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Measurement of Rotary Valve Air Leakage in a Pneumatic Conveying System

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Summary This paper explains the procedure used to determine the amount of air leakage being generated from the use of a drop-through rotary valve in a full-scale pneumatic conveying system.
When producing a set of pneumatic conveying characteristics for a test program, rotary valve air leakage is often not considered. In reality, the air mass flowrate in the conveying line will be less than the total supplied air mass flowrate due to air leakage through the rotary valve. By measuring the air leakage and adjusting the total supplied air mass flowrate to represent the actual air mass flowrate travelling through the conveying line, a more accurate representation of the conveying conditions can be obtained. Hence the design of pneumatic conveying systems can be determined more precisely.
Tests have been performed and plots have been produced showing both the pneumatic conveying characteristics before and after rotary valve air leakage has been taken into account. These results show that rotary valve air leakage can have quite an effect, with some tests losing more than 50% of the supplied air mass flowrate through the rotary valve.

1 NOMENCLATURE

A_c	leakage area through sides and ends, m^2
b	"blockage factor"
c	valve rotor clearance, mm
d	equivalent volume diameter, mm
D	rotor diameter, m
F	correction factor allowing for gas expansion
L	rotor length, m
m_f	air mass flowrate, kg s^{-1}
m_s	solids mass flowrate, kg s^{-1}
N	rotor speed, RPM
P_f	absolute air pressure, Pa abs
Q_c	clearance leakage, m^3 s^{-1}
Q_p	carry-over leakage, m^3 s^{-1}
Q_T	total leakage, m^3 s^{-1}
v_l	"leakage velocity", m s^{-1}
ΔP_t	total pipeline pressure drop, Pa
Δp_v	pressure drop across the rotary valve, Pa
ρ_{bl}	loose poured bulk density, kg m^{-3}
ρ_f	air density, kg m^{-3}
ρ_s	solids density, kg m^{-3}

subscripts

1	below rotary valve
2	above rotary valve

2 INTRODUCTION

Rotary valve air leakage is dependent on a number of issues, including system pressure, rotor clearances, material being handled, head of product above the valve and whether there is venting present. By not considering this leakage at the design phase of a pneumatic conveying system, this can result in the incorrect sizing of fans, blowers and compressors. An oversized prime mover may result in higher velocities, reduced solids throughput, increased abrasion and/or erosion of the plant, an increase in product degradation or even unnecessary over-expenditure. An undersized prime mover may result in insufficient transport velocities causing pipe blockages [1]. This paper presents results from investigations in to measuring and modelling rotary valve air leakage.

3 TEST PROGRAM

3.1 Calibrated Orifice Plate

A 17.94mm diameter orifice plate was mounted on top of a feed bin to measure the differential pressure caused by the air leaving the bin due to leakage. This orifice plate was calibrated using the set-up in Figure 1, so that for any given differential pressure recorded, it could be equated to an equivalent air mass flowrate.
The pipeline was blanked off so that all air travelled through the rotary valve. The return line was closed off so that the air went out through the orifice plate at the top of the feed bin. A 30 inch wg differential pressure meter was attached to the orifice plate, the lower pressure port being open to atmosphere.

Three methods of recording the air leakage were used: (a) the rotary valve stationary with no product in the feed bin, (b) the rotary valve running at 40 rpm with no product in the feed bin, and (c) the rotary valve stationary with 125kg of plastic pellets in the feed bin.

