Modelling the parameters of emptying an inclined pipeline in the safety management under demanding conditions

To cite this article: M Y Zemenkova et al 2018 IOP Conf. Ser.: Mater. Sci. Eng. 445 012006

View the article online for updates and enhancements.
Modelling the parameters of emptying an inclined pipeline in the safety management under demanding conditions

M Y Zemenkova¹, A A Gladenko² and Y D Zemenkov¹

¹Industrial University of Tyumen, 38 Volodarskogo str., Tyumen, 625000, Russia
²Omsk State Technical University, 11 Mira Prospekt, Omsk, 644050, Russia

E-mail: yd_zemenkov@mail.ru, gladenko1961@yandex.ru

Abstract. The work describes the method of estimating the volume of oil products during outflow and emergency discharge. Before removing the defective area, the pipeline is freed from oil products to ensure safety of repair and recovery works. The method has been tested on the main pipelines of the Tyumen Oblast. Based on the results of calculations and experiments, it was established that for the implementation of expert estimates, the error in the calculations by the methods proposed is satisfactory.

1. Introduction

The damage to the environment ultimately depends on the amount of potential oil flow and the location of the damage. The availability of data on the magnitude of the potential flow at various sections of the pipeline and the likelihood of failure on them makes it possible, at the design stage, to provide for the most effective measures to reduce damage to nature in the event of oil product leakage. At present, oil sector enterprises pay great attention to oil pipeline integrity control; decision support systems such as leak detection systems, integrity monitoring of long-distance facilities, etc. are being created.

However, the issues of instrument monitoring, detection, assessment and prediction of leakage, location, development of accurate operational calculations remain relevant [1-10].

Gravity drainage of the shutoff pipeline section with hydraulic slopes greater than 0.001 is typical for most main pipelines and occurs at full cross section. After the gravity drainage is stopped, the product remaining in the pipe is pumped out with pumps. The longest operations (percentage of the total time for the accident elimination) are: emptying of the pipeline - up to 35%; developing of a pit to collect oil - up to 9%; sealing of the internal cavity of the pipeline and preparation for conducting hot works - up to 16%; preparation of a new coil and its installation on a pipeline - up to 15% [1]. As practice shows, the duration of emptying the damaged section shut off by line valves varies widely and can amount to more than 50% of the total duration of the restoration work.

2. Materials and methods

At different times, research for the prediction and assessment of leakage and outflow models was conducted under the guidance of P.I. Tugunov, R.A. Aliev, M.V. Lurie, A.G. Gumerov, S.V. Kuklev, G.D Rosenberg, V.N. Antipyev, V.A. Polyakov, A.S. Shumailov, T.M. Bashty, S.S. Rudnev, B.B. Nekrasov, V.A. Fisher, and other well-known scientists.

At present, there are methods for calculating the outflow from pipelines, each of which has a specific physical and mathematical formulation, advantages and disadvantages. For example, the authors Donets
K.G. and Chernikin V.I. considered the process of gravity drainage of pipelines in case of accidents involving rupture of pipelines and termination of pumping [2]. They described the process of outflow by the Bernoulli equation in integral form, considering the following features:

- at the saddle point, the continuity of the liquid flow breaks, so a pressure equal to the saturated vapor pressure is established above the oil level \( p_s \);
- there is friction of the liquid against the wall of the pipe;
- the inertial term is considered.

Initial conditions for differential equations are considered in the publication of Voloshina A.P. in the following form

\[
\text{at } t=0: \ Z=H_1; \ Z'=0, \tag{1}
\]

and the continuity equation is written considering the profile of the route

\[
Qdt = \left( \frac{\pi D^2}{4 \sin \alpha} \right) \cdot dZ, \tag{2}
\]

where \( D, \alpha \) - diameter, angle of inclination of the pipeline to the horizon; \( Q \) - volumetric flow of liquid in the pipeline; \( Z \) – fluid head.

Under these conditions, it is found that the velocity of the fluid in the pipeline obeys the condition

\[
\vartheta = \frac{g \cdot D^2 \cdot \sin \alpha}{16 \cdot v} \cdot \left[ 1 - \exp \left( -\frac{32 \cdot v \cdot t}{D^2} \right) \right], \tag{3}
\]

A significant disadvantage of this technique is the fact that the velocity of the liquid in the pipeline is not related to the flow rate of the liquid from the hole, therefore, these dependencies do not include the flow coefficient that considers the actual flow rate. Here, it can be emphasized that when the product flows through an opening in an inclined pipeline, an unsteady motion is observed with a constant decrease in velocity and a change in the flow pattern. In addition, the authors considered only the laminar flow pattern of the liquid in the pipeline, which also limits the scope of application of the results obtained in practical calculations. The results of calculations [2-4 and others] showed that with an increase in the diameter of the pipeline, with an equal ratio of the area of the discharge hole to the cross-sectional area of the pipe and other equal conditions, the duration of emptying the inclined section decreases. This is because the friction pressure loss along the length of the pipeline, per unit volume of the outflowing product, decreases with increasing diameter, and the velocity, respectively, increases.

