Force Analysis of $\pi$-type Compensator in Pigging Operation

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Abstract. During the pigging operation of a certain oil depot mixed transmission pipeline, there was a $\pi$-type compensator under significant stress, resulting in apparent displacement of the bent pipe. For this problem, the OLGA software was used to simulate the pigging process of the mixed pipeline, and the impact of the fluid on the $\pi$-compensator bend pipe during the occurrence of slug flow inside the pipeline was calculated and analysed. The calculation results showed that when made a pigging for the liquid-phase fluid pipe, the pipeline pressure declined along the pipeline; and for the gas-liquid two-phase flow pipe, there would be gas accumulation at the bottom of the compensator riser, and then the slug flow was formed. Pipeline pressure at the slug flow increased suddenly, causing pressure fluctuations in the pipeline to increase, pressure drop along the pipeline decreased sharply, and pressure loss occurred at downstream; pressure fluctuations caused by slug flow generated strong fluid shock, resulting in pipeline’s jump and relative displacement, which destroyed the pipe system. The research results are of guiding significance for solving the problem of pigging operation in the multiphase pipeline and provide reference for other similar pigging operations.

1. Induction
In recent years, with the sharp increase in oil and gas demand, and the rapid development of pipeline transportation, pipelines are widely applied to various fields of industry. As the carrier of material transport, pipelines need periodical pigging after being used for a period of time. Pigging can effectively improve the cleanliness and transmission efficiency of pipelines, and are of great significance for ensuring pipelines' safety and reducing their energy consumption [1]. However, due to the varied routes of the mixed transmission pipelines, the fluctuating heights of the pipes, the complex changes of flow pattern in the pipelines, and the unreasonable operation speed of pigs, pigging operations may cause accidents and endanger production safety.

2. Pigging condition
In a pigging operation, using N2 as the gas source to push pig and water on the petrol pipeline outside the depot from the metering and pigging station, and the operation was smooth. The operating pressure is 0.4Mpa and the flow rate is 1900m3/h, and the pipeline is 800mm in diameter, 9mm in thickness and 1.5mm in corrosion allowance. There was an interruption of air supply for about half an hour,
while the end of the pipeline continued to discharge water. After half an hour, the gas source recovered and the pigging operation continued. At this time, the pipe in front of the pipe cleaner made a sound of impact, and the pipe support, which laid on the pipe gallery was about 400m long, fell off (Figure 1), as well as a π-type compensator conduit elbow plastically deformed. About 1 hour later, the pig valve of the petrol tank area received the pig whose shape was basically complete.

![Figure 1. Pipe Shelf Shedding Diagram](image1)

![Figure 2. Pigging schematic diagram](image2)

During the pigging operation, pig’s advancement in the pipeline depends on the thrust generated by the pressurized fluid of the pump. There are two specific pigging methods: 1 Use the pressure to drive the pigging to remove the dirt in front of the pig. This method is suitable for shorter pipe cleaning; 2 Use the pressure generated by the fluid leaking from the pigs to pulverize and discharge the dirt that adheres to the pipe wall. This method is suitable for long pipe cleaning, as shown in Figure 2.

The problems that may be faced during the pigging operation mainly include two aspects: 1. Due to complicated pipelines or topography fluctuations, the resistance during the pigging operation is greater than the thrust, which may cause the pigs to jam; 2. the speed of the pig running is unreasonable. If it is too slow, it will affect the pigging efficiency and extend the construction period. If it is too fast, it will result in unsatisfactory pigging, damage of the pipeline anti-corrosion coating, and mechanical damage of the pigs [2].

3. Model
OLGA software has high precision for simulating oil and gas pipelines and pigging processes. Therefore, the pigging module in the OLGA software is used to calculate the pressure in the oil and gas pipeline based on the two-fluid model, and analyze the influence of the pressure under different gas content on the oil and gas pipeline [3].

3.1. Mathematical Model
The main components of the basic mathematical equation of the two-fluid model are: mass conservation equation, momentum conservation equation and energy conservation equation.

