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Resistance coefficients of mineral tailings flowing in diaphragm control valves

V.G.Fester

Cape Peninsula University of Technology, Cape Town, South Africa

P. T. Slatter

Cape Peninsula University of Technology, Cape Town, South Africa

D. M. Kazadi

Cape Peninsula University of Technology, Cape Town, South Africa

N. S. Ramohlola

Cape Peninsula University of Technology, Cape Town, South Africa

ABSTRACT: The need to save water world-wide is forcing industry to reduce water consumption which in turn leads to increasing concentrations of the mineral tailings handled. Design criteria are shifting from turbulent flow to laminar flow. Although diaphragm valves are used extensively to control flow, there is very little experimental data available. The use of the incorrect resistance coefficient could lead to inefficient designs. The objective of this paper is to provide experimentally determined resistance coefficient data for 5 diaphragm valves ranging from 40 mm – 100 mm, in the fully open, 75%, 50% and 25% open position for laminar and turbulent flow. The problems encountered in establishing dynamic similarity for these valves and the effect that this has on the resistance coefficients is discussed. The resistance coefficients obtained for valves produced by different manufacturers are compared. The results are provided to facilitate more accurate and efficient designs.

1 INTRODUCTION

The need to save water world-wide is forcing industry to reduce water consumption which in turn leads to increasing concentrations of the mineral slurries handled. Design criteria are shifting from turbulent flow to laminar flow. For turbulent flow the loss coefficient is independent of the flow rate, whereas in laminar flow it increases with decreasing flow rate. Although energy losses in pipe fittings are often viewed as “minor losses”, these losses can dominate in short pipelines. Diaphragm valves are used extensively in the mineral processing industry to control flow, but there is very little experimental data available to the designer. The use of the incorrect resistance coefficient for highly concentrated mineral suspensions could lead to inaccurate and inefficient designs.

Pienaar et al. (2004) highlighted the fact that there was no experimental data available for flow of non-Newtonian fluids through diaphragm valves and presented results for a 40 mm. Although agreement was found with that of Hooper (1981) for laminar flow and with Perry (1997) for turbulent flow, it was not established if dynamic similarity could be obtained for diaphragm valves and if these coefficients could be used for all diaphragm valves as in the case for geometrically similar gate and globe

valves.

The objective of this paper is firstly to provide experimentally determined resistance coefficient data for 5 different sized diaphragm valves ranging from 40 mm – 100 mm, in the fully open position. We also provide experimentally determined resistance coefficients for all the valves at the 75%, 50% and 25% open position, since these valves are often used to control flow. This experimental work has been performed over a wide range of both laminar and turbulent flow conditions. Secondly, the problems encountered in establishing dynamic similarity for these valves – due to the fact that geometric similarity is not always obtained during the valve manufacturing process – and the effect that this has on the resistance coefficients is discussed. Thirdly, we compare the resistance coefficients obtained for valves of the same size, but produced by different manufacturers.

The results are provided for the use of design engineers, to facilitate more accurate and efficient designs.

2 LITERATURE REVIEW

2.1 Diaphragm valves

Valves are an integral part of slurry pipe work systems and are used to either isolate (on-off) or regulate the

flow. Diaphragm valves are versatile and can be used to isolate and regulate flow (Alderman & Heywood, 1996). There are two types of diaphragm valves, the weir type for use with less viscous fluids and the rubber-lined straight-through or dam type (Miller, 1990) that are typically used in minerals processing applications.

2.2 Definition and determination of the loss coefficient

The loss coefficient is defined as the non-dimensionalised difference in overall pressure between the ends of two long straight pipes when there is a valve installed and when there is no valve.

