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Numerical investigation of disk bypass pipeline inspection gauge with hole in disk

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ABSTRACT

Bypass Pipeline Inspection Gauges (PIGs) are widely employed as the most effective and economical devices for pipeline cleaning, maintenance, and inspection operations. The speed of these bypass PIGs significantly impacts the operational activities of pipelines. Very high or low PIG speeds may cause damage to the pipeline and the PIG itself. Therefore, it is important to control the speed of the PIG for better pigging operations. This study focuses on the influencing parameters and their impact on PIG speed. The approach of Computational Fluid Dynamics (CFD) has been utilized to model fully turbulent flow around a sample of a disk bypass PIG with a hole in the disk section for four different cases. PIG speed and pressure loss coefficient are measured to evaluate the effectiveness of the PIG. Meanwhile, two dimensionless groups are introduced based on the influencing design parameters for the movement of the disk bypass PIG, with and without a hole, to measure the optimal design parameters. The results show that a disk bypass PIG with a hole in the disk provides 5%-7% better results in terms of PIG speed and 6%-9% for the pressure loss coefficient around the PIG section. Among the four cases of a disk bypass PIG with a hole in the disk section, case-1 shows better pigging operation, with a dimensionless group value of 0.24. However, case-1 exhibits a 2.7%-22% reduction in PIG speed and a 12%-72% reduction in the pressure loss coefficient compared to other cases. Additionally, the lowest value of the presented dimensionless group indicates better pigging operation, and the optimal value of the dimensionless group is 0.24 for the design consideration of the PIG. This study holds directional significance for the design of the structural parameters of the PIG, which are useful for pipeline clean-up, inspection, and operational maintenance, and it provides reference value for related researches.

1. Introduction

Pipelines serve as the most efficient and economical means for transporting natural gas, crude oil, and chemical products. However, continuous operation leads to pipeline deterioration, potentially disrupting production if not properly maintained. Pigging operations, utilizing pipeline inspection gauges (PIGs), are standard in the oil and gas industries for regular maintenance, including cleaning, interior inspection, and dehydration. Installed using launchers, PIGs are driven by production fluid throughout the pipeline, performing various tasks until reaching the receiver station. Regardless of the operation's objective, maintaining a steady and moderate PIG speed is crucial. Optimal speeds typically range from 2 to 7 m/s for gas pipelines and 1–5 m/s for liquid pipelines. Excessive speeds can damage both pipelines and PIGs, underscoring the preference for lower travel speeds. Lower velocities have also been found to enhance cleaning and inspection performance. Consequently, analyzing and predicting PIG movement before operations is essential for estimating speed, position, and working conditions, aiding operators in controlling PIG speed and minimizing operational risks.

The utilization of a bypass PIG presents a potential solution for achieving lower PIG speeds without deferring production. Unlike traditional PIGs, a bypass PIG incorporates a bypass area, enabling fluid to flow around the PIG as it traverses the pipeline. This bypass flow mitigates the pressure differential across the PIG, consequently slowing its speed without affecting production rates. Given the significance of

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travel speed and pressure differentials in pigging operations, a comprehensive understanding of PIG speed and pressure drop, characterized by a pressure loss coefficient over the PIGs, is imperative for achieving optimal pigging performance.

Due to the potentiality of bypass PIG many experimental and numerical studies have been conducted to analysis the movement characteristics, performance, flow behaviors around the PIG, design consideration. Azevedo et al. [1] simplified and analyzed the hydrodynamic model for the bypass flow passing through the PIG wherein a simple hydrodynamic model was developed to predict PIG speed. Kohda et al. [2] and Boghi Andrea et al. [3]; Braga et al. [4] conducted an investigation on simulation of motion for bypass PIG through gas and liquid pipelines. The findings of these investigations were communicated, focusing on the movement of PIGs used in gas pipelines for drying or dehydrating during bypass flow. Kohda et al. [2] introduced a novel approach for examining the temporary occurrences resulting from pigging in gas-liquid two-phase flow. This method is also proficient in assessing the transient two-phase flow arising from alterations in pressure and flow rate. However, these prior studies were mainly focused on developing numerical model to investigate and predict the speed of PIG wherein design advancement, dimensionless groups and bypass opening percentages were not addressed as these parameters influence the pressure difference and fluid velocity around the PIG which is also affected the speed of PIG. Another similar numerical study by Nguyen et al. [5] showed the dynamic characteristics of PIG such as speed, position and gas flow of bypass PIG. They examined ideal gas, one-dimensional single-phase fluid flow through a horizontal pipeline wherein the coefficient of friction was identified in terms of Reynolds number, pipe wall roughness and compressible transient gas flow. Their proposed scheme for computation and numerically derived mathematical model has potentiality to estimate the velocity and position of bypass PIG. However, their study was not discussed about the design consideration, disk section, dimensionless groups and bypass opening percentages to enhance the performance of bypass PIG.

Static two-phase flow for conventional bypass PIG was studied by Singh, Henkes [6] using ANSYS FLUENT software. Their obtained results in terms of pressure drop coefficient showed consistency between numerical simulation and theoretical relations of Ref. Idelchik [7]. Disk bypass PIG which has a disk or deflector plate in front of nose section to control and reduce the fluid opening speed and PIG's speed was also investigated by Korban [8]; Lesani et al. [9]; McDonald, Baker [10]; Money et al. [11]; Nshuti [12]; Rabby et al. [13]; Rafat et al. [14] and Hendrix et al. [15]. Two types of PIG conventional and disk bypass PIG were analyzed by Korban [8] by using a two-dimensional static-state axisymmetric model. Flow behavior around the PIG section and correlation between governing parameter and pressure loss coefficient were also studied which has potentiality to predict the PIG speed. Design consideration and dimensionless group analysis of conventional and disk bypass PIG were not reported by Korban [8] properly. Followed to Korban [8], Xiaoyun Liang [16] performed a CFD analysis for disk PIG, conventional PIG and complex PIG. Three dimensional models for complex PIG and multi-phase condition were also studied. Xiaoyun Liang's [16] results presented a correlations of pressure loss coefficient and dimensionless group analysis based on the bypass area fraction of PIGs for all considered types. However, Korban [8] and Xiaoyun Liang [16] introduced disk bypass PIG and correlation for pressure loss coefficient but fluid velocity around the disk bypass PIG and design parameters were not reported properly. Boghi Andrea et al. [3] studied on two-phase three-dimensional model for pigging system of wax transport in a horizontal pipeline. They developed a mathematical model to couple the PIG and the wax-in-oil slurry dynamics. Their results showed that the acceleration of PIG is proportional to the square of the relative velocity for mixture. Moreover, this study identified that bypass PIG is more efficient compared to normal sealing PIG in deterring plug formation. Additionally, this study also reported that the 3D fields show advantage for wax distribution over each section of pipe section whereas the previous studied 1D model cannot properly distinguish between wax and deposited. Hendrix et al. [15] conducted an experimental and modeling study on bypass-PIG under the condition of low-pressure wherein the experimental results were used to validate their simplified 1D PIG dynamic model. Their identification referred that the average PIG speed can be properly predicted by calculating the differential pressure over the by-pass section with the well-known correlation of Idelchik [7] and the friction between the wall of pipe and the PIG with a constant value. They also reported that under the condition of low pressure the PIG motion provides oscillatory motion with high velocity excursions of PIG due to accumulation of gas that may create behind the PIG. However, to reduce these velocity excursions they used PD controller which provides positive outcomes. To identify bypass PIG's movement characteristics, pressure fluctuation, instantaneous and average PIG speed and liquid volume of PIG generation with different bypass fraction were studied for an experimental typical pigging system with horizontal, riser and up-and-down pipeline structures. Results plotted from this study refers multiple peaks in the curves of pressure fluctuation wherein each peak indicates pause state for PIG. Moreover, they reported that bypass PIGs exhibit superior adaptability compared to conventional PIGs in handling peak pressure fluctuations, and they also demonstrated a capacity for reducing liquid loading generated by PIGs. Their research specifically concentrated on bypass PIGs in low-pressure conditions, neglecting considerations for factors such as disk bypass PIGs, dimensionless groups, and bypass opening percentages. Malihe and Mansour, [17] studied on bypass PIG for inspection purpose by using sliding control numerically in MATLAB software for two cases. Results refer that used sliding mode controller have the ability to maintain the speed of PIG perfectly steady at desired range during the movement of PIG through the gas pipelines. Only speed of bypass PIG was investigated, but design consideration, pressure loss coefficient, bypass opening percentages and dimensionless group were not studied in their study. Beginning of 2020, an infrared ray-based bypass PIG speed detection approach was proposed by Chen et al.[18]. They applied

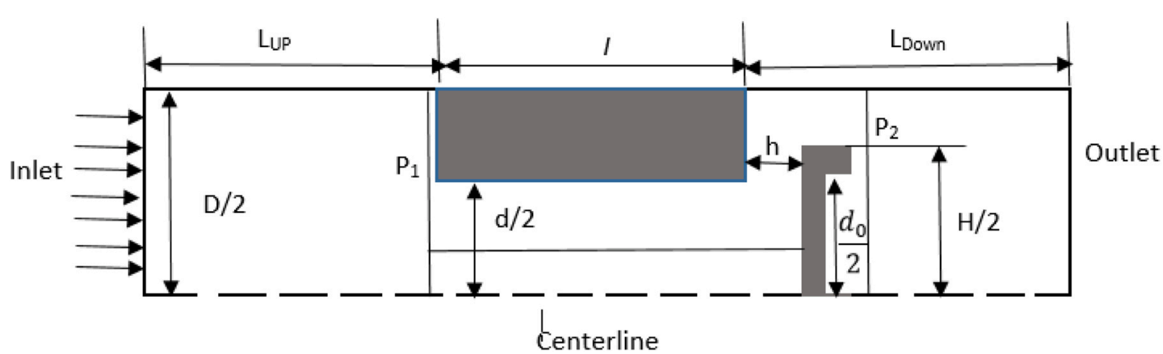


Fig. 1. Geometry of disk bypass PIG with hole.

Table 1
Common Parameters for Disk Bypass PIG with and without hole (provided by Eureka Efektif Snd. Bhd.).

