

## Fines Flowrate Estimation Using Pressure Drop

### 1. ABSTRACT

Pressure drop was calibrated to solids flowrate in a pneumatic pipeline that transports fine powder to the top of a skim milk spray dryer. This revealed that the solids flowrate was 110–160% of production, much higher than the anecdotally expected 5–50% of production. Significant fluctuations in pressure reading occurred over the measurement period, which implies poor delivery from the rotary valve into the pneumatic line. These results were used to investigate the method of Lech (2001), which predicts mass flowrate as a function of pressure drop for transport up a vertical pipeline. It was found that Lech's (2001) key assumption, that solid velocity is independent of solids loading, did not hold. Therefore, Lech's (2001) prediction method is not appropriate unless a calibration curve is generated for each dryer system.

**Key words:** *powder flow, pneumatic conveying, spray drying.*

### 2. INTRODUCTION

Pressure drop measurement is inexpensive but it is generally regarded as unreliable for determining solid particulate flowrates, due to large fluctuations that occur in pneumatic pipelines. There are more reliable methods available (Tallon and Davies, 2000) but, because of the ease of measurement, pressure drop was used to estimate solids flowrates in the fines recycle stream of a milk powder plant. Fines powder particles are carried by the drying air from the dryer or fluidised beds to the baghouse, where they are collected. They are then dropped via a rotary valve into a pneumatic line to be recycled to the top of the spray dryer. Recycle rates are currently not measured in milk dryers, but were thought to vary from 5–50% of production.

Lech (2001) established the relationship between mass flowrate and blowline pressure drop. Total pressure drop  $\Delta P_T$  is given by

$$\Delta P_T = \Delta P_s + \Delta P_g \quad (1)$$

where  $\Delta P_s$  is the pressure drop due to solid (Pa) and  $\Delta P_g$  is the pressure drop due to gas (Pa). Each of these has two components

$$\Delta P_T = \Delta P_{fs} + \Delta P_{hus} + \Delta P_{fg} + \Delta P_{hug} \quad (2)$$

where  $\Delta P_{fs}$  is the pressure drop due to solid friction (Pa),  $\Delta P_{hus}$  is the pressure drop due to hold up of solid (Pa),  $\Delta P_{fg}$  is the pressure drop due to friction of gas (Pa) and  $\Delta P_{hug}$  is the pressure drop due to hold up of gas (Pa). The combined pressure drop of the gas  $\Delta P_g$  is estimated by recording the line pressure losses when only air is transported. Therefore, the difference between the total pressure drop and that due to air is approximately the loss due to the presence of the solids

$$\Delta P_s = \Delta P_{fs} + \Delta P_{hus} \quad (3)$$

Lech (2001) then uses the Fanning equation to establish the pressure drop as a function of the mass rate in a vertical pneumatic pipeline

$$\Delta P_s = \frac{M_s U_s g L}{A} \left( \frac{f_p}{2Dg} + \frac{1}{U_s^2} \right) \quad (4)$$

where  $M_s$  is the mass flow rate of solid (kg/s),  $U_s$  is the superficial velocity of solid particles (m/s),  $L$  is the length between two pressure transducers,  $A$  is the cross sectional area of the pipe (m<sup>2</sup>),  $f_p$  is the friction coefficient due to the particles (-),  $D$  is the inside diameter of the pipe (m), and  $g$  is the acceleration due to gravity (m/s<sup>2</sup>). Equation (4) relies on a known friction coefficient,  $f_p$ , which Lech (2001) approximates from the work of Yang et al

(1980) to be a linear relationship with solids volume fraction,  $1-\varepsilon$ , for vertical transport in a pipeline

$$f_p = 0.0108 + 0.066(1 - \varepsilon) \quad (5)$$

where the solids volume fraction can be approximated by  $1-\varepsilon \approx M_s/(U_s A \rho_s)$  and  $\rho_s$  is the solids density ( $\text{kg/m}^3$ ). The approximation assumes  $\rho_s \gg \rho_g$  and is calculated from  $\varepsilon = V_g/(V_g+V_s)$  where  $V_g$  and  $V_s$  are the volumes of air and solid passing a plane in a given time. The dryer in this study has much more complicated pipework than that used by Lech (2001), with many additional bends and horizontal sections between the fines inlet and the top of the dryer. Due to particle inertia around bends and saltation in horizontal sections, the friction coefficient is expected to be significantly greater in this work.

This study establishes a calibration curve between pressure drop and mass flowrate for one particular dryer, and uses this to investigate the suitability of the approach of Lech (2001) for the prediction of mass rate from pressure drop measurements.