(1)mass conservation equation
For the gas phase, the following relationship is satisfied:

\[
\frac{\partial}{\partial t} (\rho_g V_g) = -\frac{1}{A} \frac{\partial}{\partial z} (A V_g \rho_g V_g) + \psi_g + G_g
\]  

(2)

For the fluid film around the pipe wall, the following relationship is satisfied:

\[
\frac{\partial}{\partial t} \left( V_L \rho_L \right) = -\frac{1}{A} \frac{\partial}{\partial z} \left( A V_L \rho_L V_L \right) - \psi_g \frac{V_L}{V_L + V_D} - \psi_d + \psi_e + G_g
\]  

(2)

For the droplets in the vicinity of the gas phase, the following relationship is satisfied:
\[ \frac{\partial}{\partial t} \left( \rho \rho L \right) = -\frac{1}{A} \frac{\partial}{\partial z} \left( AV \rho \rho L \right) - \psi_\rho \frac{V_L}{V_L + V_P} + \psi_g - \psi_d + G_\rho \]  
(3)

Where: \( \rho \) --- density; \( V \) --- velocity; \( A \) --- pipeline flow cross-sectional area; \( G_\rho \) --- \( f \) phase mass source; \( \psi_\rho \), \( \psi_g \), \( \psi_d \) --- rates of droplet entrainment and deposition, subscript \( g \), \( L \), \( D \) --- respectively represent gas phase, liquid phase, droplet; \( \psi_\rho \) --- The mass transfer rate between two phases, which is positive when liquid phase evaporates; \( V_L \), \( V_g \), \( V_D \) --- the volume fraction of the gas phase, liquid film, and droplets, respectively. It meets that \( V_L + V_g + V_D = 1 \).

(2)momentum conservation equation

Assuming that the internal source \( G_\rho \) enters the fluid perpendicular to the tube wall, then for the gas phase and the droplets in it, it satisfies that

\[ \frac{\partial}{\partial t} \left( \rho \rho L \right) = -\frac{1}{A} \frac{\partial}{\partial z} \left( AV \rho \rho L \right) - \psi_\rho \frac{V_L}{V_L + V_P} + \psi_g - \psi_d + G_\rho \]  
(4)

For fluid film around the pipe wall, the following relationship is satisfied:

\[ \frac{\partial}{\partial t} \left( \rho \rho L \right) = -\frac{1}{A} \frac{\partial}{\partial z} \left( AV \rho \rho L \right) - \psi_\rho \frac{V_L}{V_L + V_P} + \psi_g - \psi_d + \psi_g V_L \frac{d \rho_L - \rho_H}{\partial z} \]  
(5)

Where: \( P \) --- Pressure; \( \nu_L \) --- Relative velocity; \( \alpha \) --- The angle between the axis and the vertical of the pipe; subscript \( i \) --- Interface between gas and liquid phases; \( S_g \), \( S_L \), \( S_i \) --- They respectively represent the wet perimeter of the interface between the gas phase, the liquid film, and the gas-liquid phase; Among them, \( \nu_L \) satisfies the following relationship: When the liquid film evaporates, if \( \psi_g > 0 \) then \( \nu_L = \nu_L \); When the droplet evaporates, if \( \psi_d > 0 \) then \( \nu_L = \nu_P \). When the gas condenses, if \( \psi_g < 0 \) then \( \nu_L = \nu_L \).

(3)energy conservation equation

For the gas-liquid mixture, there is the following relationship:

\[ \frac{\partial}{\partial t} \left[ \frac{1}{2} m_c \left( E + \frac{1}{2} V_L^2 + gh \right) + \frac{1}{2} m_c \left( E + \frac{1}{2} V_L^2 + gh \right) + \frac{1}{2} m_p \left( E + \frac{1}{2} V_D^2 + gh \right) \right] = \]  
(6)

Where: \( E \) --- Energy per unit mass; \( h \) --- Elevation; \( H_\rho \) --- The enthalpy of mass source; \( U \) --- heat transmission Capacity of pipe wall; \( m_p = V_L \rho_L \), among them \( f = g, L, D \).