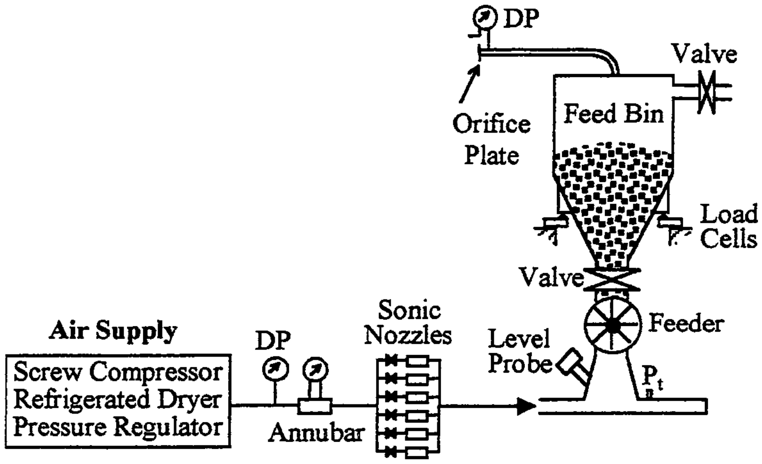

Figure 1 Orifice plate calibration

Air was fed into the system via the sonic nozzle arrangement. After steady-state was achieved, the reading on the differential pressure meter was recorded and the air mass flowrate stepped down incrementally and the process repeated. The supplied air mass flowrate, via an annubar, was also data logged onto a computer for later analysis.

3.2 Calibration Curve

Once analysis of the recorded data was complete, a graph of orifice differential pressure (as a percentage) versus orifice air mass flowrate was plotted, see Figure 2. Using curve fitting functions, a second order polynomial equation was fitted to the data points for the range $4\% \leq x \leq 90\%$. The range for $0\% \leq x < 4\%$ was interpolated from the experimentally produced curve due to such low values being hard to record accurately on the instruments used. An equation for each curve was then produced, see Equation 1 and Equation 2. These equations are used to determine the air mass flowrate of the rotary valve air leakage using the percentage reading recorded from the differential pressure meter at the orifice plate.

$$y = -3.2974\,x^2 + 0.2763\,x \qquad 0\% \leq x < 4\% \qquad (1)$$
$$y = -0.0126\,x^2 + 0.0313\,x + 0.0046 \qquad 4\% \leq x \leq 90\% \qquad (2)$$

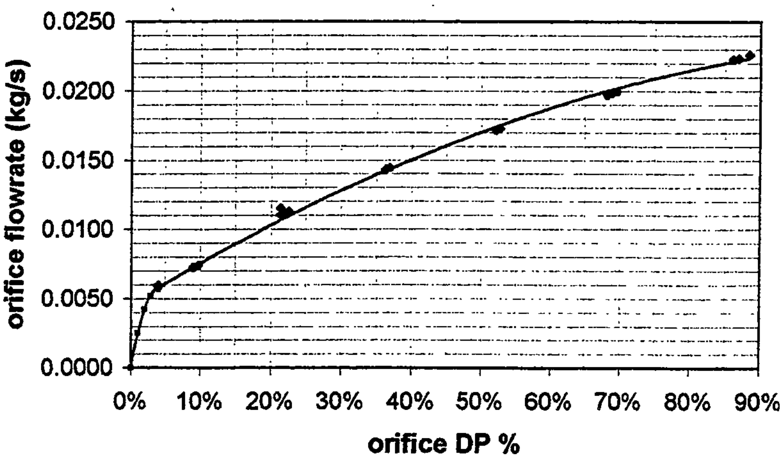

Figure 2 Calibration curve for orifice plate

4 MEASUREMENT OF AIR LEAKAGE

4.1 Full-scale testing

Plastic pellets, (ρ_{bl} = 578 kg m^{-3}, ρ_s = 897 kg m^{-3}, d = 4773 μm), were transported through a 21m horizontal pneumatic conveying system using a wide range of air mass flowrates and feed rates, see Figure 3. Two pipeline materials were used, 60.3mm ID stainless steel and 56mm ID aluminium. A data acquisition unit was used to record the tests and the data was analysed, from which, air mass flowrate versus total pipeline pressure drop was plotted to produce the pneumatic conveying characteristics shown in Figure 4 to Figure 7.
During each test the feed rates of both air and product were recorded, along with several pipeline pressures. The differential pressure reading from the orifice plate was also recorded. In most cases this value became constant once steady-state conveying was achieved but in some cases, such as in unstable flow, the differential pressure fluctuated due to varying back pressures, so a range of values was recorded.