### 3. METHOD

The dryer studied produces skim milk powder. Throughout a typical production run, the blowline pressure reading was consistent at  $\sim 21\text{kPa}$ , fluctuating from  $\sim 18\text{--}25\text{kPa}$ . A schematic of the dryer studied is shown in figure 1.

Calibration experiments were carried out with the dryer off. Powder was manually poured at a controlled rate into the top of the baghouse. A fixed speed rotary valve (NU-CON CV[4"] 1250 DEM Round) then delivered it into the pneumatic blowline. The powder used for these experiments was "start-up powder" with a  $D_{3,2}$  measured at  $108\mu\text{m}$ . The pressure gauge was a Rosemount type 113. Readings were recorded manually off the control room screen only when changes in the pressure trend line occurred. Figure 2 shows an example of the pressure readings recorded over time. The dryer fans were off during these experiments to avoid recirculation of fines to the baghouse, meaning the chamber was not under vacuum. Normal operating pressure is  $-4\text{mmWg}$  ( $-40\text{Pa}$ ), which is insignificant compared to the  $\sim 20\text{kPa}$  delivered by the blower (Robuschi type SRB41/2P,  $11.3\text{kW}$ ).

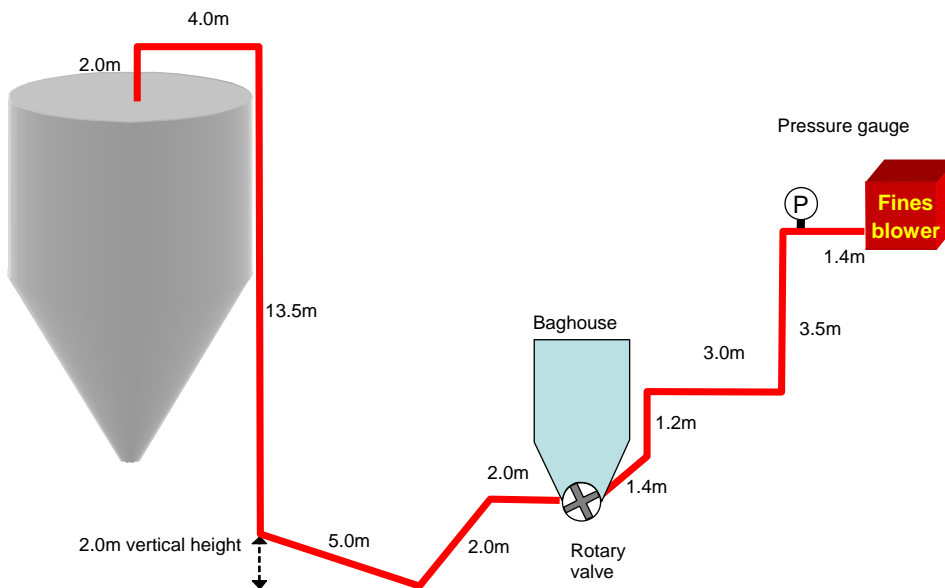


Figure 1: Schematic of pneumatic line from blower to dryer showing positions of pressure gauge and rotary valve.

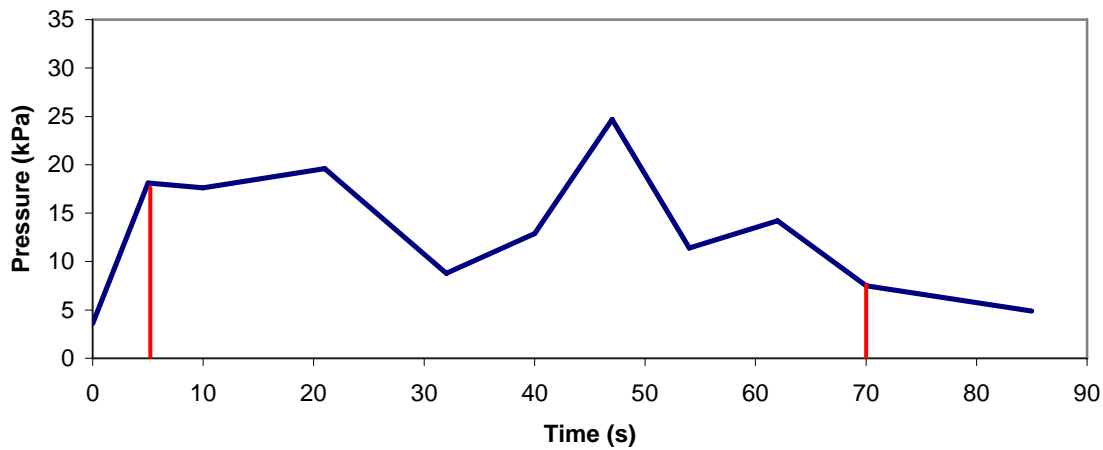


Figure 2: Trial four – pressure reading as a function of time for a manual addition rate of 61% dryer capacity.

