

Velocity Modelling for Pipeline Inspection Gauge (Pemodelan Halaju Tolok Pemeriksaan Talian Paip Gas)

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ABSTRACT

Pipeline inspection gauges (PIGs) apply in oil and gas industries, particularly in cleaning, dewatering, and inspecting pipelines. Also, both the speed and driving pressure for the PIGs operation are deduced basis on the guesswork or experience. In this study, the dynamic behaviour of PIGs in gas pipelines is investigated. The dynamic differential equations of PIG velocity are used to calculate the motion of models Solghar and Nieckele. Differential and other conditional equations are simultaneously solved by using the ODE45 built-in function of the MATLAB® software. Generally, the dynamic motion of PIGs depends on the differential pressure of the fluid and can be affected by other parameters, such as bypass area and frictional force. Therefore, we further examine and consider these parameters in modelling. We validate the modelling results by comparing them with the experimental results obtained by a PIG manufacturing company. Results show that the Solghar model is more suitable than Nieckele model in operating condition selections. The increasing bypass area and frictional force reduce the movement speed of the PIG because of the decrease in the pressure difference between the PIGs. Subsequently, a graphical user interface is created and customised in MATLAB® to automate the calculation of PIG velocity.

Keywords: pipeline inspection gauge; modelling; velocity; MATLAB

ABSTRAK

Tolok pemeriksaan talian paip merupakan peranti utama digunakan dalam bidang minyak dan gas untuk tujuan pembersihan, penyahairan dan pemeriksaan talian paip. Namun, pengiraan halaju dan tekanan pacu seringkali melalui proses agakan dan pengalaman sahaja. Dalam kajian ini sifat dinamik tolak pemeriksaan dalam talian paip gas akan dikaji. Persamaan dinamik pembezaan bagi halaju tolak daripada model Solghar dan model Nieckele digunakan bagi pengiraan pergerakan tolak. Persamaan pembezaan bersama dengan persamaan keadaan lain diselesaikan dengan fungsi ODE45 menggunakan perisian MATLAB®. Secara umumnya, gerakan dinamik tolak pemeriksaan bergantung pada tekanan kebezaan bendalir dan boleh berubah disebabkan parameter lain seperti luas aliran pintas dan daya sentuhan. Justeru, parameter seperti luas aliran pintas dan daya sentuhan dikaji kesannya terhadap pergerakan tolak dalam pemodelan ini. Hasil pemodelan ditunjukkan dalam kajian ini dan disahsahkan dengan hasil ujikaji eksperimen yang diperolehi daripada sebuah syarikat. Hasil permodelan mendapati model Solghar didapati lebih sesuai digunakan bagi keadaan pengoperasian yang dipilih dalam kajian ini berbanding model Nieckele. Selain itu, didapati peningkatan luas aliran pintas dan daya sentuhan akan menurunkan halaju tolak disebabkan perbezaan tekanan antara tolak yang lebih rendah. Antara muka pengguna grafik iaitu aplikasi dalam perisian MATLAB® turut disediakan untuk pengiraan halaju tolak secara automatik.

Kata Kunci: tolak pemeriksaan; pemodelan; halaju; MATLAB

INTRODUCTION

Pipelines are major tools used to transport oil and natural gas. However, some undesirable products, such as condensates, wax and other debris (Ohwoka 2015), may be deposited on pipeline walls during transportation and after the long-term operation of these pipelines. Pipeline inspection gauges (PIGs) are large pieces of machinery designed to clean these

unwanted deposits. 'Pigging' refers to the operation of these PIGs in the pipelines. Flow efficiency decreases along with the thickening of the deposit layers in the pipeline, and these decrease results in the rupturing of the pipeline at the worst scenario (Cordell & Vanzant 2003). Apart from cleaning or dewatering, PIGs can also be used for inspection and data collection and for ensuring the integrity of pipes. Therefore, many industries usually perform pigging to maintain pipelines

before and after the transportation of oil and natural gas. Conventional PIGs have two parts, namely, the body and the discs or cups, which serve different purposes. Other types of PIGs, including foam, gel and spherical PIGs, have also been used. Foam PIGs are produced in bullet shapes and are made of polyurethane foams with light (32 kg/m^3), medium (80 kg/m^3 to 128 kg/m^3) and heavy densities (144 kg/m^3 to 160 kg/m^3). Gel PIGs are designed to separate several products at the start of the process or to carry corrosion inhibitors in gas pipelines. Spherical PIGs are commonly used for sealing (Guo et al. 2017).

