Experimental study on pressure pulses in long-distance gas pipeline during the pigging process

Jun Zhou\textsuperscript{1}, Tao Deng\textsuperscript{2}, Jinghong Peng\textsuperscript{1}, Guangchuan Liang\textsuperscript{1}, Xuan Zhou\textsuperscript{1} and Jing Gong\textsuperscript{3}

\textsuperscript{1}Southwest Petroleum University, Chengdu, China
\textsuperscript{2}Guangzhou Petroleum Training Center, China National Petroleum Corporation, Guangzhou, China
\textsuperscript{3}China University of Petroleum (Beijing), Beijing, China

Abstract
Long-distance gas pipelines generally have complex, undulating sections. Trapped air pockets are often present at the high points or ends of pipelines. This article carries out an experimental research to figure out the transient changes. First of all, under the condition of using the pig with 231 g and the injection pressure of 0.3 MPa, the hydraulic pulse increases from 0.31 to 0.54 MPa as the liquid level rises from 1 to 8 m. And at the liquid level of 8 m, the injection pressure grows from 0.3 to 0.75 MPa and the hydraulic pulse from 0.54 to 0.95 MPa. When the interception air mass is located at the blind side of the pipeline’s end, the injection pressure is 0.75 MPa, and the hydraulic pulse decreases from 4.9 to 3.21 MPa with the increase in the void fraction. The maximum hydraulic pressure generates when the air pocket is located at the rear end of the drainage system (4.9 MPa) is far higher than that when the air pocket is located in front of the pig (1.0 MPa). Therefore, it is necessary to minimize the generation of trapped air pockets at the rear end of the pipeline system to ensure safety.

Keywords
Pressure test, water drainage, long-distance gas pipeline, undulating terrain, pressure pulse, trapped air pocket

Corresponding authors:
Jun Zhou, Southwest Petroleum University, Chengdu 610500, China.
Email: zhoujunswpu@163.com

Tao Deng, Guangzhou Petroleum Training Center, China National Petroleum Corporation, Guangzhou 510510, China.
Email: dsai1987@petrochina.com.cn

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Introduction

As one of the five major modes of transport, pipeline transportation has a profound impact on the global economic development. China’s long-distance natural gas pipelines totaled 74,300 km by 2017 and are expected to reach 104,000 km by 2020 and 163,000 km by 2025. Pressure tests are an important means to determine the safety of a new long-distance gas pipeline and eliminate the potential dangers before construction is completed and the pipeline is put into operation. Water is used as the pressure test medium for most pipelines around the world due to safety and economic considerations.\textsuperscript{1,2} In practice, compressed air is frequently used to propel a pig, which is inserted into the pipeline to drain the water. It is also used for the pressure test by pushing it to one end of the pipeline.\textsuperscript{3} It is well known that when the temperature is constant, the liquid will vaporize as the pressure is reduced to a certain critical pressure. In addition, the air dissolved in the water will come out and form air pockets. However, it is inevitable that air will be injected into the pipeline in reality. The air is pushed by the pig and will move downstream with the water flow, thereby forming bubbles or trapped air pockets at the high point or at the pipe’s end. The impact of the pressurized water on the trapped air pockets will lead to the pressure transient and hydraulic pulse. If this pressure exceeds the pressure-bearing capacity of the pipeline material, serious accidents, such as pipeline bursts, would occur. As shown in Figure 1, a domestic undulating terrain pipeline meet the regulatory requirements in the steel production, pipeline construction, pressure testing, and pigging processes. However, after the water pressure test, the pipe explosion accident occurred in the final stage of two consecutive drainages, and the locations of this two are both at the end of the pipeline.