#### 4. RESULTS AND DISCUSSION

Figure 3 compares the manual addition rate and the observed delivery rate of the powder. The observed rate is calculated from the observed time that pressure readings were elevated, rather than the time over which manual pouring occurred. Generally, the observed delivery rate is lower than the manual addition rate due to powder hold-up in the hopper feeding the rotary valve. The rotary valve is not feed rate limited over the range

investigated in this work. In addition, the pressure gauge readings differ significantly over the recording time in some trials (for example, trial four in figure 2), indicating that powder flow through the rotary valve is not even, despite attempts to manually add powder at an even flowrate. The initial increase in pressure as powder enters the blowline and the tail-off as the last of the powder is cleared by the rotary valve constitutes transients, as do fluctuations over the (supposed) continuous feeding of the rotary valve.

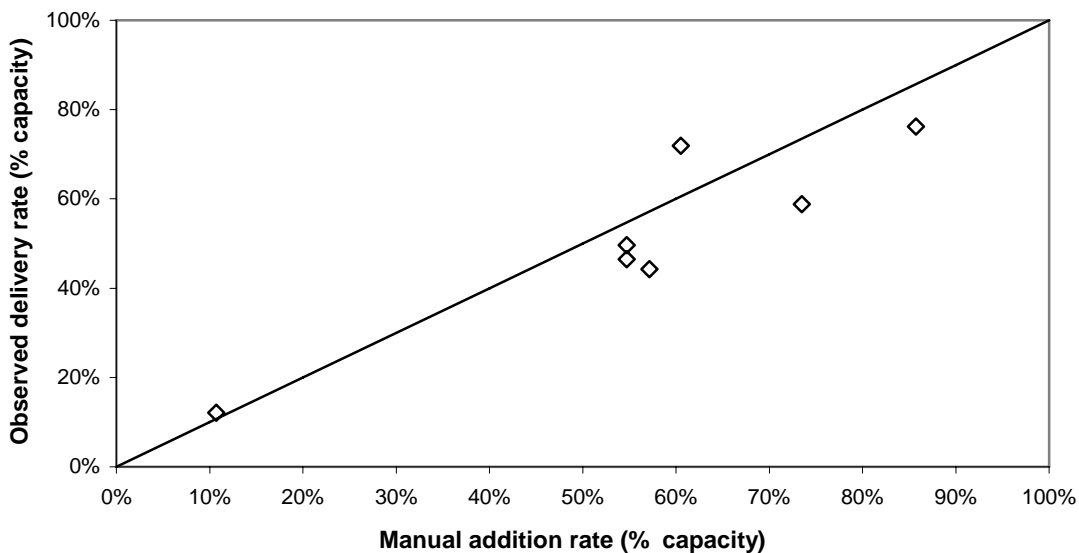


Figure 3: Observed delivery rate versus manual addition rate.

Despite the fluctuating pressure profiles, an average pressure reading is estimated by taking the area under the pressure versus time curve and

dividing it by the experiment time. Figure 4 shows the average pressure readings versus the observed delivery rate. Essentially, this is a calibration chart

for the dryer. It can be extrapolated to determine the fines recycle rates during production. Prior to starting the work, recycle rates were expected to be 5–50% of production capacity (dryer yield). However, plant pressure drop fluctuates from 18–25kPa, which indicates that fines recycle rates are much higher, ranging from 95–130% of production.

It must be noted that the experiments were planned around the expected recycle flowrates and so care should be taken when interpreting these extrapolated values. It is recommended that further measurements are made with higher experimental mass rates.