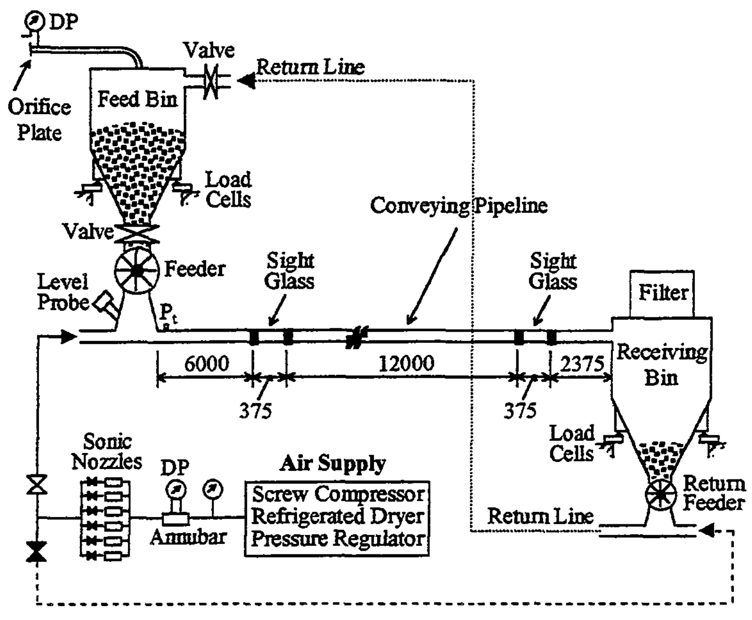

Figure 3 Full-scale test rig

Table 1 displays the results of 8 tests spread throughout the 56mm ID aluminium pipeline test program, showing the air mass flowrate supplied to the system and the air mass flowrate actually conveyed through the pipeline as a result of rotary valve air leakage. Also displayed is the percentage of air mass flowrate lost due to air leakage. For the dense-phase tests it can clearly be seen that a substantial amount of the supplied air is lost through air leakage. Due to the high back pressures generated, the air finds the easiest exit path and that is through the rotary valve and out to atmosphere.

Table 1 Test data for selected tests

Test	Total m_f (kg/s)	Orifice Pressure (% 30"DP)	Actual m_f (kg/s)	% m_f lost to leakage	m_s (kg/s)	Δp_t (kPa)
1	0.049	1.9	0.045	8.2	0.39	3.7
2	0.086	7.6	0.079	8.0	0.75	9.9
3	0.038	13.7	0.029	22.8	1.1	18.4
4	0.016	22.4	0.0051	68.0	0.15	28.5
5	0.020	27.5	0.0075	61.9	0.31	34.1
6	0.026	37.2	0.012	55.6	0.61	43.4
7	0.035	42.5	0.019	45.0	0.70	47.2
8	0.037	65.0	0.018	52.8	0.88	59.1

Figure 4 and Figure 5 represent the pneumatic conveying characteristics before and after the rotary valve air leakage had been taken into account for the 60.3mm ID stainless steel pipeline and Figure 6 and Figure 7 represent the pneumatic conveying characteristics before and after the rotary valve air leakage had been taken into account for the 56mm ID aluminium pipeline The individual data points located on the two graphs represent test data and the decimal points of each locate the actual position of each data point.
As can be seen, as total pipeline pressure drop increases, more air is lost due to air leakage and the data points shift to the left. The angle at which the dense phase region sits becomes steeper after the air leakage is subtracted from the total air mass flowrate, due to higher pipeline pressures.

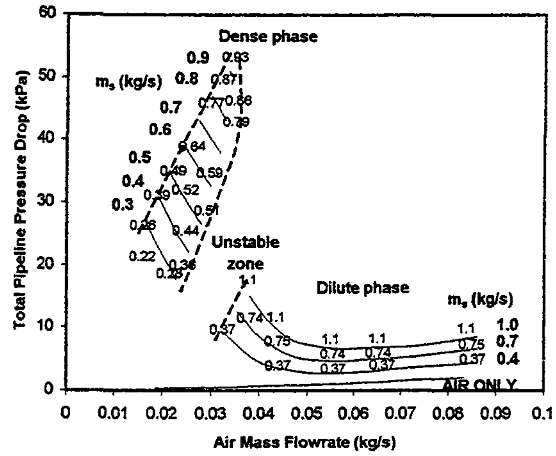

Figure 4 PCC - 60.3mm ID stainless steel
(air leakage ignored)

