CHANG CHEN
JIKUN GUO
SHIFU ZHANG
QIXIN ZHANG
FAN ZHANG
JIANTING ZHOU
and
LIGANG ZOU

Analytical model and numerical simulation on pipeline evacuation of offshore oil transportation system

This paper focus on the pipeline evacuation of offshore oil transportation system. The mathematical model for pipeline evacuation was established, and the total emptying time under different working pressure was calculated by using MATLAB software. Frictional resistance and velocity distribution of the pipe under different time intervals was analyzed. The numerical simulation for the pipeline evacuation was carried out by using ANSYS software. The pressure distribution, velocity distribution and distribution law of the fluid trajectory are calculated and discussed, which can provide references for the analysis and control of the variation of the pipeline during the evacuation operation.

Keywords: *Offshore oil transportation system; pipeline evacuation; numerical simulation; nnalytical model.*

1. Introdunction

Flexible pipelines are widely used in offshore oil transport systems and other marine engineering areas due to their large tensile strength, small bending stiffness and limited storage space acquired (Chang, et al., 2014). The pipeline must be evacuated before its withdrawal operation, so it is meaningful to explore the regulations of pipeline evacuation of offshore oil transportation system during the emptying process. Many experts and scholars have carried out relevant research on this topic. Jiang Junze established a dynamic model of emptying, which is solved by the method of characteristics (MOC), and the velocity of spherical pig and the variation of pressure drop are obtained (Jiang Jun-ze, et al., 2017). Deng Tao provided an experimental tool to simulate how the drainage pressures are affected by relevant parameters like inlet pressures of different buffer tank, flowrates, drainage pipe diameters and air contents in liquid. For the purpose of accuracy, the test system, including all lines and related facilities, is checked before hydrotest and water draining test (Tao, et al., 2015). Kristoffersen presented material and component tests on specimens taken from an X65 offshore pipeline. Results in terms of force-displacement curves are quite similar for the empty. Computer simulations of the component tests are carried out using various numerical techniques for fluid discretization and for fluid-structure interaction (Kristoffersen, et al., 2014). Deng Tao discussed the principle of segmental pressure test, and presented the motion model of pig and status of slack flow in pipe during drainage. Moreover, simulation software has been developed for pressure test and drainage under different terrains on the basis of theoretical research and tests (Tao, et al., 2014). Palabiyik had identified three flow regimes and their research results show that the overall cleaning time can be reduced by at least 25% by selecting the best removal conditions in the different stages (Palabiyik, et al., 2014). Watanabe have performed calculations model to estimate the evacuation time of the long cryogenic pipes (Watanabe, et al., 2013). Xu, Jingyuan built up a pigging mathematical model by use of a mixed Eulerean-Lagrangean method to achieve coupling the pig movement with the fluid quasi-steady state flow. Based on this model, a computer program was developed to numerically simulate pigging dynamics and the flow parameters such as volume flow rate of gas and liquid phases (Xu, et al., 2011). From the current research literature, the study of pipeline evacuation is limited. And different from previous studies, this paper established the emptying model of offshore soft pipeline from the perspective of actual operation and carried out relative numerical analysis based on ANSYS software. It is of great significance to test the pressure capacity of pipeline and the safety of operation.

2. Technological process of pipeline evacuation

When offshore oil transportation system finished the oil transfer mission, the pipeline must be evacuated before its withdrawal operation. Since all operations are dependent on the ship's equipment, the evacuation unit must provide the working vessel for emptying tasks. Evacuation unit can be

Messrs. Chang Chen, Jikun Guo, Shifu Zhang, Qixin Zhang, Fan Zhang, Army Logistics University of PLA, Chong Qing, 401311, Jianting Zhou, Air Force Research Institute, Beijing 100076, Ligang Zou, Weihai Yihe Specialty Equipment Mfg. Co. Ltd., Shandong, China. Corresponding author Chang Chen, E-mail: 408430734@qq.com

composed of air compressor, high pressure gas tank, receiving and dispensing device, high pressure spring reel and other components. The main tasks of this system are to complete the pipeline pressure test, pipeline emptying operations and transceiver pipeline pig operations. Technological process of this system is shown in Fig.1.

