle interactions. Surface fat content is strongly correlated with powder cohesiveness [12], [13], as fats in a liquid state form liquid bridges between parti-

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cles. The flowability of high fat powders is dependent on temperature, due to the wide range of melting points of dairy fats [14]. Dairy baghouses are typically operated at 70-80 ℃, so the fat exists in a liquid state.

In this study, two different powders, a skim milk powder (SMP) and a high fat milk protein concentrate (MPC) were filtered from air using a polyester needle-felt filter, at a range of temperatures and humidity levels. SMP is a very common milk powder, with very low fat content and high lactose content. SMP is generally considered a free-flowing powder, with good transport properties and good chemical stability. Stickiness in SMP has been well studied with regard to in-process fouling and caking during storage, so SMP provides a good reference powder for these experiments. Stickiness in SMP is primarily due to the glass transition of amorphous lactose, and is highly dependent on moisture content [14]. MPC contains high levels of fat and protein but relatively little lactose and is regarded as a cohesive powder, with poor flowability. As fat tends to accumulate on the particle surface in preference to lactose [11], the cohesive nature of this powder is thought to be primarily due to liquid fat. This powder is also known to cause excessive blinding in some baghouses in industry. The effects of temperature and humidity on the filtration process were studied to determine the optimum operating conditions for industrial baghouses.

II. Materials and Methods

A. Powders

The powders used in these experiments were provided by Fonterra Ltd, New Zealand. A detailed compositional analysis of these powders is shown in Table I. The particle size distributions of the two powders were measured with a Microtrac X-100 laser diffraction system, using isopropanol to suspend the particles.

TABLE I. Powder Composition

Powder	Fat	Protein	Lactose	Ash	Water
SMP	1.0%	32.6%	54.6%	8.0%	3.8%
MPC	26.2%	42.9%	22.1%	5.5%	3.3%

B. Filter Fabric

All experiments were conducted using a basic polyester needle-felt fabric with a singed surface. This fabric was provided by Canterbury Filter Services, New Zealand, and is typical of the fabrics currently used in the NZ dairy industry. The filters were cut from a used filter bag, so the fabric had been subjected to some wear prior to being used in these experiments.

In order to reduce costs, the filter samples were reused for multiple experiments. The filters were cleaned in between uses by washing in a household washing machine. Filters were visually inspected for signs of damage, and measurements of the filter resistance at the start of each run were compared to ensure that the filters were cleaned to a consistent standard and were not significantly deteriorating between uses.

C. Methods

A bench scale filter rig was constructed to allow filtration at a controlled temperature and humidity. The apparatus was designed to maintain a filtration velocity of 2.2 ms^{-1}, typical of industrial baghouses, but over a filter area of only 0.01 m^2. The apparatus was designed to allow control of humidity and temperature over a wide range. This was done by bubbling the air stream through a water tank at the required dewpoint, then heating the humid air stream to the desired temperature. Powder was introduced to the heated, humidified air stream with a small vibrating hopper upstream of the filter. Powder not adhering to the filter was collected in a jar at the bottom of the filtration chamber. The pressure drop across the filter was measured using an Intech™ LPN-DP pressure sensor, and the mass of powder on the filter and in the collector jar were weighed using a laboratory balance.

Two sets of experiments were carried out. The first set of experiments investigated the effect of temperature on the filtration process. The temperature of the air stream was varied in approximate 10 ℃ increments from 30 ℃ to 90 ℃, while the dewpoint was maintained at 20 ℃. A second set of experiments investigated the effect of humidity on the filtration process. This time, the moisture level was varied by adjusting the dewpoint between 20 ℃ and 42 ℃, while the temperature was maintained at 80 ℃. Both powders were tested at each set of conditions, to allow a direct comparison between the powders.