To determine the pumping head of a pipe line system, one needs an estimate of the frictional losses in the straight pipes and the losses caused by the various fittings. The losses in the straight pipes can be obtained from Equation (1) (Massey, 1970).

$$H_s = \frac{4fLV^2}{D2g} \quad (1)$$

The head loss in a valve can be determined using the Bernoulli equation and can be expressed in terms of the velocity energy head as given in Equation (2) (Edwards et al., 1985).

$$H_v = k_v \frac{V^2}{2g} \quad (2)$$

The loss coefficient of the valve k_v is given by

$$k_v = \frac{\Delta p_v}{\frac{1}{2}\rho V^2} \quad (3)$$

In turbulent flow the loss coefficient is independent of the Reynolds number, but in laminar flow a hyperbolic relationship exists between the loss coefficient and the Reynolds number,

$$C_{\text{valve}} = k_v \text{Re} \quad (4)$$

where C_{valve} is a characteristic of a specific valve including its dimensions (Edwards et al., 1985).

The results of such a study is usually presented as plots of loss coefficient versus Reynolds number to determine the laminar flow loss coefficient constant (C_{valve}), transition to turbulence and turbulent flow. It was demonstrated by Slatter & Pienaar (1999) that dynamic similarity can be achieved by using a Reynolds number that fully accounts for the viscous characteristics of mineral tailings as given in Equation 5.

$$\text{Re}_3 = \frac{8\rho V_{\text{ann}}^2}{\tau_y + K\left(\frac{8V_{\text{ann}}}{D_{\text{shear}}}\right)^n} \quad (5)$$

2.3 Loss coefficient data available in literature

Loss coefficient data obtained with non-Newtonian mineral tailings has been restricted to globe and gate valves (Edwards et al., 1985; Turian et al., 1998). The work found in the literature for diaphragm valves has been obtained using Newtonian fluids only (Hooper, 1981; Miller, 1990). Miller (1990) and Perry (1997) gives loss coefficient data for diaphragm valves in the fully open, 75%, 50% and 25% open position as given in Table 1 (for turbulent flow only). Pienaar et al. (2004) reported results obtained in a 40 mm rubber lined diaphragm valve and found agreement with the C_{valve} value of 1000 given by Hooper (1981). A recommendation was made that the results should be verified and that a range of different valve sizes should be tested to establish dynamic similarity.

Table 1: Loss coefficient data published in literature

Valve Opening %	Loss coefficient		
	Miller (1990)	Perry (1997)	Hooper (1981)
25	4	21	
50	1.2	4.3	
75	0.8	2.6	
100	0.8	2.3	2.0

Miller (1990) classified the loss coefficients of fittings in three classes. Class 1 are definitive loss coefficients that are based on experimental data from two or more sources which have been cross-checked. Class 2 loss coefficients are adequate for design purposes but no agreement has been found between two research programmes. Class 3 loss coefficients are suggested values for situations where experimental data are not available or where the results are from doubtful origin. Loss coefficients for diaphragm valves are classified as Class 3.

It is therefore important to do more experimental research on diaphragm valves in order to extend the database of loss coefficients available, and also to evaluate the results available in the literature.

3 EXPERIMENTAL PROCEDURE

3.1 Experimental apparatus

The valve test rig that was used for this investigation has been described in detail by Kazadi (2005) and only a very brief description will be given here. It consisted of 5 x 25 m long pipes that contain a diaphragm valve in the centre of each pipe. The rig was fitted with a 1.7 m³ mixing tank, a 100 mm progressive cavity positive displacement pump

(maximum flow rate of 11 litres per second) and two flow meters (SAFMAG 100 mm and KHRONE 50 mm). The pump was fitted with a variable speed drive to enable tests at different flow rates. The fluid was pumped to the pipes via a double pipe heat exchanger to maintain the test fluid at a constant temperature. The upstream and downstream straight pipe sections were each 12 m long to ensure fully developed flow at the inlet and redevelopment downstream of the test valve. Each pipe was fitted with 5 point pressure transducers before the test valve and 6 after the test valve to measure the pressure grade line. A Fuji Electric point pressure transducer (PPT) with a maximum range of 130 kPa with an accuracy of 0.25 % and a Fuji Electric differential pressure transducer (DP cell) of the same range were used to measure the pressure drop.

3.2 Test Valves

NATCO straight-through diaphragm valves was used for this investigation. Only one Saunders valve were used as comparison. A typical layout of the valve is given in Figure 1.