In [2], the problem of emptying a pipeline in case of sudden damage was considered. The main question of the study is the question of determining the time of the outflow of fluid from the damaged section of the pipe. The calculation was made for a pipeline 10 km long, 500 mm in diameter with a fixed 1:10 ratio of the hole area to the pipe area. It was assumed that the pipeline was filled with gasoline with a density of \( \rho = 760 \text{ kg/m}^3 \). As a result of the calculations given by the author, it turned out that in 25 minutes about 210 m\(^3\) of liquid flows out of the pipeline through the damage.

The works of Biryukov A.E, Turkin V.N., Bobrovskiy S.A., Gross S.A., Yanov B.G. deal with determining the volume of the emptying section or the time of emptying. But they consider the process simplistically, without considering a number of factors, for example, the wave structure of the fluid motion through the rupture, the time variability of the fluid flow coefficient, the one-dimensionality of the fluid motion in the pipeline, etc. In [7] various possible pipeline conditions are given, for which semi-analytical methods of leakage calculation are recommended. In practice, in case of accidents on main pipelines, the amount of oil removed from the pipeline at the third stage is determined by actual data, based on the method of emptying and available technical means.

Before removing the defective area, the pipeline is freed from oil products in order to ensure safety of repair and recovery works. The volume of the leaked and pumped out product can be determined by summing the corresponding volumes of descending sections of the accident site. Part of the descending sections is freed from the product completely. These sections are located along the profile of the route above the rupture site and their volume is equal to
\[ V = 0.25 \cdot \pi \cdot \sum_{i=1}^{n} D_i^2 \cdot l_{in}, \]  

where \( n \) - number of descending sections.

The oil product is discharged from part of the sections partially depending on the angle of their inclination to the horizon and the location relative to the point of discontinuity. For such sites, the volume of leaked oil is determined as the volume of an irregular truncated cylinder [8].

We derive a formula for calculating such volumes by introducing the following notation, using a three-dimensional coordinate system (Figure 1).

**Figure 1.** Design scheme of the pipeline with the angle of inclination \( \alpha \) with respect to the horizon 

\( \alpha \) - angle of inclination of pipeline with respect to the horizon, deg; \( h \) - height of the section, m; \( L_h \) - length of the horizon, m; \( L \) - length of the pipeline section, m.

**Figure 2.** Design scheme of the pipeline: three-dimensional diagram of a damaged pipeline; \( \alpha \) - angle of inclination of pipeline with respect to the horizon, deg; \( h \) - height of the section, m; \( L_h \) - length of the horizon, m; \( L \) - length of the pipeline section, m.
From geometric constructions it follows that:

\[ b = L_h \cdot \sin \alpha \] \hspace{0.5cm} (5)

\[ L = L_h \cdot \cos \alpha \] \hspace{0.5cm} (6)

\[ b = L_{pl} \cdot \tan \alpha \] \hspace{0.5cm} (7)

To determine the coordinates of the points B and C through which the secant plane passes, we write the following equations:

\[ x^2 + (y - R)^2 = R^2 \] \hspace{0.5cm} - circumferential equation, \hspace{0.5cm} (8)

\[ Z = 0 \] \hspace{0.5cm} - equation of the XOY plane, \hspace{0.5cm} (9)

\[ y = b \] \hspace{0.5cm} - equation of a plane intersecting XOY along a straight line KD. \hspace{0.5cm} (10)

We conduct the transformations (8):

\[ (y - R)^2 + x^2 - R^2 = 0, \] \hspace{0.5cm} (11)

or \[ y^2 - 2yR + x^2 = 0. \] \hspace{0.5cm} (12)

We solve the last equation:

for \( R \leq b \leq 2R \) we obtain the root:

\[ y = R + \sqrt{R^2 - x^2}, \] \hspace{0.5cm} (13)

and for \( 0 \leq b < R \):

\[ y = R - \sqrt{R^2 - x^2}. \] \hspace{0.5cm} (14)

Let us consider the root (13). It follows from (11) that

\[ R + \sqrt{R^2 - x^2} = b, \]

or \[ \sqrt{R^2 - x^2} = b - R. \] \hspace{0.5cm} (15)