Parameters	Disk Bypass PIG with and without hole
Pipe Diameters $\boldsymbol{D}$ ($\boldsymbol{mm}$)	274 mm
Horizontal Bypass PIG Diameter $\boldsymbol{d}$ ($\boldsymbol{mm}$)	92 mm
Upstream Pipe Length $\boldsymbol{L_{up}}$ ($\boldsymbol{mm}$)	5 D
Downstream Pipe Length $\boldsymbol{L_{down}}$ ($\boldsymbol{mm}$)	20 D
Horizontal Bypass Length $\boldsymbol{l}$ ($\boldsymbol{mm}$)	460 mm
Disk thickness $\boldsymbol{T}$ ($\boldsymbol{mm}$)	25 mm
Disk's diameter, H ($\boldsymbol{mm}$)	140 mm
Bypass opening percentages/ sleeve length ($\boldsymbol{h}$)	$5\%, 7.5\%, 10\%, 12.5\%$ *and* 15%

Table 2
Dimensionless group for various cases of disk bypass PIG (based on Eureka Efektif Snd. Bhd.).

Cases	Dimensionless group $= \frac{dl}{D^2}\frac{d_o}{H}$ and $\left(\frac{d}{D}\right)^2\frac{l}{h}$
1	0.24
2	0.44
3	0.68
4	0.75

a model of quasi-steady state bypass PIG to validate their developed experimental prototype. Obtained results report linear variation of average PIG velocity with gas flow rate wherein the variation of gas-to PIG speed remains constant for same bypass fraction. Moreover, bypass fraction's existence reduces PIG speed effectively and also alleviates PIG fluctuation. Additionally, calculated results from the developed infrared ray-based model are in good agreement with experimental data. [19] presented a numerical and experimental case study with computational fluid dynamics (CFD) method to develop turbulent flow model for bypass PIG with disk to measure dynamic velocity. The impact of parameters on differential pressure of bypass PIG was also determined to identify the optimal parameters for PIG designing. Apart from these studies, [20-28] also worked on pigging system to facilitate the pigging operation in oil and gas sector. These studies were not investigated the effect of hole in disk bypass PIG and a simplified dimensionless group instead of using multiple groups to enhance the pigging performance. Additionally, the recent studies on fluid mechanics mainly focused on nanofluids [29–33,15,34–37], impact of flowing geometries [38,39], flow characteristics of airfoil (Rafat et al., [40]), cross flow [41,42] and artificial neural networks in fluid mechanics [43,44] where study on flow characteristics of pipeline inspection gauge is limited.

The discussed literature highlights the importance of a bypass pigging system in the oil and gas industry. However, most of the literature focuses on the development of mathematical or numerical models, speed control systems, and the dynamic movement characteristics of bypass PIGs. Detailed knowledge regarding design considerations, the impact of various parameters, dimensionless groups of pipes and PIG movement characteristics has not yet been thoroughly explored in the literature. Only a few studies have examined the diameter of the bypass section, bypass fraction, and size of the deflector plate, and these were limited to one or two cases. Furthermore, there is a scarcity of studies on bypass PIGs with disks, and none have analyzed the impact of a hole section in the middle of the disk. Meanwhile, there is still a need for design improvement and performance evaluation of PIGs for effective pigging operations. To address this need, we investigated the performance of a new design in terms of PIG speed and pressure loss coefficient over the PIG section. We considered four cases with different dimensions of the disk PIG with a hole in the disk section. These cases are represented by two dimensionless parameters for the disk PIG with and without a hole, which refer to the ratio among PIG diameter, PIG length, pipe diameter, and disk diameter (detailed formulas are provided in the methodology section). Moreover, we examined the effect of bypass opening percentages on the disk bypass PIG with a hole to identify the most effective opening percentage in terms of pressure loss coefficient and PIG speed at the bypass opening section. Therefore, the objectives of this study are to:

1) Effect of hole in disk on PIG speed and pressure loss coefficient (with hole vs without hole)

2) Effect of dimensionless parameter and bypass opening percentage on PIG speed and pressure loss coefficient.

2. Methodology

2.1. Governing equations

For current CFD model of bypass flow through PIG has conducted by applying few governing equations in fluent which are presented herewith.

2.1.1. Navier-stokes equations

The governing equations for the movement of viscous fluids are typically represented by the Navier-Stokes equations, derived from the second law of Newton concerning fluid motion. Nevertheless, in the case of incompressible Newtonian fluids, the commonly employed Navier-Stokes equations are presented as:

$$\rho\left(\frac{\partial u}{\partial t}+u.\nabla u\right) = -\nabla P+\mu\nabla^2 u+f \tag{1}$$

where u is the velocity vector in x, y and z direction (u, v and w); ρ refers the fluid density; μ is the viscosity of the fluid; P is the fluid pressureand f refers the body forces. Additionally, the continuity equation is as follows:

$$\nabla.u = 0 \tag{2}$$

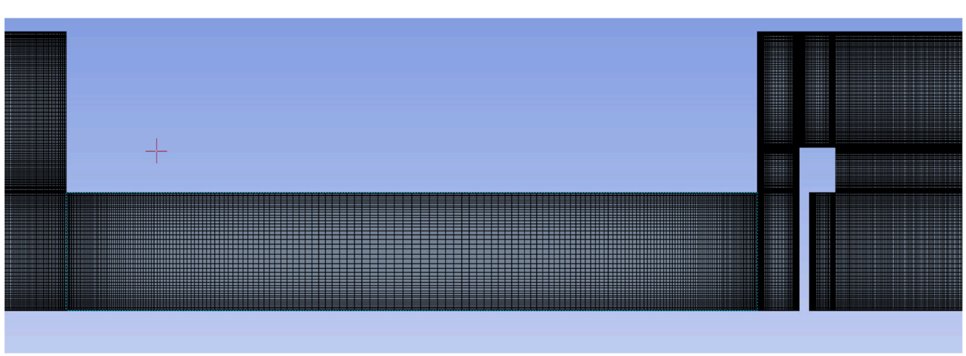


Fig. 2. Mesh at ANSYS FLUENT for 10% bypass opening percentages of disk bypass PIG with hole in disk.

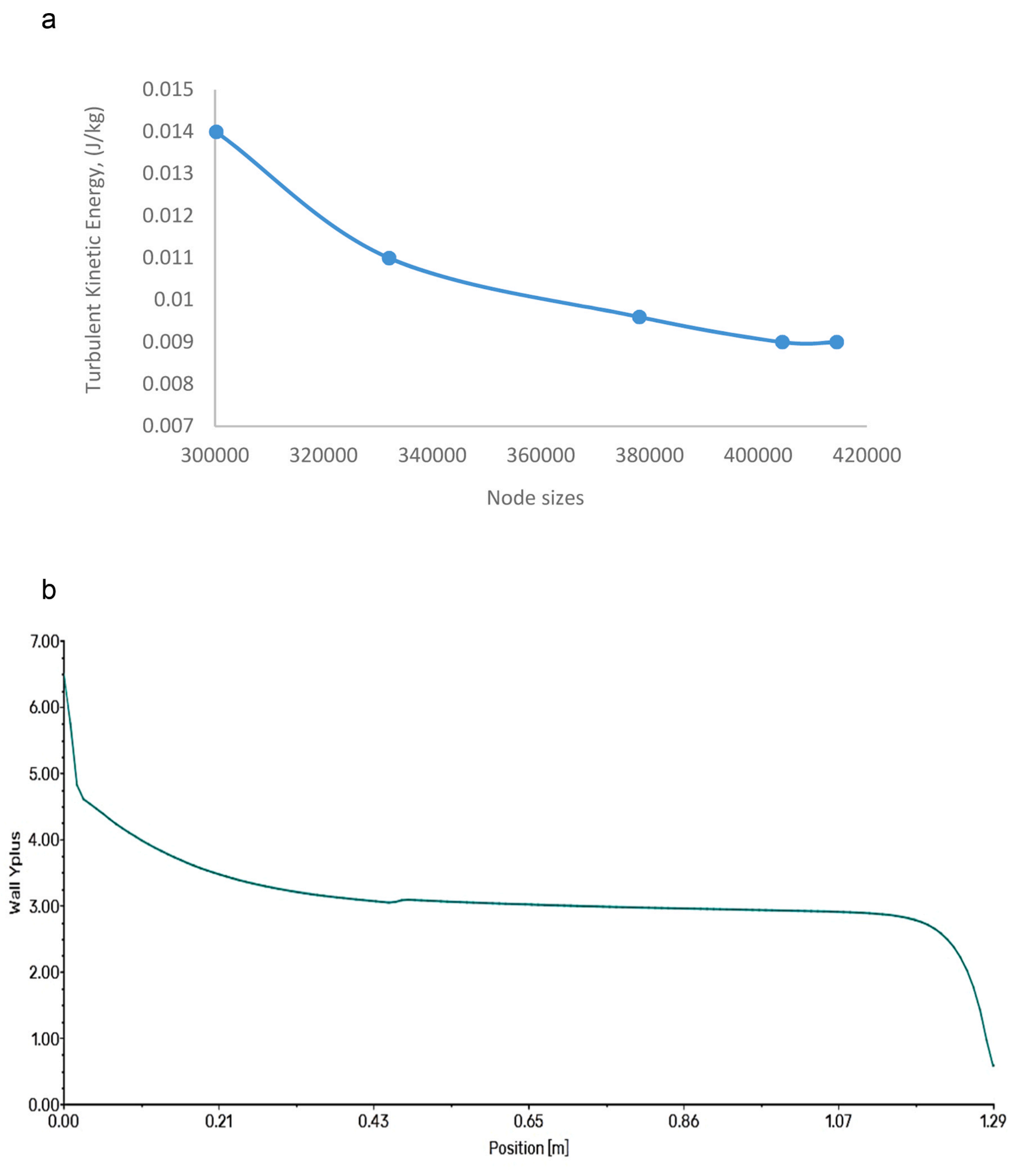


Fig. 3. (a) Comparison of velocity at bypass opening section for different grid size of disk bypass PIG with hole for 10% opening parentage and (b) The Y plus value for upstream wall.