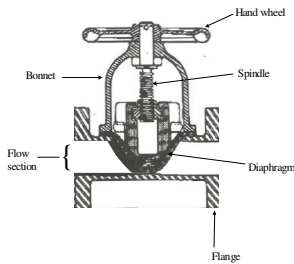


Figure 1: Schematic diagram of typical straight-through diaphragm valve.

The internal sizes and specifications of the test valves are directly related to the flow path and are given in Table 2 and 3. The dimensions refer to the diagrams presented in Figure 2.

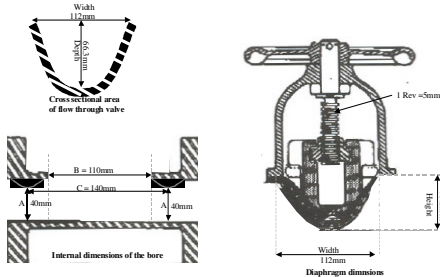


Figure 2: Internal dimensions of NATCO valves

Table 2: Internal specifications of test valves

NOMINAL BORE [mm]	CROSS SECTIONAL AREA		BORE DIMENSIONS [mm]		
	DEPTH [mm]	WIDTH [mm]	A	B	C
40	83	121	26	45	65
50	140	181	36	67	81
65	165	200	40	88	125
80	197	245	42	111	140
100	254	267	62	128	150

Table 3: Diaphragm dimensions

NOMINAL BORE [mm]	DIAPHRAGM DIMENSIONS		
	Height [mm]	Width [mm]	mm Per revolution
40	36	47	4.5
50	47	66	2.7
65	63	92	6.3
80	69	114	6.3
100	75	130	5.4

3.3 Experimental procedure

The position of the valves for the various openings was established and the number of revolutions to obtain the same position when testing the various fluids. The test fluids were water and kaolin slurries of 10 % and 13 % by volume. These fluids were chosen to demonstrate the difference in the loss coefficient for laminar and turbulent flow behaviour. Furthermore, tests were conducted using water in turbulent flow. The results available for the 40 mm valve (Pienaar et al., 2004) were done using kaolin. Kaolin represents yield pseudoplastic behaviour (Slatter & Pienaar, 1999) which is common for mineral tailings. The rheological parameters were obtained using tube viscometry. This method was selected because the valve test rig consists of 5 different pipe sizes and straight pipe test results could be used to produce a plot of shear stress versus shear rate using at least three pipe diameters. The tests were done daily to account for the changes in rheological behaviour of the kaolin slurry. The rheological parameters for the 10% and 13 % kaolin are given in Table 5.

Table 4: Rheological characteristics of kaolin slurries

DATE	DENSITY [kg/m ³]	C _v [%]	τ_y	K	n
19/04/2005	1164	10	16.5	1.85	0.305
26/04/2005	1174	10.5	16.5	3.29	0.246
5/05/2005	1211	12.8	29.9	10.0	0.202
11/05/2005	1223	13.5	27.6	0.83	0.473

3.2.1 Analysis of results

The static pressure is measured along the length of the pipes, both upstream and downstream, by means of eleven pressure taps. For the evaluation of the results obtained in this work, points close to the valve were excluded.

The steps in calculating the loss coefficient were as follows:

- The slope and intercept were determined upstream and downstream using the selected data points in the fully developed region. The experimental error obtained when comparing the straight pipe tests with the Colebrook-White equation on the rig is within 20 %. If the difference between the slope of the upstream and downstream pipes was greater than 20 %, the results were discarded.
- The pressure was calculated at the centreline of the valve both upstream and downstream.
- The pressure drop across the valve (Δp_{valve}) was determined by subtracting the downstream pressure from the upstream pressure at the centre line of the valve.
- The loss coefficient, k_v , was then calculated using Equation 3:

The loss coefficient constant, C_{valve} , is defined as the hyperbolic constant as given in Equation (4).

$$C_{\text{valve}} = k_v \text{Re} \quad (4)$$

The loss coefficients were evaluated using the logarithmic least square error.

$$E = \sum \left(\ln \frac{C_{\text{valve}}}{\text{Re}} - \ln k_{v \text{ obs}} \right)^2 \quad (6)$$

C_{valve} is obtained by minimising E for each valve size.

