Leakage Position of Pipeline on the Underground Diffusion of Crude Oil

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Abstract. Although underground pipeline transportation of crude oil is critical, very few studies have been found in the literature addressing the effects of the pipeline leakage position. To fill the gap, in this study, the influences of the leakage position of a pipeline on the underground diffusion of crude oil were investigated numerically. The results showed that the leakage position largely affects the shape of crude oil diffusion. The diffusion contour of the crude oil changes from shapes of inverted U and ellipse to circle when the leakage positions are located at the top, side and bottom sections of the pipeline. It was known based on numerical results that the leakage position shows limited influence on axial diffusion width and radial diffusion depth of crude oil. Empirical relationships were developed to predict the axis diffusion width and radial diffusion depth. The outcomes of this study provide a technical guidance for the underground pipeline transportation safety and the related emergency management.

1. Introduction
Oil is a major liquid fuel, and it is also the basis of most other liquid fuels. It is formed by refining petroleum or crude oil, which is a very complex mixture of components, composed of many different types of hydrocarbons of various molecular weights. Unprocessed petroleum is usually called crude oil, which is a dark brown, greenish-fluorescent, viscous oily liquid with a special odor. It is a mixture of liquid hydrocarbons such as alkanes, aromatic hydrocarbons, and olefins. As the transportation of crude oil much relies on underground pipeline, the relevant accidents mostly start with the leakage because of its flammability and explosivity [1]. Oil leakage can occur through mechanical failure, operational error natural hazard, corrosion of pipelines, third party activity and sabotage, while a statistic indicated that during 1976 and 1998 there are 5,724 leakage accidents in Nigeria [2]. The situation is getting worse as it is estimated that approximately 40% of the world-wide pipeline network has reached its project life (estimated in 20 years) [3].

Pipeline transportation of crude oil not only is significant to save lives and properties, but also avoids the pollution to the surrounding environment. If the leakage of oil is not treated in time, the oil will move rapidly in the porous medium (e.g. soil) under the gravity and concentration gradient. The situation gets worse when the leakage flow encounters surface or underground water flow, while the diffusion processes could be accelerated, resulting in serious pollution of water resources and soil. Under the event with big leakage, the oil that migrates through the soil will continue infiltrating the upper part of the pipeline over time until it reaches the surface and gradually accumulates on the ground. Serious fire or
explosion accidents will happen when it contacts open fire or high-temperature, or even under radiation (e.g. solar radiation). Due to the invisibility of the leakage diffusion of buried pipelines, the dynamic process is more complicated than the leakage of pipelines laid on the ground.

Numerical tools have been largely utilized to address the influences of factors on the diffusion processes of oil products. Qi et al. [4] used a numerical tool to simulate the leakage point of oil pipeline, showing the distributions of velocity, temperature. Zhu et al. [5] used Fluent software to study the oil flows from damaged submarine pipelines with different leak sizes.

The high volume of numerical studies is much due to the difficulty of undertaking experiments and the follow-up underground measurements. Those numerical tools could be effective tools for the relevant analysis after the validation, which is able to provide more detailed information when comparing to experiments. For example, the numerical results can provide the concentration contour of the oil, which is kind of impossible for the experiments.

Although previous studies have been largely on the diffusion mechanisms of oil, less studies were undertaken on the influences from leakage position. There is still less information, from the fundamental, about quantitatively addressing the influences of the leakage positions on the crude oil diffusion. For example, Chuvilin et al. [6] investigated the migration processes of oil products in porous media under the influences of physical factors such as soil porosity and salt content. Waddill et al. [7] investigated the influences of residual saturation on oil recovery by simulating the diffusion and migration processes of LNAPL (Light Non-Aqueous Phase Liquid) in sandy unsaturated soils. Halmemies et al. [8] found that seepage velocities of gasoline were three (sandy till and peat) to five (gravely sand) times faster than with diesel oil. Abdul [9] analyzed the migration characteristics of oils in sandy porous media through one-dimensional sand column experiments.

Therefore, under the above mentioned research gap, the processes of the leakage of crude oil through underground pipeline were analyzed numerically, and the influences of the leakage position on underground oil diffusion were addressed. Furthermore, empirical relationships were developed for the prediction of underground oil diffusion.

2. Methodology

2.1. Numerical theories

The experimental cost of leakage and diffusion of buried pipelines is very high. At the same time, the pipeline leakage and the related processes are complicated, while the difficulty increases to much even with the underground measurement. Due to the complexity of the experimental measurement, computational fluid mechanics as a multidisciplinary tool has been adopted for this study, involving computer science, fluid mechanics, mathematical theory of partial differential equations, and numerical analysis [10].

