Numerical Analysis of Friction Factor in Perforated and Slotted Horizontal Filters used to dewater Opencast Mines

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ABSTRACT

The horizontal wells have been using for dewatering purpose in the mining industry for several years. Based on unique characteristics, those horizontal filters are recommended to compromise both the mechanical strength and the hydraulic performance. Pressure drop along the horizontal well is the main factor that affects the performance of a wellbore. The pressure drop is caused by four separate factors: wall friction, perforation roughness, inflow acceleration and mixing effects. In this work, numerical analysis was implemented with different types of perforated and slotted pipes to investigate the effects of two first factors: wall friction and peforation roughness. The simulated data using ANSYS 14.5 was analyzed using universal velocity distribution law in combination with the roughness function. The results revealed that the roughness friction factor is not just dependent on Reynolds number. The semi-empirical relations correlated with numerical data were acquired to estimate the roughness friction factor in perforated or slotted pipes.

Keywords: Perforation roughness, horizontal filters, dewatering, opencast mines

1. Introduction

The horizontal directional drilling (HDD) technology has been experimented in the mining industry to dewater opencast mines (Eichler & Drebenstedt, 2014) (Mansel, Drebenstedt, Jolas, & Blankenburg, 2012). This technique is adapted from the petroleum industry and the utility construction. To effectively, and economically apply this new method of dewatering, it is recommended to use perforated or slotted pipes as filters during its installation (Tran & Drebenstedt, 2014) (Tran & Drebenstedt, 2015). However, those filters have to fulfill both mechanical strength and hydraulic aspect. Regarding hydraulic performance, the pressure drop of flow along the horizontal filter plays an important role and significantly affects the productivity of the dewatering system. This paper addresses the first phase of the study on the pressure drop along the horizontal filters without inflow through the wall: the effect of perforation roughness.

The effect of perforation roughness and inflow through the wall were studied quite thoroughly in the literature (Jiang, Sarica, Ozkan, & Kelkar, 2001) (Su & Gudmundsson, 1998) (Ze Su & Gudmundsson, 1993) (Su & Gudmundsson, 1994). However, these studies mostly varied the size, the phasing, and the density of circular perforations. This presented work focuses on the size, the geometry, and the perforated/slotted ratio of different filter pipes using the numerical analysis. Those pipes had a strong correlation between perforated/slotted rate, the size, and shape of cavities. In the simulated study, the pipes with an inner diameter of 50mm, the 4mm wall thickness, and the 920mm perforated/slotted length were used. The perforated/slotted ratio varied from 2%, 3% to 5%. The shapes of cavities were circular, axially or perpendicularly rectangular-like slotted. The widths of cavities varied from 1.5mm, 2mm to 3mm. The Reynolds number ranged between 10,000 and 80,000 with the increment of 5,000. There was no flow through the perforations or slots.

2. Background

The flow friction factor in a pipe can be calculated from at least two approaches. First, measuring the pressure drop and the friction factor obtained from the following equation

$$f_M = \frac{\Delta P}{\frac{L}{D}\frac{\rho U^2}{2}} \quad (1)$$

where f_M is the conventional Moody friction factor.

Second, measuring the velocity profile near the wall, then calculating the friction velocity u^* using universal velocity distribution law, which will be used to obtain the wall shear stress τ_w. From the wall shear stress, the friction factor is calculated

$$f_M = \frac{8\tau_w}{\rho U^2} \quad (2)$$

The flow friction caused by the perforation roughness in pipes is different from protrusion roughness, such as sand grain roughness. It was proved that the friction due perforation roughness could be analyzed by the universal velocity distribution law. The universal velocity distribution law describes the profile of velocity near the boundary of a surface. This law incorporated with Reynolds number and friction factor, applied to a smooth and circular pipe, has following form (Ze Su & Gudmundsson, 1993)