Few descriptions of the hydraulic pulse phenomena that occur during the final stage of the pigging process can be found in published studies of pipeline pigging.\textsuperscript{4}

![Figure 1. The pipe rupture caused by abnormal overpressure.](image-url)
Theoretical studies of hydraulic transients due to the impacts of water on trapped air pockets are almost nonexistent. Through experimentation, Hamam and McCorquodale\textsuperscript{5} found that air pockets tend to cluster at locations in a pipeline where the pipe diameter changes abruptly. Jönsson\textsuperscript{6} found through experiments that when the transient flow in a sewage pump stopped suddenly, the maximum pressure pulse that resulted from the trapped air pocket inside the pipe could reach three to four times the inlet pressure (Figure 2). Zhou et al.\textsuperscript{7} studied the characteristics of air–water flows by rapidly filling a horizontal pipeline and found that different types of pressure fluctuations occur for various ratios of the area of the air vent to the cross-sectional area of the pipeline (d/D ratio). If d/D = 0.2, the maximum pressure could reach 15 times the inlet pressure. Therefore, due to the impact of pressurized water on trapped air pockets, the maximum pressure pulse is often relatively large and may pose a serious threat to the operation of the pipeline. Hence, relevant studies are important for guiding on-site operations and ensuring the safety of pipelines.

**Research progress**

Air pockets are often present in the undulating sections and at the blind end of a pressurized water pipeline. The impact of a pressurized flow of water on trapped air pockets will cause hydraulic transients. Benfratello\textsuperscript{8} first defined this process of hydraulic transients and divided the water hammer process into two stages. In the first stage, the initial rigid water column is in motion, the water can be considered to be incompressible, and the water hammer pressure oscillates relatively slowly. In the second stage, the head of the water column reaches the orifice of the air vent, resulting in violent changes in the flow and further leading to water hammer
process. De Martino et al.9 asserted that as the upstream hydraulic head, the cross-sectional area of the orifice of the air vent and the air volume increase, the duration of the water hammer stage decreases, and a maximum pressure peak occurs. They developed a theoretical prediction model that produced results that were consistent with experimental data. They also claimed that the maximum pressure increased with increasing upstream pressure and cross-sectional area of the air vent, and that the volume of the air pocket had no significant effect on the maximum pressure within the study range. Kolp,10 Holley,11 Viparelli,12 and Cardie et al.13 theoretically and experimentally analyzed the hydraulic process in which the air inside a pipeline is vented by rapidly filling the pipeline with water. They found that water hammers were generated when the trapped air was vented and that the pressure changed at high frequencies when the air was vented from the system. Based on Holley’s results and field studies, Burton and Nelson14 found that trapped air pockets can result in sharp increases in the water hammer pressure in a water pipeline system. Albertson and Andrews15 and Andrews16 experimentally and theoretically investigated trapped air pockets based on the transient process of air venting in two pipeline structures. In their experiment, exhaust valves were installed at the highest point of the pipe and at the riser at the end of the pipe.

Martin17 proposed a simplified model that can predict pressure fluctuations when the valve of a sealed single pipeline that contains a trapped air pocket at its rear end is opened rapidly. This model does not consider the compressibility of water and the pipeline or the changes in the length of the water column. The results showed that the peak pressure at the trapped air pocket was far higher than the inlet pressure. However, the results were not verified with experimental data. Cabrera et al.,18 Fuertes et al.,19 Izquierdo et al.,20 and Ghidaoui and Karney21 improved Martin’s model by considering the changes in the length of the water column and using a gas equation and an energy loss equation that are more consistent with actual conditions. They also discussed the applications of the rigid model and noted that the compressibility can be ignored when the rate of change of the internal and kinetic energy is significantly less than 1. Liu and Suo22 proposed a completely rigid water column model that considers actual factors, such as the energy loss at the upstream inlet, the time that the valves are opened, and the changes in the elevation. They discussed the applications of the rigid model and recommended that it be used when the trapped air pockets are relatively small. Jönsson,6 Abreu et al.,23 Karney and McInnis,24 Chaiko and Brinckman,25 Lee and Martin,26 Lee,27 and Bergant et al.28,29 established an elastic model that considers the compressibility of water. They also solved the control equation using the method of characteristics. Karney and McInnis24 proposed a theoretical elastic and rigid mixed water column method that not only simplifies the control logic but also increases the computational speed. Zhang and Vairavamoorthy30,31 proposed an improved model based on the method of characteristics that considers the transient shear stress between the pipe wall and the fluid. The calculation results showed that the transient shear stress can affect the maximum pressure; in addition, when there are two or more trapped air pockets, the transient shear stress has an
insignificant impact on the maximum pressure at the first air pocket. Epstein\textsuperscript{32} introduced a relatively convenient integration method that comprehensively considers the motion of the air–water interface and the compressibility of the liquid. Epstein’s method makes predictions based on a simple set of simultaneous equations and is very accurate compared to numerical methods. In addition, Epstein’s method is easy to implement, considers the compressibility of water in a mixed flow, and can predict the time that complete compression is achieved and the maximum pressure of the compressed air bubbles.

