Study on the Operation Safety and Reliability of a Waxy Hot Oil Pipeline with Low Throughput Using the Probabilistic Method

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ABSTRACT: When the hot oil pipeline is running at a low throughput, it easily enters into an unstable condition, which seriously threatens the safety of the hot oil pipeline operation. In this study, the unsteady heat transfer and flow mathematical models for the hot oil pipeline system were established first by comprehensively considering the uncertainty of parameters during pipeline operation, such as the operating parameters (throughput and oil temperature), physical properties of crude oil (freezing point, viscosity, and thixotropic parameters), and environmental parameters (buried deep soil temperature and soil thermal conductivity). Then, the efficient Latin hypercube sampling (LHS) stochastic numerical algorithm was applied and further developed to quantitatively describe the operation safety of hot oil pipelines with low throughput in the form of probability. On the basis of the abovementioned research, the qualitative relationship between pipeline flowrate and friction loss is obtained. Finally, taking an actual crude oil pipeline as an example, the failure probabilities of the pipeline under different operating conditions were analyzed in detail. Combined with the target safety level of pipeline operation, the minimum allowable throughput of pipelines was determined. This study revealed the flow and heat transfer law of hot oil pipelines with low throughput and determined its operation safety and reliability under different operating conditions.

1. INTRODUCTION

In recent years, as China’s onshore oil fields enter the end of exploitation, the oil field output shows a downward trend year by year, which leads to the long-term low-throughput operating conditions of the crude oil pipeline and has a downward trend of decay.1 In addition, in the process of offshore oil and gas resources exploitation, the pipeline will inevitably face the trouble of low throughput operation in the early and middle stages of production.2 The problem of low throughput generally refers to the pipeline whose throughput is lower than the minimum allowable volume of the pipeline when it is being heated.3 However, 80% of crude oil produced in China easily solidifies and has high viscosity. Once the pipeline enters the operating condition of low throughput, if not properly handled, the pipeline will fall into a vicious circle of continuous decreasing pipeline throughput and increasing transmission pressure, which will eventually lead to a full shutdown of the pipeline.4,5

When the pipeline is running under the condition of low throughput, the throughput, heat dissipation, friction, and other factors are constantly changing with time. At this point, the pipeline is in a complex state of hydraulic and thermal instability, and many parameters such as the pipeline operation parameters, oil property parameters, and environmental parameters are significantly uncertain. To solve this problem, the traditional method is to add a “safety factor” on the basis of iterative solution of steady-state flow and heat transfer calculation formula, and its purpose is to ensure the safety of pipeline operation with low throughput as far as possible. Generally speaking, the safety factor is obtained based on a lot of design practices, which can reflect certain statistical characteristics, but for different regions and types of pipelines, there is a large range of values. Additionally, the engineering practices show that the increasing safety factor cannot guarantee the absolute safety of the pipeline, and it is also not related to the quantitative reliability of pipeline. Meanwhile, because of the lack of complete theoretical analysis and derivation, the determination of the safety factor is usually based on personal experience, with strong individual subjectivity and variability. From here, we can see that the traditional deterministic analysis method is difficult to describe the influence of parameter changes on the safety of the flow process, and it is unable to give a scientific and accurate
description and evaluation on the safety of the operation of pipelines with low throughput.

The probabilistic method is an effective method to deal with the problem mentioned above, which has been widely used in nuclear industry,6–9 power system10,11 transportation,11,12 and other fields. At present, there are two ways to study failure probability: historical data statistics and failure mechanism analysis. Historical data statistics is the most widely used method at home and abroad. Through the collection of extensive accident data and the analysis of previous risk data, the failure data were obtained by the statistical analysis method and the relevant failure database was established.13–17 However, this method is relatively simple and can most objectively describe the risk itself. However, the premise of this method research is to establish reliability database, such as the European pipeline history failure database. Another research direction is the failure mechanism analysis method. The basic idea is to use the limit analysis method, which is mainly applied to the reliability analysis of the gas pipeline. In solving the failure probability, there are four methods to estimate the failure probability: analytic method,21 first-order quadratic distance method, Monte Carlo method, and statistical analysis method.

Based on this, an unsteady flow and heat transfer theory-based model is adopted in this study to quantitatively analyze the safety and reliability of the operation of the pipeline with low throughput, taking into account the uncertainty of relevant parameters. The study not only provides important theoretical and technical support for scientific management of pipelines under low throughput but also has an extremely important engineering application value for the safe operation, energy conservation, and emission reduction of oil pipelines.