Let us square the left and right parts:

\[ R^2 - x^2 = (b - R)^2. \]

After the transformations, we obtain

\[ x_{1,2} = \pm \sqrt{R^2 - (b - R)^2}. \] \hspace{0.5cm} (16)

Now we can write the coordinates of 3 points through which the horizontal secant plane passes:

\[ m.A \quad (0;0;L), \]

\[ m.B \quad (\sqrt{R^2 - (b - R)^2};b;0), \]

\[ m.C \quad (-\sqrt{R^2 - (b - R)^2};b;0). \] \hspace{0.5cm} (17)

We solve the system of equations:

\[
\begin{vmatrix}
 y_A z_A 1 \\
 y_e z_B 1 \\
 y_C z_C 1
\end{vmatrix} \cdot x + 
\begin{vmatrix}
 z_A x_A 1 \\
 z_e x_B 1 \\
 z_C x_C 1
\end{vmatrix} \cdot y + 
\begin{vmatrix}
 x_A y_A 1 \\
 x_e y_B 1 \\
 x_C y_C 1
\end{vmatrix} \cdot z = 
\begin{vmatrix}
 x_A y_A z_A \\
 x_e y_B z_B \\
 x_C y_C z_C
\end{vmatrix}. \] \hspace{0.5cm} (18)

The determinant for \( x \)

\[
\Delta x = \begin{vmatrix}
 0 & L & 1 \\
 b & 0 & 1
\end{vmatrix} = L \cdot b - L \cdot b = 0. \] \hspace{0.5cm} (19)

The determinant for \( y \)
\[ \Delta y = \begin{vmatrix} L & 0 & 1 \\ 0 & \sqrt{R^2-(b-R)^2} & 1 \\ 0 & -\sqrt{R^2-(b-R)^2} & 1 \end{vmatrix} = L \cdot \sqrt{R^2-(b-R)^2} + \\
+ L \cdot \sqrt{R^2-(b-R)^2} = 2L \cdot \sqrt{R^2-(b-R)^2}. \]  

The determinant for \( z \)

\[ \Delta z = \begin{vmatrix} 0 & 0 & 1 \\ \sqrt{R^2-(b-R)^2} & b & 1 \\ -\sqrt{R^2-(b-R)^2} & b & 1 \end{vmatrix} = b \cdot \sqrt{R^2-(b-R)^2} + \\
+ b \cdot \sqrt{R^2-(b-R)^2} = 2b \cdot \sqrt{R^2-(b-R)^2}. \]  

The main determinant of the system (18)

\[ \Delta = \begin{vmatrix} 0 & 0 & L \\ \sqrt{R^2-(b-R)^2} & b & 0 \\ -\sqrt{R^2-(b-R)^2} & b & 0 \end{vmatrix} = b \cdot \sqrt{R^2-(b-R)^2} + \\
+ b \cdot L \sqrt{R^2-(b-R)^2} = 2b \cdot L \sqrt{R^2-(b-R)^2}. \]  

We write the equation of the plane:

\[ 2L \sqrt{R^2-(b-R)^2} \cdot y + 2b \sqrt{R^2-(b-R)^2} \cdot z = 2Lb \sqrt{R^2-(b-R)^2} \]  

Dividing the left and right sides by \( 2 \cdot \sqrt{R^2-(b-R)^2} \), we obtain

\[ L \cdot y + b \cdot z - L \cdot b = 0, \]  

or

\[ z = \frac{L \cdot (b-y)}{b}. \]  

We proceed to determine the volume of a truncated cylinder:

\[ V = \int_{ABCD} z \cdot dx \cdot dy = \int_{0}^{b} dy \int_{\sqrt{R^2-(y-R)^2}}^{b} \left( L \cdot b - L \cdot y \right) \cdot dx = \\
= b \int_{0}^{b} \left( L \cdot b - L \cdot y \right) \cdot \sqrt{R^2-(y-R)^2} \cdot dy = \\
= 2 \cdot L \int_{0}^{b} \sqrt{R^2-(y-R)^2} \cdot dy - \frac{2L}{b} \int_{0}^{b} \sqrt{R^2-(y-R)^2} \cdot dy. \]  

We transform the second integral:

\[ \int_{0}^{b} \sqrt{R^2-(y-R)^2} \cdot dy = \int_{0}^{b} (y-R) \cdot \sqrt{R^2-(y-R)^2} \cdot dy = \\
= R \int_{0}^{b} \sqrt{R^2-(y-R)^2} \cdot dy + \int_{0}^{b} (y-R) \cdot \sqrt{R^2-(y-R)^2} \cdot dy. \]  