So far, research on pressure transients in water pipeline systems due to the impact of water on trapped air pockets has achieved significant progress. However, few of the published studies have focused on pipeline systems in the oil and gas industries, and almost no one have addressed pressure transients caused by trapped air pockets in pipeline systems. An undulating pipeline in China has exploded twice\textsuperscript{4} at its end, which indicates that a very high transient pressure (exceeding the pressure-bearing capacity of the pipeline material) was generated in the pipeline during the pigging process. Based on the previous discussion, the impact of the water flow on the trapped air pockets can generate a very high transient pressure, which might be the main cause of the explosion accidents. Therefore, to understand the mechanism by which hydraulic pulses form during the pigging process and to evaluate their ability to cause the pipeline to burst, it is necessary to thoroughly investigate the transient characteristics of air pockets that are impacted by the water flow during the pigging process, particularly the relevant pattern of changes in the maximum hydraulic pulse.

**Experimental pressure testing and draining apparatus**

An experimental apparatus was constructed with the experimental undulating pipe pressure testing and draining system in the Multi-phase Flow Research Group at China University of Petroleum (Beijing).\textsuperscript{33} This system was designed and constructed based on the section of the long-distance gas pipeline in China in which the accidents had occurred. The onsite undulation section is about 1700 m in length and 120 m in height. The experimental apparatus consists of six parts (Figure 3). Each part is introduced in detail as follows.

1. Gas supply system provides the power for the pigging process. Specifically, there are two air compressors in total. One is for normal use and the other is for backup. Each of them can provide a gas pressure of 0.8 MPa and a gas volume of 3.4 Nm\textsuperscript{3}/min.
2. Spherical pig system consists of pig launcher, pig receiver, and pig braking device.
3. Water supply system has a lift head of 90 m and a rated displacement of 90 L/min.
4. Water back system: the return pump has a head of 25 m and a rated flow of 3 m\textsuperscript{3}/h.
5. Pipe system includes fluctuation pipe lines, compression resistance hoses, elbows, butterfly valves, ball valves and drains, and so on. Undulation pipe-lines are made of stainless steel and plexiglass, with diameters of $\Phi 57 \times 3$ mm and $\Phi 63 \times 6$ mm.

6. Drainage system consists of a water tank and water drainage valves.

**Experimental scheme**

Air pockets often form in the undulating segments of a pipeline and at its sealed end. Their locations and volumes have a significant impact on the transient pressure that is generated in the pipeline system.\textsuperscript{34–36} Therefore, when studying the effect of the presence of trapped air pockets on the transient pressures generated in a pipeline system, the volumes and locations of the air pockets must be considered. During the pigging process, trapped air pockets may be located in front of the pig or at the rear end of the drainage system. In the experiment, the volume of the air pocket in front of the pig was adjusted by controlling the liquid level in the downhill pipe section, and the volume of the air pocket at the rear end of the drainage system is adjusted by controlling the three pipe sections at the outlet of the drain-pipe that are separated by butterfly valves. As shown in Figure 4, air pockets a and b are both 0.42 m long, and air pocket b is 0.84 m long. The air pockets are labeled 1, 2, 3, and 4 and have lengths of 42 cm (a or c), 84 cm (b), 126 cm (a + b or b + c), and 168 cm (a + b + c), respectively. The length of the air pocket is adjusted by opening or closing the butterfly valves at different locations.
Experimental steps