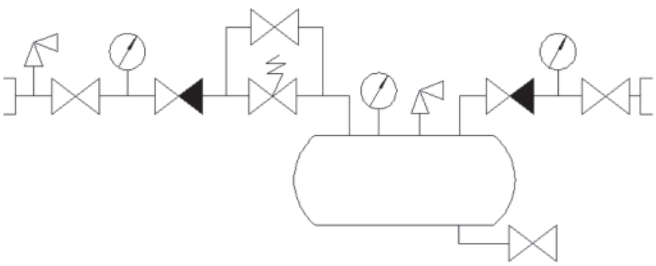

Fig.1 Flow chart of pipeline evacuation of offshore oil transportation system

3. Analytical model for pipeline evacuation process

Based on the analysis of actual situation of pipeline evacuation, the basic pipeline evacuation model can be established. Fig.2 shows the schematic diagram of whole process.

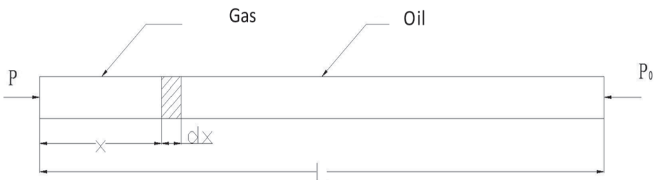

Fig.2 Sketch of evacuation model

At time t, the gas-liquid interface reaches the position of d_1, where the distance from interface to pipe entrance equals x. Time dt later, the gas-liquid interface reaches the place of d_2, moving distance of dx in the direction to the pipe outlet.

Combined Planck formula (Fabbri and Navarro-Salas, 2005) and Reynolds number formula (Solsvik, 2017), equation (1) can be obtained.

$$\begin{cases} \dfrac{1}{\sqrt{\lambda}} = 2\lg\left(\mathrm{Re}\sqrt{\lambda}\right) - 0.8 \\ \mathrm{Re} = \dfrac{vD}{\upsilon} \end{cases} \tag{1}$$

In equation (1), λ is the friction coefficient of liquid part. Re is the Reynolds number of liquid section. v is the velocity of liquid segmet. υ is the kinematic viscosity of liquid part.

At time t, taking the liquid section in pipeline as the research object, the force analysis of it can be analyzed as follows. The left side of the liquid section suffered pressure P, and right side of the liquid subjected to pressure P_0. Moreover, it effected by frictional resistance f of pipeline. Equation (2) can be derived according to Newton's law.

$$\begin{cases} PS - P_0 S - f_t = m_t a_t \\ m_t = \gamma S(L - X) \\ v = \dfrac{dx}{dt} \\ a = \dfrac{dv}{dt} \end{cases} \tag{2}$$

In equation (2), S is the cross sectional area of pipeline. f_t is the friction force of liquid part at time t, m_t, is the quality of liquid part at time t, a_t is the acceleration of liquid part at time t, γ, is the severe of liquid section. Formula (3) can be derived according to formula of friction loss along path.

$$h_f = \lambda \frac{L - X}{D} \frac{v^2}{2g} \tag{3}$$

Formula (4) can be deduced based on law of Newton inner friction.

$$\begin{cases} \tau = \mu \dfrac{du}{dy} = \dfrac{D\gamma}{4} i \\ f_t = \tau \pi D(L - X) \\ i = \dfrac{h_w}{L - X} \\ h_w = h_f + h_j \approx K h_f \end{cases} \tag{4}$$

In formula (4), τ is average shear stress on the pipe interface. i is the slope of pipeline. h_w is total friction loss, h_f is pipe friction loss, h_j is local friction loss, K is proportional coefficient. Formula (5) can be derived based on equation (1) to equation (4).

$$\begin{cases} \dfrac{P - P_0}{\gamma\left(L - X\right)} - \dfrac{\lambda K}{2Dg}\left(\dfrac{dx}{dt}\right)^2 = \dfrac{d^2 x}{dt^2} \\ \dfrac{1}{\sqrt{\lambda}} = 21\mathrm{g}\left(\dfrac{\sqrt{\lambda} d}{\upsilon}\dfrac{dx}{dt}\right) - 0.8 \end{cases} \tag{5}$$

4 Numerical model for pipeline evacuation process

4.1 The establishment of geometric model

Offshore oil transportation system adopt the air head emptying mode for oil extraction operation. When the oil supply operation is completed, air is injected into the pipe under the action of the air compressor. The pigger moves in the direction of the pipe outlet under the action of compressed air, and the remaining oil was drain out from the pipeline. Considering that the model is a gas-liquid mixing model, a two-dimensional planar gas-liquid mixed VOF model is adopted as shown in Fig.3.

