

Study on Restart Safety of Waxy Crude Pipelines Based on Reliability Principle under Constant Flow

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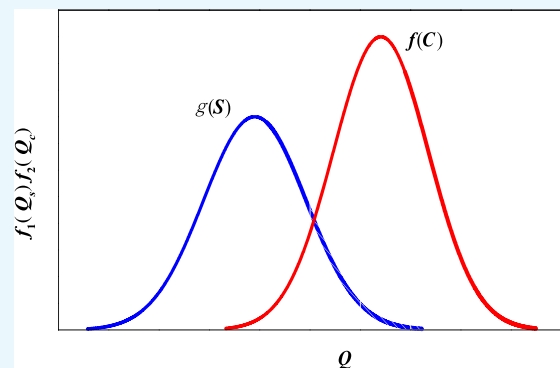
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ABSTRACT: The restart process of waxy crude pipelines is an unsteady thermo-hydraulic coupling process, which mainly includes two modes of the constant flow and constant pressure in industry. However, some parameters involved in the restart process have obvious uncertainties, such as the operating parameters, physical parameters of crude oil, environmental parameters, and pipeline parameters, resulting in the traditional deterministic method that cannot scientifically describe the safety of the pipeline restart process. To do this, this study introduces the reliability-based limit state method and interference principle into the safety evaluation of waxy crude pipelines during the restart process. Considering the random fluctuation characteristics of the mentioned parameters, the restart physical process, the flow and heat transfer mathematical model, and the restart failure limit state function were established. On this basis, the failure probability during the restart process for one waxy crude pipeline under constant flow was determined. This research has realized the quantitative evaluation of restart safety of waxy crude pipelines.



1. INTRODUCTION

The production of waxy crude oil worldwide is increasing rapidly, and more than 80% of crude oil produced in China is waxy crude.¹ For this type of crude oil, when the temperature drops below the wax appearance temperature (WAT), the viscosity of crude oil will increase significantly due to the wax precipitation from the crude oil. When the amount of precipitated wax reaches 2 to 3% in crude oil, crude oil will gelate as a whole and then lose fluidity. When the pipeline starts up again, the crude oil will show thixotropy, viscoelasticity, and yield stress.^{2,3} After the pipeline is shut down, the gelation of crude oil caused by the drop in oil temperature may cause the whole pipeline to fail during the restart process. Therefore, restart safety is one of the core problems faced in the operation of waxy crude pipelines.

For a long time, the deterministic analysis methods have been used to evaluate the restart safety of waxy crude pipelines, including the traditional minimum starting pressure estimation method based on the force balance relationship⁴ and numerical algorithms.^{5–13} Taking numerical algorithms as an example, a “safety factor” is often added to the iterative solution of steady-state flow and heat transfer calculation formulas to ensure the safety of pipeline operation. Generally speaking, the safety factor is obtained on the basis of a large number of practices, which can reflect certain statistical characteristics, but for different regions and different types of pipelines, its value has a large range of variation. In other words, this method of increasing the “safety

factor” cannot guarantee the absolute safety of the pipeline nor is it connected with the quantitative reliability of the pipeline. In addition, the evaluation effect of pipeline restart is usually affected by thermal parameters (such as the heating capacity, heat dissipation, etc.), dynamic parameters (such as the flow rate, pressure, etc.), environmental parameters, and oil physical parameters. However, during the restart process, the transportation volume, heat dissipation, friction, etc., are constantly changing over time, and many parameters have significant uncertainty. In this case, the pipeline is in a complex hydraulic and thermally unstable state. For example, the statistics of TuHa crude oil transported by crude oil pipelines in Western China show that its density varies between 800 and 855 kg/m³, the freezing point varies between –3 and 19 °C, and the standard deviation of freezing point can reach 3.7 °C.¹⁴ Therefore, it is difficult to scientifically evaluate the safety of the pipeline restart process using traditional deterministic methods.