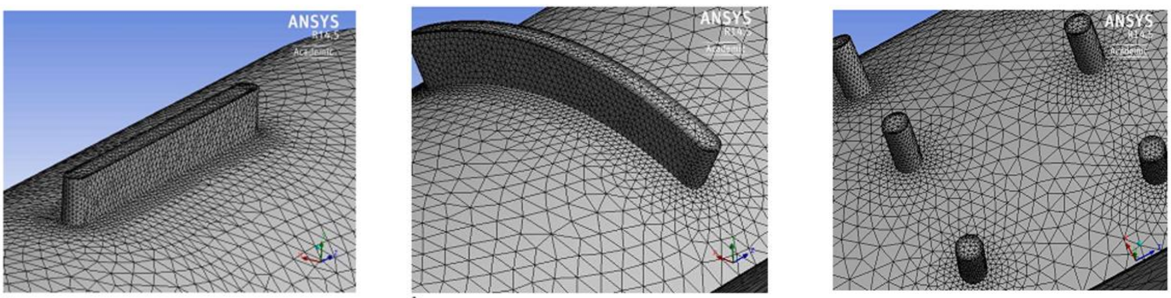
$$\sqrt{\frac{8}{f_{MS}}} = 2.5\ln\left(\frac{Re}{2}\sqrt{\frac{f_{MS}}{8}}\right) + A - 3.75 \quad (3)$$

The universal velocity distribution law is valid for smooth surfaces and also for uniformly rough surfaces.
To use this law for a rough surface, a parallel shift called *roughness function* $\Delta u/u^*$ is employed. The roughness function is normally a constant and not dependent on Reynolds number.

$$\sqrt{\frac{8}{f_{MR}}} = 2.5\ln\left(\frac{Re}{2}\sqrt{\frac{f_{MR}}{8}}\right) + A - 3.75 - \frac{\Delta u}{u^*} \quad (4)$$

3. Simulation Setup and the Filter Pipes

To calculate the pressure drop along the different perforated/slotted pipes, an academic finite volume code ANSYS Fluent 14.5 was employed. The numerical simulations used the SIMPLE, standard k-ε turbulent model, which was previously used and proved to have good agreement with experimental results (Abdulwahid, Dakhil, & Injeti, 2013). The fluid was water, entered the pipes at 25°, with constant density of $\rho = 998.2\ kg/m^3$, and the viscosity of $\mu = 0.001\ kg/ms$. It was also assumed that no-slip boundary condition along the isothermal walls. The inlet Reynolds number ranged from 10,000 to 80,000. The pipes were assumed hydraulically smooth on unperforated or non-slotted areas. Two initial conditions were taken into account: the mass flow at the inlet and the pressure at the outlet.
The pipes were uniformly perforated or slotted with different sizes, different shapes, and different ratios. To be convenient, in this work, the pipes with circular perforations are called Circular Perforated Cavity (CPC) pipes, the pipes with rectangular-like slots on the wall and along the pipe's axis are named Axial Slotted Cavity (ASC) pipes, and the pipes with rectangular-like slots on the wall and perpendicular to the pipe's axis are called Perpendicular Slotted Cavity (PSC) pipes. These pipes had 2, 3 and 5 percent of open ratio. The widths of cavities varied from 1.5mm, 2mm to 3mm. A total of 27 pipes were calculated.
The flows in pipes were discretized within ANSYS Meshing environment before solved by the Fluent solver. In the calculating process, symmetries were used to reduce computational time and resource. The computational meshes for different flows in pipes are shown in **Error! Reference source not found.**.



a, b, c,

Figure 1: Computational meshes of flows in pipes: a. ASC pipe; b. PSC pipe; c. CPC pipe

4. Results

4.1 Effect of Cavity Shapes

Simulated data showed that flows in pipes with different cavity shapes produced a different pressure drop. It can be seen in Figure 2 that with the ASC and PSC pipes, the friction factors reduced with the increase in Reynolds number. These friction factors are even smaller than that in regular pipes with small Reynolds number. This effect can be explained due to less contact area between flow and pipe's wall area while the perforations have not yet had an effect on flow profile. However, friction factor in CPC pipes showed the increase with the increase of Reynolds number from 45,000 to 50,000. The friction coefficients in CPC pipes are smaller than that of ASC and PSC pipes with Reynolds number under 50,000. It increased and became larger than in ASC and PSC pipes with bigger Reynolds number.