4 RESULTS

The straight pipe data are shown as plots of friction factor versus Reynolds number for laminar and turbulent flow. Agreement within 20 % was found when compared to the Fanning friction factor and the Blasius equation.

The loss coefficient data were presented as a function of the Reynolds number. A typical plot is given in Figure 4 of kaolin slurry and water in a 40 mm valve in the 50 % open position.

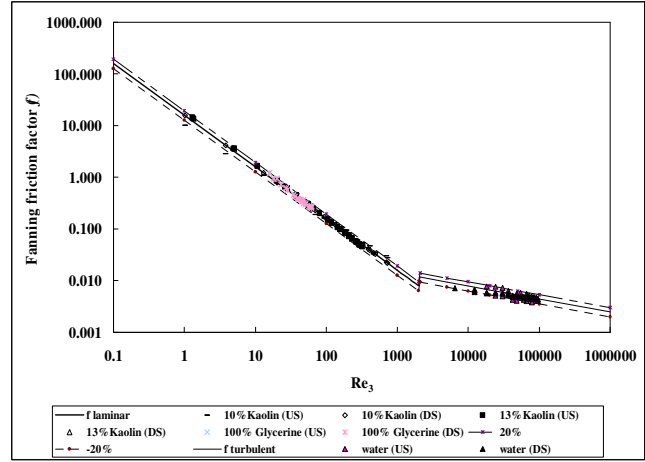


Figure 3: Comparison of experimental and calculated friction factors

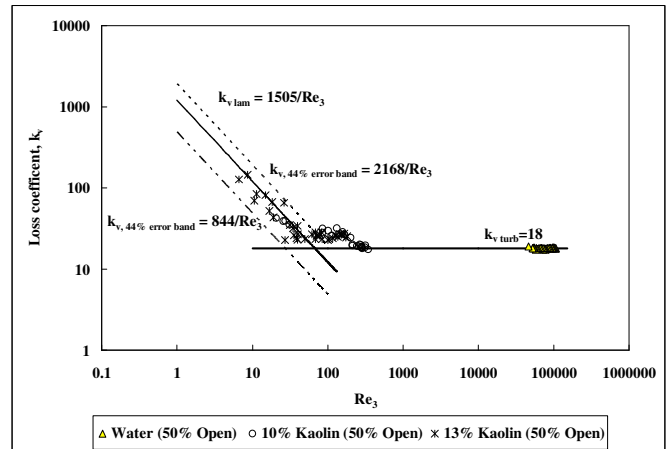


Figure 4: Typical loss coefficient versus Reynolds number plot obtained for Natco valve (11)

A summary of the loss coefficient data obtained for the NATCO valves each at the various openings are given in Figure 5 for laminar flow and in Figure 6 for turbulent flow.

A comparison of a 65 mm Saunders valve with that of a NATCO valve of the same size at all the openings is given in Table 5.

Table 5: Comparison of loss coefficient data for Natco and Saunders valves

Valve position opening (%)	Saunders' Valve		NATCO Valve		% Difference	
	C_{valve}	k_v	C_{valve}	k_v	C_{valve}	k_v
25	3887	32.1	3511	62.9	11%	49%
50	1086	5.9	2133	15.5	49%	62%
75	587	2.2	522	2.8	12%	24%
100	205	0.6	766	1.3	73%	52%

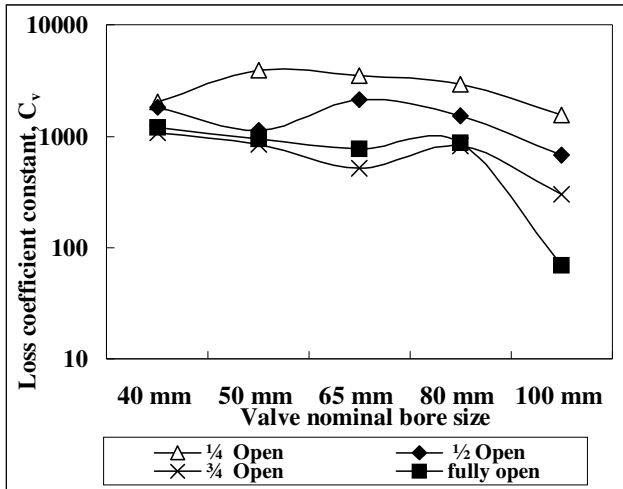


Figure 5: Laminar flow loss coefficient constant, C_{valve} as a function of valve size

