Study on the Bridge Plugging Law of Pipeline Particles in Liquid-Solid System

Zhen Liu, Sen Lv, Xiaohua Ma, Chenwei Liu *

China University of Petroleum (East China), Qingdao. China

* Corresponding Author Email: liuchenwei1986@126.com

Abstract. Bridge plugging of solid particles is a common phenomenon in the field of oil and gas engineering, and it mostly occurs in liquid-solid. However, as a basic problem involving many fields, the current research focuses on the funnel flow system driven by gravity, and the exploration of liquid phase driving system is relatively few. In this paper, a visual particle pipeline bridge plugging test system was constructed and evaluated. The particle bridge plugging test experiment with particle/pore size ratio between 0.26-0.6 in liquid-solid system was carried out, and the influence of particle/pore size ratio on bridge plugging was analyzed. The results show that when the particle/pore size ratio is less than 0.28, the pipeline will not be blocked by particles. With the increase of the particle/pore ratio from 0.39 to 0.60, the number of particles required for the particles to form a stable bridge at the hole becomes less, the easier it is to form a stable bridge blocking structure, and the probability of bridge blocking is higher. The number of particles in the flow decreases with the increase of particle/pore size ratio before particle plugging. After the plugging is formed, the upstream pressure increases sharply, the flow rate decreases sharply and tends to be stable, and the flow rate corresponding to the plugging of large particles is higher. It has important guiding significance for further clarifying the bridging mechanism of particles in the flow environment.

Keywords: Enter key words or phrases in alphabetical order, separated by commas.

1. Introduction

In the field of oil and gas engineering, the transportation and migration of solid substances such as wax [1], hydrate [2] and asphaltene [3] in gathering pipelines and porous media may be blocked. The migration and plugging of hydrate, wax and sand in reservoirs, wellbores and pipelines will lead to the increase of flow resistance along the way, or even shutdown, causing safety accidents.

The universality of the particle bridge plugging problem makes the study of its plugging law has important scientific significance and practical value. It was not until 1963 that Harmens et al [4]. reported the scientific discussion of particle plugging. Subsequently, extensive research has been carried out on the plugging configuration and density change of the particle system, as well as the plugging behavior and critical characteristics of the particles flowing out of the confined space. However, the current research mainly focuses on the problem of gravity-driven plugging and the research on particle bridge plugging in liquid-solid flow system is more focused on the exploration of the threshold of plugging size, and there are few studies on the probability of bridge plugging and the flow after plugging.

Therefore, this paper focused on the particle bridging plugging link, and built the visual pipeline particle bridging plugging experimental system. Based on this, the particle pipeline bridging plugging experiment under liquid-solid two-phase conditions was carried out, and the particle/pore size ratio was explored which has important guiding significance for further clarifying the bridging mechanism of particles in the flow environment, evaluating the probability of bridging plugging, and discriminating the occurrence of bridging plugging.

2. Experimental Materials and Methods

2.1. Materials

PA plastic (nylon 66) with a density of 1150 kg · m^{-3} is a solid-phase particle used in experiments (Figure 1.). Tap water is used as the experimental fluid to transport solid particles in the experiment.

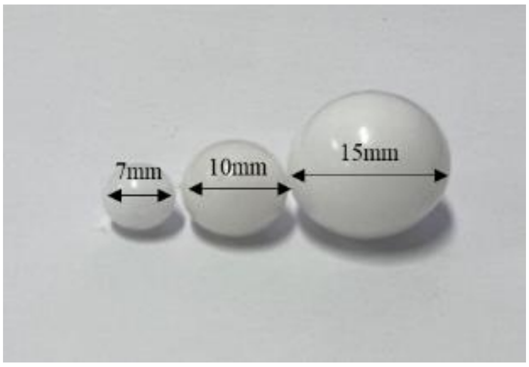


Figure 1. PA plastic spherical particles

2.2. Experimental apparatus

The visualized particle pipeline bridge plugging test system is comprised of four main modules: the experimental pipeline module, the supply and discharge module, the control module and the data acquisition module as shown in Figure 2, which can realize the simulation of the plugging process of solid particles at the pipe shrinkage. Among them, the supply and discharge module provide liquid-solid two-phase and flow cycle power for the experimental pipeline, the experimental pipeline module provides the path of each phase migration, and the control module controls the liquid flow rate, the release of solid particles and the change of shrinkage holes; the data acquisition module records the liquid flow, pressure and plugging process in the experimental test.