Fluent is one of the most popular CFD (Computational Fluid Dynamics) tools used by researchers. It provides four kinds of multiphase flow models: Volume of Fluid (VOF) model, Euler model, Mixture model and Wet-Steam model [5,11]. Among them, VOF model, Euler model and Mixture model are commonly used to solve multiphase flow, while the VOF model is suitable for calculating the flow of plug, bubbly flow, seepage, pore flow or free surface flow. The VOF multiphase flow model is more suitable for the simulation of leakage and diffusion of buried pipelines than other multiphase flow models. Therefore, the VOF multiphase flow model was used in this study to solve the leakage problem. For the completeness of the article, some features of Fluent, including the control equations, are briefly introduced here.

Among them, the continuity equation is as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_x)}{\partial x} + \frac{\partial (\rho u_y)}{\partial y} + \frac{\partial (\rho u_z)}{\partial z} = 0$$  \hspace{1cm} (1)

Where $u_x$, $u_y$, and $u_z$ are the velocity components following the $x$, $y$, and $z$ directions, respectively, m/s; $t$ is the time, s; and $\rho$ is the density, kg/m$^3$.

The momentum conservation equation is given as follows:
\[
\frac{\partial (\rho u_x)}{\partial t} + \nabla \cdot (\rho u_x u) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial z} + \rho f_x
\]  
(2)

\[
\frac{\partial (\rho u_y)}{\partial t} + \nabla \cdot (\rho u_y u) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \rho f_y
\]  
(3)

\[
\frac{\partial (\rho u_z)}{\partial t} + \nabla \cdot (\rho u_z u) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z
\]  
(4)

Where \( f_x, f_y, \) and \( f_z \) are unit mass forces following the x, y, and z directions, respectively, \( \text{m/s}^2 \); \( \tau \) is the viscous stress, \( \text{Pa} \); and \( P \) is the pressure on the fluid microelement, \( \text{Pa} \).

The energy conservation equation is:

\[
\frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\rho E u) = \nabla \cdot [k_{\text{eff}} \nabla T - \sum_j h_j \mathbf{J}_j + (\tau_{\text{eff}} \cdot u)] + S_h
\]  
(5)

\[
E = h - \frac{p}{\rho} + \frac{u^2}{2}; h_j = \int_{T_{\text{ref}}}^T C_p \mathrm{d}T; T_{\text{ref}} = 298.15 \text{K}; k_{\text{eff}} = k + k_i
\]  
(6)

Where \( E \) is the total energy, \( \text{J/kg} \); \( h \) is the enthalpy of component \( j \), \( \text{J/kg} \); \( J_j \) is the diffusive flux of component \( j \); and \( k_{\text{eff}} \) is the effective heat transfer coefficient, \( \text{W/(m·K)} \).

The kinetic energy equation is:

\[
\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho u u) = \frac{\partial}{\partial x} [(\mu + \frac{\mu_j}{\sigma_k}) \frac{\partial u}{\partial x}] + \frac{\partial}{\partial y} [(\mu + \frac{\mu_j}{\sigma_k}) \frac{\partial u}{\partial y}]
\]  
(7)

The energy dissipation rate equation is:

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho \varepsilon u) = \frac{\partial}{\partial x} [(\mu + \frac{\mu_j}{\sigma_k}) \frac{\partial \varepsilon}{\partial x}] + \frac{\partial}{\partial y} [(\mu + \frac{\mu_j}{\sigma_k}) \frac{\partial \varepsilon}{\partial y}]
\]  
\[+ \frac{\partial}{\partial z} [(\mu + \frac{\mu_j}{\sigma_k}) \frac{\partial \varepsilon}{\partial z}] + \frac{C_{\text{dz}} E}{k} \text{Gi} - C_{\text{z2}} \rho \frac{E}{k}
\]  
(8)

Where \( u, v, \) and \( w \) are the velocity components following the x, y, and z directions, respectively, \( \text{m/s} \); \( P \) is the pressure on the fluid microelement, \( \text{Pa} \); \( t \) is the time, \( \text{s} \); and \( \rho \) is the density, \( \text{kg/m}^3 \).

2.2. Numerical model

This study mainly focuses on the diffusion of crude oil pipeline with a small hole leakage, taking a buried oil pipeline in Shanxi of China as an example. It was assumed that the diffusion was a steady state leakage diffusion stage, and the pressure during the whole process can be approximately considered constant. We used SolidWorks 3D mechanical design software to establish a geometric model that is in line with the actual situation.