2. COMPUTATIONAL METHODS

There are three core issues involved in analyzing and mastering the operation characteristics of a waxy hot oil pipeline with low throughput: (1) unsteady flow and heat transfer model; (2) probability distribution model of uncertain parameters; and (3) stochastic numerical simulation algorithms.

2.1. Unsteady Flow and Heat Transfer Model. During the operation of the hot oil pipelines, it is in a complex state of hydraulic and thermal instability, especially after the low-volume pipeline enters the unstable working area. When using numerical simulation to calculate the problem of pipelines with low throughput, the numerical solution method of the unsteady process should be established first, and then, the flow and heat transfer process can be analyzed.

For buried hot oil pipelines, the oil, soil, and atmosphere constitute a thermal system (see Figure 1). Therefore, the complete description includes the heat transfer of the oil in the pipeline and the heat conduction of the soil outside the pipeline. A description of the physical model is given in ref 6. Based on the assumptions and simplifications, a mathematical model describing the thermal system of the buried hot oil pipeline is established as follows.

2.1.1. Tube Flow Heat Transfer Equation.

\[
C_p \frac{dT}{d\tau} - \frac{T}{\rho} \frac{dp}{d\tau} - \frac{fV^3}{2D} + \frac{4q}{\rho D} = 0
\]

(1)

where \(C_p\) is the specific heat capacity of crude oil at constant pressure, \(J/(\text{kg} \cdot ^\circ\text{C})\); \(T\) is the crude oil temperature, \(^\circ\text{C}\); \(\tau\) is the time, \(s\); \(\rho\) is the average density of crude oil, \(\text{kg}/\text{m}^3\); \(\beta_0\) is the expansion coefficient of crude oil, \(^1/\text{C}\); \(p\) is the average pressure of the pipe section, Pa; \(f\) is the Darcy hydraulic friction coefficient; \(V\) is the average velocity of crude oil, \(\text{m}/\text{s}\); \(D\) is the effective inner diameter of the pipe, \(\text{m}\); and \(q\) is the heat flux from the oil flow to the pipe wall, \(\text{W}/\text{m}^2\).

2.1.2. Heat Conduction Equation of the Wax-Deposited Layer, Tube Wall, and Anticorrosive Layer.

\[
\rho_i C_i \frac{dT}{d\tau} = \frac{\partial}{\partial r} \left( \lambda_i \frac{\partial T}{\partial r} \right) + \frac{1}{\rho_i C_i} \frac{\partial q}{\partial \theta}
\]

\(i = 1, 2, 3\)

(2)

where \(i = 1, 2, 3\), respectively, correspond to the wax deposition layer, steel pipe wall, and anticorrosive layer of the pipeline; \(T_i\) is the temperature of layer \(i\); \(\lambda_i\), \(C_i\), and \(\rho_i\) are the thermal conductivity, specific heat capacity, and density of the layer \(i\), respectively; and \(r\) and \(\theta\) represent the two directions of the polar coordinates.

2.1.3. Soil Heat Conduction Equation.

\[
\rho_s C_s \frac{dT}{d\tau} = \frac{\partial}{\partial x} \left( \lambda_s \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda_s \frac{\partial T}{\partial y} \right)
\]

(3)

where \(T_s\) is the soil temperature, \(^\circ\text{C}\); \(\rho_s\), \(C_s\), and \(\lambda_s\), respectively, represent soil density \((\text{m}^3/\text{kg})\), specific heat capacity \((\text{J}/(\text{kg} \cdot ^\circ\text{C}))\), and thermal conductivity \((\text{W}/(\text{m} \cdot ^\circ\text{C}))\).

2.1.4. Join Conditions. The heat transfer process of crude oil in the pipeline, wax-forming layer, pipe wall, anticorrosive layer, and soil is interrelated, meeting the following requirements:

\[
\lambda_1 \frac{dT_1}{dr} \bigg|_{r=R_0} = \alpha_0 (T - T_0)
\]

(4)

\[
\lambda_k \frac{dT_k}{dr} \bigg|_{r=R_k} = \lambda_{k+1} \frac{dT_{k+1}}{dr} \bigg|_{r=R_k}, \quad k = 1, 2
\]

(5)

\[
T_{l \mid r=R_k} = T_{l+1 \mid r=R_k}, \quad k = 1, 2
\]

(6)

\[
\lambda_s \frac{dT_s}{dr} \bigg|_{r=R_k} = \lambda_s \frac{dT_s}{dr} \bigg|_{r=R_k}, \quad k = 1, 2
\]

(7)

\[
T_{s \mid r=R_k} = T_{s \mid r=R_k}
\]

(8)
where, \( \alpha_s \) is the heat transfer coefficient of oil flow to the inner wall of the pipeline, W/(m²·°C); \( T_0 \) is the temperature of the inner wall of the pipeline, °C.