2.1.2. The $\mathbf{k}-\epsilon$ *turbulence model*

Boussinesq eddy viscosity equation is as follows.

$$-\rho\overline{u_i'u_j'} = \mu_i\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \frac{2}{3}\rho k\delta_{ij} \quad (3)$$

Wherein $k = \frac{1}{2} \quad u_i'u_j'$ is referred as turbulent kinetic energy, μ_i stands for turbulent viscosity, and $k\delta_{ij}$ refers to Kronecker delta.

$$\mu_i = \rho C_\mu \frac{k^2}{\epsilon} \quad (4)$$

However, the transport equation for turbulent kinetic energy is as follows:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho c - Y_M + S_k \quad (5)$$

here, G_k refers the turbulence kinetic energy production amount for the actual gradients of velocity; G_b refers the turbulence kinetic energy generation amount because of the buoyancy force, which is zero for current study and the fluctuating dilation is referred as Y_M refers the compressible fluid.

$$G_k = \quad -\rho\overline{u_i'u_j'}\frac{\partial u_j}{\partial x_i} \quad (6)$$

Furthermore, the transport equation for turbulence dissipation rate is as follows:

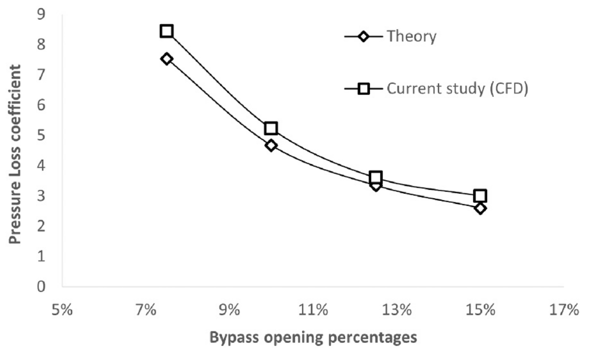


Fig. 4. Variation of Pressure Loss coefficient between CFD model and theory.

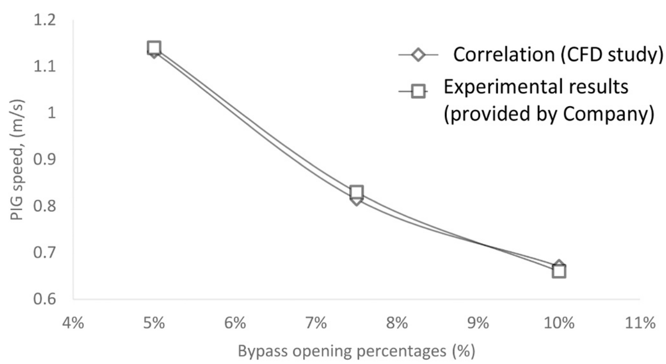


Fig. 5. Comparison between PIG speed by using developed correlation and experimental data from Eureka Efektif Sdn. Bhd. for different bypass opening percentage of disk bypass PIG with hole in disk.

Table 3
Variation of PIG speed for different bypass opening percentages between developed correlation and experimental results.

Bypass opening percentages	PIG speed (m/s)		
	Developed correlation (CFD results)	Experimental result by Eureka Efektif Snd. Bhd.	Error (%)
5%	1.131765	1.14	0.70
7.50%	0.814779	0.83	1.81
10%	0.671021	0.66	1.67

$$\frac{\partial}{\partial t}(\rho\epsilon)+\frac{\partial}{\partial x_i}(\rho\epsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial\epsilon}{\partial x_j}\right]+\rho C_1 S_\epsilon-\rho C_2\frac{\epsilon^2}{k+\sqrt{\nu\epsilon}}+C_{1\epsilon}\frac{\epsilon}{k}C_{3\epsilon}G_b+S_\epsilon \tag{7}$$

$$C_1=\max\left[0.43,\frac{\eta}{\eta+5}\right],\eta=S\frac{k}{\epsilon}\ and\ S=\sqrt{\frac{1}{2}(\frac{\partial U_j}{\partial x_i}+\frac{\partial U_i}{\partial x_j})^2}$$

$C_{1\epsilon}$, $C_{2\epsilon}$ and $C_{3\epsilon}$ are constants, σ_k and σ_ϵ are the turbulent Prandtl numbers for k and ϵ respectively. S_k and S_ϵ are user-defined source terms. For the model of realizable $k-\epsilon$ the value for these constants are followed.

$C_{1\epsilon}$=1.44, $C_{2\epsilon}$=1.92, $C_{3\epsilon}$=0.09, σ_k=1.0 and σ_ϵ=1.3

2.1.3. Fluid dynamics properties of PIG

Bypass PIG motion inside a pipe is usually calculated by using force balance between frictional force F_{fric} and driving pressure force F_P which represents as $F_P = \Delta PA$ where ΔP is the differential pressure and A is the cross-sectional area of pipe. However, the differential pressure is normally characterized as Pressure Loss coefficient K which is expressed as

$$K=\frac{\Delta P}{\frac{1}{2}\rho_{bp}U_{bp}^2} \tag{8}$$

where, U_{bp} is the fluid velocity at bypass section relative to PIG speed.

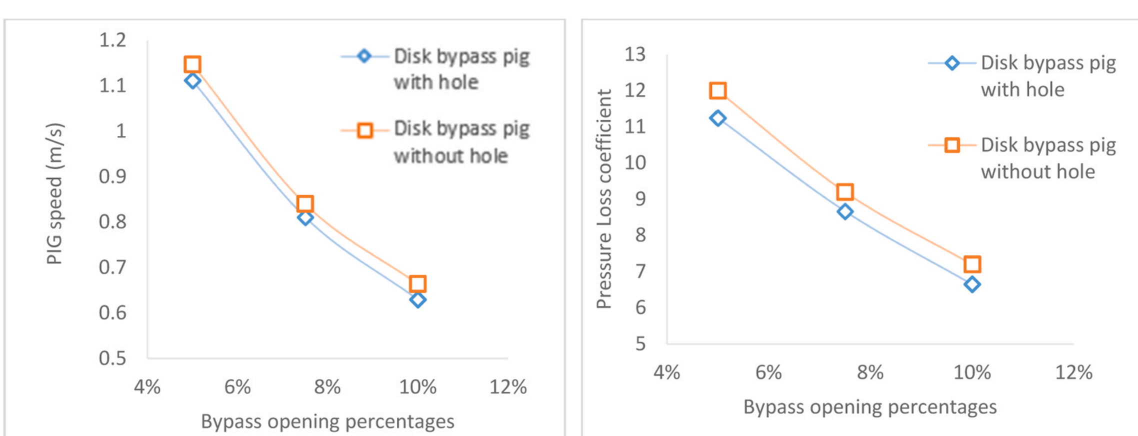
The usual approach involves applying an equation of force balance to determine the movement of the PIG in conjunction with fluid flow through the pipeline. This equation is outlined as follows:

$$m\frac{dV_{pig}}{dt}=(P_1-P_2)A-mg\sin\theta-F_c \tag{9}$$

where, m and V are the mass and velocity of the PIG, respectively, P_1 and P_2 express the pressure at each side of the PIG and F_c is the axial contact force acting on PIG with the inside surface of the pipe known as the contact force.

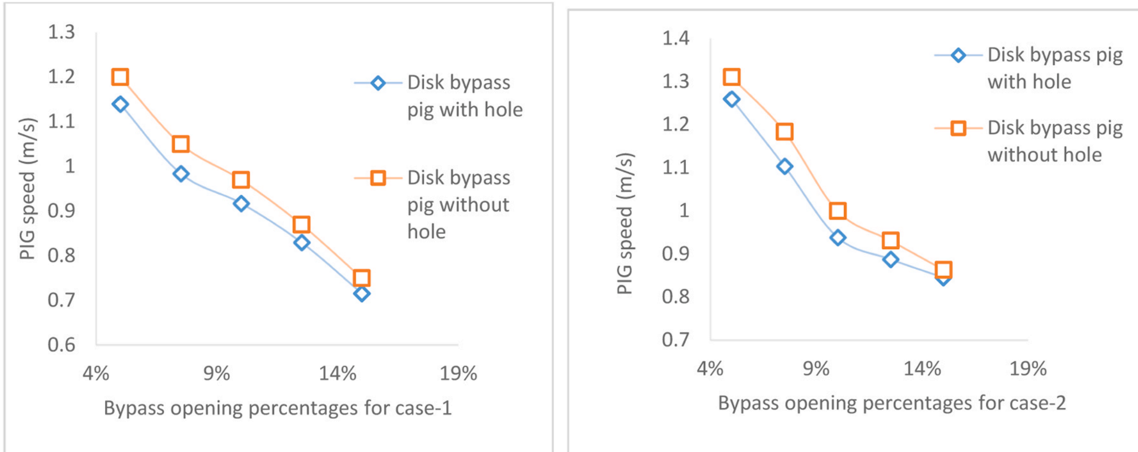
2.1.4. Initial and boundary conditions

This study introduces a Computational Fluid Dynamics (CFD) model of a disk bypass pig. To investigate the PIG speed and differential pressure, turbulent steady-state flow through a 2D axisymmetric pipe with a bypass disk PIG section is depicted in Fig. 1. The parameters for the geometry and fluid are detailed in Section 2.2. Boundary conditions included a constant outlet pressure at the outlet and a constant velocity at the inlet. A stationary wall with a no-slip condition was applied for the boundary condition of the pipeline's wall, PIG, and disk. The bypass disk



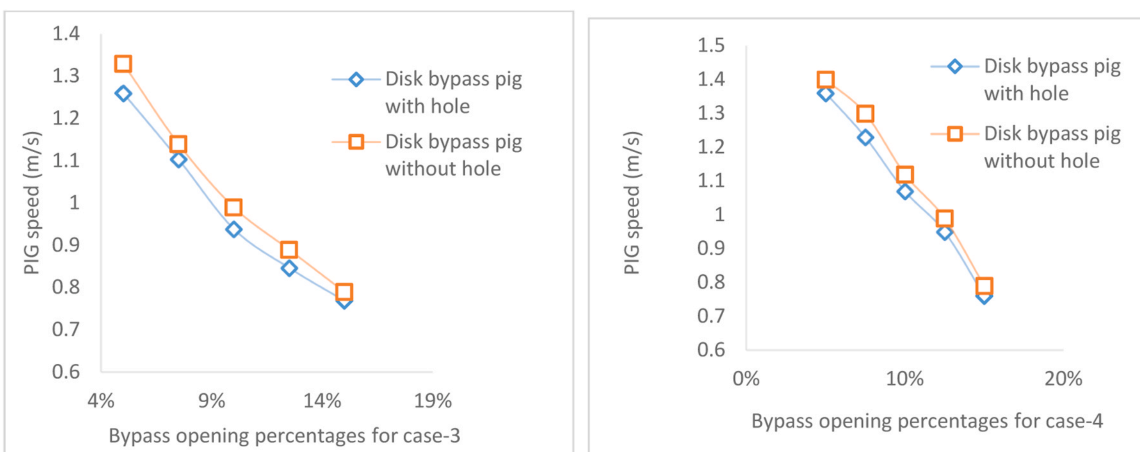
(a) (b)

Fig. 6. Effect of hole in disk of bypass PIG on (a) PIG speed (m/s) and (b) Pressure Loss coefficient.