The pipe is a circular cross-section, called Q235. Its length is 6.0 m, while the pipe inner diameter is 0.5 m, and the pipe wall thickness is 0.008 m. The geometric model is shown in Figure 1. The buried depth of the pipeline is 1.5 m. The leakage happened 3.0 m away from the entrance, and its diameter is 0.05 m, considering located directly at the top, bottom or the horizontal side of the pipeline. A 3D model of leakage and diffusion was established, with a dimension of 6 m cube, as shown in Figure 2.

The properties for modelling inputs were determined before performing numerical studies. The crude oil studied in this paper was originated from Yanchang oilfield, China. The specific simulation parameters are as shown in Tab.1. For all the simulations, we assumed that there is a small hole leakage, the initial speed of the leakage port is set to 0.5 m/s.
Table 1. A summary of properties of crude oil, air and soil for modelling inputs

| Component | Property               | Value                  |
|-----------|------------------------|------------------------|
| Crude oil | Density                | 840 kg/m³              |
|           | Specific heat capacity | 2090 J/k·K             |
|           | Thermal conductivity   | 0.149 W/m·K            |
|           | Viscosity              | 5 mm²/s                |
| Air       | Density                | 1.225 kg/m³            |
|           | Specific heat capacity | 1006.43 J/k·K          |
|           | Thermal conductivity   | 0.0242 W/m·K           |
|           | Viscosity              | 1.7894 ×10^-5 mm²/s    |
| Soil      | Porosity               | 0.45                   |
|           | Viscosity coefficient  | 4.72×10^9 m^-2         |
|           | Inertia resistance coefficient | 2.1×10^7 m^-1 |

Figure 1: A schematic of the pipeline in this study

Figure 2: Numerical model of leakage diffusion of buried oil pipeline

The block method of ICEM CFD software was adopted for the meshing. The total number of grids is 1.14 million, where the grid quality is above 0.5 with a grid angle of above 27 degrees. To ensure the modelling accuracy, mesh refinement was carried out on the top of the leak hole and near the leak hole of the model where the model structures are with special focus. For those places far from the leakage, the grids are less fine to reduce the CPU calculation time but without comprising the modelling accuracy. Under the case, the change ratio of the grid is not too large. This kind of meshing methodology is to ensure both the quality of the mesh and the number of meshes. In addition, it ensures the accuracy of calculation and speeds up the computation. The meshing effect is shown in Figures 3 to 6.

2.3. Boundary Conditions

The boundary conditions are following the practice. As the leakage of crude oil inside the pipeline is driven by the pressure, the leakage inlet was considered as the pressure inlet. To reduce the computing
requirement, a 6 m cube was used for the computational domain. Under the case, a symmetry boundary condition was assumed for the four sides and the bottom of the computational domain, where the top surface of the domain was considered as pressure outlet. The pipeline was considered as no-slip wall.

Figure 3: Integral grid model

Figure 4: The grid around the pipe

Figure 5: The grid near the hole

Figure 6: The pipeline grid diagram

3. Results and Discussion

3.1. Concentration distribution along the time

After the leakage of the crude oil, two-phase flow occurs with the air in the pores of the soil, gradually displacing the gas in the pore space and changing the volume fraction of the crude oil in the multi-empty medium [12]. Different leak locations were simulated to obtain the concentration distribution of crude oil in the pipe at different time, as shown in Figures 7 to 9.

As shown in Figure 7, when the leakage position is at the top of the pipeline, the crude oil begins to leak along the tube wall through the leakage hole. As the crude oil is affected by the capillary resistance, the viscous resistance of porous media and the inertia resistance, and the diffusion of crude oil is slow. When the crude oil continues leaking, the capillary resistance decreases. At the same time, due to the wake effect and gravity, the crude oil diffuses along the pipeline wall to the leakage hole gradually.

The diffusion rate of oil in porous media increases gradually, and the distribution of crude oil gradually decreases from the inside to outside along the leak hole. When the leakage lasts for 10 s, the distribution of crude oil concentration is approximately arched. When the leakage lasts for 400 s, the crude oil bypasses the oil pipeline and moved to the area below the pipeline. As the leakage increased, the upward spread of the crude oil gradually expanded. The crude oil concentration distribution shows
a nearly inverted “apple” shape. When the leakage lasts for 1400 s, the crude oil concentration distribution shows an approximate inverted U shape. With the increase of the leakage time, crude oil continues spreading along the radial and axial directions of the pipeline, and the leakage area continues expanding.