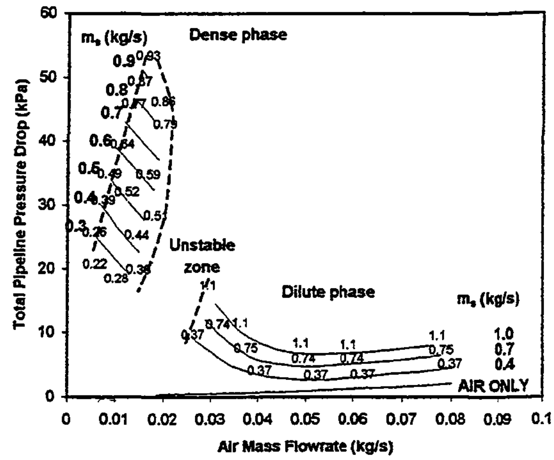

Figure 5 PCC - 60.3mm ID stainless steel
(air leakage included)

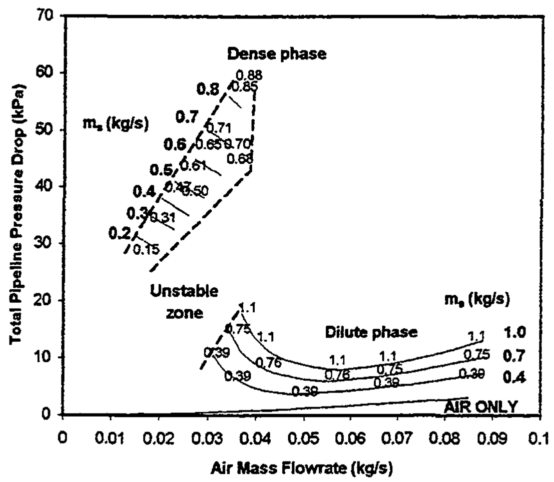

Figure 6 PCC - 56mm ID aluminium
(air leakage ignored)

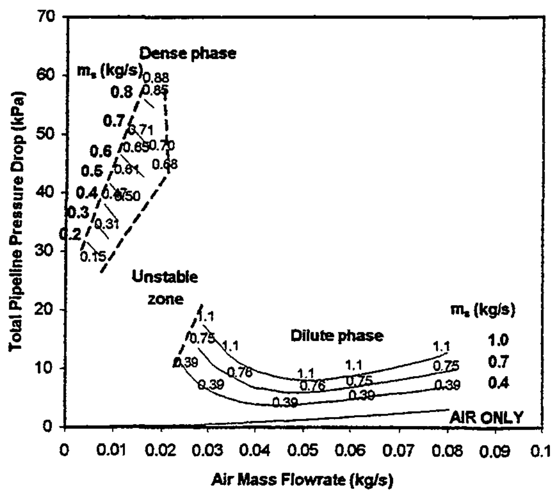

Figure 7 PCC - 56mm ID aluminium
(air leakage included)

4.2 Estimating Leakage

There are several methods available which can be used to estimate rotary valve air leakage. Previous work has been carried out into the determination of rotary valve air leakage, two approaches are explained below. Another method is by using the rotary valve manufacturer's air leakage curve.
From the experimental rotary valve air leakage results shown in Figure 5 and Figure 7, air leakage curves have been produced for the 60.3mm ID stainless steel pipeline and the 56mm ID aluminium pipeline and are displayed in Figure 8, Figure 12 and Figure 13, by plotting rotary valve outlet pressure versus air leakage.

4.2.1 Marcus Method

In determining rotary valve air leakage, Marcus [3] includes both carry-over leakage, Q_p, which is the transfer of air from the pipeline to the hopper through the empty pockets of the rotary valve, and clearance leakage, Q_c, which is present between the rotor and valve housing.