(a) (b)

Fig. 7. Effect of hole in disk on PIG speed for (a) case-1 and (b) case-2.



(a) (b)

Fig. 8. Effect of hole in disk on PIG speed for (a) case-3 and (b) case- 4.

PIG was assumed to be stationary inside the pipeline for simulation purposes. Additionally, it was assumed that the downstream and upstream flows were fully coupled by the PIG.

In Fig. 1, *D* is pipe diameters, *d* is horizontal bypass PIG diameter, L_u is upstream pipe length, L_{down} is the downstream pipe length, l is the horizontal bypass length, *H* the is disk diameter, *T* the is disk thickness, d_0 is the disk's hole diameter and *h* is the distance between disk and PIG body which is also referred as bypass opening percentages.

The fluid in the pipeline is a single-phase gas; ii) The gas is ideal gas; iii) The gas is incompressible through the bypass port; iv) The PIG moves under a steady state; v) The stiffness of the pipeline is large enough to keep the diameter unchanged during pigging.

2.2. Parameters

The parameters for disk PIG with is prescribed in Table 1. Table 1 prescribes all the parameters which are same for both geometries. Between these two geometries the difference is that disk PIG with hole have Disk's hole diameter (d_0) and distance of disk's hole from disk's top (s) which are 92 mm and 24 mm. Water was considered as flowing fluids over the pipeline at room temperature.

2.3. Dimensionless group

The considered dimensionless groups to optimize the potential PIG performance in pipeline for this study is as follow:

Dimensionless group $\frac{dl}{D^2}\frac{d_0}{H}$ for disk bypass PIG with hole and $\left(\frac{d}{D}\right)^2\frac{l}{h}$ for disk bypass PIG without hole

wherein, pipe diameter is *D* (*mm*), horizontal bypass length is *l* (*mm*), disk diameter is *H* (*mm*), disk's hole diameter is d_0 (*mm*). For disk bypass PIG with hole, the first part of the dimensionless group represents ratio between PIG's diameter and horizontal length with main pipe's diameter whereas second part represents ratio between disk's hole diameter and disk diameter. In general, first part represents relationship between PIG and main pipe and second part represents relationship between disk and disk hole. While for disk bypass PIG without hole, first part represents relationship between PIG and main pipe and second part represents relationship between disk and PIG.

The specified parameters are used to optimize the dimensions of the PIG for the purpose of the PIG performance in future sections.

However, the value of dimensionless group for all case are prescribed

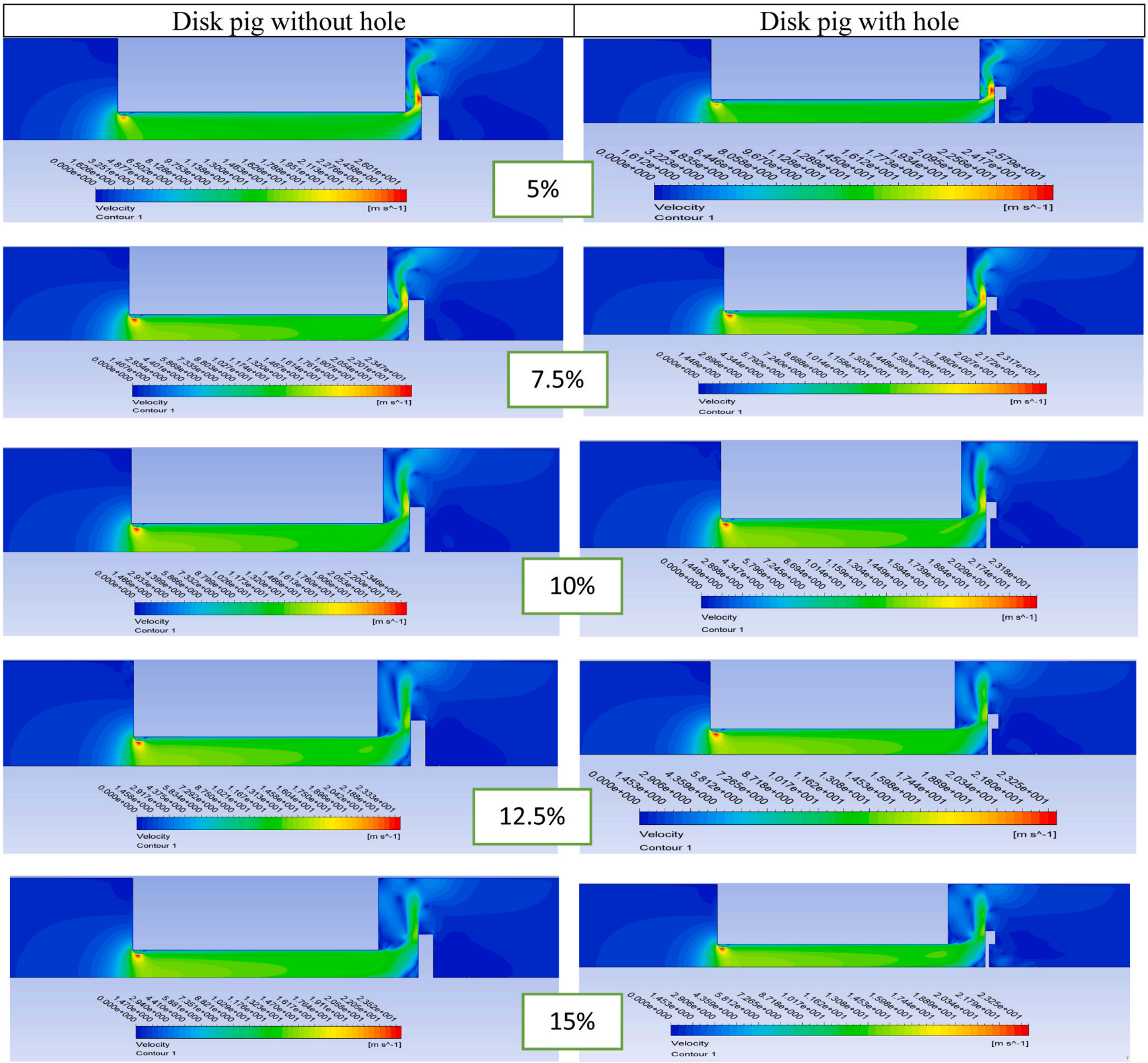


Fig. 9. Velocity contour of case-1 for disk bypass PIG without hole and with hole.

in Table 2 wherein case-1 shows lowest value and case-4 shows highest value. The 1st part of the dimensionless group represents the aspect ratio among pipe's diameter, PIG's diameter and length whereas 2nd part represents aspect ratio between the diameter of disk and disk hole. Compared to pipe's diameter, the suitable length and diameter of PIG will be identified by the 1st part and compared to disk diameter, the suitable diameter of the disk hole will be identified by using the 2nd part.

2.4. *Grid independency test*

Five different grid sizes were applied and tested to analysis the effect of fluid velocity at bypass opening section for 10% opening percentage of disk PIG with hole in disk section. From result it is emphasized that there is no significant difference among the results from four grid sizes which have shown at Fig. 3a. Beyond all the grids Grid 3, 4 and 5 provide almost similar results of turbulent kinetic energy; therefore, for this present study the grid size 414456 has been used for all simulation. The mesh applied in this study is shown in Fig. 2. The Y plus value for the upstream wall is illustrated in Fig. 3b, denoting the distance from the first grid cell to the surface. Given that turbulent flow fully develops on the upstream side of the computational model, the Y plus value is measured at this location. The Y plus value ranges from 1 to 7, indicating the high accuracy of the numerical model.

2.5. *Validation*

Numerical model justification is performed by validation with theoretical or experimental studies. The current numerical study was validated against theory of pressure loss coefficient and experimental data of PIG speed provided by Eureka Efektif Sdn. Bhd.