1. Close the butterfly valve at the pigging brake and turn on the air compressor to increase the air pressure upstream of the pigging brake to the preset pressure. Turn off the air compressor and maintain the pressure in the pipe section upstream of the pigging brake.
2. Open the spherical valve at the pigging brake to allow the downstream pipe section to be connected to the outside environment and simultaneously open the spherical vent valve at the trapped air pocket control section.
3. Control the water injection rate to a moderate level to allow the air in the pipe to be completely vented. Close the spherical valve at the trapped air pocket control section when water starts to flow out of it.
4. Close the inlet valve at the water injection section after the liquid level reaches the predetermined level to complete the water injection and air venting process. Then, close the spherical valve at the pigging brake to ensure that the inside of the pipe is sealed off from the outside environment.
5. Open the quick connector of the pigging brake and insert the pig. Then, close the quick connector and examine the fixing device to determine whether the requirements have been met.
6. Close each butterfly valve at the trapped air pocket control section. Then, open the drain valve at the bottom of the pipe section according to the experimental requirements and close the drain valve after all of the water has drained.
7. Turn on the data acquisition system and simultaneously open the spherical valve at the receiver, the butterfly valves at the trapped air pocket control section, and the butterfly valve at the pigging brake to complete the experimental data acquisition process.
8. Simultaneously close the butterfly valve at the pigging brake and the spherical valve at the receiver after the pig enters the receiver and open the air vent at the pigging brake to release pressure. Then, open the receiver to retrieve the pig after the pressure inside the pipe reaches the same level as the outside atmosphere.
9. Clean the experimental site, process, and store the data, and prepare for the next set of experiments.
During the experiment, the quick joints of the pig brakes are continuously worn, causing the gaskets caught therein to be severely worn as well, which would affect the airtightness of the system. So, it is necessary to fill the pipeline with water before the experiment start. During the process of water injection, the gas in the pipeline should be discharged as cleanly as possible, and the gas content should be controlled by manual adjustment, thus resulting in certain uncertainties.

**Hydraulic pulse phenomenon**

When a straight plate pig is used to clean the undulating pipe in the experiment, the pressure along the undulating pipe section exhibits similar variations under various conditions. The pressure changes of the four measuring points (P1–P4) along the pipeline are shown in Figure 5. The electromagnetic detector, shown as L1–L10 in Figure 5, is used to get the pig velocity data.

Figure 6 shows the pressure changes for the four measurement points (P1–P4) along the pipeline. Throughout pigging, the pressure at the transmitter outlet (P1) maintained at the highest of the four measurement points. The reason is that the drive pressure (P1) must overcome the axial contact dynamic friction (including the downstream resistance and the friction between the pig and the pipe wall) to drive the pig drain. Therefore, the pressure at point P1 is higher than that at other downstream measurement points. The pressure at the bend (P2) is slightly lower than P1 before the pig reaches the bend. Since the friction resistance to the pig is greater than the hydraulic pressure caused by the difference in height between the

![Figure 5. Location of the measuring points and the elbow.](image-url)
outlet and the bend, P2 is equal to P1 after the pig passes the bend. The pressure at point P3 (high point) is the lowest. Due to the influence of hydraulic pressure, the pressure at the receiver (P4) is slightly higher than that at P3. Since the diameter of the drain pipe is smaller than the diameter of the undulating pipe, the water in the pipe is somewhat hindered. The pig’s speed is lower than that of the air at the entrance. Whenever the pig passes through the curved section, the P1 increases to overcome the relatively increased resistance, causing P1 to increase as the pigging time increases. However, P1 is less than 0.4 MPa during the whole pigging process, hence it cannot cause damage to the pipeline system. However, at a later stage of the pigging process, the instantaneous high pressure recorded at the receiver (P4) suddenly rises from 0 to 1.2 MPa and then quickly returns to zero.