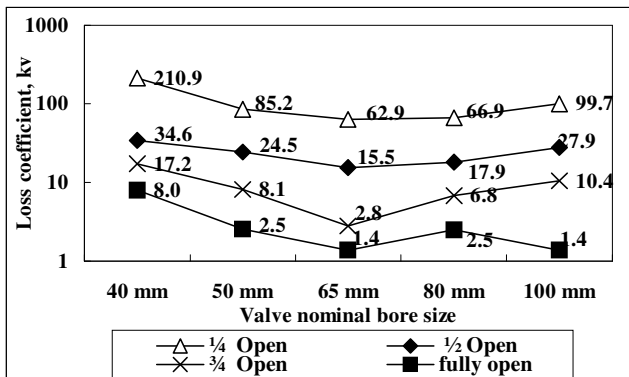


Figure 6: Turbulent flow loss coefficient, k_v , as a function of valve size

5 DISCUSSION

An important part of this work was to investigate the existence of dynamic similarity and whether it was suitable to use the results published in literature, which give no indication of the valve size. One of the precursors for establishing dynamic similarity is the existence of geometric similarity. Although the flow path is very complicated around the diaphragm, the geometric similarity was in this case evaluated as the height ratio of the flow gap between the diaphragm and the bore internal surface when the valve is fully open and at the specified valve opening. Unlike the case of globe valves and gate valves, dynamic similarity could not be established and a characteristic value of C_{valve} had to be obtained for each of the valve sizes. The diaphragm valves are rubber lined and this process is done by hand and this could be the reason for the lack of geometric similarity. Globe and gate valves are machined and this can be exactly reproduced. A factor needs to be found to account for the difference in geometry, but that was not part of this investigation.

In laminar flow, the loss coefficient constant decreased with increasing valve opening and valve size. However, the experimental scatter of results could be up to 50 % or more as shown in Figure 4. The results in Figure 5 have been determined for each valve. The loss coefficient constant is dependant on the range selected when applying Equation (6). If the results for all the valves are compared, however, it is difficult to see the individual trends for each valve since the scatter is significant. But compared to the results given by Hooper (1981), the values obtained are $\pm 300\%$ for the range of valves tested as demonstrated in Figure 7. Clearly, the value 1000 is not sufficient for design purposes. The reason for the experimental data scatter needs to be investigated further, since the straight pipe results are within 20 % of theoretical values.

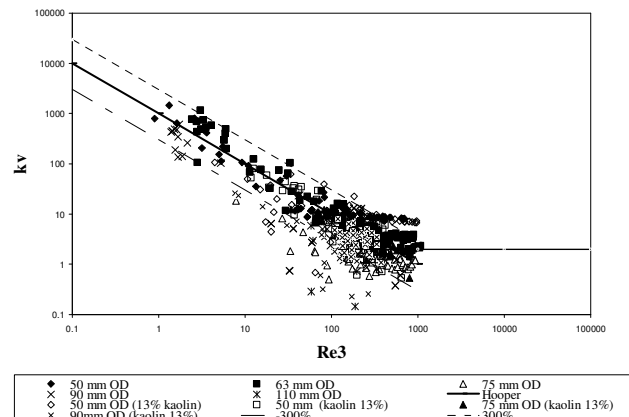


Figure 7: Comparison of all valves with that of Hooper (1981)

In turbulent flow the loss coefficient decreased with increasing valve opening as expected. From Figure 6 it appears as if a minimum is obtained for a 65 mm valve. The reason for this is not yet understood. The effect of the valve opening is significant. The ratio of the loss coefficient of each valve opening to that of the fully open position is given in Figure 8.

