Modeling ingress losses into a horizontal landfill gas well: reconciling 2D turbulent flow and quasi-1D approximation

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1 Introduction

This document details on the steps that the author has followed to try to incorporate turbulent ingress head losses with the Darcian flow head loss through porous media in a horizontal landfill gas well to produce a model for calculating the head loss characteristics across the gas well for efficient extraction of landfill gas[2]. The horizontal well is a pipe with equidistant apertures penetrating the length of a landfill, with a vacuum inducing pump at the outlet and the far end blocked. The well is supported by a thin lamina of gravel and drains a cylindrical volume of gas generating medium around it. In [2], a quasi-1D model for this system was developed and implemented in MATLAB/Octave, but a computational study in COMSOL [1] has shown that the quasi-1D construction overlooks the highly localized turbulent structures at the ingress apertures. The purpose of the current project was to attempt to incorporate these local head losses into the quasi-1D model.

2 COMSOL Model Review

To generate the simplified MATLAB/Octave model, a COMSOL model was created to compare against. The gas well can be simplified to a 2D axisymmetric analogue. The circular apertures are replaced by axisymmetric slits of equivalent area that wrap around the well, essentially splitting it into individual pipe segments. The specifications of the nominal model are given in Table 1.

Symbol	Variable	Value	Units
μ	Dynamic viscosity	0.000014291	$Pa \cdot s$
R_{gas}	Gas constant	287	J/kg/K
r_p	Pipe radius	0.0762(3")	m
r_g	Outer radius gravel domain	1	m
r_w	Outer radius waste domain	10	m
t	Pipe wall thickness	0.00711(0.28")	m
l	Pipe segment length	15	m
E	Pipe wall roughness	$1.5 imes 10^{-6}$	m
L	Wall length	420	m
r_h	Hole radius	0.00635(0.25")	m
n_h	Holes per section	6	-
n	Pipe segments	28	-
Т	Temperature	288.15	K
P_{atm}	Atmospheric pressure	101325	Pa
P_{out}	Outlet pressure (Open BC)	98825	Pa
P_{out}	Outlet pressure (Closed BC)	95075	Pa
C	Generation rate	1×10^{-6}	$kg/s/m^3$
k_{g}	Gravel permeability	1×10^{-5}	m^2
k_w	Waste permeability	1×10^{-8}	m^2
ϕ	Porosity	0.55	-
k	Turbulent kinetic energy	0.00016	m^2/s^2
ϵ	Turbulent dissipation rate	0.005	m^2/s^3

Table 1: Model Specifications

3 COMSOL Java Interface

The Java API for COMSOL was used to automate the data generation, extraction, and sorting. The procedure for this is detailed in [4]. The rationale for using this interface over the COMSOL Parametric Sweep was to export data after each parameter shift, as opposed to exporting after the complete scan. Additionally, it allows for the entire parameter space to be run at once. However, the COMSOL .mph files are not saved using the Java API (requires libraries that are not available, refer to model.save), so all necessary data must be explicitly extracted.

COMSOL uses a parametric solver, which can utilize previous solutions for faster convergence. Since this solver is not designed for changing geometries, it runs into convergence issues if the involved parameters change the geometry. COMSOL parametric sweep is an alternative to this which works for changing geometries and converges as fast as a Java scan. For initial tests and setup, it is highly recommended to use the Parametric Sweep with the parametric solver¹ that is available within COMSOL.

Some errors with the COMSOL GUI have been known to occur, one notable error is the GUI being inconsistent to the Java code generated from the same file. This phenomenon was observed for one file and the source of the disparity is yet to be identified. To ensure the credibility of the .mph file it is advisable to export its associated Java file and check for any discrepancies.

4 Parametric Scan

The data stored from the parametric scans have been limited to pressure values at our points of interest at the ingresses. Two probing points for each ingress have been selected at seven pipe thicknesses $(7 \times t)$ from the center of the ingress on either side of the ingress; one within the turbulent pipe domain and the other within the porous lamina. The parameters being changed are shown in Table 2.

Symbol	Parameter	Test range	Unit
P_{out}	Outlet pressure	88825:1250:100075	Pa
k_w	Waste permeability	$10^{-6:-1:-12}$	m^2
l	Pipe Segment length	7.5:7.5:30	m
n_h	Number of holes	1, 2, 4, 6	-
n	Number of pipe segments	6:27	-
C	Generation Rate	$10^{-5:-1:-7}$	$kg/s/m^3$

Table 2: Te	esting Ranges	The colon operator	represents	the MATLAB	/Octave linspace f	function.)
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For the closed boundary case, the outlet pressure was fixed at the median value of our testing range, while varying other parameters. However, for the open boundary, lower pressure tends to cause convergence problems, so a pressure value for stable convergence was used.