The above conservation equations of mass, momentum and energy apply to all flow patterns.

3.2. Physical model
The $\pi$-type compensator is shown in Figure 3. The fluid passed through four pipe bends (respectively labeled as observation points 1, 2, 3, and 4) successively in the compensator. Now taking this compensator as an example to analyze the force. Using OLGA to simulate the pigging, and the boundary conditions were set by the inlet node and the outlet node. The inlet node was the closed boundary, and the outlet node was the pressure boundary.

4. Analysis of results

Gas-liquid flow flowed in the pipeline, and the gas-liquid two phases show different macroscopic motion laws—flow patterns, different flow pattern simulation results are as follows

Figure 4 shows the pipeline pressure fluctuation curve when the GOR=0. The four curves respectively represent the pressure fluctuations at the 1 to 4 observation points. As it shows, in the pigging, if the fluid in the pipeline is liquid phase, the pressure of the pipeline at the elbow is almost unchanged;

![Figure 4. The result of pressure when GOR=0](image)

Adjusting gas content, the pressure condition of pipe after generating slug flow was shown in Figure 6. From the figure, it can be seen that the pressure fluctuation at the observation point 1 was obvious, and the pressure jump value was higher than other points. The pressure at observation point 2 also fluctuated significantly, while the pressure fluctuations at observation points 3 and 4 were not obvious. Comparing Figure 4, it can be seen that the pipeline pressure after generating slug flow was obviously increased, and the increased part was mainly at the elbow upstream of the pipeline.
After the slug flow was formed in the pipeline, increased the gas content further. Figure 7 shows the calculation results of the pipeline pressure after the gas volume in the pipeline increased by 1 times, and Figure 8 shows the calculation results after the increase of 4 times. From the figures, we can see that the pressure fluctuation amplitude in the pipeline increased with the increase of gas content in the pipeline: When the gas content increased by 1 times, the pipeline pressure increased by about 42%; when the gas content increased by 4 times, the pipeline pressure increased by about 25%. Among four observation points of the pipeline, the pressure fluctuation of observation point 1 and 2 on the upstream was greater than point 3 and 4.

After the increase of gas content, the change of flow pattern in the pipe was complicated, as shown in Figure 9. According to the figure, the slug flow, bubble flow, stratified flow, and annular flow in the pipe appeared alternately. In the horizontal pipe, there were mostly stratified flow, and sometimes the bubble flow. In the curved pipe, there was slug flow. And in the vertical pipe section, there was annular flow.

Compared Figure 6~8, the pressure fluctuation at observation point 1 was the most obvious, and as can be seen from Figure 9, slug flows were more likely to occur at observation points 1 and 2, indicating that the most significant position of the pressure fluctuation caused by the slug flow is at the No. 1 elbow of the pipeline, and the action time was also the longest compared with other elbows; Compared Figure 4–5 with Figure 6–8, when slug flow occurs in the pipeline, the pressure fluctuations at the upstream of the pipeline were significant, but at the downstream of the pipeline were not obvious. And in the downstream pipeline, there is a distinct loss of pressure. The No. 4 elbow, which should have been under high pressure, had a pressure value similar to that of No. 3 elbow. It can be seen that the pressure of the downstream pipe was seriously damaged due to the slug flow.
The pressure curves of different gas content in pipeline at the observation point 1 in the pigging is shown in figure 10. Compared the pressure fluctuation curves of different gas content, it can be seen that the influence of gas content on the pipeline pressure was very obvious: when there was a single-phase flow in the pipeline, the pressure value of the pipeline did not fluctuate significantly; when the gas content was increased, the pressure value of the pipeline was obviously raised and lowered. Moreover, with the increase of gas content, the fluctuation interval of pipeline pressure was larger and the fluctuation time was longer.

According to figure 10, the pressure of the fluid in the pipe at No. 1 elbow can be known, thus calculate the thrust generated by the fluid in the pipe as\[4,5\]

$$F = A \times \Delta \rho$$

(7)

Where, $F$ is the force generated by the fluid in the pipe; $\Delta \rho$ is the pressure difference between before and after the fluid in the pipe at No. 1 elbow, that is, the difference between the pressure produced by the fluid in the pipe under pigging and the pressure at the outlet of the pipe. $A$ is the cross-sectional area of the pipe.