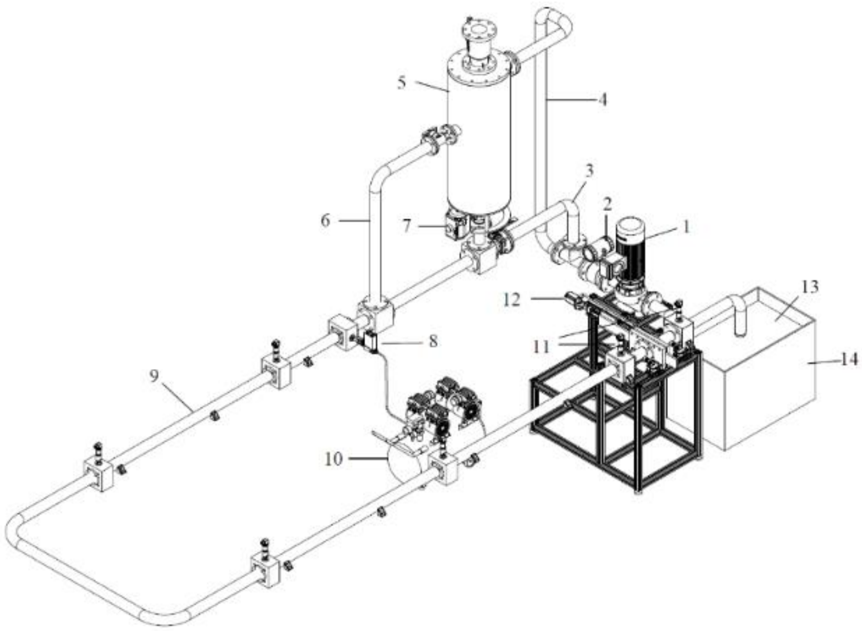


Figure 2. Schematic diagram of the fully visible particle bridge plugging test system

1-centrifugal pump; 2-liquid flowmeter; 3-transparent connecting tube 1;4-transparent connecting tube 2; 5-particle storage tanks; 6-transparent connecting tube 3; 7-Pneumatic ball valve; 8-pneumatic ball valve; 9-transparent loop; 10-Air compressor; 11-Pressure sensor; 12-orifice plate control system; 13-filter plate; 14-Liquid storage tank

2.3. Experimental Procedures

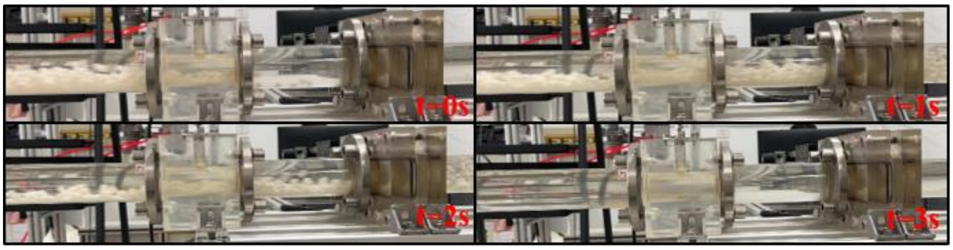
The experimental steps for liquid-solid system pipeline particle bridge plugging law are as follows: Firstly, prepare the experimental particles and fill the liquid storage tank; then connect the data acquisition signal line to the data acquisition box, start the system and ensure the normal acquisition and storage of the signal; The moving test hole plate would be controlled to form a specific size of the necking structure; A certain number of experimental particles then be filled into the tank, and the fluid injected through the pipeline until the preset height. Then the parameter acquisition system and the camera should be started to record the plugging process. Subsequently, the pneumatic ball valve is activated to permit the particles to enter the pipe and flow to the orifice plate. In the event of a plugging, the pump is halted and the solid particles currently in transit through the shrinkage hole prior to the plugging are collected and subjected to a second round of testing. If the filter on the reservoir is not obstructed, all particles that have been intercepted should be collected and the experiment repeated.