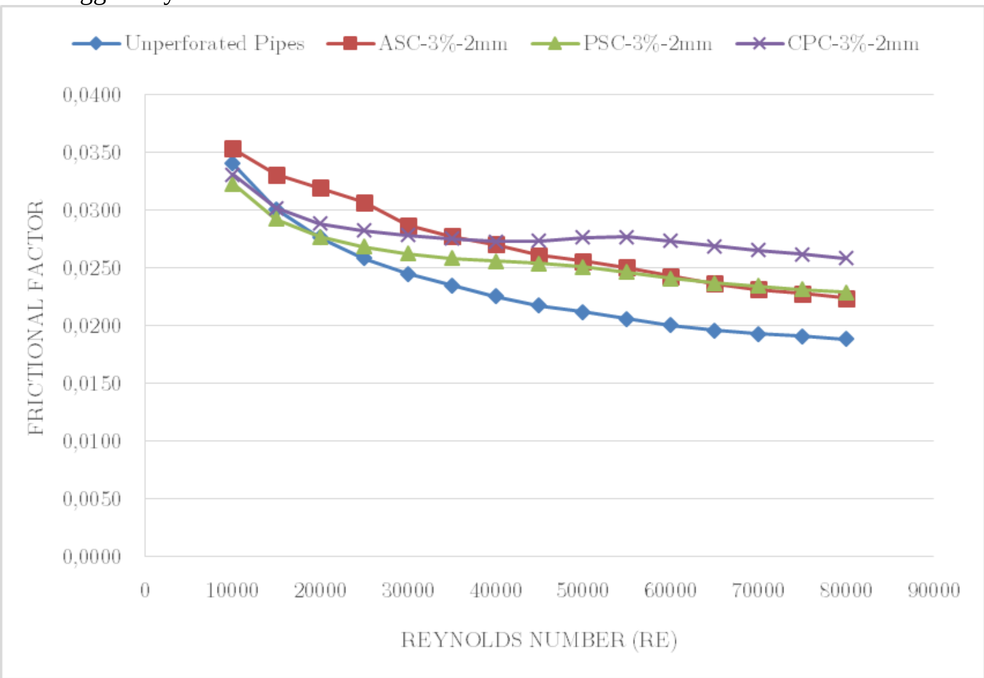


Figure 2: Friction factors in pipes with 3% perforation ratio, 2mm size

4.2 Effect of Perforation/Slot Ratio

It was observed that with the same type of cavity shape and the same size, flows in pipes incurred greater pressure drop with higher perforated/slotted rate. This observation was shown in. It can be seen that frictional factors are slightly smaller than that of in smooth pipe at small Reynolds number (<20,000). However, it managed to grow and proved to be bigger with an increase in open area and Reynolds number. These results agreed with the results from other studies when it comes to increasing perforated density