The average specific cake resistance and deposition ratio for each run were determined from the filtration equation (1), using the pressure drop and cake mass measurements at the start and end of the run.

$$\Delta P_{total} = \Delta P_{filter} + k_d \alpha c_i v_f^2 t \quad (1)$$

ΔP_{total} is the total pressure drop across the filter, ΔP_{filter} is the pressure drop due to the filter medium (pressure drop at the start of the run), k_d is the deposition ratio (proportion of powder which adheres to the filter), α is the specific cake resistance, c_i is the powder concentration in the inlet air stream (determined from the measured powder and air flows), v_f is the filtration velocity, and t is time.

A Kruskal-Wallis (K-W) test was carried out to compare the differences in specific cake resistance or filter deposition between operating conditions with the scatter within sets of repeats. This was used in preference to an ANOVA F test as the scatter appeared non-normal in distribution. Where the K-W test indicated significant differences, a Mann-Whitney U test was used to directly compare pairs of conditions, to determine whether the effect occurred over the entire temperature or humidity range tested. A 95% confidence level was used for both tests.

Filter cake samples were examined under a microscope to observe the cake structure and determine possible mechanisms for the differences.

III. Results and Discussion

A. Comparison between Powders

The MPC powder had a much lower resistance than the SMP, and much higher deposition under equivalent conditions. Several filter cake samples were examined under a microscope to determine possible mechanisms for the difference in cake resistance. A comparison of filter cakes formed at 80 ℃ under dry conditions supported the mechanism proposed by Morris and Allen [2], that particle stickiness promotes the formation of dendritic structures, whereas non-sticky particles are more likely to penetrate into the gaps in the cake, filling the void space and resulting in a lower porosity. The MPC filter cakes had a highly dendritic structure, with many large void spaces, consistent with observations that MPC is a very cohesive powder, while the SMP filter cakes had a denser, more uniform structure (Fig. 1). Differences in structure were also apparent at a macroscopic level, with the MPC filter cakes having an uneven, clumpy appearance, while the SMP filter cakes were smoother and more uniform (Fig. 2). The void spaces resulting from the clumpy structure of the MPC cake are on a scale much larger than the particle size. Both powders have number-distribution mean (D10) size around 30 μm, while the porous structures are hundreds of microns in size, as seen in Fig. 1. This indicates that porosity is strongly dependent on the formation of multi-particle superstructures and is not simply related to the size of individual particles. Some minor differences were also observed between SMP filter cakes formed at different conditions, although these were far less pronounced than the differences between powder types.

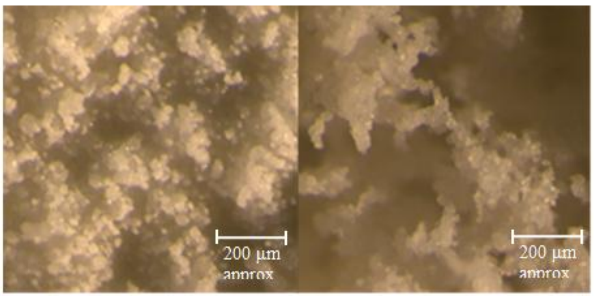

Figure 1. Microscopic structure: SMP at left, MPC at right

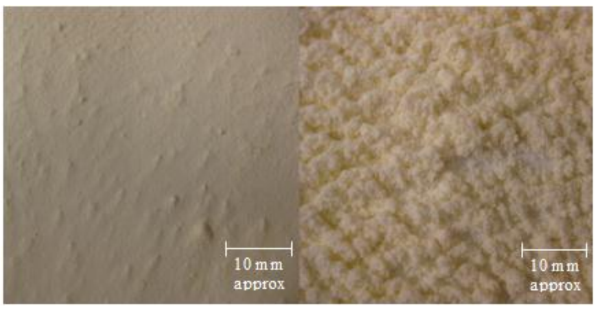

Figure 2. Filter cake appearance: SMP at left, MPC at right

B. Temperature Variation

Temperature changes had very different effects on the cake resistances of the different powders. All results were consistent with the observation of Miller and Laudal [1] that more cohesive powder results in a more porous filter cake.