Based on the literature research and research purpose [5], considering the performance of the experimental system, the test here mainly explores the influence of the size ratio (k: particle size/pore size ratio) of the overcurrent particles and the shrinkage hole on the particle plugging. Among them, the change of k value is realized by selecting different particle diameter and shrinkage hole size combination. As mentioned above, this paper has three particle diameters of 7 mm, 10 mm and 15 mm and three shrinkage apertures of 50 mm, 38 mm and 25 mm, and the range of k is from 0.2 to 0.6.

3. Results and Discussion

The size ratio of the overflow particles to the shrinkage holes is a key evaluation index that affects particle plugging [6]. Two classical flow and plugging conditions are discussed below, where the liquid-phase flow rate v is set to 1 m·s^{-1}.

3.1. Normal Flow of Particles in the Pipe



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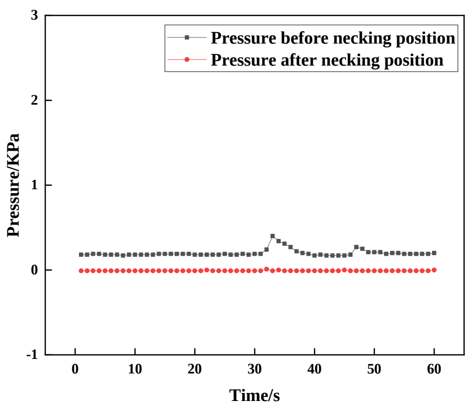

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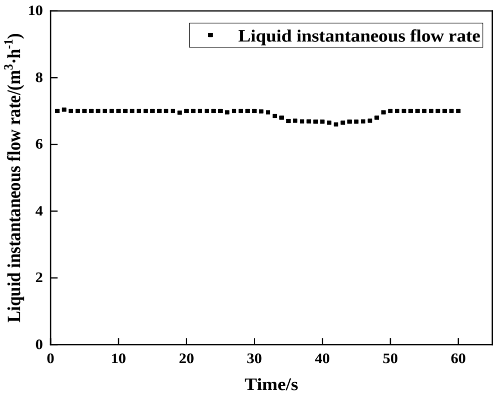


(c)

Figure 3. k=0.28 v=1 m·s^{-1} particle flow through orifice diagram(a), pipeline pressure (b) and flow rate diagram (c)

Figure 3. (a) shows the process of 7 mm solid particles flowing through the 25 mm hole.

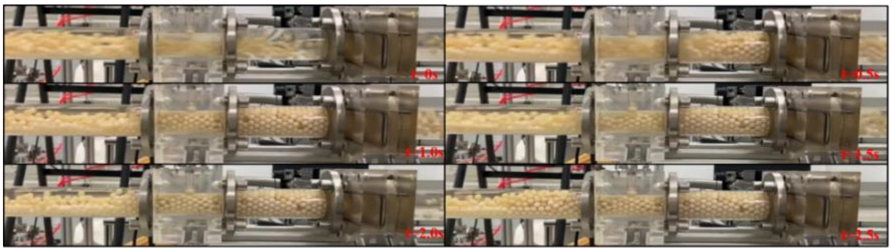
Due to the large density and the flow rate, the solid particles are mostly concentrated in the lower half of the pipeline and flow with the liquid phase. With the sudden contraction of the flow section of the orifice, the flow velocity of the fluid increases significantly, resulting in the dispersion of the solid particles in the whole flow section within a short distance at the back end of the orifice. As the flow rate returns to the initial level, the particles flow back to the bottom of the pipe. Due to the small k value, there is no obvious particle accumulation in the front end of the shrinkage hole, and there is no plugging in the whole process. All particles finally pass through the shrinkage hole.

Figure 3. (b) and (c) show the corresponding pressure and flow changes during the flow of 7 mm solid particles through the 25 mm hole. As shown in the figure, before the release of solid particles (before Time A), the pipeline flow and the pressure before and after the necking nipple have reached stability. After the particle release valve is opened, the solid particles together with the liquid quickly enter the horizontal pipeline. The high pressure head in the particle storage tank results in an increase in pressure at both the front end of the downstream shrinkage hole and the downstream end. Meanwhile, the discharge capacity of the power pump is reduced by the increase in the discharge outlet pressure, which is manifested as a decrease in the liquid supply flow. Once the solid particle release valve at point B is closed, the pressure at the front end of the hole begins to decrease gradually, returning to the previous pressure level over a period of time (point C).