4.2 Grid partition

As a result of the two-dimensional plane model, this paper uses the plane scan method for rectangular grid division, and

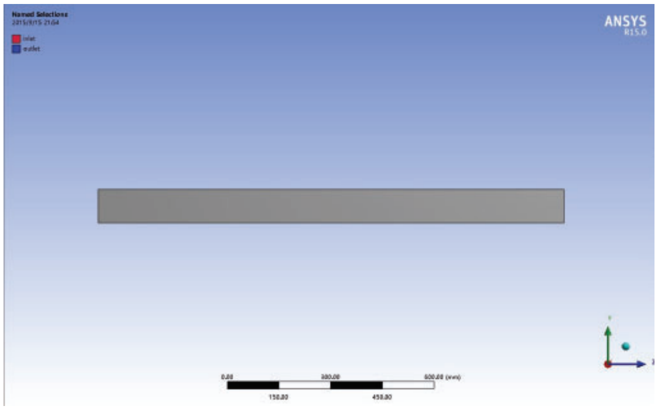

Fig.3 Pipe evacuation model

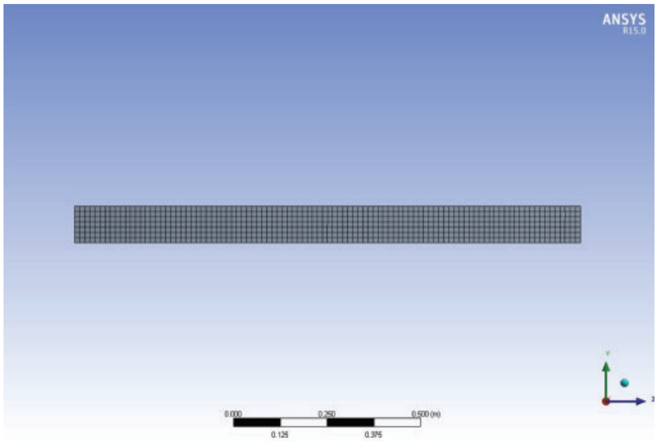

Fig.4 Grid partition of pipe evacuation model

sets the left end of this model as outlet. Meanwhile, the right end of this model was set as inlet. The final number of grid are 30354, the number of nodes are 4560 as is shown in Fig.4.

4.3 Governing equation

(1) Continuity equation

The quality of the system is expressed in integral form, showing as equation (6).

$$m = \iiint_{V(t)} \rho dV \tag{6}$$

According to the conservation of mass theorem, equation (6) could transform into equation (7).

$$\frac{dm}{dt} = \frac{d}{dt}\iiint_{V(t)} \rho dV = 0 \tag{7}$$

Equation (7) is the Lagrange integral form of continuous equation. Combined equation (7) with transport equation and Gaussian formula, Euler's form of continuous equation can be obtained as equation (8).

$$\frac{d\rho}{dt} + \nabla \square (\rho u) = 0 \tag{8}$$

In equation (8), $\frac{d}{dt}$ represents material derivative, and $\frac{d}{dt} = \frac{\partial}{\partial t} + u \ \square\nabla$. For incompressible fluids, the density equation is constant, and the continuous equation can be transformed as follows.

$$\nabla \square \mathrm{u} = 0 \ or \ \frac{\partial u_1}{\partial x_1} + \frac{\partial u_2}{\partial x_3} + \frac{\partial u_3}{\partial x_3} = 0 \tag{9}$$

(2) Momentum equation

The momentum of the moving fluid element can be expressed as:

$$udm = \rho u dV \tag{10}$$

The momentum conservation principle is that the momentum change rate of the fluid system is equal to the sum of the external forces of the system.

$$\iiint_{V(t)} \rho dV = \sum F \tag{11}$$

In equation (11), the external force mainly includes the volume force (mass force) and the area force. Combining the tensor form of the stress, the Renault second transport equation and the Gaussian formula, the momentum equation can be simplified as equation (12).