2.1.5. Boundary Conditions. Because of the symmetry of the calculation region, the right half of the pipeline physical model in Figure 1 was taken for study in this study, and the boundary conditions that need to be followed were as follows:

When \( x = 0, \) \( 0 \leq y_l \leq H - R_3 \)

\[
\frac{\partial T}{\partial x} = 0
\]  

(9)

When \( x = 0, \) \( H_0 + R_3 \leq y_l \leq H \)

\[
\frac{\partial T}{\partial x} = 0
\]  

(10)

When \( y = 0 \)

\[
\frac{\partial T_s}{\partial y} = 0
\]  

(11)

When \( x = L \)

\[
\frac{\partial T}{\partial x} = 0
\]  

(12)

When \( y = -H \)

\[
T_l = T_n
\]  

(13)

where, \( \alpha_s \) is the heat transfer coefficient from the pipeline surface to the atmosphere, W/(m²·°C); \( T_s \) is the atmospheric temperature, °C; and \( T_n \) is the soil thermostatic layer temperature, °C.

2.2. Probability Distribution Model of Uncertain Parameters. Theoretically, almost all physical quantities have uncertainty. In order to make the reliability analysis reliable and efficient, we need to identify the uncertainty variables that have important influence on the limit state function. Among the parameters related to the operation of the hot oil pipeline with low transmission capacity, the operating parameters (outbound oil temperature, throughput, and pressure), physical properties of crude oil (density, viscosity, thixotropic parameters), and environmental parameters (buried depth of the pipeline, buried deep ground temperature, soil thermal conductivity, etc.) have obvious uncertainties.

2.2.1. Operation Parameters. Pipeline capacity and outbound oil temperature are related to the operating conditions of the transfer pump and heating furnace. Even without considering the adjustment of the artificial transmission plan, the pipeline capacity, outbound temperature, and other operating parameters of the pipeline also fluctuate within a certain range under a given combination of the transfer pump and heating furnace. According to the SCADA system online monitoring data statistics, the distribution of each variable mentioned above can be determined.

2.2.2. Physical Properties of Crude Oil. The fluctuation of the physical property parameters of pipeline crude oil is related to the properties of incoming oil, thermal history, and shear history. Additionally, it is also related to the measurement uncertainty in the process of physical property measurement.

2.2.3. Environmental Parameters. The oil pipeline stretches for thousands of kilometers, with different buried depths, soil properties, and climate conditions. The uncertainty of the abovementioned parameters can be described by the distribution type and relevant model parameters (such as the mean value, standard difference, etc.) by means of statistical analysis. For parameters with a sufficient sample, the determination of parameter probability distribution includes selection of the distribution type, estimation of distribution parameters, and test of the fitting effect. In this study, the absolute value of the correlation coefficient between parameters was less than 0.5, so the correlation between parameters was ignored, and they were regarded as independent variables. According to the statistical results of related uncertain parameters of the western crude oil pipeline and sino-Luohe line, the main uncertain parameters considered in this study are shown in Table 1.

| Classification | Uncertain Parameter |
|---------------|---------------------|
| Operation parameters | throughput, outbound temperature |
| Physical properties of oil | freezing point, viscosity, thixotropic parameters |
| Environmental parameters | buried deep soil temperature, soil thermal conductivity |

2.3. Stochastic Numerical Simulation Algorithm: LHS Sampling Method. In the reliability evaluation, Monte Carlo (MC) simulation is a classic and most widely used method for failure probability. In many reliability assessments based on MC simulations, the sample size has certain requirements, and the number of random simulations performed is around \( 10^3 \) to \( 10^6 \). In order to reduce the calculation cost, Latin hypercube sampling (LHS) is adopted in this study to improve the sampling efficiency of the random algorithm. LHS is an improved MC method, whose sampling method is stratified sampling to ensure that all sampling areas can be covered by sampling points. Compared with the MC method, LHS can greatly reduce the sampling number that was required to reach the specified accuracy and improve the reproducibility of sampling results.