Due to the gravity, the radial leakage is faster than the axial leakage. However, because the leakage is too small, it is not completely converged in the computational domain. The distribution of crude oil concentration in the whole area shows an inverted U shape because of the less distribution of the crude oil in the pipeline, and it presents a narrow arc-shaped boundary area with a wide upper and lower width.

According to Figure 8, the diffusion of crude oil in the soil is also affected by capillary resistance, wake effect and gravity force when the leakage is on the side of the pipeline. At the early stage of the leakage, the crude oil through the leakage hole began to diffuse horizontally and vertically along the pipe wall, but the diffusion rate was low. When the crude oil continues leaking, the resistance to capillary drag is reduced. Because of wake flow and gravity, crude oil gradually spreads along the pipe wall outside the leak hole.

Crude oil concentration distribution gradually decreases from inside to outside along the leakage hole. When the leakage lasts for 10 s, the distribution of crude oil concentration shows an approximate crescent shape. When the leak lasts for 400 s, the crude oil bypasses the oil pipeline and moves to the area above the pipeline. Due to the gravity, the radial leakage of the pipeline is faster than the axial leakage, and the crude oil concentration distribution is similar to the cashew shape. With the increase of leakage, the upward spread of crude oil gradually expanded. When the leakage lasts for 1400 s, the crude oil surrounds the wall around the leakage. When the leakage lasts for 2400 s, the crude oil concentration distribution gradually changes from cashew shape to approximate elliptical shape. When the leakage lasts for 3600 s, the area of the ellipse continued expanding. The crude oil concentration distribution is close to the bottom of the domain and gradually decreases from the inside to the outside. It also presents a curved border area with a narrow width and a wide margin.

Figure 7: Radial concentration distribution of crude oil along the time

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As can be seen from Figure 9, when the leakage position is directly at the bottom of the pipe wall, at the initial stage, the crude oil at the leak hole begins to leak along the pipe wall. Under the gravity, the crude oil migrates faster below the leakage port than on both sides of the leakage port, and the crude oil appears an approximate circular symmetrical distribution around the cross-section of the pipeline. When the leakage lasts for 10 s, the crude oil concentration distribution shows an approximate ship shape and gradually decreases from inside to outside. When the leakage lasts for 400 s, the crude oil concentration distribution represents an approximately apple shape. When the leakage lasts for 1400 s, the distribution of crude oil concentration changes to an ellipse. When the leakage is 3600 s, the crude oil concentration distribution reaches the bottom of the computational domain. At this time, the leakage area is mainly in a cylindrical area that is vertically downward from the surrounding pipe wall at the leak hole. After that, the crude oil leaks steadily over the time. Similar to the leakage position of the side, the crude oil continues diverging along the radial and axial directions of the pipe, and the diffusion area continues increasing as well. Radial leakage shows a relatively faster rate than that of the axial leakage, which is due to the gravity. When the leakage position is at the bottom, the wake effect is relatively large. The elliptical leakage area under this condition is more obvious than the side leakage.

3.2 Comparison along the time
The maximum axial diffusion width and radial diffusion depth changes along the time, as shown in Figure 10. It can be seen that when crude oil migrates axially inside the soil, it is mainly affected by the surface tension and capillary force. At the initial stage, the crude oil diffuses rapidly inside the soil and gradually displaces liquid and air in the soil pore space. At this time, the surface tension and capillary action of crude oil are relatively large, so the axial diffusion width increases rapidly. But when the leakage lasts more than 400 s, as the crude oil continues entering the soil, other forces begin to decrease except the gravity, so the velocity of the crude oil in the axial diffusion width begins to decrease. Under the effect of the gravity, crude oil continues diverging, but the radial depth is not too different. In summary, the axial diffusion width and radial diffusion depth of crude oil are not affected by the leakage positions.
Figure 9: Crude oil concentration when the leak hole is located at the bottom of the pipe

Regarding the maximum axial diffusion width, it is a little surprise that the leakage hole of the top of pipeline shows a relatively faster axial diffusion width along the time when comparing to the other two. This may be because of the gravity that when the leakage hole is located at the bottom of the pipeline the crude oil flow is much on the vertical diffusion, which results in a relatively less diffusion following the axial direction. The trend for vertical diffusion is quite straightforward that the leakage hole at the bottom shows the maximum diffusion depths along the time, then comes to the leakage hole at the side and the top of the pipeline.