**Experimental results and discussion**

In order to study the transient instantaneous pressure, this article focuses on analyzing the receiver’s pressure change during the experiment. Figure 7 shows the pressure changes at different locations (P1: air injection pressure, P4: pressure at the receiver, P5: pressure in front of the air pocket valve). It can be seen from the figure that pressure fluctuations are similar patterns under different experimental conditions. Each pressure curve (P1, P4, and P5) has a different degree of decline at first, where P5 drops the most. Subsequently, the pressures P4 and P5 have different degrees of increase, of which P4 instantaneously increases to 3.18 MPa; finally, the pressures P1, P4, and P5 fluctuate and tend to be stable. The reasons for this trend are as follows:

1. As shown in Figure 5, when the valves at the air pocket and the receiver were opened simultaneously, the upstream water column rapidly filled the

![Figure 6. Pressure fluctuation using straight plate pig.](image-url)
trapped air pocket. When the pig pushed the water column and accelerated its movement, the water pressure was converted to kinetic energy. As a result, P5 decreased. The initial pressure of the water sealed in the receiver was slightly higher than the pressure of the trapped air pocket. When the valve at the receiver was opened, P4 decreased. Because of its compressibility, the air behind the pig continuously expanded as the pig moved. Consequently, P1 decreases.

2. Because the water column rapidly filled the air pocket, the water columns at both ends rapidly compressed the trapped air pocket, which resulted in a rapid increase in the pressure. Because of the compressibility of air and the inertia of the water column, the pressure of the compressed trapped air pocket was far higher than the air injection pressure behind the pig. Therefore, P4 and P5 both increased suddenly, and a transient high pressure was generated at the receiver.

3. After a large amount of water had filled the air pocket, the large air pocket was divided by water into multiple small air pockets. As the mixing of air and water intensified, small air pockets eventually burst and dispersed in the liquid phase in the form of small air bubbles. Some air bubbles clustered at the top of the pipe, while the rest were carried (Figure 8). The mixing of air and water resulted in pressure oscillations. As the dissipation of the mixing energy intensified, the pressure gradually stabilized.

The gas will move downstream with the liquid flow in the form of bubbles or air masses under the action of the pig, and a trapped air mass will be formed at the
Figure 8. The process of water filling air pocket.
high point of the undulation section or at the end of the pipe. If the pig suddenly accelerates or opens the valve quickly, the pig will compress the air mass or the water flow to impact the air mass, causing gas–liquid eruption, noise, pipe vibration, and large pressure pulse. The instantaneous high pressure of this regular fluctuation is defined as a hydraulic pulse in the study.

A field analysis indicated that both pipes burst accidents happened in the drainage’s final stage. In both accidents, the pipe burst at its rear end. Therefore, the instantaneous high pressure is speculated to have been the cause of the pipe burst accidents.

Liquid level

Four different pigs were used in the experiment (see Table 1). Figure 9 shows the effect of the liquid level on the maximum hydraulic pulse when the air injection pressure was within a certain range (0.3–0.75 MPa) (the abscissa represents the
Because the distance between the downward-inclined pipe section and the measurement point was relatively short (<10 m), the attenuation of the pressure wave that was generated at the air pocket as it propagated to the measurement point is ignored. Thus, the difference in the hydraulic head between the two points is approximately equal to the difference in the liquid level. The results in Figure 9 show that regardless of which pig was used, the hydraulic pulse exhibited a similar variation pattern: the maximum hydraulic pulse increased with decreasing air–water ratio in the downdip pipe. The occurrence of this phenomenon can be explained by the three effects of the liquid level on the hydraulic pulse:

1. In this experimental system, the pig can achieve a very high acceleration even with an air injection pressure of 0.3 MPa. The pig can reach a relatively high velocity within a short period of time and exerts a significant impact on the air in front of it. Because the length of the air section in front of the pig decreases with increasing liquid level in the downward-inclined pipe section, the buffer effect of the air section on the impact of the pig decreases, and the air section can be more easily compressed, which results in an increase in the pressure in this section.
2. When the liquid level is relatively high, the pig can only move a short distance. Because of the relatively small decrease in the pressure that results from expansion, the upstream driving air can do more work on the pig.
3. When the pig compresses the air, as the length of the air section decreases, the loss in its kinetic energy decreases due to frictional resistance. As a result, the pig does more work on the air, and the air pressure increases more.