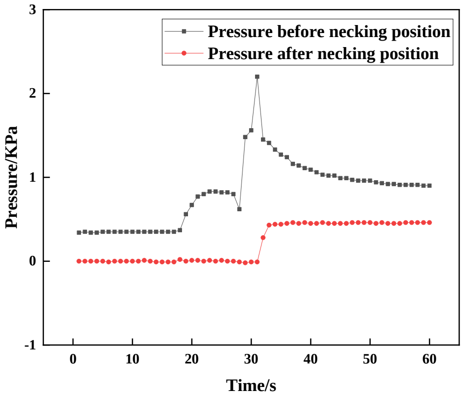
In contrast, the displacement of the power pump has been slightly decreased until the flow rate gradually recovers at C. Compared with the change of pressure, the change of flow rate lags slightly. As the particles migrate towards the necking hole, the increase in liquid-solid two-phase flow resistance results in a slight rise in pressure at the front end of the hole, which then decreases rapidly. However, the pressure remains slightly higher than that corresponding to single-phase flow. Correspondingly, the flow rate gradually begins to decrease, though this decrease is slight. Once the solid particles have exited the pipeline, the front-end pressure rapidly reverts to the initial single-phase flow pressure level. The corresponding flow rate then increases gradually and ultimately reaches the level of the single-phase flow. However, the recovery speed is markedly slower than the front-end pressure.

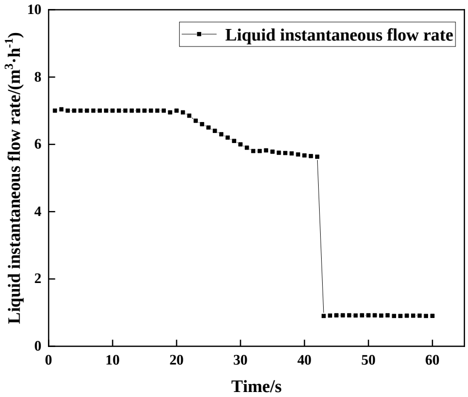
3.2. Plugging of Particles in the Pipe

At a flow rate of $v=1\ m\cdot s^{-1}$, the 10 mm particle may become trapped within a 25 mm orifice, Figure 4 illustrates an instance of such a plugging: In the initial stage, the concentration of particles at the front end of the solid phase flow is relatively low, resulting in the majority of particles passing through the orifice. As the particle concentration rises, some particles initially remain at the periphery of the orifice and at the lower end of the pipe wall, gradually accumulating over time. The accumulation of particles at the base of the pipe causes subsequent particles to flow towards the upper central region of the pipe, where they become retained around the periphery of the eyelet and at the upper end in proximity to the pipe wall. This results in the formation of an annular band of particles, yet the length of the band at the base of the pipe is consistently greater than that observed at the top. The increase in the length of the accumulating annular band resulted in an increase in the length of the reduction, and the intermediate annular space could still be overflowed with particles. Until 2s, particles formed a bridge at the orifice, preventing subsequent particles from passing through. These particles rapidly accumulated at the upstream end of the plugging, resulting in a gradual increase in the length of the forming segment plug.



(a)





(b) (c)

Figure 4. k=0.4 v=1 m·s^{-1} particle flow through orifice diagram(a), pipeline pressure (b) and flow rate diagram (c)

Figure 4. (b) and (c) show the corresponding pressure and flow changes during the flow of 10 mm solid particles through the 25 mm hole.