We obtain
\[
V = 2L \int_0^b \sqrt{R^2 - (y-R)^2} \cdot dy - \frac{2L}{b} \int_0^b \sqrt{R^2 - (y-R)^2} \cdot dy - \frac{2L}{b} \int_0^b \sqrt{R^2 - (y-R)^2} \cdot dy.
\]  

We combine in this expression the first two terms:
\[
V = \frac{2 \cdot Lb - 2 \cdot LR}{b} \int_0^b \sqrt{R^2 - (y-R)^2} \cdot dy - \frac{2L}{b} \int_0^b \sqrt{R^2 - (y-R)^2} \cdot (y-R) \cdot dy.
\]

Using table integrals, we obtain:
\[
V = \frac{-2L(b-R)}{b} \left\{ \frac{y-R}{2} \sqrt{R^2 - (y-R)^2} + \frac{R^2}{2} \arcsin \left( \frac{y-R}{R} \right) \right\} _0^b - \frac{2L}{b} \left\{ \frac{1}{3} \left[ R^2 - (y-R)^2 \right]^{3/2} \right\} _0^b.
\]

We substitute the limits:
\[
V = \frac{2L}{b} \left\{ \frac{(b-R)}{2} \left[ \sqrt{R^2 - (b-R)^2} + \frac{R^2}{2} \arcsin \left( \frac{b-R}{R} \right) \right] + \frac{R^2}{2} \cdot \frac{\pi}{2} \right\} + \frac{2L}{b} \left\{ \frac{1}{3} \left[ R^2 - (b-R)^2 \right]^{3/2} \right\}.
\]

Thus, using table integrals when solving (28), it is possible to obtain the volume of product to be pumped out:
\[
V = \frac{2L}{b} \left\{ \frac{(b-R)}{2} \left[ \sqrt{R^2 - (b-R)^2} + \frac{R^2}{2} \arcsin \left( \frac{b-R}{R} \right) + \frac{\pi \cdot R^2}{2} \right] + \frac{R^2}{2} \cdot \frac{\pi}{2} \right\}.
\]

We obtain a solution for another root (2.50) \((0 \leq b < R)\). Using equations (14), we obtain
\[
R + \sqrt{R^2 - x^2} = b,
\]

or
\[
\sqrt{R^2 - x^2} = R - b.
\]

Let us square the left and right parts:
\[
R^2 - x^2 = (R-b)^2
\]

After the transformations, we obtain
\[
x_{1,2} = \pm \sqrt{R^2 - (R-b)^2}.
\]

Arguing in the same way as for the previous root (13), we obtain the equation of the plane (25).

We now turn to determining the volume of a truncated cylinder for the root (14):
\[
V = \iint_{ABCD} z \cdot dx \cdot dy = \int_0^b dy \int_0^{\frac{b}{L} \cdot (b-L \cdot y) \sqrt{R^2 - (R-y)^2}} \frac{L \cdot b - L \cdot y}{b} \cdot dx = \int_0^b \frac{L \cdot b - L \cdot y}{b} \cdot 2 \sqrt{R^2 - (R-y)^2} \cdot dy = 2L \int_0^b \sqrt{R^2 - (R-y)^2} \cdot dy - \frac{2L}{b} \int_0^b \sqrt{R^2 - (R-y)^2} \cdot dy.
\]
We obtain

\[ V = 2L \cdot \frac{b}{0} \sqrt{R^2 - (R - y)^2} \cdot dy - \frac{2L}{b} \cdot R \int_{0}^{b} \sqrt{R^2 - (R - y)^2} \cdot dy - \]

\[ - \frac{2L}{b} \int_{0}^{b} \sqrt{R^2 - (R - y)^2} \cdot (y - R) \cdot dy. \]  

(37)

We combine in this expression the first two terms:

\[ V = -\frac{2L}{b} \cdot \frac{b}{0} \sqrt{R^2 - (R - y)^2} \cdot d(R - y) - \]

\[ - \frac{2L}{b} \int_{0}^{b} \sqrt{R^2 - (R - y)^2} \cdot (R - y) \cdot d(R - y). \]  

(38)

We use table integrals:

\[ V = -\left(\frac{2L(b - R)}{b}\right) \left\{ \frac{R - y}{2} \cdot \sqrt{R^2 - (R - y)^2} + \frac{R^2}{2} \cdot \arcsin\left(\frac{R - y}{R}\right) \right\} \int_{0}^{b} \int_{0}^{b} \]

\[ - \frac{2L}{b} \left\{ \frac{2}{3} \left[ R^2 - (R - y)^2 \right]^{3/2} \right\} \int_{0}^{b} \]  

(39)