Under the action of the thrust force, the velocity of the fluid in the pipe reaching the tip of the $\pi$-type compensator can be calculated by the following equation according to the kinetic energy theorem $[4,5]$:

$$\left(F - mg\right)h = \frac{1}{2}mv^2$$

(8)

Where, $m$ is the quality of the fluid in the pipe; $g$ is the acceleration of gravity; $h$ is The running height of the fluid in the pipe; $v$ is the velocity of the fluid reaching the top of the $\pi$-type compensator.

According to the principle of momentum conservation of fluid mechanics, ignoring local friction, the impact force of the fluid on the top of the $\pi$-type compensator is

$$F_y = -\rho \dot{Q}v$$

(9)

Where, $F_y$ is the impact force of the fluid at the top of the $\pi$-type compensator; $\dot{Q}$ is the elbow outlet flow. The calculation results are as follows:

| Table 1. The calculated result of the impact force of the fluid on the pipe under different gas content |
|-------------------------------------------------|-----------------|----------------|----------------|----------------|
| $\Delta \rho$ (Pa)  | $F$ (kN)         | $v^2$          | $v$ (m/s)      | $F_y$ (kN)     |
| GOR=1               | 250000           | 11.915         | 55.523         | 7.45           | 20.641          |
| GOR=10              | 600000           | 28.596         | 272.376        | 16.50          | 101.255         |
| GOR=20              | 850000           | 40.511         | 427.271        | 20.67          | 158.837         |
From the calculation results in Table 1, it can be seen that comparing the results of GOR=1~50, the pipe received the greatest impact when GOR=20, which was 158.837kN; the fluid velocity reached 20.67m/s at the top of the riser. According to the pipeline model, using Autopipe software to analyze, it can be seen that under the force of 158.837kN, the maximum vertical displacement at the elbow of the pipeline was 175.42mm, with the largest component in the Y direction and the second component in the Z direction. The displacement diagram is shown in Figure 11:

![Figure 11. Displacement of compensator bend](image1)

![Figure 12. The stress of compensator bend](image2)

The stress distribution at the elbow of the compensator was shown in Figure 12. It was found that the stress at the bent pipe of the compensator was about 123Mpa, which was far greater than the stress at the horizontal pipe and higher than the allowable stress value. The stress at the elbow was about 2 to 3 times of the stress at the horizontal pipe. Compared with the horizontal pipe, the riser was the part with concentrated stress, especially the top of the riser. The high-speed impact of the fluid in the pipe increased the stress of the bend pipe at the top of the riser, so the displacement of the pipe at this location was also the most serious part of the entire compensator.

5. Conclusion
The OLGA was used to simulate the pigging operation, and the pipe section forming the slug flow was analyzed with AutoPIPE. The conclusions are as follows:

(1) For single liquid phase fluid in the pigging, the pipeline pressure decreased along the pipeline; for gas-liquid two-phase flow, the pipeline pressure fluctuated greatly at the bent pipe where the gas gathered.

(2) When the gas content increased, a bubble or slug flow was generated in the pipe, and the slug flow formed in the bend at the bottom of the compensator riser. The slug flow increased the pressure fluctuation, the pressure drop along the pipeline decreased sharply, and the loss of pressure occurred at downstream.

(3) The high-frequency alternating load generated by slug flow would form a strong fluid shock, which would have a strong destructive effect on the pipe, especially the bend of the riser. It caused the pipe to jump on the pipe rack and generated relative displacement with the pipe support, thus endangering the production safety.

(4) It is recommended that the bottom and top of the riser, which are easy to gather gas, should be reinforced and monitored in real time to control the pressure and flow at the inlet of the pipeline, or set the exhaust valve at the top of the riser to prevent the gas from gathering at the bottom of the riser to form a slug, so as to ensure the safety of operation.

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