PIG motion during pipeline operation must be explored further. These PIGs must move at a constant velocity that ranges from 2 m/s to 7 m/s in gas pipelines and from 1 m/s to 5 m/s in liquid pipelines to achieve an optimum flow efficiency (Tiratsoo 1992). PIG velocity is usually deduced on the basis of guesswork or experience. An optimum running data can be obtained through experiments. However, this method requires considerably long time and is therefore considered infeasible.

Two types of methods are generally used to control PIG velocity. The first method is the passive control method, which controls the flow rate or fluid pressure of PIGs. However, this method may cause fluctuation in velocity, especially in gas pipelines, due to the compressibility of gas. Some studies have efficiently circumvented this problem. For example, Esmailzadeh et al. (2006) manipulated flow rate to control velocity, Dykhnó et al. (2002) set a sufficient level of fluid pressure to move PIGs, and Tolmasquim and Nieckele (2008) maintained the maximum or minimum fluid pressure. The second is the active control method, which involves the addition of a bypass that allows fluid to flow through the PIG body, thereby reducing the differential pressure between their nose and tail. A sufficient level of driving pressure must be set to move PIGs. However, high differential pressure can negatively affect the stability and efficiency of the machinery (Deng et al. 2013). Moreover, PIGs cannot move when the pressure difference is lower than the frictional force that acts on pressure (Gupta & Sircar 2016).

The friction coefficient or frictional force that acts on the PIG movement is usually denoted by static friction because this coefficient or force can be influenced by many factors during the operation of PIGs. Thus, this parameter is difficult to determine. The selected material for sealing the disc is a parameter that affects friction coefficient or frictional force. Polyurethane is considered the best sealing material due to its elasticity, flexibility and abrasion resistance (Ohwoka 2015). However, some alternative sealing materials, including polymeric materials or composites with high resistance to heat and abrasion, are also available (Zhang et al. 2017). The diameters of sealing discs must also be larger than the internal diameters of pipes for the sealing and separation effect. The ideal diameters for these discs range from 102% to 105% of their internal diameters (Winters 2014). An oversized disc shrinks and fits into the pipeline, and the friction generated by the strain from compression is known as post buckling (Nieckele et al. 2001).

To address these gaps, the aim of this study is conducted by examining the PIG velocity through modelling approaches based on published mathematical models. The bypass flow and friction force that resulted from the usage of different materials are also considered and investigated in the modelling process.

METHODOLOGY

Modelling was performed by using the mathematical models of Solghar and Davoudian (2012) and Nieckele et al. (2001). The differential equations in these models were solved simultaneously by using ODE45 in MATLAB®. Then, we compared the models to determine which of them can generate results that are closest to the experimental data obtained from a PIG manufacturing company located in Selangor, Malaysia. A graphical user interface was also created in MATLAB® to help users input the parameter values required for calculating PIG velocity. Various bypass areas (0%, 3% and 8%) with different material options were added to the selected model for precise and rapid prediction.

GOVERNING EQUATIONS

The first model was developed on the basis of Solghar and Davoudian's mathematical model (hereinafter referred to as 'model Solghar'). The force balance that acts on the PIG system was defined as follows:

$$m \frac{dV_{pig}}{dt} + C_d V_{pig} = (p_t - p_n)A - mg \sin \beta - F_c \quad (1)$$

where m , t , V_{pig} , C_d , $p_t - p_n$, A , g , β and F_c denote the PIG mass, time, PIG velocity, damping coefficient, pressure difference, cross-section area of the pipe, gravity acceleration, elevation angle and contact force, respectively. Table 1 shows the numerical values for these parameters.

TABLE 1. Numerical values of the parameters in model Solghar

Parameter	Value	Unit
PIG mass, m	2500	kg
C_d	0.74	N.s/m
F_c	200	N
Pipe diameter, d	0.7938	m
Density, ρ	8.716	g/m^3
Temperature	27	$^{\circ}\text{C}$
Pressure	98.5	bar
β	0	$^{\circ}$
g	9.81	m/s^2

The following assumptions are used in this model:

1. The fluid is continuous, compressible and behaves similar to a Newtonian liquid.
2. The fluid has a single-phase and unidirectional flow.