$$\rho \frac{du}{dt} = pf + \nabla \square \sigma \tag{12}$$

(3) Energy equation

e represents the internal energy of the unit mass fluid. ρe represents the internal energy of the unit volume fluid. $\frac{1}{2}\rho u \square u$ represents kinetic energy of unit volume fluid. So, the total energy contained in the unit volume of fluid can be formulated as $E = \rho e + \frac{1}{2}\rho u \square u$. The principle of energy conservation can be expressed as equation (13).

$$\frac{d}{dt}\iiint_{V(t)} \rho\left(e + \frac{1}{2}u \square u\right)dV = \sum W + \sum Q \tag{13}$$

In equation (13), $\sum W$ represents the sum of power made by internal and external forces per unit time, $\sum Q$ represents the total energy transformed into system in unit time.

4.4 Solver and parameter setting

Two-dimensional single-precision pressure-based transient model *VOF (Volume of Fluid)* was select as computational model, and k–ε solver equation was selected as viscosity equation. The method of dealing with the standard wall function was applied to the near wall. Air and diesel-liquid was choosen as research media. During the stage selection, air was selected in stage 1, and the diesel-liquid was selected in stage 2. In the process of setting of the solution method, *SIMPLEC* was selected as the pressure velocity correlation form, what is more, appropriate relaxation factor, proper computational accuracy was set for iterative calculation.

5 Results and analysis

5.1 Analysis of pipeline evacuation analytical model

During the research process, the ThinkPad T430 computer which is equipped with 4 cores 2GHz processor and 16GB capability of memory has been used as experimental hardware platform, using MATLAB 2016a software for 8 threads parallel computing related procedures.

Formula (5) can be transformed to the differential equation between dx and dt. Total length L=1350m, inside diameter of pipeline d = 98mm. Total emptying time T was calculated when the compressor working pressure are taken different values. For example, pressure equal to 0.7MPa, 1.0MPa and 3.0MPa. The results are shown in Table 1.

Table 1 Calculation result of total emptying time

Compressor working pressure P(MPa)	3.0	1.0	0.7
Total emptying time T(s)	194.58	361.14	448.65

The frictional resistance of pipeline and velocity distribution of marital unit under different time intervals are presented in Figs.5 and 6.