Figure 1: Output Mass for Open Boundary

¹Parametric solver is available in the Advanced Settings of Parametric Sweep in the COMSOL GUI

5 COMSOL Model Setup

The geometry of the COMSOL file can be understood from the .mph files, ergo, requires no detailed instructions.

The COMSOL model was created in two parts; the turbulent flow regime of the pipe and the Darcian flow in the porous media. In the turbulent regime, the model was set to be compressible (Ma < 0.3) with an outlet having P_{out} set as fixed pressure value at one end of the well. The pressures at the ingresses of the turbulent regime were equated to the corresponding pressure values at those ingresses obtained from Darcy's law. The radial and axial velocities were first initialized to zero for the closed boundary condition which revealed that the radial velocities are minimal throughout the entire pipe domain excluding the vicinity of the ingress. Moreover, the axial velocities showed a linear variation within the pipe domain which supported previous evidence[2]. Hence, the radial velocities for subsequent setups were initialized to zero for the entire domain and the axial velocities were initialized from the predicted linear Reynolds number variation given in [2]. The initial value for pressure for the entire pipe domain was set to the atmospheric pressure. Within the porous media, the pressure values have been initialized by a linear function. The pressure increases from P_{out} to P_{atm} moving radially outwards from the pipe exterior ($r_p + t$) to the exterior of the waste layer (r_w).

For the closed boundary case, the outer radius of the waste layer at r_w is set to have no flow across it and the pressure at this point varies with the applied outlet pressure. An important characteristic of this setup is that the absolute pressure within the domain never approaches atmospheric levels and the entire domain is essentially under vacuum throughout most of our test range. The mass collected from the domain is always equal to the mass generated in the waste layer.

The open boundary model has been created identically with the exception that the outer radius of the waste layer is set to have a fixed inlet pressure equal to atmospheric pressure (P_{atm}) . The mass collected in this case varies directly with the applied pressure as shown in Figure 1. The available data suggest that there are fixed differences in the mass collected from the domain due to the ingresses with varying pressures, which proposes that it relates to the geometry of the ingress rather than the applied pressures, supported by observing the mass output for changing l in Figure 1.

6 Juxtaposition with the quasi-1D model in MATLAB/Octave

6.1 Closed Boundary

When compared to the equivalent MATLAB/Octave setup the results, they have a similar pressure profile as shown in Figure 2, which indicates a fair degree of accuracy. This can be attributed to the mass collected in both systems being the same, as both are equal to the mass generated in the systems. For both cases, it was noteworthy that for the entire test range of the outlet pressure, the pressure at the pipe's closed end never exceeded the outlet pressure by more than a fixed pressure difference which we will call P_m . P_m changes with varying lengths of the pipe segments and is much lower than the applied pressure difference. For our nominal case, P_m is about 500 Pa.

6.2 Open Boundary

When compared with the MATLAB/Octave solution, this case gives results as shown in Figure 3. This data is obtained from a generic case and the pressure discrepancy persists for all cases. As we would expect, the data from COMSOL approaches the maximum possible pressure within the well, while there is a substantial pressure difference in the MATLAB/Octave solution. The disparity in both curves can be attributed to the output masses being different in both cases as shown in Figure 1. This disparity may be resolved by either forcing the ingress pressure losses or the masses collected through the ingresses. Both options are explored hereunder.

7 COMSOL Files and Datasets

To create a model for the ingress head loss, the datasets were generated from COMSOL Java API of the test variables given in Table 2, excluding the parameters that were deemed unrealistic or showed convergence complications. For future use, the simulations have also been run on COMSOL using parametric scan via the parametric solver. The incomplete or missing scans are given in Table 3.



Figure 2: Closed BC Pressure Profile

Parameter	Case	Deficient Files	Error Type
C	Closed Boundary	.mph & .csv	Unrealistic Conditions
n	Open Boundary	.mph & .csv	Convergence Issues
n	Closed Boundary	. mph	Convergence Issues
n_h	Open Boundary	.mph	Convergence Issues

Table 3: COMSOL Deficient Files & Datasets

8 Ingress Loss Modeling

The incongruity between the quasi-1D and 2D models stems from the head loss at the ingresses. For the quasi-1D solution, the losses over the ingresses are not accounted for, so the system opts to disperse the head loss over the porous domain as shown in Figure 4. Consequently, we need to incorporate the ingress losses into the quasi-1D solution, which is done by forcing the model to use the correct pressure predicted in the gravel layer by COMSOL to solve for the integration constant a_a defined in appendix B in [2].