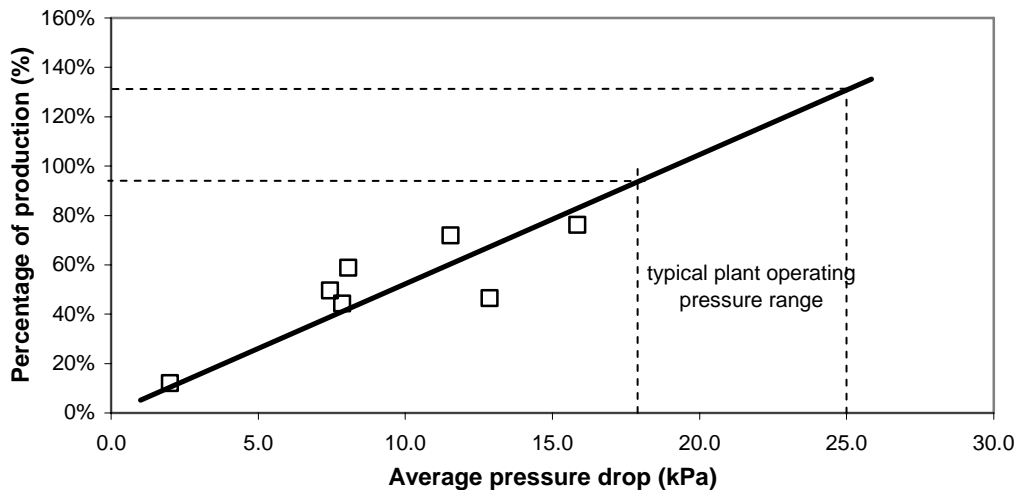


Figure 4: Calibration curve for average pressure drop versus the observed delivery rate.

It is useful to establish the scientific basis of this calibration. Lech's (2001) prediction is based on steady flow and makes a number of approximations: firstly, the linear approximation of friction coefficient with solids volume fraction as discussed above; and secondly, that particle velocity in the blowline is independent of solids loading. In addition, Lech (2001) uses the time dependent mass flowrate  $M_s$  in equation (4), but this work uses the time-averaged "observed delivery rate" and time-averaged "pressure drop" due to the fluctuating nature of the measurements.

The second approximation, that particle velocity in the blowline is independent of solid loading, needs some discussion. The Robuschi blower used in the dryer delivers an air rate that varies as a function of the delivery pressure head (according to the performance chart for the blower). For selected values of solids mass loadings covering the range used in this work, table 1 lists the mean pressure drop from the calibration in figure 4, the air rate from the manufacturer's performance chart, and calculated solids volumetric loading using a solids density of 1280 kg/m and  $1-\varepsilon = M_s / (Q_a \rho_s)$  where  $Q_a$  equals the volumetric flowrate of air (m<sup>3</sup>/s).

Selected solids mass loadings $M_s/M_c \times 3,600$	Average pressure drop $\Delta P$	Air delivery rate $Q_a \times 3,600$	Volumetric solids loading $1-\varepsilon$	Air delivery velocity $U_{A0}$	Particle velocity $U_{S1}$
% capacity	kPa	m <sup>3</sup> /h	[-]	m/s	m/s
15	2.9	560	0.00072	19.8	14.94
30	5.7	557	0.00145	19.7	12.49
45	8.6	553	0.00219	19.6	10.97
60	11.5	550	0.00294	19.5	9.91
75	14.3	547	0.00370	19.3	9.12
90	17.2	543	0.00447	19.2	8.49

Table 1: Estimated solids volumetric loadings and particle velocities. Average pressure drop is calculated from the correlation in figure 4. Air delivery rate is interpolated from the performance chart of the Robuschi blower for a shaft speed of 2,960rpm.

The air delivery rate can be used to calculate the particle velocity by considering the momentum balance immediately before and after the solids' addition to the blowline. Momentum must be conserved so, using a per second basis

$$M_{A0}U_{A0} = M_{A1}U_{A1} + M_{S1}U_{S1} \quad (6)$$

where  $M_A$  and  $M_S$  are the mass rate of air and solid (kg/s),  $U_A$  and  $U_S$  are the velocity of air and solid (m/s), 0 is "before" and 1 is "after". As  $M_A = \varepsilon\rho_A A U_A$  and  $M_S = (1-\varepsilon)\rho_S A U_S$ , the conservation of momentum equation can be rewritten as

$$\rho_{A0}U_{A0}^2 = \varepsilon\rho_{A1}U_{A1}^2 + (1-\varepsilon)\rho_{S1}U_{S1}^2 \quad (7)$$

where  $\varepsilon$  is voidage (-). Particle velocity is the difference between the air velocity and its terminal velocity,  $U_{S1} = U_{A1} - U_T$ . Substituting for  $U_{A1}$

$$\rho_{A0}U_{A0}^2 = \varepsilon\rho_{A1}(U_{S1} + U_T)^2 + (1-\varepsilon)\rho_{S1}U_{S1}^2 \quad (8)$$

This equation shows that particle velocity is dependent on solids loading and not independent as assumed by Lech (2001). To calculate particle velocity is reasonable to assume that  $U_T \ll U_S$  for pneumatic transport of particles smaller than 100 $\mu$ m. Equation (8) can be rearranged to give  $U_{S1}$

$$U_{S1} \approx \sqrt{\frac{\rho_{A0}U_{A0}^2}{\varepsilon\rho_{A1} + \rho_{S1}(1-\varepsilon)}} \quad (9)$$

where the air density is calculated as a function of system pressure, and  $\rho_{A0}$  is taken as equal to  $\rho_{A1}$ . The air supply velocity  $U_{A0}$  and the particle velocity  $U_{S1}$  are shown in table 1.