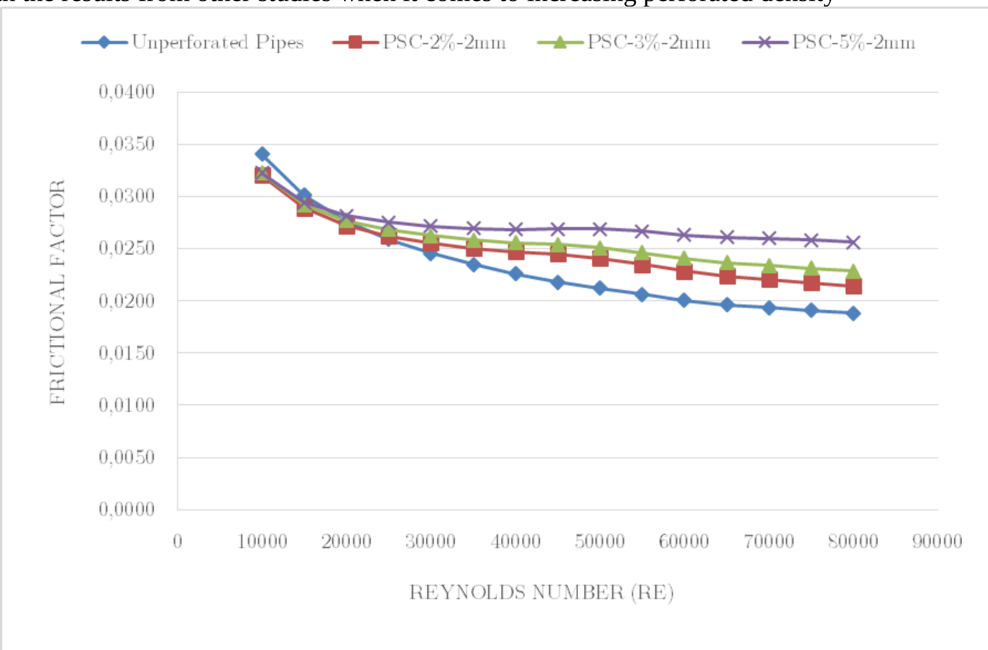


Figure 3: Friction factors in PSC pipes with 2mm size

4.3 Effect of Perforation/Slot Size

The observed data showed that with the same type of cavity and the equal open ratio, the flows in pipes incurred different pressure drop. Figure 4 indicated that ASC and PSC pipes produced small differences of frictional factors with various perforated/slotted sizes. With Reynolds number under around 50,000, they were rarely different, however, with bigger Reynolds number, the larger sizes seemed to produce the greater frictional factors, hence the more significant pressure drop. Other than that, with the CPC pipes, flows proved to have a significant difference in friction factors. The smallest size of 1.5mm had a far smaller friction factor compared with the bigger sizes as well as with the unperforated pipes. Friction factors increased according to increased Reynolds number. Furthermore, it is still in agreement with the result of other pipes: bigger perforated/slotted size tends to produce larger pressure drop due to increased Reynolds number.

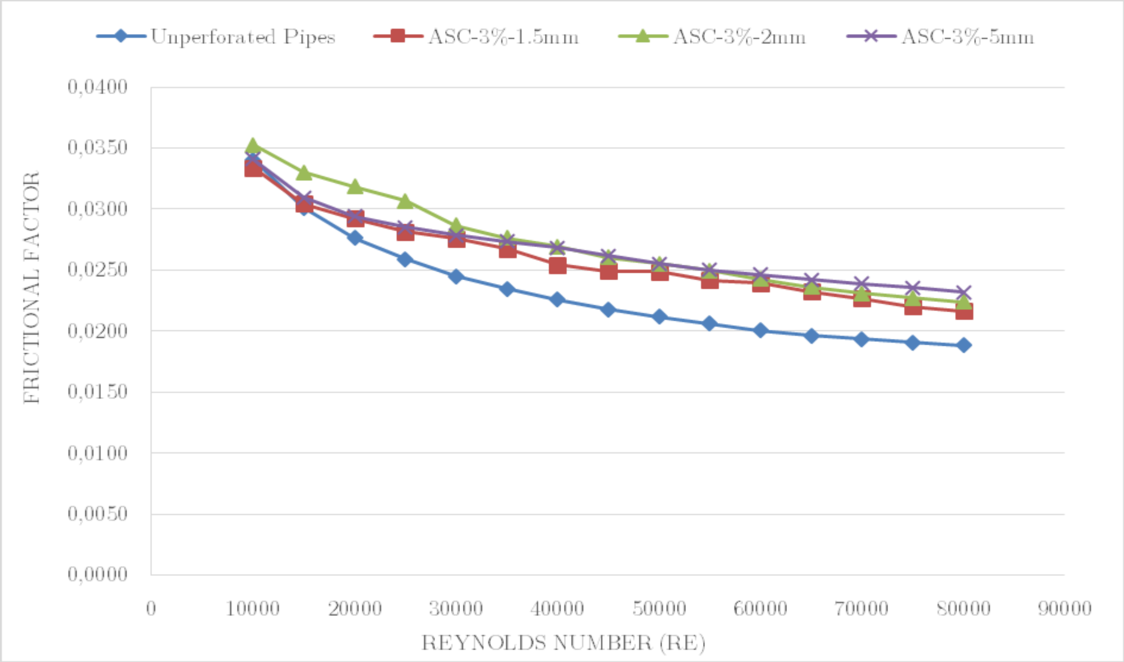


Figure 4: Friction factors in ASC tube with 3% open ratio

5. Discussions

The effort to analyze the influence of perforation roughness on the pressure drop in perforated/slotted pipes has been made using Blasius-type curve fitting, equivalent sand grain roughness, and universal velocity distribution law. However, according to Ze Su et al. (Ze Su & Gudmundsson, 1993), the Blasius-type curve fitting is not suitable for perforated/slotted pipes due to non-correlation found. The equivalent sand grain roughness used in the Haaland equation as followed

$$\frac{1}{\sqrt{f_{MR}}} = -1.8\log[\frac{6.9}{Re} + \left(\frac{\varepsilon}{3.7D}\right)^{1.11}] \quad (5)$$