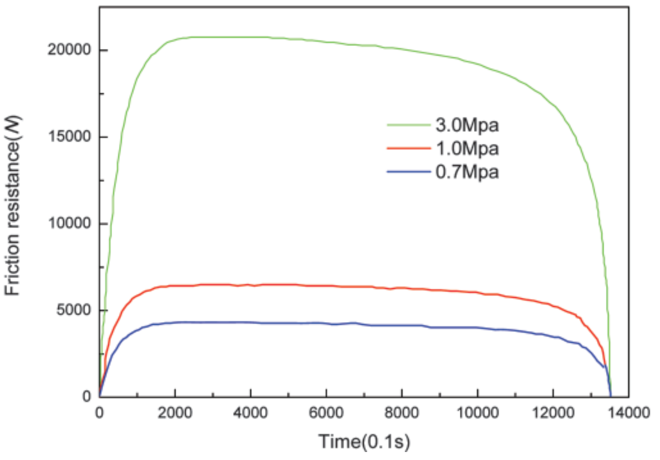

Fig.5 Frictional resistance varies with emptying time

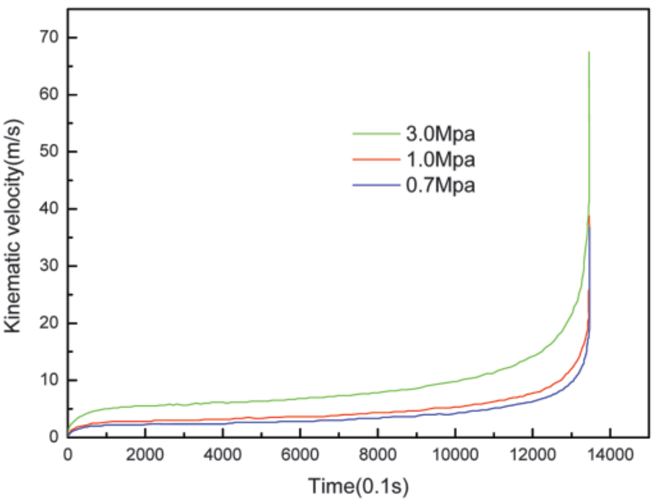

Fig.6 The speed varies with the emptying time

In Fig.5, as the emptying time increases, the frictional resistance begins to increase rapidly to a certain value, then it decreases at a very slow rate. At a certain point in time, the frictional resistance is decreasing to zero rapidly. In Fig.6, the velocity of emptying material increases gradually with the increase of emptying time, and when approaching the end of pipeline, the speed of it increased rapidly. Some reasons may account for this phenomena. At the beginning of the evacuation operation, the pipeline was filled with liquid, lead to a larger medium friction resistance and a slower medium emptying speed. With the continuously promoting of emptying operations, the gas volume gradually increased, and the liquid volume decreased gradually. As a result, the friction resistance decreased, the emptying speed gradually increased. When the liquid section is empty, the pipeline is full of gas, and the emptying speed reaches its maximum value.

5.2 Analysis of numerical simulation results

(1) Pressure distribution regulation

Pressure change nephogram during the pipeline evacuation procedure can be obtained according to the iteration calculation result as shown in Fig.7.

During the evacuation operation, the position that connected to the outlet of the high pressure air tank of the air compressor have higher pressure. The static pressure is decreasing along the fluid flow direction, and reaches the minimum value at the outlet of pipeline. Because the air section of the friction resistance is small, while the diesel section frictional resistance is larger. So, the safety check should focus on the key point of the exhaust inlet considering the pressure capacity of the pipeline and the safety of the pressure.

(2) Velocity distribution regulation

Fig.8 shows the velocity distribution vector diagram during pipeline evacuation procedure.

The velocity of the internal fluid gradually increases along the direction of the pipeline evacuation. From the radial direction, there is a minimum value at the inlet of the exhaust and the maximum value at the outlet. As time goes on, the frictional resistance of the whole pipeline is decreasing, so the fluid speed along the emptying direction is increasing. What is more, there is a boundary layer close to the pipeline wall. Thus, the closer to the pipe wall, the smaller is liquid speed.