These calculations show that Lech's (2001) equation (4) cannot be used to predict pressure drop, because particle velocity is not independent of solids loading and because the presence of bends in the pipework means that friction coefficients are unknown. However, using an experimentally-determined calibration curve between solids loading and pressure drop, Lech's (2001) equation can be applied in reverse to estimate experimental friction

coefficients. Figure 5 shows that these experimental values are far greater than those expected for transport up a vertical section of pipe from equation (5). Engineers typically account for the bends and horizontal sections of pipework using an effective pipeline length, which can be applied as a factor  $L_e/L$  in equation (4). For this work,  $L_e/L$  ranges between four and seven and is flowrate dependent.

## 5. CONCLUSIONS

Fines recycle rates are not currently measured in spray dryers. This experimental study produces a calibration curve relating fines flowrate to blowline pressure drop for a skim milk powder dryer. Anecdotally, it was expected that recycle rates would correspond to 5–50% of production. The results show otherwise, with predicted recycle rates of 95–130% of production.

The experimental procedure used mass flowrates in the anecdotal range, producing average blowline pressure drops up to 10kPa. Typical production averages 21kPa, fluctuating between 18–25kPa. Therefore, the plant recycle rates predicted above are extrapolated, indicating a need for further experimental work. Fines flowrate was modelled by accounting for the pressure loss due to friction of solids and gas, using the equations of Lech (2001). Lech's (2001) key assumption, that particle velocity is independent of solids loading, does not hold. Also, the complex pipework means that the experimental friction factors were significantly greater than Lech's (2001) approximation, necessitating a large flowrate dependent correction factor  $4 < L_e/L < 7$  to account for the complex pipework. Thus, Lech's (2001) predictive equations can only be used in conjunction with system calibration.

A major problem with these trials was the fluctuation in pressure readings due to poor delivery of fines to the blowline via the baghouse and rotary valve. It is recommended that more reliable methods be used to estimate fines flowrate.

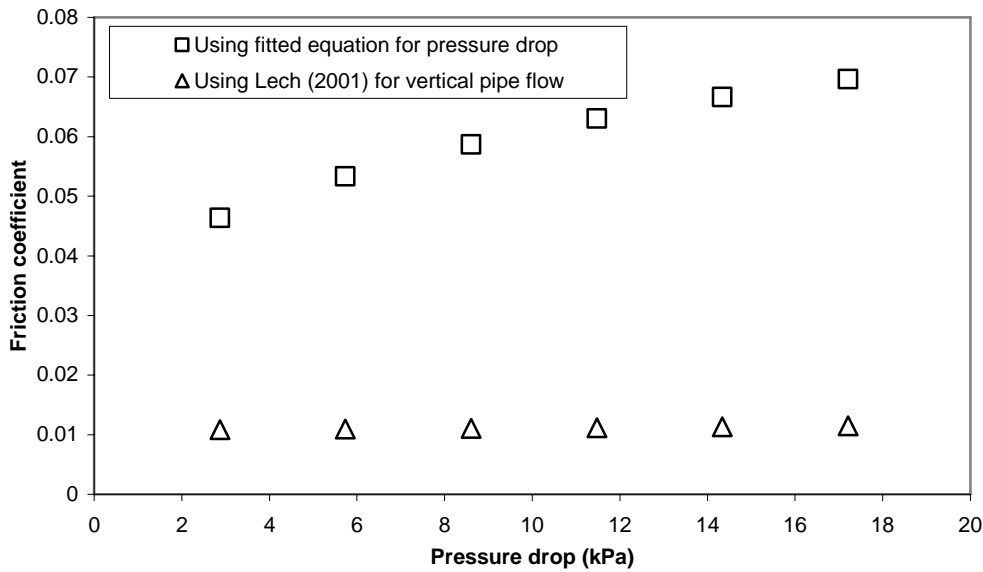


Figure 5: Average pressure drop versus friction coefficient ( $f_p$ ).

## 6. AUTHORS' AFFILIATIONS

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