2.5.1. *Validation against theory*

For validation, the pressure loss coefficient theory for the disk bypass PIG, as formulated by Xiaoyun Liang [16], was considered. The pressure loss coefficient was computed using the current CFD model and

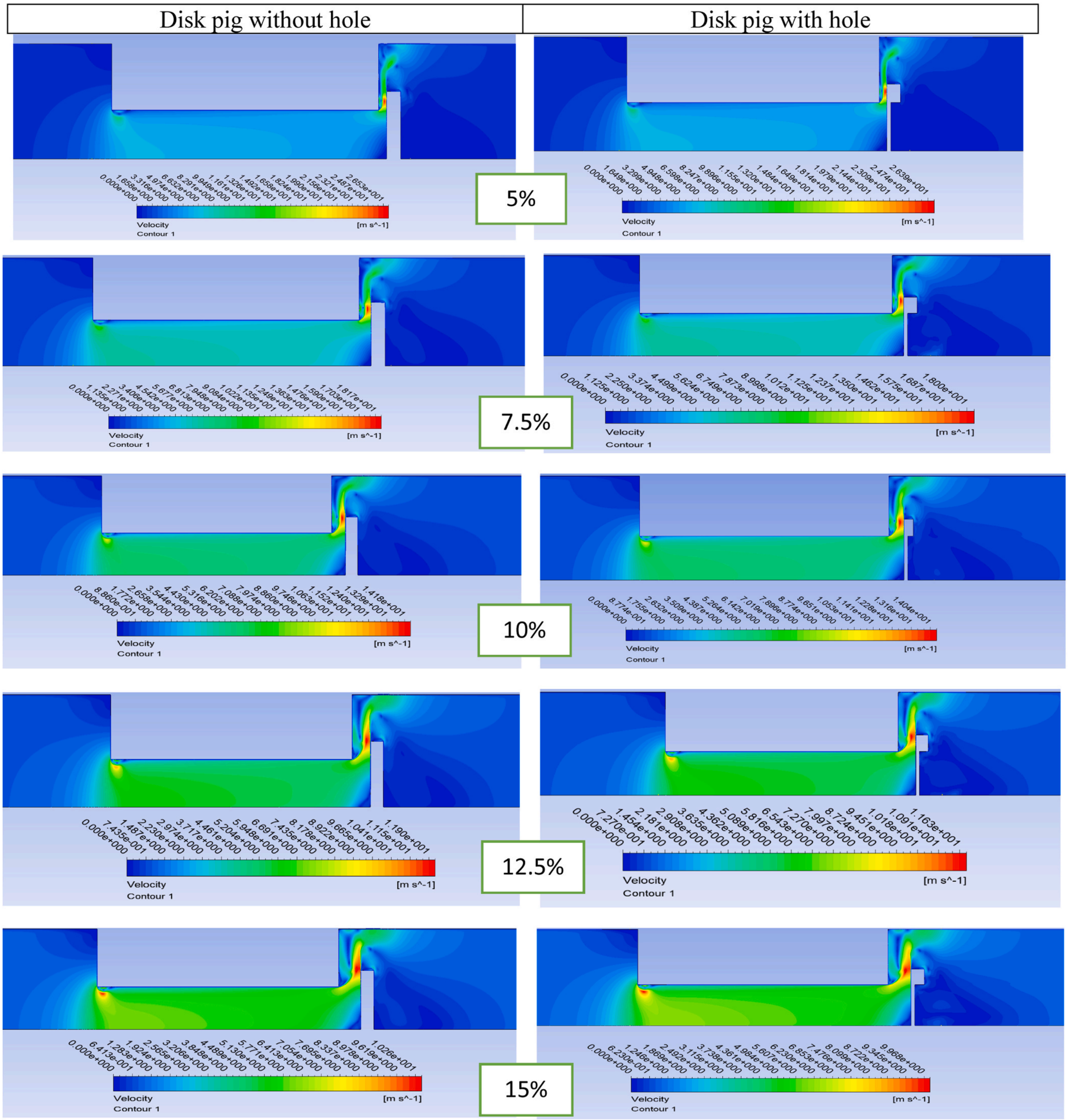


Fig. 10. Velocity contour of case-2 for disk bypass PIG without hole and with hole.

compared with the theoretical outcomes. The representative fluid chosen for the analysis was butane, with bypass opening percentages of 7.5%, 10%, 12.5%, and 15% at room temperature. The findings, illustrated in Fig. 4, reveal commendable agreement between the pressure loss coefficient obtained from the current CFD study and the theoretical values, with a maximum deviation below 10%. The equation governing this relationship is as follows:

$$K_{dp}' = 0.5\left(1-\frac{d^2}{D^2}\right)^{3/4} + 2\frac{H}{d} + \frac{0.155d^2}{h^2} - 1.85 \tag{10}$$

where, K_{dp}' is the pressure loss coefficient. Additionally, D, d, h and H present the diameter of main pipe, diameter of bypass section, distance of disk from PIG body and height of disk, respectively.

2.5.2. *Validation against experimental results*

For this purpose, PIG speed from current CFD model was validated against experiment results provided by Eureka Efektif Sdn. Bhd. To validate against experimental results, a correlation was developed for determining PIG speed of disk bypass PIG with hole in disk by using experimental data and curve fitting of data method since proper correlation or method to determine PIG speed for this type of PIG is not available in literature yet. Water with 5%, 7.5% and 10% bypass opening percentage was applied for experimental work. The results are

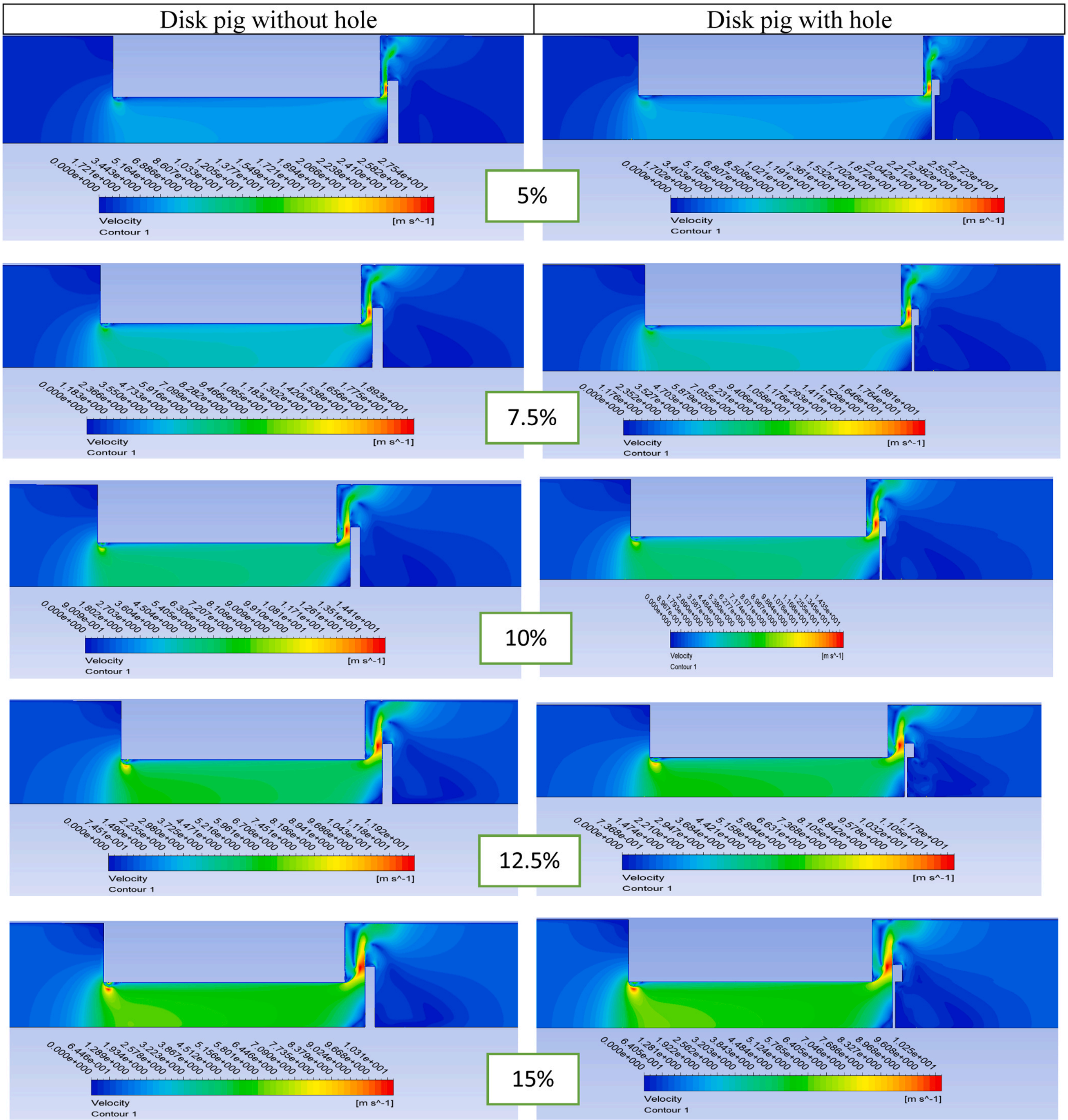


Fig. 11. Velocity contour of case-3 for disk bypass PIG without hole and with hole.

presented in Fig. 5 and Table 3, which refer that PIG speed from correlation by using CFD results showed good agreement against experiment results within maximum 1.81% error. Therefore, to calculate PIG speed for disk bypass PIG with and without hole at disk, the developed correlation can be applied appropriately. The correlation for PIG speed is as follow-

$$v_{PIG} = v_{BP} - \left(\frac{d}{D}\right)^2 \times \left(\frac{h}{H}\right) \times \frac{1}{2} \sqrt{\frac{\rho}{2 \times \Delta p}} \tag{11}$$

Here, v_{PIG} is the PIG speed, v_{BP} is the fluid velocity at bypass section, D is pipe diameters, d is horizontal bypass PIG diameter, H the is disk diameter, h is the distance between disk and PIG body which is also referred as bypass opening percentages, Δp is the differential pressure and ρ is the density.

3. Results and discussion

3.1. Effect of hole in disk on PIG speed (with hole vs without hole)

The bypass PIG with a hole in the disk and without a hole in the disk were compared based on PIG speed and pressure loss coefficient, as shown in Fig. 6. The PIG speed for the disk bypass PIG with and without a hole in the disk was calculated using the developed correlation of PIG speed in section 2.5.2. The results from Fig. 4 indicate that the presence

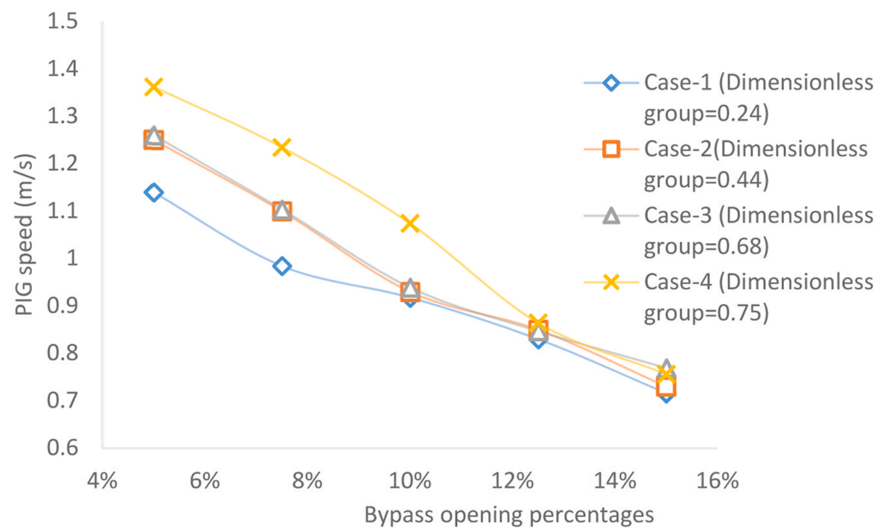


Fig. 12. Effect of bypass opening percentages to PIG speed (m/s) for all cases.