3. Radial deformation is neglected.
4. The friction coefficient is assumed to be a function of wall surface roughness and Reynolds number.
5. The heat flux is in a quasi-equilibrium state.

The second model was developed on the basis of Nieckele et al.'s model (hereinafter referred to as 'model Nieckele'). The force balance that acts on the PIG system was expressed as follows:

$$m \frac{dV_{pig}}{dt} = (p_1 - p_2)A - mg \sin \beta - F_c V_{pig}, \quad (2)$$

where $p_1 - p_2$ denotes the drop-in pressure across the PIG, and the other symbols denote the same definitions as mentioned previously. Table 2 shows the parameter values in this model.

TABLE 2. Numerical parameter values

Parameter	Value	Unit
m	3	kg
F_c	40	N
Pipe diameter, d	0.1	m
Density	1.37	kg/m ³
Temperature	27	°
Pressure	2.03	bar

The following assumptions are used in this model:

1. The fluid is continuous, compressible and behaves similar to a Newtonian liquid.
2. The fluid has a single-phase and unidirectional flow.
3. The fluid has an isothermal flow.
4. The friction coefficient is estimated by assuming a fully developed flow.

The aforementioned models use pressure drop terms in their governing equations. Pressure drop can be calculated as follows:

$$\Delta P = \frac{1}{2} \rho C \left[\left(\frac{A}{A_b} \right)^2 \left(\frac{Q}{A} v \right) \right]^2, \quad (3)$$

where ρ denotes fluid density, C denotes the pressure drop coefficient, A denotes the cross-sectional area of the pipe, A_b denotes the bypass area, Q denotes the volumetric flowrate and v denotes the PIG velocity.

The bypass areas were set to 0%, 3% and 8% and calculated as follows:

$$A_b = \frac{\text{Bypass percentage}}{100} * A, \quad (4)$$

$$A = \frac{\pi d^2}{4}. \quad (5)$$

The contact force exerted on the oversized sealing disc can be determined by considering all the moments that act

on the disc. The contact force and relevant moments were computed as follows:

$$F_{wall} = \frac{M_c + M_t + M_p + M_h}{(\mu * r * (r - r_p) + R(1 - \cos(\beta)) - t * \cos(\beta) / 2)}, \quad (6)$$

$$M_{c/t} = \frac{Et^3 r_p}{24R}, \quad (7)$$

$$M_h = \frac{ER^2 t}{1 - \nu^2} \int_0^\beta \frac{\alpha - \sin(\alpha)}{a + r_p / R} (1 - \cos(\alpha)) d\alpha, \quad (8)$$

$$M_h = 2 * \Delta P * R \left[\frac{R\beta}{2} - \frac{R * \sin(2\beta)}{4} + r_p * (1 - \cos(\beta)) \right], \quad (9)$$

$$\text{Oversize} = \frac{r_s - r}{r} \text{ and} \quad (10)$$

$$\text{Clamping rate} = \frac{r_p}{r_s} \quad (11)$$

where M_c , M_t , M_p and M_h denote the compression stress, tensile stress, moment due to pressure and moment due to hoop stress, respectively. Moreover, E denotes the Young's modulus of the sealing disc, t denotes the thickness of the sealing disc, ν denotes the Poisson's ratio, r_s denotes the radius of the sealing disc and r_p denotes the radius of the spacer disc. Other undefined parameters were also used as symbols during the modelling to facilitate calculation. After the calculation of the wall force, the contact force was determined according to the relationship between the wall and contact forces.

RESULTS AND DISCUSSION

MODEL VALIDATION

Models Solghar and Nieckele are constructed by using the data from Solghar and Davoudian (2012) and Nieckele et al. (2001), respectively. Figure 1 plots velocity against time for model Solghar by using the data in Table 1.

Figure 1 shows that PIG velocity rapidly increases and becomes constant at approximately 1.6 m/s. The initial movement of the PIG is driven by the force that resulted from the great pressure difference between the front and back of the PIG. This result agrees with the simulated PIG velocity performed by Solghar & Davoudian (2012) (i.e. approximately 1.6 m/s). Figure 2 plots velocity against time for model Nieckele by using the data in Table 2.