SMP exhibited lowest resistance at 30 ℃, peaking at 50 ℃ and then remaining fairly constant over the 60-90 ℃ range (Fig. 3). This can be explained by the effect of humidity on the lactose glass transition. As all runs had a constant dew point of 20 ℃, the relative humidity was highest at the lowest temperatures tested, and thus T_g was also lowest. In the 50-90 ℃ range, the chamber temperature was below T_g, implying that lactose was not sticky within this temperature range. As the chamber temperature reduced from 50 to 30 ℃, the increasing relative humidity caused a lowering of T_g, so that at 40 ℃, T_g was only 30 ℃, while at a chamber temperature of 30 ℃, T_g was 0 ℃. The consequent increase in lactose stickiness resulted in more cohesive particles and hence a more porous filter cake.

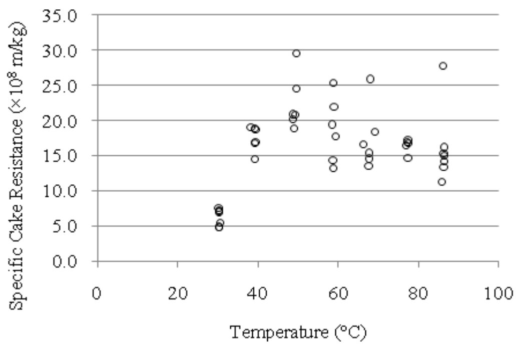

Figure 3. Effect of temperature on SMP filter cake

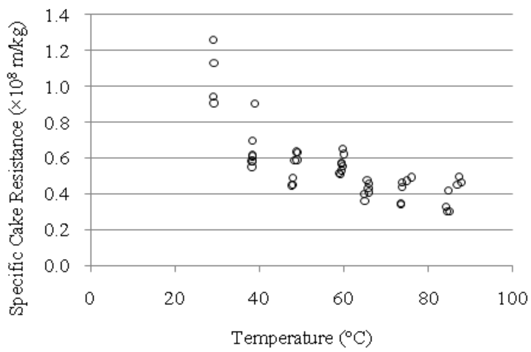

Figure 4. Effect of temperature on MPC filter cake

MPC exhibited the highest resistance at 30 ℃, decreasing with increasing temperature (Fig. 4). This is consistent with the hypothesis that liquid fat is the main source of stickiness in this powder. Higher temperatures result in increased melting of the fats, causing increased particle cohesion and hence a more porous cake structure. The effect is most pronounced at the lower end of the temperature range tested, with a U-test finding no significant differences in the 70-90 ℃ range. As these temperatures are well above the reported melting range of milk fat, it is likely that the fat was completely melted, with cohesion consequently at a maximum. Under all conditions, the cake resistance was much lower for the MPC powder than for the SMP.

The deposition ratio for SMP was lowest at low temperatures, with no significant variation over the 60-90 ℃ range (Fig. 5). This is contrary to expectations that increased stickiness at low temperatures would result in greater deposition. Two likely mechanisms may contribute to this effect. Firstly, the dendritic structure of the cake under sticky conditions may result in fragility, so that some of the powder breaks off the filter. Secondly, particles may agglomerate in the airflow upstream of the filter, and these agglomerates may settle out of the flow due to gravity before reaching the filter. The lack of variation in the 60-90 ℃ range is unsurprising, given the high T_g level in this temperature range, and the lack of variation observed in the cake resistance. In contrast, the deposition ratio for the MPC powder showed no significant variation with temperature (Fig. 6), even at the lowest temperature conditions where differences in the cake resistance were observed. The trend observed for SMP also contrasts with the high deposition levels observed for the highly cohesive MPC powder.