However, the average relative error of this method was up to 60% when increasing the ratio of perforation diameter and pipe inner diameter to 0.25.

The last method of using universal velocity distribution law gave the higher accuracy with the average relative error of 20%. Hence, in this presented work, the universal velocity distribution law was employed to analyze the simulated data.

To apply universal velocity distribution law in incorporated form with friction factor and Reynolds number, the constant A of the smooth test pipes in Equation (3) should be obtained with simulated data.

significantly change with changing Reynolds number, which agrees well with the previous investigations that A should be a constant. The average resulted value of A is 5.23, and it is well satisfied with the value of A, which ranging from 5 to 5.5. Hence, the incorporated form of the universal velocity distribution law for perforated/slotted pipes becomes

$$\sqrt{\frac{8}{f_{MR}}} = 2.5\ln(\frac{Re}{2}\sqrt{\frac{f_{MR}}{8}}) + 1.41 - \frac{\Delta u}{u^*} \quad (6)$$

Interestingly, by plotting the roughness function, which derived from simulated data based on Equation 6**Error! Reference source not found.** versus Reynolds number, a linear correlation was found. The correlations for some pipes are shown in **Error! Reference source not found.**Figure 5. Let R_f denote the roughness function. Therefore, the linear correlation between R_f and Re is expressed as

$$R_f = \frac{\Delta u}{u^*} = a_1 R_e + a_2 \quad (7)$$

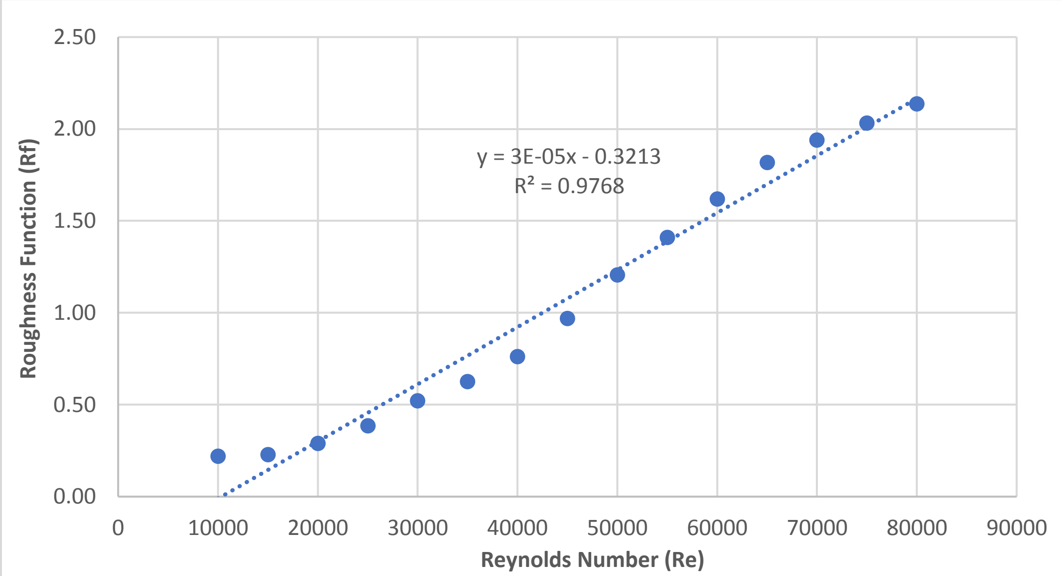


Figure 5: Roughness Function vs. Reynolds number for PSC pipe - 3% - 1.5mm

The excellent result of the linear correlation between the roughness function and Reynolds number demonstrated that for the pipes in this research, the roughness function could not be a sole function of relative roughness geometry. In another word, it strongly depends on the Reynolds number. The reasons for this result might be the different distribution patterns of the cavities on the pipe wall as well as the various shapes of cavities, in comparison with the pipes conducted by Ze Su. The effort to create a correlation for entire pipes has been made, however, up to the time reported, no single correlation was found. Therefore, for the purpose of investigating a more complex situation, where there is the presence of influx through the perforations, the linear correlation between roughness function and Reynolds number will be used respectively for each pipe.