The LHS and MC approaches are employed to simulate a normal distribution with a mean value and standard deviation of 180 and 22.5. Moreover, the performances of the two sampling methods with different sample sizes are compared in the perspective of relative errors of mean values and standard deviations, which are given by eqs 14 and 15, respectively. In order to validate the repeatability, the sampling experiments are repeated 20 times for each sample size.

\[
\varepsilon_\mu = \left| \frac{\mu - \bar{\mu}}{\mu} \right| \times 100\%
\]  

(14)

\[
\varepsilon_\sigma = \left| \frac{\sigma - \bar{\sigma}}{\sigma} \right| \times 100\%
\]  

(15)

Figures 2–5 represent the comparisons of relative errors of mean values and standard deviations between LHS and MC, given a normal distribution. It can be seen from the figures that (1) at the same sample size, the relative error of MC is more than 10 times larger than that of LHS; (2) the relative error of LHS decreases more rapidly with the increase in sample size, for instance, the maximum relative error of standard deviation is reduced to 1% when the sample size is 500, but more than 10,000 samples are needed for MC to reach the same order of accuracy; and (3) LHS shows advantages such as good repeatability, strong representation, and sample saving. The
information mentioned above indicates that LHS is more efficient than MC.

3. RESULTS AND DISCUSSION

In the case of a certain pipeline, the transient operation characteristic of the flowrate and friction loss will be discussed. The density of the transporting crude oil is 862.4 kg/m³, and the correlation between viscosity and temperature is given as follows

\[
\mu = K \gamma^n \quad (20 \degree C \leq T < 38 \degree C) \quad (16)
\]

\[
K = 851.85 e^{-0.42(T-33)} \quad (20 \degree C \leq T < 38 \degree C) \quad (17)
\]

\[
n = -0.8554 + 0.044T \quad (20 \degree C \leq T < 38 \degree C) \quad (18)
\]
3.1. Evaluation of the Operation Safety of the Pipeline with Low Throughput. It can be seen from Figures 6 and 7 that with the difference in the heating temperature and length of preheating, the operating characteristics of pipelines are also different when operating at low throughput. It should be noted that 400, 500, and 600 represent the pipeline flowrates.

The relationship between throughput and friction resistance over time can be divided into three categories: (1) For a period of time, the pipeline throughput is maintained at a certain value, during which the friction resistance gradually increases. When the friction resistance of the pipeline exceeds the lift provided by the pump under this throughput, it enters a vicious cycle of decreasing throughput and increasing friction resistance, which eventually leads the pipeline to stop flowing. (2) The throughput of the pipeline remains unchanged, and the friction resistance increases with time until it is stable. In other words, the pipeline system can operate stably under the throughput. (3) The throughput of the pipeline remains unchanged, during which the friction resistance increases first and then decreases with time and finally becomes stable. Under the throughput, the pipeline system can operate stably.

The change in flowrate and friction resistance with time is related to the change in oil temperature. According to the different preheating times and heating temperatures, the variation of oil temperature in the pipeline is also different. For the case that the oil temperature had been increased before the throughput sudden drop in the pipeline, at the initial moment of 0, on the one hand, the throughput of the pipeline decreased, the heat dissipation of crude oil in the pipeline increased, and the oil temperature along the pipeline gradually decreased, which means that the inlet temperature gradually decreased (see Figure 8), the viscosity of oil increased, and thus the friction resistance increased. Before the pipeline system reaches a new balance, once the friction resistance exceeds the head provided by the pump, it will enter into a vicious cycle of increasing friction resistance and decreasing throughput and eventually lead the pipeline to stop flowing, that is, it falls into the first category. If the friction resistance in the process of increasing does not exceed the head provided by the pump always, the pipeline system will reach a new balance and keep stable operation, that is, it falls into the second category.

3.2. Minimum Allowable Throughput of the Pipeline. The minimum allowable throughput of the pipeline is an important technical parameter in the practical operation of hot oil pipelines, which can avoid the pipeline entering the unstable working area. However, the previous method is mostly used to solve the pipeline characteristic curve to determine the minimum allowable throughput of the hot oil pipeline, but this method adopted the steady-state algorithm and could not provide the relationship between pressure and flowrate with time.