We substitute the limits:

\[ V = \frac{2L \cdot (b - R)}{b} \left\{ \frac{(b - R)}{2} \cdot \sqrt{R^2 - (R - b)^2} + \frac{R}{2} \cdot \arcsin\left(\frac{R - b}{R}\right) \right\} + \]

\[ + \frac{2L}{b} \left\{ \frac{1}{3} \left[ R^2 - (R - b)^2 \right]^{3/2} \right\}. \]  

(40)

Thus, using table integrals when solving (36), it is possible to obtain the volume of product to be pumped out:

\[ V = \frac{2L \cdot (b - R)}{b} \left\{ \frac{(b - R)}{2} \sqrt{R^2 - (R - b)^2} - \frac{R}{2} \arcsin\left(\frac{R - b}{R}\right) + \frac{\pi R}{2} \right\} + \]

\[ + \frac{2L}{b} \left\{ \frac{1}{3} \left[ R^2 - (R - b)^2 \right]^{3/2} \right\}. \]  

(41)

Checking the formulas (for \( b = R \)), we obtain a well-known formula for the volume:

\[ V = \frac{2L}{b} \frac{(b - R)}{2} \sqrt{R^2 - (R - b)^2} - \left( R^2 \arcsin\left(\frac{R - b}{R}\right) + \frac{\pi R}{2} \right). \]  

(42)

The obtained formulas (32) and (41) cover the entire range of values of the quantity \( b \): \( 0 < b < 2R \). Formulas (32) and (41) are fairly simple and convenient for practical use in express analyzes in the field, and are also easily implemented using software packages.

3 Conclusion
The method has been tested on the main pipelines of the Tyumen region. Theoretical assumptions about an increase in the error of calculations with an increase in the total length of the controlled sections \( L \), with an increase in emergency \( x_a \), after emergency distances \( (L - x_a) \), etc. have been experimentally confirmed. Based on the results of calculations and experiments, it was established that for the implementation of expert estimates, the error in the calculations by the methods proposed is satisfactory.
References

[1] Sviridova L T et al 1989 Emergency repair of main oil pipelines in swamps Transport and Storage of Oil and Petroleum Products (Moscow: VNIIOENG) 60 p

[2] Donets K G and Chernikin V N 1963 Gravitational emptying of the pipeline from viscous oils and oil products Transport and Storage of Oil 11 pp 3-6

[3] Shumailov A S et al 1981 Controlling leaks of oil and petroleum products on main pipelines during operation Transport and Storage of Oil and Petroleum Products 10 (Moscow: VNIIOENG) 80 p

[4] Shumailov A S, Gumerov A G and Moldavanov O I 1992 Diagnostics of Main Pipelines (Moscow: Nedra) 291 p

[5] Biryukov A E and Turkin V N 1983 Determination of the time of emptying the pipeline during its rupture on reclamation systems Hydrological and Melioration Calculations and Characteristics of Some Areas of Siberia and Kazakhstan Coll. of Sc. Papers (Omsk) pp 58-63

[6] Bobrovsky S A. Determination of the time of idling oil pipelines in the elimination of accidents / Gubkin MINKhiGP Moscow: 1963, issue.45-p.181.

[7] Ministry of Fuel and Energy 1996 Methodology for Determining Damage to the Natural Environment in Case of Accidents on Main Oil Pipelines (Moscow: TransPress) 66 p

[8] 2008 Monitoring of Hydrodynamic and Technical Characteristics of Pipeline Systems ed Zemenkov Yu D (Tyumen: Vector Book) 445 p

[9] 2018 Safety guide Methodological Recommendations on the Classification of Man-made Events in the Field of Industrial Safety at Hazardous Production Facilities of the Oil and Gas Industry Approved by the Order of the Federal Service for Environmental, Technological and Nuclear Supervision of January 24, 2018 No. 29 [Electronic resource]. - Access mode: http://sudact.ru/law/prikaz-rostekhnadzora-ot-24012018-n-29-ob/rukovodstvo-po-bezopasnosti-metodicheskie-rekomendatsii/ (access date: 1.04.2018)

[10] 2016 On choosing multicomponent multiphase system separation progress optimization criteria IOP Conf. Ser.: Mat. Sc. and Eng. 154(1)

[11] Chekardovskiy M N, Chekardovskiy S M and Ilyukhin K N 2016 Methods for determining the thermodynamic parameters of gas compressor units of main gas pipelines IOP Conf. Ser.: Mat. Sc. and Eng. 154(1)

[12] Gorelik J B, Shabarov A B and Sysoyev Yu S 2016 The dynamics of frozen ground melting in the influence zone of two wells Earth’s Cryosphere 12 (1) pp 59