The release of the particles resulted in an increase in pressure at the front end of the orifice and a concomitant decrease in the flow rate of fluid supplied by the power pump. Following the closure of the particle release valve, the front pressure began to decline. However, the downstream orifice soon formed a bridge, resulting in the inertial momentum of the water flow continuing to exert pressure on the front of the plugging. This resulted in a sharp rise in pressure, which was significantly higher than that observed in a non-blocking situation. The negative pressure wave generated by the water flow is transmitted in the reverse direction and is subject to the resistance of the pipe wall and the resistance of the water flowing from upstream of the pipeline. This resistance gradually diminishes, resulting in a rapid decrease in pressure at the front end, which then gradually stabilizes. The final stabilization value of the pressure at the front end is higher than in unidirectional flow due to the significant increase in resistance to fluid flow through the orifice caused by the accumulation of particles at the front end of the orifice, which is clogged. Concomitantly, the downstream pressure also rises rapidly at the moment of plugging formation and stabilizes at a higher pressure level. The pressure difference between the two ends at the diameter-reducing short section was also higher than in single-phase flow, primarily due to the formation of a blocked section that augmented the resistance to flow. Concurrently, the rise in pressure at the front end led to a decline in pump flow, which subsequently stabilized at a markedly lower level than the initial flow. It is important to note that the change in flow rate occurred with a temporal lag relative to the change in pressure, due to the distance between the power pump and the downstream diameter-reducing short section.

3.3. Bridge Plugging Particle/Pore Size Ratio Thresholds and Probabilities

The experimental findings on particle overflow at three flow rates (3.5, 7 and 9 m/s) under varying particle/porosity ratios are illustrated in Table 1. For tests with *k* = 0.28 (7/25 mm) and 0.26 (10/38 mm), no plugging was observed at all three flow rates. For other combinations of particle/pore ratio, plugging was produced at different flow rates. In addition, K.V. Sharp et al [7]. have investigated the phenomenon of particle plugging in overflow orifices, with the majority of their findings indicating that the critical particle/pore ratio for the formation of critical clogging is approximately 0.33. This value is in close alignment with the conclusions drawn from the tests conducted in this study.

Table 1. Table of particle bridging situations under different parameter combinations

Particle/pore size ratio (k)	Liquid flow (m^3/h)	Number of plugging	Probability of plugging (%)
0.28(7/25 mm)	3.5	0	0
	7	0	0
	9	0	0
0.26(10/38 mm)	3.5	0	0
	7	0	0
	9	0	0
0.39(15/38 mm)	3.5	20	100
	7	15	75
	9	4	20
0.40(10/25 mm)	3.5	17	85
	7	14	70
	9	1	5
0.60(15/25 mm)	3.5	20	100
	7	20	100
	9	6	30

Figure 5. illustrates the blocking probability at varying flow rates for three distinct values of k that cause the blocking phenomenon. As the liquid phase flow rate increases, the blocking probability exhibits a declining trend, with smaller values of k exhibiting a more pronounced decrease. To ascertain the underlying cause, it is necessary to consider the manner in which the experimental device adds solid-phase particles. For particles of the same kind, the conical structure of the characteristics of the particles' adding speed is essentially constant. As the liquid-phase flow rate increases, the concentration of solid-phase particles is reduced, potentially falling below the corresponding particles permitted by the maximum permissible overflow. Consequently, particles cannot accumulate in front of the reduced-size orifice, thereby reducing the probability of clogging dramatically. Furthermore, an increase in velocity will result in the suspension of particles, a more complex trajectory, stronger dispersion, and reduced accumulation of suspended particles at the bottom of the front end of the eyelet. Concurrently, enhanced particle impact on the arch structure will lead to a reduction in the probability of particle plugging.

Figure 6. illustrates the bridging plugging for varying values of k. For the 15/25 mm granular aperture combination, the probability of clogging significantly increases at all flow rates as k=0.39 is increased to k=0.60. This is due to the width of the annular baffle wall between the distance between the aperture and the pipe wall is 12.5 mm, which is greater than the centre of gravity of the 15 mm granular particles. Consequently, the two particles in the periphery can be readily and consistently retained in the baffle wall. Therefore, the key to the bridging clogging is the middle two particles. The phenomenon of bridge clogging can be attributed to the two particles situated in the central region. In contrast, for the 15/38 mm particle-aperture combination, the centre of gravity of the two peripheral particles (7.5 mm) exceeds the length of the baffle wall, which the retention of the two particles at the baffle wall becomes unstable when the wall is 6 mm thick. The formation of an arch bridge under this combination requires the accurate coordination of the four particles, which significantly reduces the probability of clogging compared with the former.