Table 4
PIG speed reduction percentages (%) for disk PIG with hole from without hole for all case.

Bypass opening percentages	Fluid velocity reduction percentages (%) at V_3 for disk PIG with hole			
	case-1	case-2	case-3	Case-4
15%	7.334337	4.853129	2.064269	3.797468
12.50%	4.57575	4.482717	4.640912	3.90625
10%	3.172095	5.250597	6.077792	3.603604
7.50%	2.407228	3.921569	6.747829	3.030303
5%	1.648722	3.28125	3.86608	2.857143

of a hole in the disk reduced the PIG speed by 5–7% and the pressure loss coefficient by 6–9%. Meanwhile, with the increase of bypass opening percentages, PIG speed also decreased gradually. Generally, at the bypass section, pipeline fluids suddenly pass through a smaller area, which results in an increase in fluid velocity and a decrease in pressure. Based on Bernoulli's principle, at a constant flow rate, a smaller flow passing region provides more drastic fluid flow at the inlet and outlet valve, causing the fluid to generate more energy loss as it passes through the bypass valve, thus producing a larger pressure drop. The pressure difference created due to sudden contraction helps to drive the PIG through the pipeline. In the meantime, the disk in front of the bypass opening section acts as a barrier and obstacle for fluids, which reduces the fluid velocity at the bypass opening section. This reduction in fluid velocity at the bypass opening section also results in a reduction in PIG speed. Moreover, the presence of a hole in the disk creates a recirculation zone and vortices at the bypass opening section, which reduces PIG speed by affecting the differential pressure. Therefore, it can be said that to control and reduce the high velocity of fluid, the use of a disk in front of the opening section helps the fluid as well as the PIG to reduce the speed to a certain level. Instead of using a plain disk, a rough disk containing a hole is modeled, which provides better outcomes to reduce the speed of the PIG by affecting the differential pressure and opening velocity of fluids. Moreover, higher bypass opening percentages also help to reduce fluid velocity at the bypass opening section and pressure loss coefficient.

To observe the consistency of better performance in terms of PIG speed for the disk bypass PIG with a hole compared to without a hole, four different cases are considered. The obtained results for the PIG speed of the four cases are presented in Figs. 7 and 8. The results showed that for all cases, the disk PIG with a hole provided more reduction in PIG speed compared to the disk PIG without a hole for all considered bypass opening percentages. Because of the hole section in the disk, the velocity of the fluid at the bypass opening section encounters some obstruction, which reduces the pressure and velocity of the fluid at the

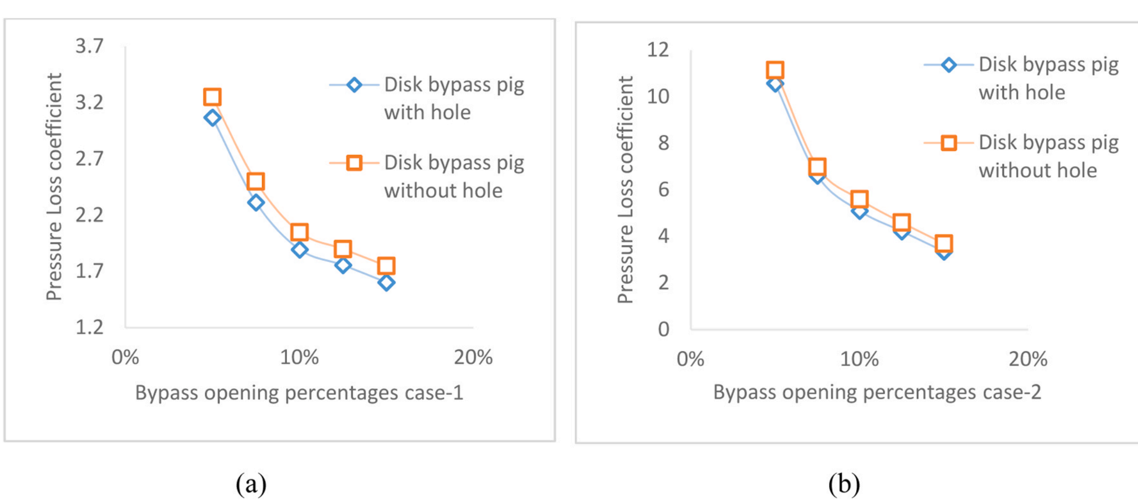
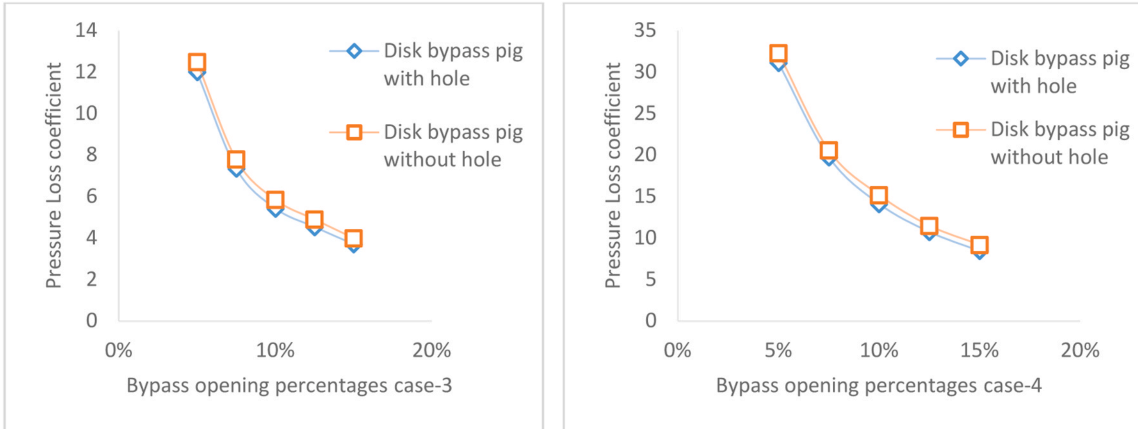


Fig. 13. Effect of hole in disk of bypass PIG on Pressure Loss coefficient for (a) case-1 and (b) case-2.



(a) (b)

Fig. 14. Effect of hole in disk of bypass PIG on Pressure Loss coefficient for (a) case-3 and (b) case-4.

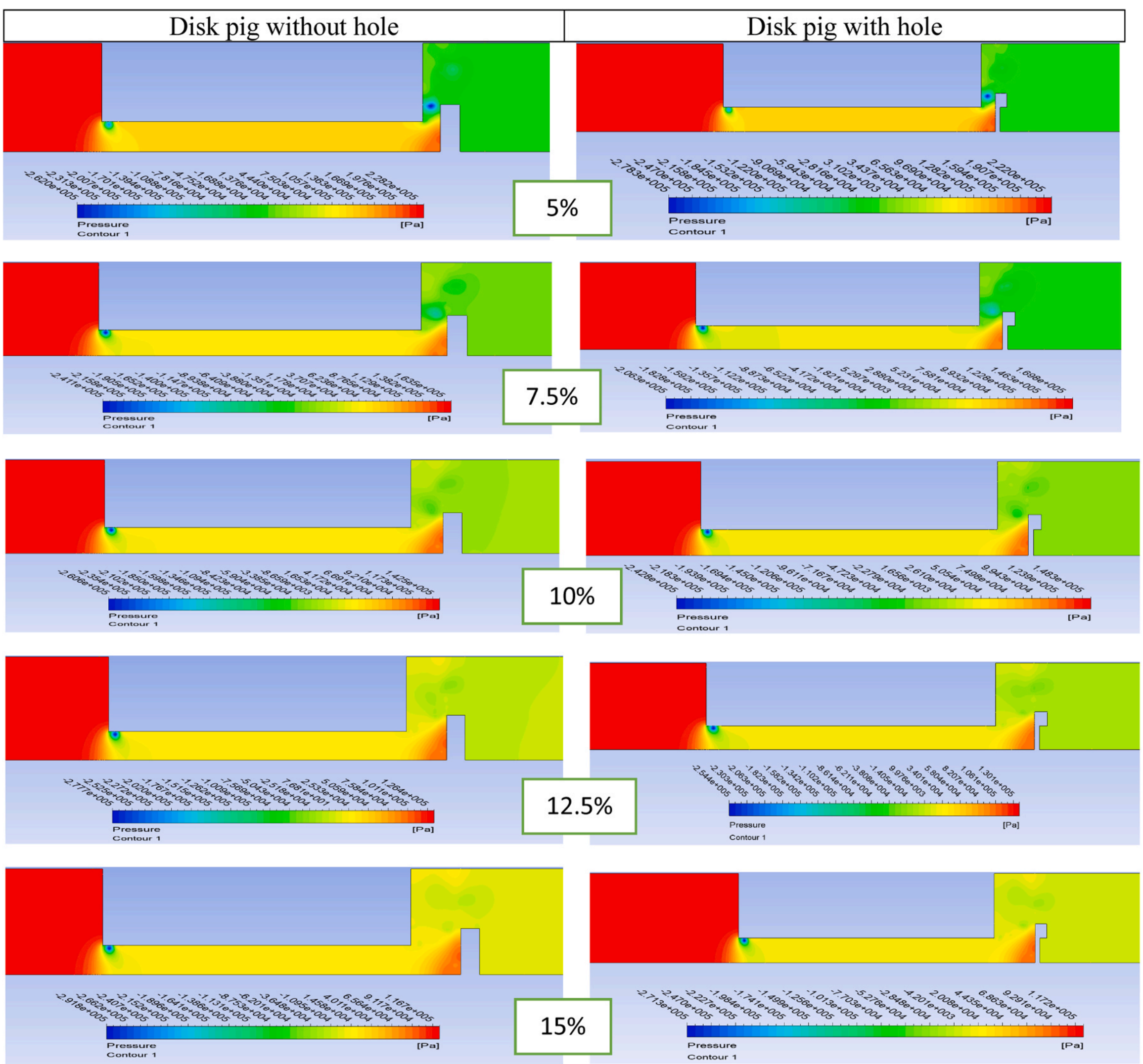


Fig. 15. Pressure contour of case-1 for disk bypass PIG without hole and with hole over bypass section.