Air injection pressure

The air injection pressure is an important parameter that controls the movement of the pig. Figure 10 shows the impact of the air injection pressure on the changes in the maximum hydraulic pulse during the pigging process at liquid levels of 1.0, 4.0, 6.0, and 8.0 m. The experimental results show that the higher the air injection pressure was, the greater the maximum hydraulic pulse. This is because as the air
injection pressure increases, the pig can acquire more energy and reach a higher velocity. Thus, the greater the impact of the pig on the air section was the higher the pressure of the compressed air, the more intense the downstream transient changes.

Trapped air pocket

A pig with a quality of 334.6 g and an interference of 3.9% was used in the experiment. During the experiment, trapped air pockets were artificially generated at the rear end of the pipe system under controlled conditions at two possible locations: a middle position with a water column at both ends of the air pocket and a blind end position with a water column at one end and the pipe at the other end. Figure 11 shows the effect of the volume of the air pocket on the maximum hydraulic pulse when the air injection pressure was within a certain range (0.3–0.75 MPa); the abscissa represents the volume of the air pocket (air pocket numbers 1, 2, 3, and 4.

Figure 10. Maximum pressure of hydraulic pulse versus gas pressure for different types of pigs.
signify that the air section has a length of 0.42, 0.84, 1.26, and 1.68 m, respectively), and the ordinate represents the peak value of the hydraulic pulse generated during the pigging process. At various air injection pressures, the maximum hydraulic pulse had similar variations regardless of where the trapped air pocket was located; the maximum hydraulic pulse decreased with increasing air content (length of the air section). This occurred because a longer air section caused a greater buffering effect of the air section on the impact of the pressurized water flow, which made it more difficult for the air to be compressed, increased the friction loss between the water and the pipe wall and the dissipation of the air–water mixing energy, and consequently decreased the hydraulic pulse pressure.

The effect of the volume of the air pocket in front of the pig on the maximum hydraulic pulse was also studied. The air content was controlled by adjusting the liquid level. Figure 12 shows the experimental results (the air contents of the water that corresponded to liquid levels of 1, 4, 6, and 8 m were 14, 8, 4, and 0 L, respectively). A comparison of Figures 11 and 12 shows that while the hydraulic pulse phenomenon occurred in all of the cases in which a trapped air pocket was present, regardless of its location, the maximum hydraulic pulse that was generated when the air pocket was located in the downward-inclined pipe section was far smaller than that generated when the air pocket was located at the outlet of the drainpipe. The case in which an air pocket is located at the rear end of the drainage system has a more significant detrimental impact on the safety of a pipeline than the case in which an air pocket is located in front of the pig. Therefore, it is necessary to prevent the formation of air pockets at the rear end of a pipeline system during the pigging process to prevent accidents.

Figure 11. Maximum pressure of the hydraulic pulse versus volume of trapped air pocket: (a) at the end of the pipe and (b) in the middle of the water.
Field experiment

A field experiment was conducted to further verify the long-distance gas pipelines pressure pulse phenomenon. It can be seen from Figure 13 that the pipeline is 5.94 km and the elevation is 1449.19 m, the lowest point of 1299.43 m, and the highest of 1550.64 m.
In order to record the process of drastic pressure changes during the under-shooting phase of the pig, a high-frequency pressure sensor suitable for measuring dynamic pressure changes was used. Considering the limited construction site conditions, and to ensure the continuous acquisition of experimental data, notebook computers and USB-type data acquisition devices easy to carry and install were used to monitor and record field data. As shown in Figure 14, a low-frequency pressure sensor and data acquisition devices were installed on the gas injection head, and a high-low frequency pressure sensor and data acquisition devices were installed on the head of drain end.