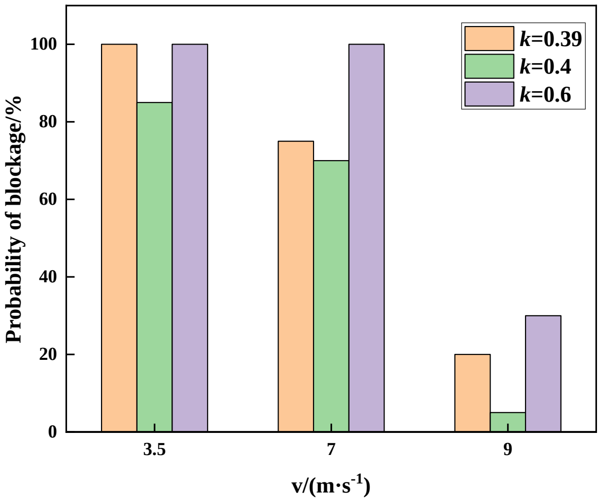
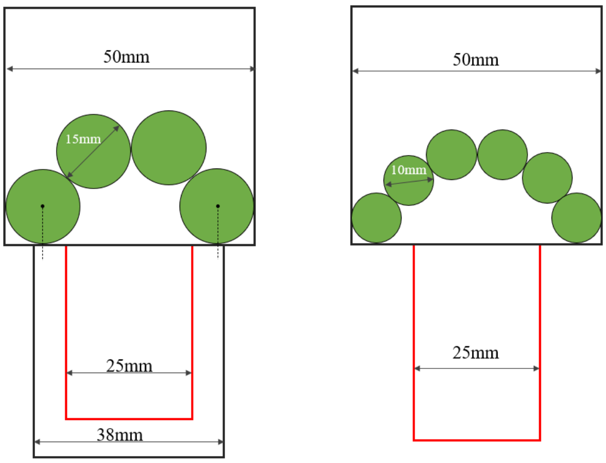


Figure 5. Plugging probability diagram with different aperture ratios

For 10 mm particles, although the k-value for a plugging probability of 15/38 mm is smaller than that of 10/25 mm, the probability of plugging is higher. The reason for this phenomenon is illustrated in Figure 6(b): the formation of a bridge plugging requires the presence of a minimum of six particles when 10 mm particles traverse a 25 mm aperture. Furthermore, the two peripheral particles are situated within the baffle wall around the aperture, which facilitates the formation of a stable stagnation. In other words, the key to clogging lies in the middle four particles. This explains why the probability of plugging of the 15/38 mm is similar to that of the 10/25 mm. Additionally, the two outer particles of 15/38 mm are constrained by the right-angle mechanism formed by the pipe wall and the retaining wall. In contrast, the four particles of 10/25 mm exhibit more random transport, which reduces the probability of arch structure formation. Furthermore, the 10 mm particles are lighter than the 15 mm particles, facilitating dispersion throughout the cross-section of the pipeline. However, this also increases the likelihood of damage to the arch structure formed by collision, which further reduces the probability of plugging.



(a)k=0.60 (b)k=0.40

Figure 6. Bridge building diagram with different k values

4. Conclusions

In this study, a visual particle bridge plugging experimental device was employed to conduct particle bridge plugging test experiments in liquid-solid systems with particle/porosity ratios ranging from 0.26 to 0.6 and liquid-phase flow rates ranging from 3.5 to 9 m3/h. The plugging parameters, including the flow rate after plugging, pressure before and after the orifice, and so forth, were analyzed. The results demonstrated that no plugging occurs when the particle/porosity ratio is less than 0.28. Furthermore, as the particle/porosity ratio k is increased from 0.39 to 0.60, and the number of particles required to form a stable bridge plugging at the orifice decreases, this facilitates the formation of a stable bridge plugging structure and increases the probability of bridge plugging. Under the assumption of a constant particle release rate, an elevated liquid-phase flow rate results in a lower particle concentration in the pipeline cross-section, which in turn reduces the probability of bridge plugging.

Acknowledgments

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