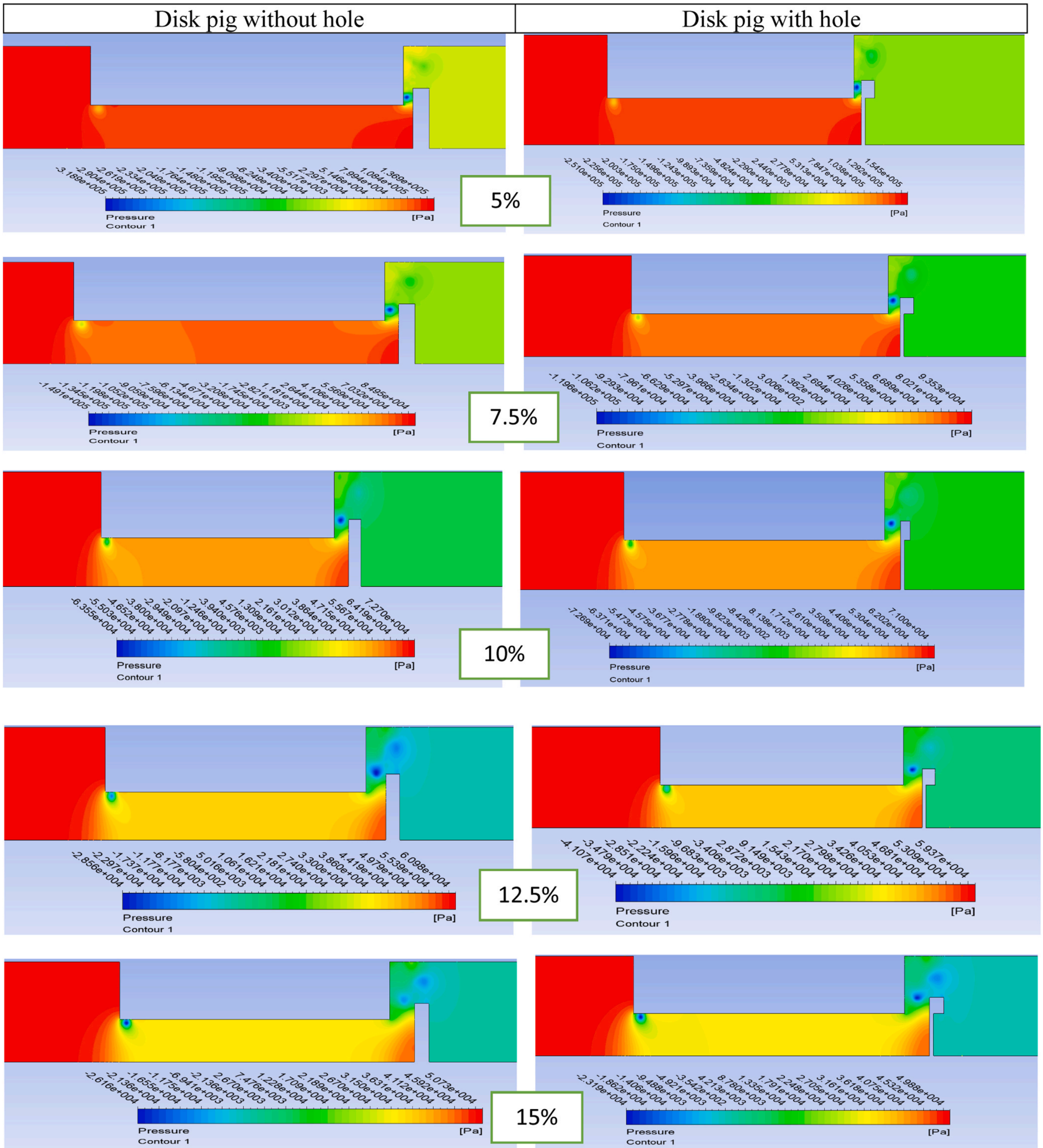


Fig. 16. Pressure contour of case-2 for disk bypass PIG without hole and with hole over bypass section.

bypass opening section, thereby reducing the PIG speed. The velocity contour for cases 1–3 is provided in Figs. 9 to 11 to present and compare the velocity of the fluid over the PIG section for both the disk PIG with and without a hole.

From the figures, it is evident that the velocity distribution of the fluid over the PIG section for the disk PIG with a hole indicates a lower value compared to the disk PIG without a hole. In Case-1 (disk PIG without a hole) with a 5% bypass opening percentage, the maximum and minimum velocities were 26.01 m/s and 1.628 m/s, respectively. Meanwhile, for Case-1 (disk PIG with a hole) with a 5% bypass opening percentage, the maximum and minimum velocities were 25.79 m/s and 1.612 m/s. Additionally, the 15% opening percentages showed the lowest value for velocity distribution, while the 5% opening percentage showed the highest for Case-1. An increase in bypass opening percentages from 5% to 15% resulted in an almost 10% reduction in fluid velocity at the bypass opening section.

Furthermore, Figs. 8 and 9 indicate that Case-2 and Case-3 also exhibit similar trends in velocity distribution over the PIG section. The

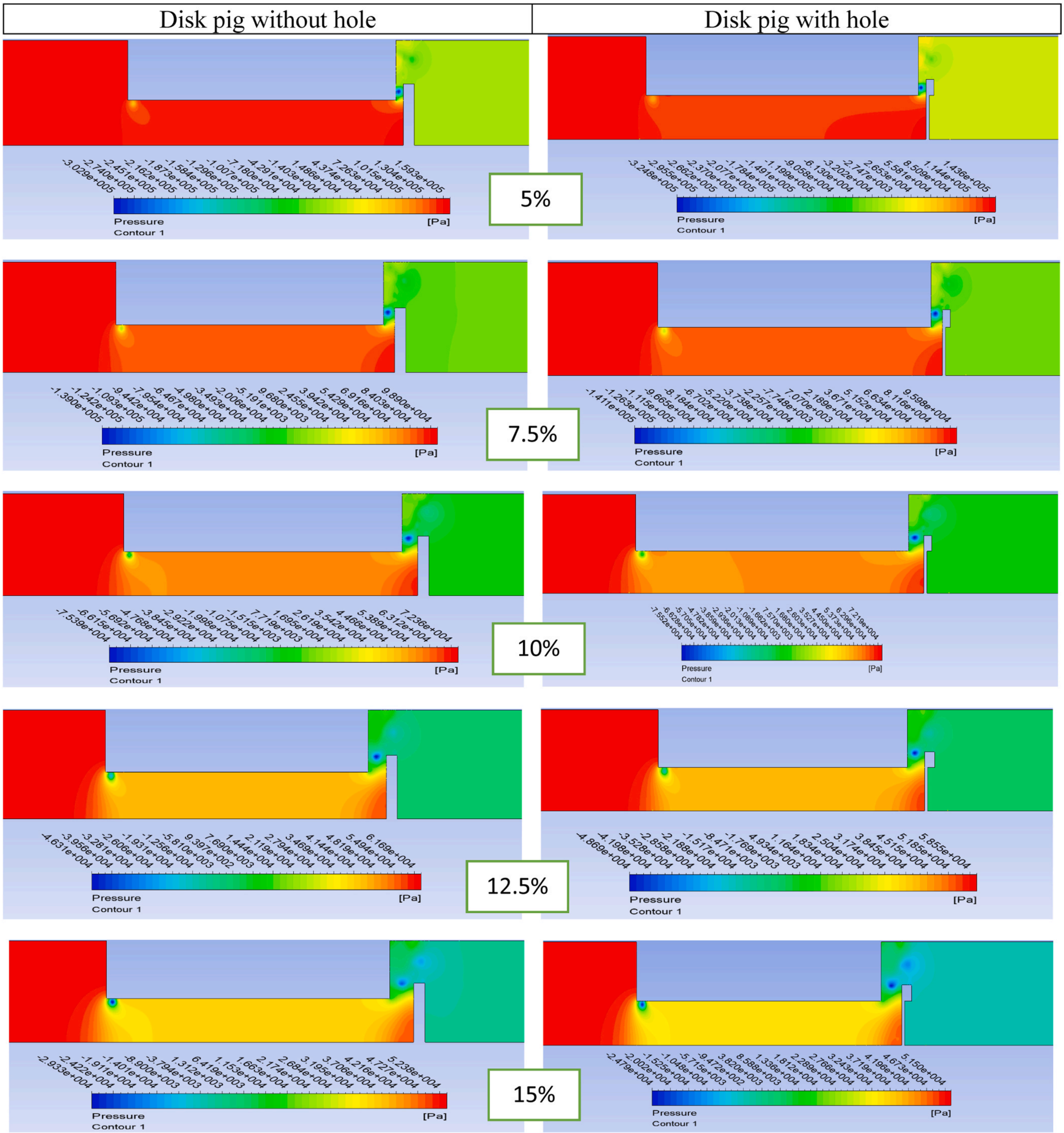


Fig. 17. Pressure contour of case-3 for disk bypass PIG without hole and with hole over bypass section.

velocity contour figures also depict vortices at the disk section, which typically result in a reduction in fluid velocity at the bypass opening section. The formation of these vortices was further attributed to shear induced by the no-slip condition along the boundary layers of the disk, the PIG, and the downstream wall.