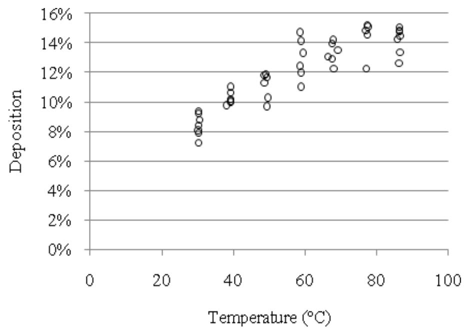

Figure 5. Effect of temperature on SMP deposition

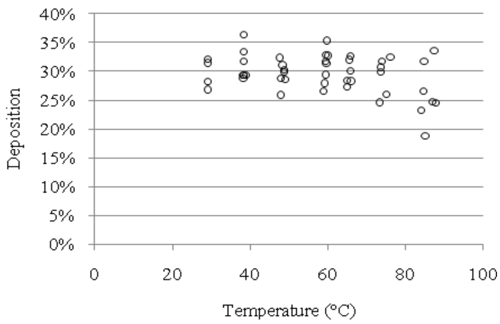

Figure 6. Effect of temperature on MPC deposition

C. Humidity Variation

The SMP cake resistance was significantly lower at 14% and 17% RH than at 6% RH, consistent with the increase in stickiness (Fig. 7). It is uncertain how the trend varies across the range, with a U test finding no significant differences between adjacent conditions except for between the 14% and 17% RH conditions. This suggests that increased cohesion begins to have an effect on the filtration process at a point somewhere between the glass transition (7% RH), and the sticky point (approx 20% RH), as expected. In addition, SMP filter cakes formed at high humidity levels appeared visually to be slightly rougher on the surface than those formed at low humidity, which suggests a more porous cake structure, although this difference was far less pronounced than the differences between the SMP and MPC powders.

Results from the MPC powder showed no significant dependence on humidity (Fig. 8), which is consistent with fat being the major cause of stickiness in this powder. Once again, the MPC showed a much lower resistance than the SMP under all conditions tested. The deposition ratio for SMP was also strongly affected by the humidity, with much lower deposition at high humidity levels (Fig. 9).This confirms the results of the temperature tests, in that increased cohesion was correlated with decreased deposition. The deposition at 6% RH was not significantly different at a 95% confidence level from the 8% RH condition, suggesting that the effect only occurs above a threshold of 8% RH. The MPC deposition showed no clear dependence on humidity (Fig. 10), although once again the deposition was much higher for MPC than for SMP.

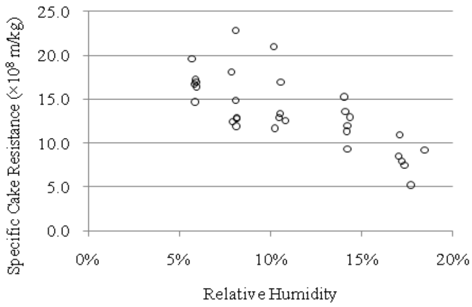

Figure 7. Effect of humidity on SMP filter cake at 80 ℃

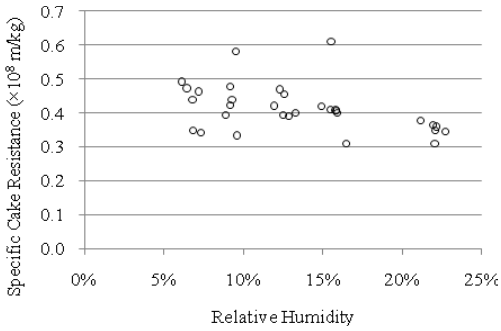

Figure 8. Effect of humidity on MPC filter cake at 80 ℃

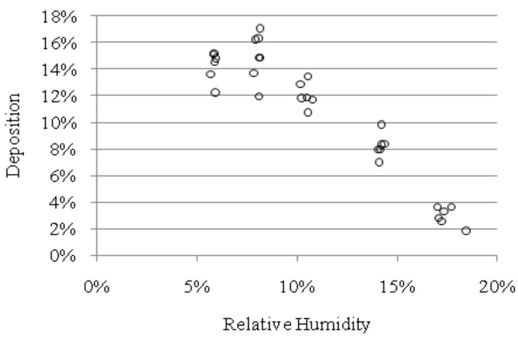

Figure 9 – Effect of humidity on SMP deposition at 80 ℃

The exact sticky point for the filtration process investigated in this work is uncertain, but is likely to be close to that measured by the particle bombardment method used by Paterson *et al* [5], due to the similarity with this method. The $T-T_g$ levels tested here (up to 30 ℃) are below the critical level of 37 ℃ reported in that study. Higher humidity levels could not be tested as the stickiness of the powder above 17% RH caused the powder feed system to block. It was therefore not possible to determine whether any turning points in the cake resistance or deposition trends occur at the sticky point.