Marcus [3], uses the following method for estimating the total air leakage,

$$Q_T = \left(\frac{P_{f1}}{P_{f2}}\right)(Q_c + Q_p) \tag{3}$$

The clearance leakage is given by,

$$Q_c = 36\, F\, A_c \sqrt{\frac{2\Delta p_v}{\rho_{f1}}} \tag{4}$$

where,

$$F = \frac{1}{3.5}\left[4.35 - \frac{P_{f1}}{P_{f2}}\right] - 0.2 \tag{5}$$

and the carry-over leakage is given by,

$$Q_p = \frac{\pi}{4} D^2 L\, N \tag{6}$$

Marcus' method results in numerous curves being produced depending on the rotary valve speed, as can be seen in Figure 8. However, in the current research, different rotary valve speeds have not resulted in different air leakage curves being produced. A single curve for each of the stainless steel and aluminium pipelines results, as indicated in Figure 8, where the comparison between the Marcus method and the experimental results can be seen clearly.

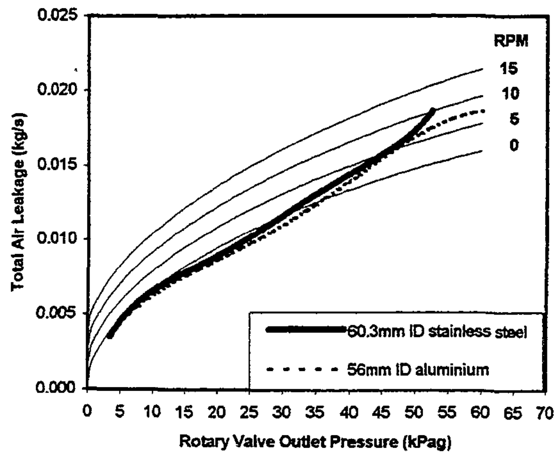

Figure 8 Marcus method versus experimental results

4.2.2 Reed Method

Reed et al. [4] uses an empirical method to estimate rotary valve air leakage. During his experiments, Reed found that carry over leakage was negligible.

$$Q_T = 0.0001\, b\, v_l L\, c \qquad (7)$$

where b is taken from either Figure 9 or Figure 10 depending on whether static or actual conditions are required and v_l is taken from Figure 11.

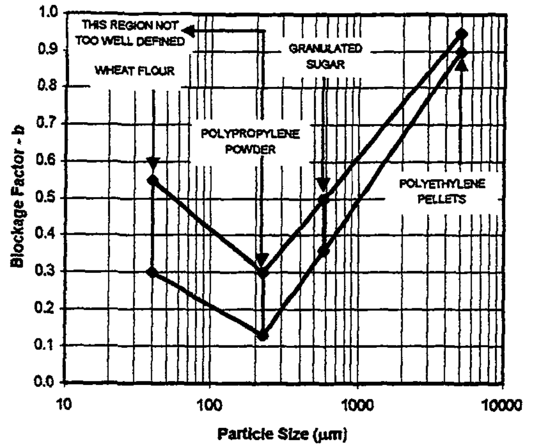

Figure 9 Static blockage factor [4]

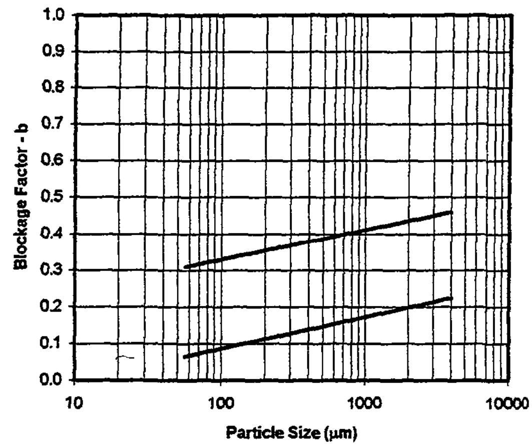

Figure 10 Actual blockage factor [2]