**Drainage process phenomenon**

As shown in Figure 15, when the pig approached the end of the pipeline, the pig quickly pushed downstream fluid, causing a significant increase in drainage flow. Disturbance of water was intensified with the flow rate increased, sludge existed in the bottom of the pipe would be discharged with the water, and water became cloudy and yellowish. After turbid water drained, water quality recovered and gas–liquid eruptions phenomenon appeared at the end of the pipeline. High-speed flow of gas and water mixture erupted and formed a long liquid column; when the gas continuously discharged is accompanied by a harsh sound, it could be judged that the pig arrived at the receiver.

**Field hydraulic pulse phenomenon**

The specification of field pipe was Φ1016 × 15.9 mm, with the steel grade of X80 and drainage pipe diameter of Φ219 mm. The type of pig was straight plate pig with a mass of 700 kg, two XHP1070-type compressors with rated pressure 2.2 MPa and
rated flow 0.5 Nm³/s. Pressures at the air injection end and drainage end measured by field experiments are shown in Figure 16.

Figure 16 is a graph showing the pressure change at the end of the water injection system measured in the field test. The entire process lasts for about 28.4 h, as
described below. First, the pressure at the gas injection end increased from 0.77 to 1 MPa, and the growth rate is fast at 0–1 h. The pressure gradually increases to 2.36 MPa from 1 to 26 h. After 4 min, the pressure rapidly drops from 2.36 to 1.6 MPa, and the pressure drops to 1.16 MPa. Meanwhile, the pig went to the receiver. At a certain gas injection rate (the gas injection boundary condition is constant current), the pig moves relatively slowly within 0–1 h. This is because in the early stage of the movement, the pig not only overcomes the large static friction resistance but also overcomes the static pressure resistance formed by the height difference about 100 m between the gas injection point and the highest point. After the pigging process lasts for 26 h, the pig moves to the lowest point of the pipe with the pressure of 2.36 MPa. When the gas pressure is higher than the elbow resistance and the downstream hydraulic resistance, the pig begins to accelerate. The downstream resistance decreases as the length of the uphill section continues to decrease. The pig continues to accelerate in the upward section and the pressure drops from 2.36 to 1.65 MPa in 4 min. After the pig passes through the high point, the air in the downward section is compressed, continuing to push the downstream liquid, and the resistance the increases. Then, the air compressor is turned off, resulting in a decrease in pressure drop. When the pig reaches the receiving end, it indicates the end of gas injection. At this time, the pressure is about 1.16 MPa, and the whole process is about 28.4 h. The pressure at the terminal of gas injection is about 1.16 MPa, and the whole process lasts about 28.4 h.

At the beginning, the water flow in the downward section is flowed by gravity. As the liquid level drops, the pressure at the wellhead decreases, resulting in the pressure of drainage system end to slowly decline from 2.5 to 0 MPa. In addition, the valve’s opening angle determines the pressure drop rate. In the case where the drain valve has a certain opening angle, the discharge flow rate decreases with the decrease in liquid level, so the pressure drop rate also reduces. Since the water in the downdip section is discharged by gravity, the head’s pressure is about 0. Throughout the pigging process, this pressure is maintained at zero for a long period of time, occasionally fluctuating.

As the pig’s movement immediately accelerates, the liquid level of the downhill section at the pipeline’s end rises. Consequently, the pressure rises instantaneously. On the contrary, the liquid level drops and the pressure recovers while the pig slows down or stops moving. At 26 h, a pressure pulse appears at the end of the pipe, and the instantaneous pressure is about 5.7 MPa, which quickly drops to 2.5 MPa. Due to the fast speed of the pig, the disturbance of the downstream fluid is enhanced, resulting in water hammer and pressure pulse. The air is compressed when the pig runs in the downhill section, and the downstream pressure first increases and then declines. As the opening angle of the drain valve increases and the upstream pressure accelerates, the liquid level drops faster. Thus, the pig’s speed is reduced. Finally, the pig reaches the receiver under a pressure of 1.16 MPa.