Figure 10: The maximum (a) axial diffusion width and (b) vertical diffusion depth along the time

It can be also concluded from the above comparison that the hazards of diffusion leakage is much dependent on the leakage position when with the same leakage holes. The influence of the leakage is much obvious at the early stage of the diffusion, while the influence becomes less obvious along the time. This can be evidence by the Figures 10(a) and 11 that differences under three leakage positions keeps increasing within a period of time, about 1000 s for the cases in this study. After the 1000 s, the differences seem to keep almost constant that no big expansion were found along the time. This is
reflected by the increasing rates of the maximum axial and vertical diffusion distance that the rates are similar for these three scenarios.

3.3 Empirical models for leakage prediction
To benefit the risk assessment, it is important to know the axial and radial diffusion distance after the leakage along the time. Those numerical results from the above sections were used for the development of empirical models. Those regression lines are shown in Figures 11 and 12. The line with squares are for the numerical results and line with circles are for the fitted values. It can be seen from the figures that although there are differences between the numerical and fitted results, the trend of the maximum axial and vertical diffusion distances along the time are quite reflected by the fitted lines. It should be mentioned that the fitting accuracy is compromised by the one-stage fitting. The fitting accuracy can be improved if different stages can be considered, but the practical implementation is kind of limited when the stages need to be identified as well.

![Figure 11: Fitting diagram of the maximum axial diffusion width when leak hole is located at: (a) the top; (b) the side; and (c) the bottom of pipeline](image)

The relationship between the maximum axial diffusion width and the time are concluded by Eq. (9). It represents the maximum diffusion width of crude oil caused by leakage of the top, side and bottom of the pipeline, respectively:

\[
\begin{align*}
y &= -2.0 \times e^{\frac{t}{457.3}} + 2.4 \\
y &= -1.8 \times e^{\frac{t}{452.1}} + 2.1 \\
y &= -1.7 \times e^{\frac{t}{449.2}} + 2.2
\end{align*}
\]

Where \( y \) represents the maximum axial diffusion width (m); and \( t \) represents the leakage time (s).
Figure 12: Fitting diagram of the maximum vertical diffusion depth when leak hole is located at: (a) the top; (b) the side; and (c) the bottom of pipeline

Similarly, using the data in Figure 13 to formulate the relationship between the maximum longitudinal diffusion depth and the time when crude oil leaks from the top, side, and bottom of the pipeline. The relationship is shown in Eq. (10) crude oil caused by leakage of the top, side and bottom of the pipeline, respectively:

\[
\begin{align*}
  y &= -11.8 e^{-t/804.1} + 12.3 \\
  y &= -9.3 e^{-t/5193.3} + 10.0 \\
  y &= -7.9 e^{-t/3549.2} + 8.7
\end{align*}
\]  

(10)

Those relationships reflected in Eqs. (9) and (10) are only for the studied cases in this study, namely for the crude oil of 0.5 m/s in the pipeline with a leakage hole of 0.05 m diameter. The related relationship can provide a reference for the related risk assessment for crude oil leakage. The related studies on various crude oil speed and leakage size will be undertaken in our future work.

4. Conclusions

The leakage diffusion of buried crude oil pipelines under different leakage hole positions was analyzed numerically along with the maximum axial diffusion width and the maximum radial diffusion depth. The following conclusions can be addressed:

(1) The position of the leak affects the shape of crude oil diffusion. When the leakage happened at the top of the pipeline, crude oil concentration distribution showed an approximate arch shape first, and then inverted “apple” and inverted “U” shape. When the leakage is located on the side, the cloud profile of the crude oil concentration changes from an approximately crescent shape to a cashew shape, and
finally to an elliptical shape. When the leak is located directly at the bottom, the crude oil concentration distribution cloud map changes from an approximately boat shape to an “apple” shape and finally to a circle.

(2) At the early stage of leakage, the axial diffusion width of crude oil increased rapidly. When the leakage lasts more than 400 s, the variation of the axial diffusion width of crude oil begins to decrease. In general, the axial diffusion width and radial diffusion depth of crude oil are not significantly affected by the location of the leak, while the influences are much on the early stage of the leakage.

(3) Empirical models were developed for the addressed cases in this study. The fitting data show quite good trend with the numerical results. The regression of the data has proved that the related empirical models for the prediction of crude oil along the axial and vertical directions with the along are possible. Limitations also apply for this study regarding the influence of leakage positions. The first is that the related numerical results have not been validated by experiments. This is because of the limited experimental data in the literature. Secondly, the empirical models are only applicable to the crude oil speed of 0.5 m/s with a leakage hole of 0.05 m. The related investigations will be taken in our future study.

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