This pressure is obtained from the COMSOL data by fitting a quartic polynomial

$$p_{ing} = c_1 i^4 + c_2 i^3 + c_3 i^2 + c_4 i^1 + c_5 i^0, \tag{1}$$

where c_n are constants and *i* is the ingress position. The values of c_n were obtained from the parametric scan data and are calculated based on the input conditions. Depending on the input conditions, the polynomial for pressure loss was created and added to the corresponding quasi-1D section pressure to simulate the pressure outside the ingress, namely in the gravel layer; resulting in the following calculation:

$$a_a = \left\{ p_{\mathcal{B}}^2 - (p_i + p_{\text{ing}})^2 + \frac{\mu}{k_b} RTC_b \left(\frac{1}{2} (r_{\mathcal{B}}^2 - r_{\mathcal{A}}^2) + r_{\mathcal{A}}^2 \ln \frac{r_{\mathcal{A}}}{r_{\mathcal{B}}} \right) \right\} / \left\{ \ln \frac{r_{\mathcal{A}}}{r_{\mathcal{P}}} - \frac{k_a}{k_b} \ln \frac{r_{\mathcal{A}}}{r_{\mathcal{B}}} \right\},$$
(2)

where the term $(p_i + p_{ing})$ is supposed to simulate the pressure inside the gravel layer. This condition is only applicable for the open boundary case in MATLAB/Octave, as the closed boundary case is modeled independently of the ingress losses. The characteristics observed for the variables are detailed hereinafter.



Figure 3: Open BC Pressure Profile

8.1 Closed Boundary

As expected, changing the geometry alters the resistance to the flow within the pipe. Reducing n_h increases the resistance to flow at the ingress, resulting in higher losses. Increasing l results in greater mass generation in porous laminae and higher pipe wall friction fostering higher losses.

As the ingress loss is a very localized phenomenon, there is no significant change that occurs with changing k_w as expected[1].

Changing the outlet pressure does not produce an appreciable difference in the ingress pressure drop. This can be attributed to the mass generated in the system being constant.

Increasing the generation rate of the system tends to increase the pressure throughout, resulting in some regions in the domain exceeding atmospheric pressure, yielding impractical conditions.

8.2 Open Boundary

The geometry change for the open boundary shows the same characteristics as the closed boundary condition; increasing resistance results in higher ingress head loss. Changing k_w tends to have no effect as previously discussed. Additionally, changing the generation rate has inappreciable impact in the system, which can be attributed to a significant fraction of the mass collected coming from the open boundary and not inner generation. Changing outlet pressure in this case, does in fact, change the ingress pressure drop. The lower the outlet pressure, the greater the pressure drop across the ingresses due to the increased mass being drawn through the ingress.

Incorporating the ingress losses in this case tends to cause a drop in pressure along the pipe due to less mass being collected from the porous domain as seen in Figure 3, which proves that forcing ingress losses is not a viable solution for this case. Forcing ingress losses tends to decrease the mass collected from the system, resulting in reduced pressure drop across the shared domain boundary and causing the pressure to drop in the porous domain as shown in Figure 4.



Figure 4: Open BC Radial Pressure Profile

9 Forced Darcy Pressure Loss

In the open boundary case, the pressure loss across the porous domain remained fairly constant for all parameters. At the ingress closest to the outlet, the pressure drop across the porous domain was minute (< 10Pa), which reduced to null when moving to the closed end of the well. So, to replicate this in MATLAB/Octave, the pressure was changed to these values to force the model; resulting in the following solution for a_a

$$a_a = \left\{ p_{\mathcal{B}}^2 - p_{d_i}^2 + \frac{\mu}{k_b} RTC_b \left(\frac{1}{2} (r_{\mathcal{B}}^2 - r_{\mathcal{A}}^2) + r_{\mathcal{A}}^2 \ln \frac{r_{\mathcal{A}}}{r_{\mathcal{B}}} \right) \right\} / \left\{ \ln \frac{r_{\mathcal{A}}}{r_{\mathcal{P}}} - \frac{k_a}{k_b} \ln \frac{r_{\mathcal{A}}}{r_{\mathcal{B}}} \right\},\tag{3}$$

where

$$p_{d_i} = p_{atm} - p_c \times \left(\frac{n-i}{n}\right) \tag{4}$$

and p_c is the maximum pressure drop across the porous media. However, this results in the reduction in the overall mass collected from the porous domain resulting in the same outcome as before. It reduces the pressure drop in the pipe even further resulting in almost no pressure loss over the turbulent domain as shown in Figure 5.

To check whether this method can yield any results whatsoever, a value for p_c was selected which forced the masses in the quasi-1D solution to match the values known from COMSOL. This enforces the solution to use a set value of integration constant a_a yielding the solution given in Figure 6. The value of p_c was assigned empirically but it showed that the pressure profiles match if the masses in both solution are the same, which reveals that the solution is possible with the quasi-1D but it is not clear where the inadequacies lie. This same process can be repeated for all test parameters with the understanding that the variation of assigned pressures is not always linear axially, yielding that there is a possible solution equating the quasi-1D model to the COMSOL model.



Figure 5: Forced Darcy Pressure Loss Profiles



Figure 6: Arbitrary p_c Pressure Profile

References

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