3.2. Effect of dimensionless parameters and bypass opening percentages on PIG speed for disk bypass PIG with hole in disk

For the four different cases of the bypass PIG with a hole in the disk, PIG speed is shown in Fig. 12 for various bypass opening percentages. The results indicate that PIG speed decreases as bypass opening percentages increase for all cases. Among all cases, Case-1 showed the most significant reduction, while Case-3 showed the least reduction for all opening percentages, with 15% opening showing the most reduction and 5% showing the least. However, the 5% opening has the smallest opening area compared to 15%, resulting in the highest differential pressure at 5% opening percentage, leading to higher PIG speed compared to 15%. Nevertheless, the 15% opening percentage showed a 6.4–48% reduction in PIG speed compared to 5%, 7.5%, 10%, and 12% bypass opening percentages. Following this trend, it can be inferred that PIG speed can be reduced by increasing the sleeve length. Moreover, due

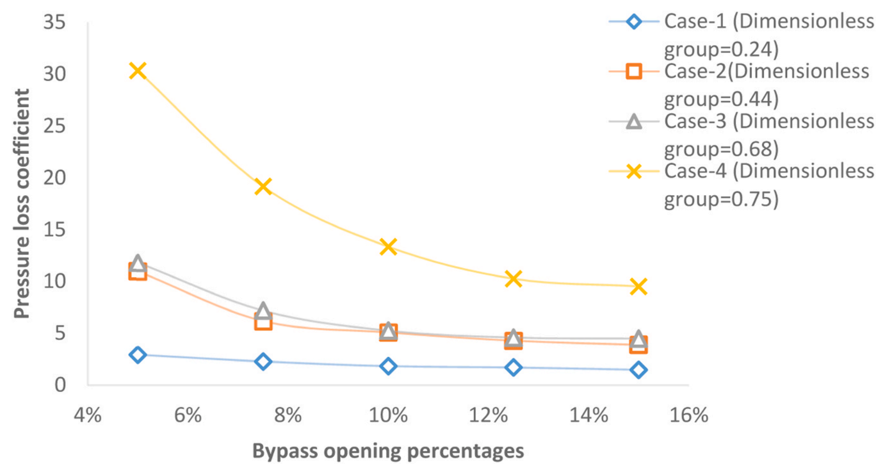


Fig. 18. Effect of bypass opening percentages to pressure loss coefficient for all cases of disk bypass PIG with hole in disk.

Table 5
Pressure Loss coefficient reduction percentages (%) of disk PIG with hole compared to without hole for all case.

Bypass opening percentages	Pressure Loss coefficient reduction percentages (%) for disk PIG with hole			
	case-1	case-2	case-3	Case-4
15%	5.605327	5.236358045	3.910981358	3.657479
12.50%	7.407407	5.438804677	5.623372913	4.038983
10%	7.489035	8.946378062	7.175692167	7.039853
7.50%	7.524836	8.112678773	7.443104639	6.555627
5%	8.363613	9.152168585	7.321990518	8.283615

to the variation in the value of the presented dimensionless group, Case-1 exhibited better reduction (2.7–22%) in PIG speed compared to other cases. Meanwhile, Case-1 had a dimensionless number of 0.24, which provided better pigging performance in terms of PIG speed, while Case-4, with a dimensionless number of 0.75, exhibited the lowest pigging performance. This is attributed to the geometrical parameters of Case-1 compared to other cases. Therefore, it can be concluded that the geometrical parameters combined in one dimensionless group significantly affect PIG speed. However, changes in the fluid flowing area and differential pressure were the main reasons for the variation in PIG speed.

Additionally, the reduction percentages for PIG speed of disk PIG with hole compare to without hole is presented in Table 4. Results show that case-1, 2, 3 and 4 provide maximum 7.33%, 5.25%, 6.74% and 3.91% advantage in terms of PIG speed. The calculation process of reduction percentages provides below:

$$Reduction\,percentages(\%) = \frac{V_3 \text{ for disk PIG withou t hole} - V_3 \text{ for disk PIG with hole}}{V_3 \text{ for disk PIG without hole}} \times 100\%$$

3.3. *Effect of hole in disk on Pressure Loss coefficient (with hole vs without hole)*

The effect of the pressure loss coefficient of the four cases is presented in Figs. 13 and 14. The results indicate that for all cases, the disk PIG with a hole provided a lower pressure loss coefficient compared to the disk PIG without a hole for all bypass opening percentages. Due to the reduction of fluid velocity and pressure loss over the PIG section, the disk bypass PIG with a hole has provided the lowest value for the pressure loss coefficient compared to the disk PIG without a hole. The pressure contour for Cases 1–3 is shown in Figs. 15, 16, and 17 to represent the pressure distribution over the PIG section, wherein it is clear that the pressure distribution for the disk PIG with a hole showed the lowest value for pressure compared to the disk PIG without a hole for all cases. In the meantime, by increasing the bypass opening percentages from 5% to 15%, the pressure has decreased by almost 48%.

3.4. *Effect of dimensionless parameters and bypass opening percentages on Pressure Loss coefficient for disk bypass PIG with hole in disk*

Fig. 18 displays the pressure loss coefficient of the flowing fluid around the bypass PIG for different bypass opening percentages. The results indicate that increasing the opening percentages leads to a reduction in the pressure loss coefficient for each case, with Case-1 exhibiting the lowest pressure loss and Case-4 showing the highest. Consequently, among the cases, Case-1 demonstrated better performance in terms of pressure loss coefficient, while Case-4 exhibited the lowest performance compared to the other cases. The variation in pipeline construction for the bypass PIG, disk, bypass opening section percentages, and hole in the disk contributes to the observed variation in pressure loss coefficient. Additionally, different values of the dimensionless group result in varying pressure loss coefficients across different cases. Increasing the dimensionless group value also corresponds to an increase in the pressure loss coefficient. However, Case-1 demonstrates a 12–72% reduction in pressure loss coefficient compared to Cases 2, 3, and 4. Furthermore, regarding bypass opening percentages, 15% exhibits the highest reduction in pressure loss coefficient compared to other percentages. Specifically, the 15% opening percentage shows a 32–90% reduction in pressure loss coefficient compared to 5%, 7.5%, 10%, and 12% bypass opening percentages. The variation in parameters such as PIG diameter, PIG length, disk diameter, disk length, pipe diameter, and bypass opening percentages across different cases, represented as dimensionless numbers, contributes to the observed variation in differential pressure and pressure loss coefficient. Therefore, it can be concluded that the performance of the pigging system depends on various geometrical parameters or dimensionless groups and bypass opening percentages, as these parameters mainly control the fluid flow rate, behavior, and differential pressure around the PIG, thereby aiding its movement over the pipelines.

Additionally, the reduction percentages for pressure loss coefficient for disk PIG with hole compare to without hole is presented in Table 5. Results show that case-1, 2, 3 and 4 provide maximum 8.36%, 9.15%, 7.44% and 8.28% advantage for pressure loss efficient.

4. Conclusion

A bypass pig with a hole in the disk section was studied using ANSYS FLUENT software and the control volume approach. The numerical model was validated by developing a correlation for PIG speed with experimental data provided by Eureka Efektif Sdn. Bhd. Four cases with different parameters, along with five different bypass opening percentages (5%, 7.5%, 10%, 12.5%, and 15%), were considered to show the effect on PIG speed and pressure loss coefficient. The developed correlation of PIG speed for validation was used to calculate PIG speed in this study. Moreover, to identify the optimal geometrical parameters of the disk bypass PIG, a dimensionless group was presented which represents the relationship among dimensional parameters of the PIG, main pipe, and disk. However, the key findings refer to-

- The numerical results from developed correlation of PIG speed showed good agreement against experimental results provided by Eureka Efektif Sdn. Bhd with maximum 2% error. Therefore, this correlation can be applied appropriately for disk bypass PIG with and without hole.
- Disk bypass PIG with hole provide almost 7% better results in terms of PIG speed and almost 9% less pressure loss coefficient compared to disk bypass PIG without hole. Therefore, it can be said that the use of disk bypass PIG with hole in disk provides better pigging operation compared to disk bypass PIG without hole.
- The presented dimensionless group is able to identify the optimized dimensional parameters for whole geometry of disk bypass PIG with hole. In order to demonstrate the dimensionless group, four cases were considered wherein case-1 showes better pigging operation whose value for dimensionless group is 0.24. However, case-1 shows a 2.7–22% reduction for velocity at bypass opening section and a 12–72% reduction for pressure loss coefficient compared to case-2 (dimensionless group = 0.44), case-3 (dimensionless group = 0.68) and case-4 (dimensionless group = 0.75). From this investigation, it can be stated that the lowest value of presented dimensionless group shows better pigging operation.
- Apart from these, the impact of bypass opening percentages was also investigated by using 5 different percentages (5%, 7.5%, 10%, 12.5% and 15%) wherein 15% showes better pigging performance based on fluid velocity at bypass opening section and pressure loss coefficient compared to others. However, 15% opening percentage shows a 6.4–48% reduction in velocity at bypass opening section and a 32–90% reduction in pressure loss coefficient compared to 5%, 7.5%, 10% and 12% bypass opening percentages. Therefore, it can be reported that higher opening percentage shows better pigging operation compared to lower percentages.

For this study it can be concluded that disk bypass PIG with hole in disk is potential for pigging operation as it provided lowest PIG speed and pressure loss coefficient compared to disk bypass PIG without hole in disk. Future study will cover the details experimental investigation, different design consideration for main body and disk section of the PIG and impact of different fluid mediums.

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CRediT authorship contribution statement

Md Insiat Islam Rabby: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Siti Ujila Masuri**: Conceptualization, Funding acquisition, Project administration, Resources, Writing – review & editing. **Ahmad Syakir Fariz Bin Samsul Kamal**: Funding acquisition, Project administration, Resources, Supervision. **Abdul Aziz Bin Hairuddin**: Resources, Supervision, Writing – review & editing. **Nuraini Bt Abdul Aziz**: Supervision, Writing – review & editing. **Zulkiflle Bin Leman**: Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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