6. Conclusion

Numerical simulations were performed to investigate the friction factors of perforated and slotted pipes due to cavity roughness. The pipe flows Reynolds numbers were in the range from 10,000 to 80,000. The pipes had an inner diameter of 52mm and the outer diameter of 60mm. A total number of 27 virtual pipes has been numerically investigated. The shapes of cavities were ASC, PSC, and CPC with varying opening ratios from 2%, 3% to 5%. The sizes of cavities were 1.5mm, 2mm, and 3mm. The numerical CFD code used was ANSYS Fluent 14.5, which employed SIMPLE algorithm, second order scheme, STANDARD $k - \varepsilon$ turbulent model to calculate pressure drop as well as flow behavior in pipes with cavities on the wall.

The simulated data revealed that the friction factor in perforated or slotted pipes depends on various parameters such as the shapes of cavities, the opening ratio, and the size of the opening. At small Reynolds number (<15,000), the friction factor sometimes showed to have a lower value than that of in regular pipes. This phenomenon might be the result of less contact area between flow and pipe wall, in the meantime, the cavity vortices have not had effects on main flow. At high Reynolds number (75,000-80,000), the friction factor proved to have up-to-60% larger value compared to plain pipes. General speaking, the CPC pipes produced the most pressure drop. It increased when the opening ratio and opening size increased. The friction factor of perforation roughness is independent of perforation phasing and the cavity depth in this presented work.

The universal velocity distribution law in combination with roughness function was employed to analyze the simulated data. Unlike the research by Ze Su et al., which showed the linear function of roughness function and the ratio of cavity/pipe diameter, the simulated data showed the dependent relationship between roughness function and

Reynolds number. An excellent linear correlation was found when plotting roughness function versus Reynolds number. The result might come from the different distribution patterns as well as the shape cavities. The linear correlation established for each pipe. However, no single correlation for whole pipes was found and reported. For the future investigation, when the flow enters pipes through cavities, the respective correlation for individual pipe will be employed.

Bibliography

Abdulwahid, M., Dakhil, S., & Injeti, N. (2013). Numerical Investigation of the Turbulent Flow Parameters Distribution in a Partly Perforated Horizontal Wellbore. *Vol. 9*(ISSN: 1857-7881), pp. 372-387.

Eichler, R., & Drebenstedt, C. (2014). Innovative Dewatering Concepts for Open Cast Mines Using Horizontal Wells (HDD-Wells). *Mine Planning and Equipment Selection*, pp. 697-706.

Jiang, W., Sarica, C., Ozkan, E., & Kelkar, M. (2001). Investigation of the Effects of Completion Geometry on Single-Phase Liquid Flow Behavior in Horizontal Wells. *Vol. 123*, pp. 119-126.

Mansel, H., Drebenstedt, C., Jolas, P., & Blankenburg, R. (2012). Dewatering of Opencast Mines using Horizontal Wells.

Su, Z., & Gudmundsson, J. (1998). Perforation Inflow reduces Frictional Pressure Loss in Horizontal Wellbores. *19*, pp. 223-232.

Su, Z., & Gudmundsson, J. S. (1994). Pressure Drop in Perforated Pipes: Experiments and Analysis.

Tran, D. H., & Drebenstedt, C. (2015). Considerable Aspects to Select Filter Wells for Dewatering. *Scientific Reports on Resources Issues*, pp. 199-204.

Tran, D., & Drebenstedt, C. (2014). Challenges during Horizontal Directional Drilling (HDD) Wells Installation for Dewatering Opencast Mines. *Scientific Reports on Resources Issues*, pp. 135-145.

Ze Su, & Gudmundsson, J. (1993). Friction Factor of Perforation Roughness in Pipes.