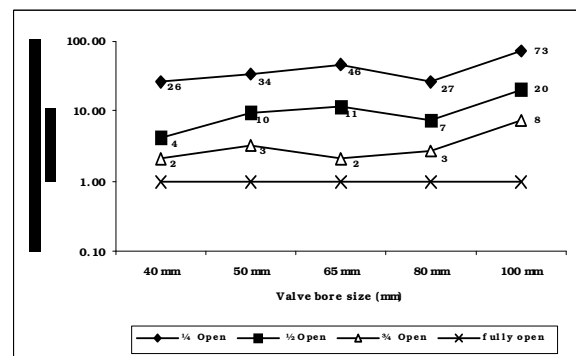


Figure 8: Ratio of loss coefficient at various valve openings

The implication of these values is that it gives that factor at which the valves' velocity head would

increase if the valve were closed from fully open position to a specific position. For example, the velocity head of the 40 mm bore valve at 25% open was 26 times the head velocity of the same valve at fully open position. This underpins the fact that in pipeline design, a mere positional switch of the valve from the fully open position to quarter open can add a significant head loss to the pipeline system, which needs to be taken into account for efficient design.

Comparison with the values given by Perry (1997) and Miller (1990) are given in Figure 9 and Figure 10 respectively. The ratios are to show the multiple factor at which the loss coefficient of the valve would be underestimated by if Perry's postulated value were to be used in pipe design for turbulent flow regime. For example, a 40 mm bore valve at 50% open has an experimental loss coefficient of 34.57, whereas Perry postulates 4.3. The ratio of the two values is 8.04. Thus the velocity head (Equation 2) would be underestimated by a factor of 8 if the loss coefficient of 4.3 was used instead of the experimentally determined value of 34.57.

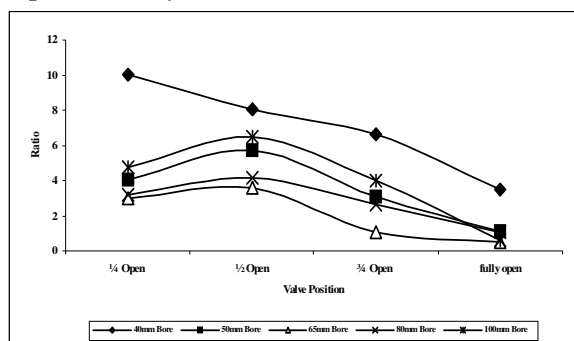


Figure 9: The experimentally determined loss coefficients compared to Perry (1997)

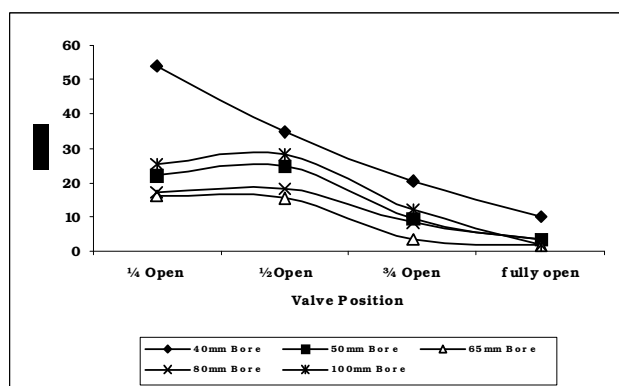


Figure 10: Ratio of the experimentally determined loss coefficients compared to Miller (1990)

It is obvious that these values cannot be used for all sizes of valves.

6 CONCLUSIONS

Mineral tailings were tested in straight-through Natco diaphragm valves to determine the loss coefficients in laminar and turbulent flow and to compare it to the results available in the literature for valves in the 25 %, 50 %, 75 % and fully open position.

Qualitative trends were confirmed but no quantitative agreement was found. The loss coefficient data found in this work was orders of magnitude higher than that found in the literature. The effects of the differences in the final design have been demonstrated.

When comparing results from valves manufactured by two different companies, it was clear that the same loss coefficients could not be used. The Saunders valves gave lower results than the Natco valves in turbulent flow. The scatter of results in laminar flow needs to be investigated and reduced first before a final answer can be given about valve performance in laminar flow.

Loss coefficient data for diaphragm valves remains class 3, but the results published here can be used for design when dealing with these specific valves.

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