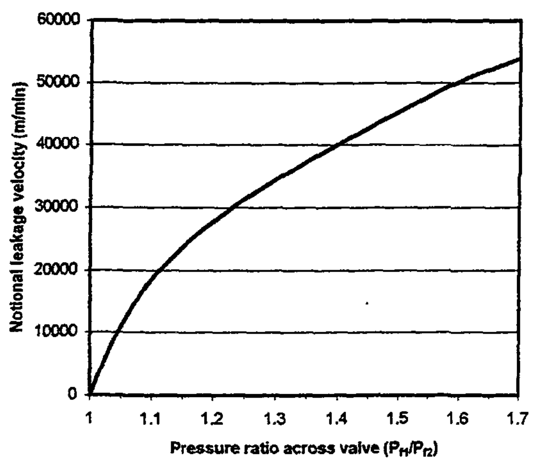

Figure 11 Leakage velocity versus pressure Ratio for a 10 pocket rotary valve

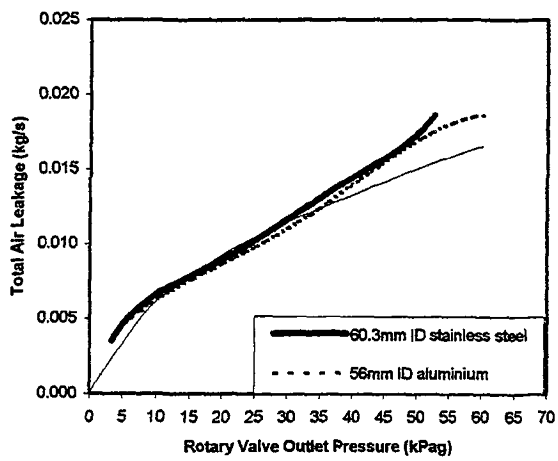

Figure 12 Reed method versus experimental results $b_{act} = 0.35$ (from Figure 10)

Reed's method [4] produces one curve to represent rotary valve air leakage as is shown in Figure 12. The comparison between the Reed method and the experimental results is clear and another observation is that the Reed curve is similar to the curve for zero RPM in the Marcus method.

4.2.3 Manufacturer's Curve

The Waeschle ZGR 250 rotary valve specifications have an air leakage curve as shown in Figure 13. The experimental results show a higher rotary valve air leakage than the manufacturer's specifications indicate.

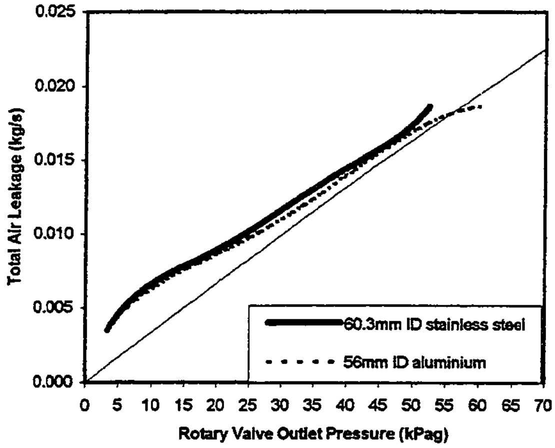

Figure 13 Manufacturer's curve versus experimental results

This may be due to the age of the rotary valve and the clearances being larger now than when the valve was new or possibly the method used in both cases to determine the rotary valve air leakage is different, hence resulting in a slight difference in the curves.

5 CONCLUSION

Rotary valve air leakage can be quite substantial. In the test program calculations showed that up to 68% of the supplied air was being lost through the rotary valve due to air leakage for the worst cases.

This test program has allowed the more precise determination of pneumatic conveying characteristics by representing the actual air mass flowrate travelling through the pipeline rather than the supplied air mass flowrate from which some is being lost through the rotary valve.

Comparisons with existing methods used to determine rotary valve air leakage showed differences to the experimental results. The main difference with the Marcus [3] method is that a different curve is produced for each rotary valve speed, whereas in testing it was found that only one curve was produced regardless of the rotary valve speed. As mentioned previously, the manufacturer's air leakage curve showed a different result to the experimental curve, which could possibly be put down to either wear of the rotary valve through it's life or maybe a difference in the method used to quantify the air leakage.

Notice must be taken that the air leakage curves produced from this testing are only accurate for this particular rotary valve, the most important issue is the method in which the air leakage is being recorded.

Further work is planned using larger pipeline diameters and also using a larger diameter rotary valve. Further comparisons can then be made with respect to the degree of rotary valve air leakage in a variety of pneumatic conveying systems.

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