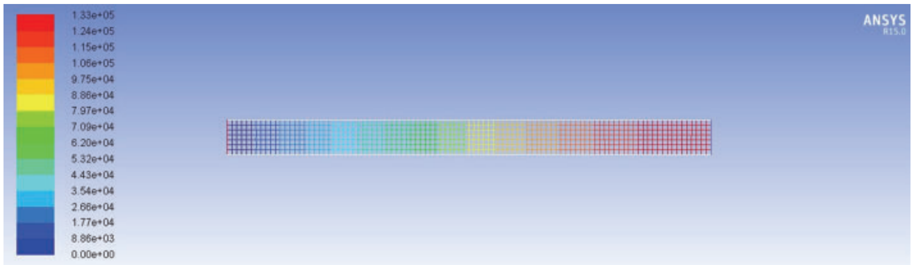

Fig.7 Pressure change nephogram

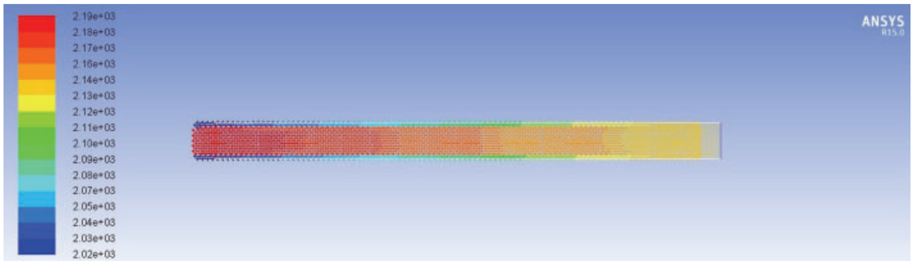

Fig.8 Velocity distribution vector diagram

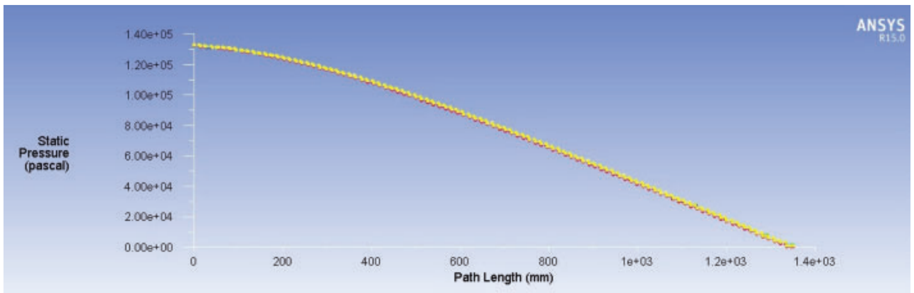

Fig.9 The relationship between fluid trajectory and static pressure

(3) Orbit distribution regulation

The relationship between fluid trajectory and static pressure during pipeline evacuation procedure can be obtained according to the calculation result (Fig.9).

In the process of evacuation, the internal fluid mainly includes air, diesel and the two gas-liquid mixture. The pressure at the inlet section reaches its maximum value, which is the maximum pressure that compressor can provide. Accompany with the fluid movement, the static pressure continues to decrease and eventually reaches the minimum at the exit.

6. Conclusion

This paper focuses on the evacuation process of offshore oil transportation system, and the mathematical model of the pipeline emptying is established. Based on actual situation, the total emptying time is 194.58s when the working pressure of the compressor is 3.0MPa. What is more, the friction resistance and velocity distribution of pipeline under different time interval is analyzed. The numerical model of pipeline is established by using the ANSYS software, and pressure distribution, velocity distribution, distribution of fluid particles are analyzed. It is of great significance to test the pressure capacity of pipeline and the safety of operation.

Acknowledgments

This paper is supported in part by The National Key Technology R&D Program of China (2017YFC0806306), Education Science fund of the Military Science Institute of Beijing, China (No.2016JY481), and Chongqing Graduate Scientific Research Innovation Project, China (No.CYB17148).

Reference

1. Chang, C., Shi-Fu, Z., Xie Jun, E. A. (2014). QFD-based Research on Coastal Oil and Water Transmission System. *Journal of Sichuan Ordnance*, 6(12): 82-87.
2. Fabbri, A., Navarro-Salas, J. (2005). Einstein-Planck formula, equivalence principle, and black hole radiance. *International Journal of Modern Physics D*, 14(12): 2213-2217.
3. Jiang Jun-Ze, Zhang Wei-Ming, Yong Qi-Wei, Ming, J. (2017). Analysis of the Influencing Factors and Mechanism of Gas Draining Rate of Mobile Pipeline. *ACTA Armamentarii,* 38(3): 585-592.
4. Kristoffersen, M., Casadei, F., Børvik, T., Langseth, M., Hopperstad, O. S. (2014). Impact against empty and water-filled X65 steel pipes - Experiments and simulations. *International Journal of Impact Engineering,* 71(6): 73-88.
5. Palabiyik, I., Olunloyo, B., Fryer, P. J., Robbins, P. T. (2014). Flow regimes in the emptying of pipes filled with a Herschel-Bulkley fluid. *Chemical Engineering Research & Design,* 92(11): 2201-2212.
6. Solsvik, J. (2017). Turbulence modelling in the wide energy spectrum: Explicit formulas for Reynolds number dependent energy spectrum parameters. *European Journal of Mechanics B-Fluids*, 61170-176.
7. Tao, D., Bin-Tao, X., Yu Da, E. A. (2015). Test system for water draining after hydrotest of oil/gas pipelines. *Oil & Gas Storage, Transportation*, 34(12): 1305-1309.
8. Tao, D., Jing, G., Yu Da, E. A. (2014). Influence of complex terrain on the pressure test and drainage of long-distance gas pipeline. *Oil & Gas Storage & Transportation*, 33(12): 1326-1330.
9. Watanabe, H., Sun, J., Yamamoto, N., Hamabe, M., Kawahara, T., Yamaguchi, S. (2013). Evacuation time of cryogenic pipes for superconducting power transmission. Physica C-Superconductivity and Its Applications, 494292-296.
10. Xu, J., Li, C., Liu, B., Liu, J. Numerical Simulation of Pigging Operation in Gas-Liquid Two-Phase Flow Pipelines [M]. 2011 International Conference on Pipelines and Trenchless Technology. Beijing; Pipeline Division of ASCE. 2011: 477-491.