In this study, based on the idea of reliability, it can achieve quantitative evaluation on the operation security of the hot oil pipeline with low throughput by solving the unsteady flow and

Table 2. Distribution Models and Parameters of the Stochastic Variables

| variable | distribution model | standard deviation | variable coefficient |
|----------|--------------------|--------------------|---------------------|
| outbound oil temperature/°C | normal distribution | 1.5 |                       |
| outbound throughput/m³·h⁻¹ | normal distribution | 0.06 |                       |
| underground temperature/°C | normal distribution | 1.0 |                       |
| buried depth/m | normal distribution | 0.1 |                       |
| freezing point/°C | normal distribution | 1.0 |                       |
| thermal conductivity of soil/W·m⁻¹·°C⁻¹ | normal distribution | 0.10 |                       |

“It should be noted that for parameters that are not directly given standard deviation, the standard deviation can be obtained by the product of the mean and the coefficient of variation. minimum allowable throughput of the pipeline with low throughput will be confirmed.

Table 3. Failure Probability of Each Input under Different Ground Temperature Conditions

| soil temperature/(°C) | flowrate (m³/h) 300 | 400 | 500 | 600 | 700 |
|-----------------------|----------------------|-----|-----|-----|-----|
| −5                    | 2.6 × 10⁻⁵           | 1.3 × 10⁻⁴ | 2.4 × 10⁻⁴ | 8.9 × 10⁻⁵ | <10⁻⁶ |
| 5                     | 4.8 × 10⁻⁴           | 3.6 × 10⁻⁴ | 7.6 × 10⁻⁵ | <10⁻⁶ | <10⁻⁶ |
| 15                    | 6.8 × 10⁻⁴           | 5.9 × 10⁻⁵ | <10⁻⁶ | <10⁻⁶ | <10⁻⁶ |

Figure 8. Relationship between temperature and time under different conditions.

Figure 9. Minimum allowable throughput of the pipeline.
heat transfer model of waxy crude oil. Then, combined with the target safety level required for specific pipelines, the minimum allowable throughput of the pipeline can be determined, as shown in Figure 9. In this way, the pipeline not only can have the same safety under different transportation conditions but also the operational parameters can be adjusted according to the actual conditions (such as the operating parameters, ambient temperature, etc.), so that the pipeline operation is always in a clear safe state.

3.3. Specific Example of a Pipeline. In this section, a specific pipeline is used to study the operation safety of the pipeline with low throughput under different conditions. The basic conditions for calculation are as follows: The distance between the calculation stations is 80 km, the outer diameter of the pipeline is 720 mm, the wall thickness is 8 mm, the thermal conductivity of the soil is 1.25 W/(m·°C), the maximum pressure capacity of the pipeline is 4 MPa, and the freezing point of the pipeline crude oil is 33 °C. The uncertainty values of relevant parameters are shown in Table 2. The characteristics of a single centrifugal pump are as follows:

\[
Q = \left( \frac{500 - H}{0.0013} \right)^{1.75} \text{ (100 m}^3/\text{h} \leq Q \leq 1300 \text{ m}^3/\text{h})
\]

(20)

Combined with the research of this paper, when the soil temperature in the buried depth of the pipeline is \(-5 °C, 5 °C,\) and \(15 °C,\) the failure probability of the pipeline in operation with different throughputs can be obtained, as shown in Table 3.

As can be seen from Table 3, for most operation conditions, the failure probability of the pipeline operation decreases by about 1 order of magnitude for every 10 °C increase in ground temperature at the same transportation flowrate. In addition, it can also be obtained from Table 3 that, if the target safety level of the pipeline is \(1 \times 10^{-6},\) then when the soil temperature is \(-5 °C, 5 °C,\) and \(15 °C,\) the corresponding minimum allowable throughputs are \(700 \text{ m}^3/\text{h,} 500 \text{ m}^3/\text{h,}\) and \(400 \text{ m}^3/\text{h,}\) respectively.

4. CONCLUSIONS

The method proposed in this study can be used to evaluate the operation characteristic of the pipeline with low throughput. Different from the previous steady-state algorithm, the unsteady flow and heat transfer model is established in this study. On this basis, the operation characteristic of the pipeline with low throughput was evaluated by analyzing the uncertainty of crude oil physical properties, pipeline environment, and operating conditions. According to the target safety level, the minimum allowable throughput was also determined under specific conditions.

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Notes

The authors declare no competing financial interest.

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