Nieckele et al. (2001) focused on the simulation of PIG with bypass. The bypass area measures approximately 3% with a varying mass flow rate. For comparison, the simulated maximum velocity in Nieckele et al. (2001) is approximately 2.2 m/s, and this value agrees with the simulation performed in the present study, which shows the maximum velocity of approximately 2.3 m/s.

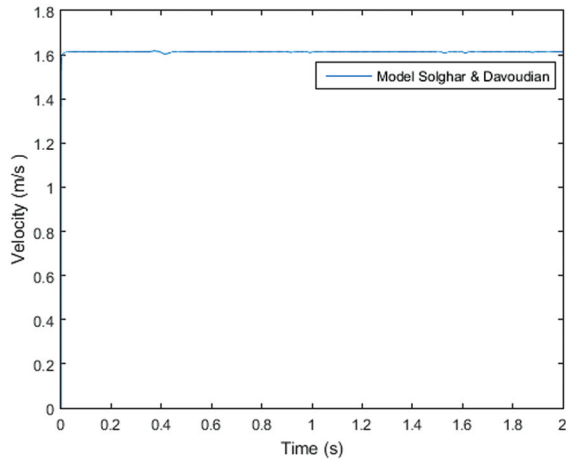


FIGURE 1. Velocity vs. time plot of model Solghar

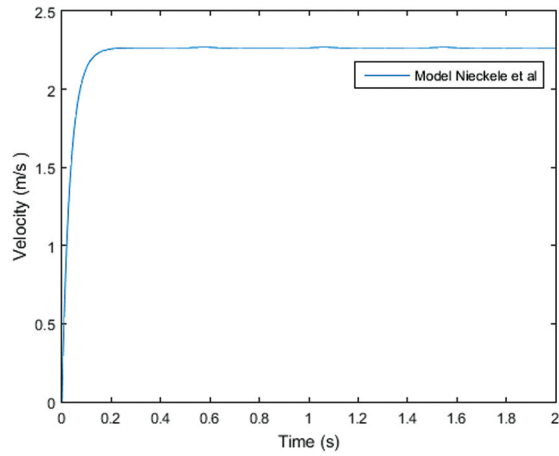


FIGURE 2. Velocity vs. time plot of model Nieckele

COMPARISON BETWEEN MODEL SOLGHAR AND MODEL NIECKELE

The model validation results show that both models can be used in modelling the other cases. For comparison, the data used for the modelling were compared with the experimental data, and calculation accuracy was determined by plotting the comparison results into graphs. The experimental work was conducted with bypass areas of 0%, 3% and 8% and under a pressure range of 6-7 bars. Table 3 shows the experimental parameters, and Table 4 presents the value of the set parameters for the modelling.

TABLE 3. Experimental parameters

Parameter	Value	Unit
PIG diameter	0.254	M
Volumetric flowrate	0.05	m ³ /s
Time	94	s

TABLE 4. Value of the set parameters

Parameter	Value	Unit
Mass	30	kg
Temperature	27	°C
Contact force	200	N
Density	4.8	kg/m ³

Table 5 shows the experimental data of captured velocity for various bypass areas of the PIG.

TABLE 5. Experimental data

Bypass (%)	Velocity (m/s)
0	1.30
3	0.65
8	Does not move

Figures 3-5 show the PIG velocity for models Solghar and Nieckele under bypass areas of 0%, 3% and 8%, respectively.