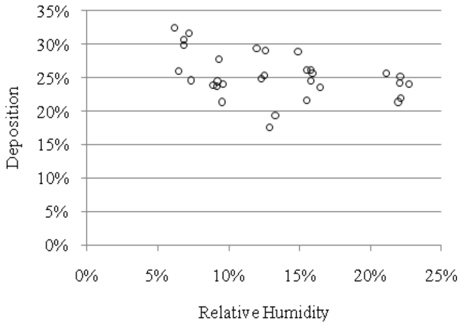

Figure 10. Effect of humidity on MPC deposition at 80 ℃

D. General Discussion

All results confirm the observations of Miller and Laudal [1], that increased particle cohesion results in a more porous filter cake structure. This implies that cohesion is beneficial to the operation of baghouses, as increased cake porosity results in lower pressure differentials across the filter, and therefore reduces operating costs. The dependence of SMP cake resistance on humidity was expected, due to the effect of humidity on glass transition.

The effect of temperature on SMP appears to be solely due to the associated change in relative humidity, confirming expectations that lactose is the primary cause of stickiness in SMP. Similarly, the dependence of MPC cake resistance on temperature, but not humidity, confirms expectations that fat is the primary cause of cohesion in this powder. However, as industrial baghouses are usually operated at temperatures well above the fat melting range, ordinary variations in baghouse temperature are unlikely to have any measurable effect on the baghouse performance. Increases in humidity may offer slight improvements in baghouse performance with SMP; however the flow on effects on other aspects of processing may negate any benefits obtained.

It appears that powder cohesion is not sufficient as a universal predictor of powder deposition. Deposition in SMP was negatively correlated with cohesion; however the highly cohesive MPC powder showed much higher deposition. In addition, the deposition of MPC was not affected by changes in cohesion due to temperature variation. This difference in behaviour is most likely due to differences in the filter cake strength between the two powders. Particles adhering to the filter cake may be subject to subsequent dislodgement due to bombardment from other incoming particles. The liquid fat in the MPC powder would be expected to reinforce liquid bridges, consolidating inter-particle bonds in the filter cake. In the SMP, however, the high viscosity of the amorphous lactose should limit consolidation, so that bonds remain weak, and particles are more likely to be dislodged from the filter cake.

The conclusions that can be drawn are limited by the large degree of scatter in the data. Several possible causes of the scatter were investigated, however ultimately the scatter could not be prevented. Variation in the temperature and moisture content of the powder supplied to the rig was found to have a minimal effect, ruling this out as a cause of the scatter. The vibrating hopper was extremely sensitive to changes in compressed air pressure, resulting in variation in the powder feed rate, however this showed no correlation with the variation in the resistance or deposition. The filter cake frequently suffered slight damage during removal from the apparatus, resulting in some variation in the cake mass measurement. This can account for some, but not all, of the scatter in the data. Nevertheless, analysis with the Kruskal-Wallis statistical test confirms that conclusions can confidently be drawn, despite the scatter.

IV. Conclusions

More cohesive milk powders form more porous filter cakes during collection in baghouses. The primary mechanism for this is that sticky powders form dendritic structures, impeding the penetration of particles into the void spaces in the filter cake. In low fat powders, stickiness is mainly due to the lactose glass transition, and is consequently highly dependent on relative humidity. In powders with a high fat content, stickiness is primarily due to liquid fat, and depends on temperature, with stickiness reducing markedly at temperatures below 40 ℃, the upper end of the melting temperature range of milk fats.

The proportion of powder depositing on the filter varies greatly between powders and conditions. For SMP, the deposition is reduced by increased relative humidity. In MPC powder, the deposition is not affected by either temperature or humidity. The deposition for MPC is generally much higher than for SMP, however the lower specific cake resistance results in a lower overall pressure drop for MPC.

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