**Conclusion**

This study investigated the characteristics of hydraulic transients that result from the impact of water on trapped air pockets during the pigging process in an
experimental undulating pipe pressure testing and draining system. Besides, we also explored the effects of the liquid level, air injection pressure, pig, and volume and location of the trapped air pocket on the maximum hydraulic pulse. The pressure changes at the measurement points along the pipe and the reasons of the hydraulic pulses’ formation during the pigging process were analyzed. We have obtained the following conclusions.

The maximum hydraulic pulse exhibited similar variations when pigs with different masses and interferences were used; the maximum hydraulic pulse increased with decreasing air–water ratio (increasing liquid level) in the downdip section. As the liquid level increases from 1 to 8 m, the hydraulic pulse increases from 0.31 to 0.54 MPa on the condition of using 231 g pig and injection pressure of 0.3 MPa. The higher air injection pressures behind the pig caused more work to be done on the pig; the faster the pig speed, the greater the impact of the pig on the air bag, the easier the downstream air bag is to compress, and the maximum hydraulic pulse increases. As the liquid level rises to 8 m, the gas injection pressure is increased from 0.3 to 0.75 MPa, and the hydraulic pulse from 0.54 to 0.95 MPa. However, the effects of the interference and the pig’s weight on the maximum hydraulic pulse were unclear in this experimental system. This may be because the interference and mass ranges of the selected pigs were within the non-sensitive ranges of the experimental system. Therefore, other relevant factors must be considered to optimize the pigging type.

In addition, at various air injection pressures, the maximum hydraulic pulse exhibited similar changes when a trapped air pocket was located at the rear end of the drainage system regardless of its position (in the blind end position or the middle position). The maximum hydraulic pulse decreased with increasing air content (increasing length of the air section). When the interception air mass is located at the blind side of the end of the pipeline, the injection pressure is 0.75 MPa, and the hydraulic pulse decreases from 4.9 to 3.21 MPa with the increase in the void fraction. While the hydraulic pulse phenomenon occurred in all of the cases in which a trapped air pocket was present regardless of its location, the maximum hydraulic pulse that was generated when the air pocket was located at the rear end of the drainage system was far greater than that generated when the air pocket was located in the downward-inclined pipe section. The case in which an air pocket is located at the rear end of the drainage system (hydraulic pulse pressure: 4.9 MPa) has a more significant detrimental impact on the safety of a pipeline than the case in which an air pocket is located in front of the pig (hydraulic pulse pressure: 1.0 MPa). Therefore, it is necessary to minimize the generation of trapped air pockets at the rear end of a pipeline system during the pigging process.

The pigging experiment of the undulating pipeline by straight plate pig in field further verified instantaneous high pressure appeared at the end of pipeline in the last stage of pigging process. And its value was much higher than the other points during the entire pigging process, which is called the hydraulic pulse phenomenon. And the real reason for the explosion pipe line is that the hydraulic pulse generated at the end of the pigging process exceeded the maximum ultimate pressure that the pipe could withstand.
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ORCID iD

Jun Zhou https://orcid.org/0000-0003-3230-6306

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**Author biographies**

Jun Zhou, lecturer, works at the School of Petroleum Engineering, Southwest Petroleum University, mainly engaged in the optimization design of oil&gas gathering and distribution system and multiphase flow research.

Tao Deng, senior engineer, works at China National Petroleum Corporation Guangzhou Petroleum Training Center, mainly engaged in multiphase flow theory research of oil&gas pipelines.

Jinghong Peng, Ph.D., is currently studying at the School of Petroleum Engineering, Southwest Petroleum University. His Ph.D. research focuses on multiphase flow theory and experimental research in oil&gas gathering and distribution systems.

Guangchuan Liang, professor, doctoral tutor, works at the School of Petroleum Engineering, Southwest Petroleum University, and has long been engaged in basic theoretical research on oil&gas gathering and distribution systems and gas storage systems.

Xuan Zhou, master, is currently studying at the School of Petroleum Engineering, Southwest Petroleum University. Her research direction is multiphase flow theory of oil&gas gathering and distribution systems.

Jing Gong, professor, doctoral tutor, works at China University of Petroleum (Beijing), has long been engaged in flow assurance and multiphase flow theory of oil&gas gathering and distribution systems.