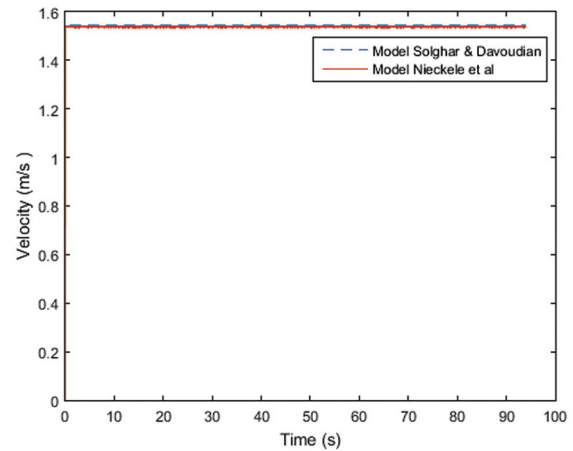


FIGURE 3. PIG velocity under a 0% bypass area

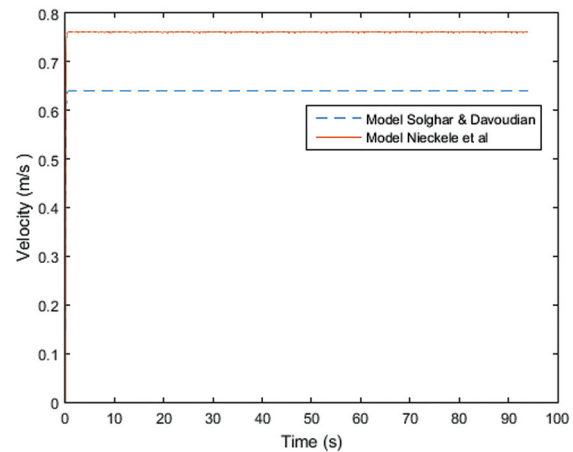


FIGURE 4. PIG velocity under a 3% bypass area

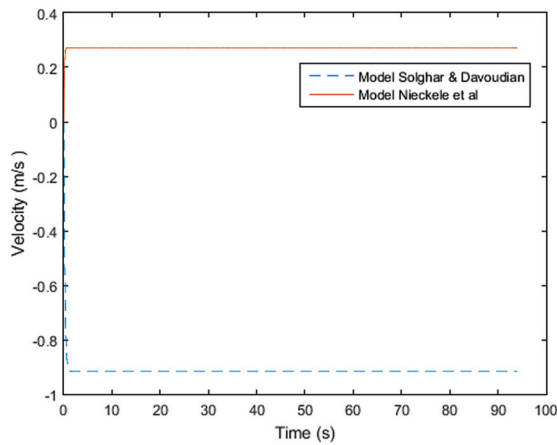


FIGURE 5. PIG velocity under an 8% bypass area

Compared with the mode Nieckele, model Solghar is more suitable due to its smaller relative error. Solghar has 10% relative error to the experimental data, whereas Nieckel has 12% for the 3% bypass area case. Meanwhile, in the 8% bypass area, Solghar shows a more accurate prediction similar to the experimental data, that is, the PIG does not move, whereas Nieckele shows a 0.25 m/s PIG velocity. However, in the 0% bypass area, both models predict the same velocity, which is 1.54 m/s. Table 6 shows the simulation results of PIG velocities at different bypass areas performed by models Solghar and Nieckele.

TABLE 6. Simulation results of PIG velocities at different bypass areas

Bypass area (%)	Velocity (m/s)	Velocity (m/s)
	Model Solghar	Model Nieckele
0	1.54	1.54
3	0.58	0.73
8	Does not move (negative value)	0.25

RELATIONSHIP BETWEEN BYPASS AREAS AND VELOCITY

The PIG velocity decreases along with an increasing bypass area. The PIG cannot move when the bypass area is extremely large. The negative velocity value indicates that the driving pressure is insufficiently high. Table 6 shows the relationship between bypass area and velocity.

The simulation data of models Solghar and Nieckele clearly show that the velocity decreases along with an increasing bypass area because of the decreasing pressure difference between the front and back of the PIG (Table 6). This pressure difference reaches its highest point when no bypass exists. The existence of a bypass allows a small stream flow between the front and back of the PIG and thus reduces the pressure difference.

RELATIONSHIP BETWEEN CONTACT FORCE AND VELOCITY

The deformation of the sealing disc generates a contact force that acts on the PIG. Having an oversized sealing disc, which has a size that is 102%-105% of the pipeline diameter (Winters 2014), increases the normal frictional force in the pipeline. Furthermore, increasing the diameter of the sealing disc intensifies the contact force. Figures 6 and 7 show the relationship between contact force and PIG velocity.

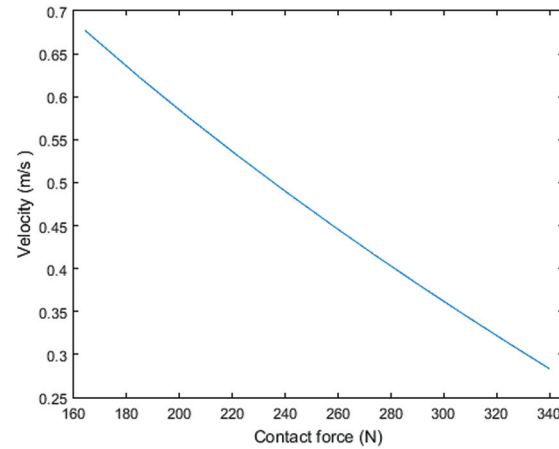


FIGURE 6. Relationship between contact force and PIG velocity in model Solghar

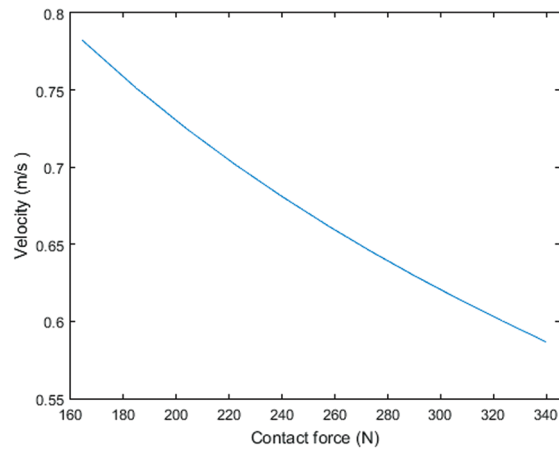


FIGURE 7. Relationship between contact force and PIG velocity in model Nieckele

Figures 8 and 9 illustrate the relationship of sealing disc diameter with contact force and PIG velocity in both models. The simulation results from the both models show the same characteristics, thereby indicating that increasing the sealing disc diameter intensifies the contact force yet reduces the PIG velocity. A great contact force affects the movement of the PIG after reacting in the opposite movement direction according to Newton’s third law of motion.

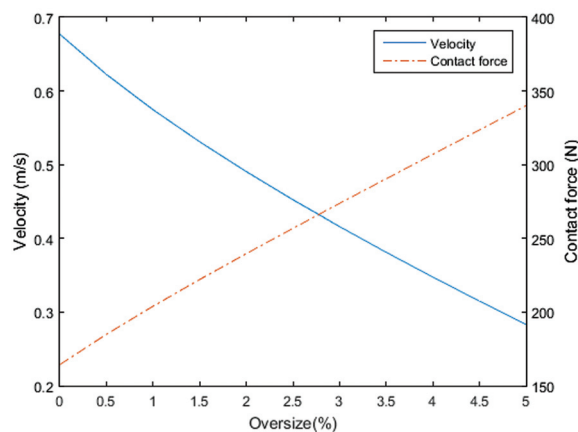


FIGURE 8. Relationship of sealing disc diameter with contact force and PIG velocity in model Solghar

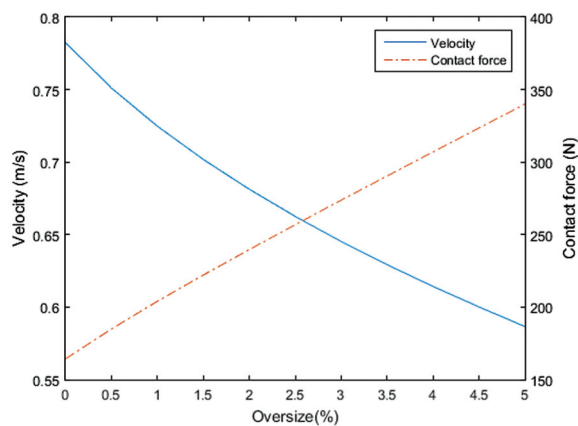


FIGURE 9. Relationship of sealing disc diameter with contact force and PIG velocity in model Niecekele

CONCLUSION

IGs show the best efficiency when moving at an optimum constant velocity. In this study, two models are constructed to calculate PIG velocity under different operating conditions. Modelling is performed on the basis of the findings of Solghar and Davoudian and Niecekele et al. Both models are subsequently compared with the experimental data with bypass areas of 0%, 3% and 8%. The modelling results indicate that model Solghar is more suitable than model Niecekele for the investigated operating conditions and parameters. Furthermore, increasing the bypass area results in the lowering of the movement speed of the PIG because of the decrease in the pressure difference. Meanwhile, a large sealing disc diameter corresponds to great oversize and contact force, both of which reduce PIG velocity.

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