At present, the probabilistic method is an effective method to solve this type of uncertainty problem, and the reliability-based

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design and assessment (RBDA) method, as one of them, has been used in aerospace and structural engineering, etc. In the 20th century, the reliability ideas began to apply in the oil and gas industry. For example, the International Organization for Standardization (ISO) promulgated the world's first technical specification based on reliability design methods on April 1, 2006: "Petroleum and Natural Gas Industry-Pipeline Transportation Systems-Limit State Methods Based on Reliability" (ISO 16708).¹⁵ In 2007, Canada revised the standard Z662-07 "Oil and Gas Pipeline System", first adding the RBDA method of the pipeline structure as an informative appendix.¹⁶ In 2012, China promulgated and issued GB/T29167-2012,¹⁷ which is equivalent to adopting ISO 16708, introducing the reliability theory into the field of China's oil and gas industry. Pan introduced the pipeline risk expert scoring method proposed by Muhlbauer, which has attracted extensive attention from the domestic oil and gas storage and transportation industry.^{18–20} Qu put forward the evaluation index and corresponding calculation formula of the reliability of oil and gas pipelines in China and analyzed the establishment method of the reliability model of the pump station system based on the investigation of the calculation theory and method of the reliability index of foreign pipelines.²¹ Relatively speaking, the oil and gas industry has a relatively late start in the research and application of reliability methods to solve petroleum pipeline engineering, and the corresponding theory and engineering experience are relatively lacking.

Based on the above research studies, this study applies the reliability method to the safety evaluation of waxy crude pipelines during the restart process and considers the random fluctuation characteristics of parameters. On this basis, the physical process, the flow and heat transfer mathematical model, and the restart failure limit state function of waxy crude pipelines were established. This research provides new methodological support for the safe and economic operation of waxy crude pipelines.

2. RELIABILITY-BASED METHOD

At present, reliability-based design and evaluation methods have been widely adopted in the fields of aerospace, structural engineering, etc.^{22–27} Its core is to comprehensively evaluate the impact of various random variables on system security and use the failure probability in a specific limit state to quantify the system risk. The implementation of this method can be divided into the following steps: first, establish the limit state equation by identifying the relevant failure mode; second, establish the probability distribution model of each random variable in the limit state equation through the uncertainty distribution of each variable; then, the limit state equation is solved to calculate its failure probability; finally, the failure probability under each failure mode (limit state) is compared with the target reliability to determine whether the system is safe. For those who do not meet the safe requirements, it is necessary to adjust the design or operating parameters and take measures such as maintenance of the in-service pipelines and then recalculate the failure probability before evaluating it. Following this theory, the restart safety of waxy crude pipelines is evaluated later.

3. MODEL ESTABLISHMENT OF THE WAXY CRUDE PIPELINE'S RESTART PROCESS

When analyzing the restart process of waxy crude pipelines, the model describing the restart process needs to be first established,

involving the oil temperature distribution along the pipeline, the rheological characteristics of crude oil (especially thixotropy), and the friction–flow relationship during pipeline restart. A comprehensive description of this process involves the heat transfer and flow issues of the pipeline's normal transportation process, shutdown process, and restart process.

3.1. Normal Transportation Process of Waxy Crude Pipelines. The pipeline normal transportation process is the basis to study the shutdown temperature drop and restart process. According to the hydraulic and thermal processes of buried crude pipelines, this study abstracts the physical model shown in Figure 1. Among them, the heat transfer process

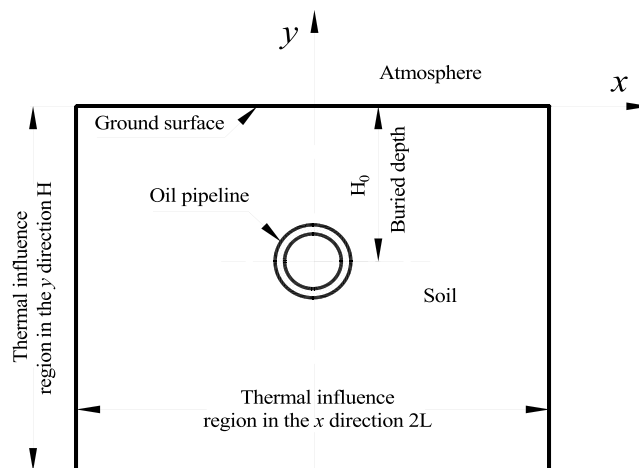


Figure 1. Sketch map of the physical model.

includes heat release from crude oil to the inner wall of the wax deposition layer, heat transfer between the wax deposition layer, pipe wall, anticorrosion layer, and other media, and heat transfer from the outer wall of the pipe to the surrounding soil (including the heat conduction of the soil and the exothermic of the soil to the atmosphere).

For crude oil in the pipeline, the description of the flow process involves the continuity (eq 1), momentum (eq 2), and energy (eq 3) and heat transfers (eq 4). The expressions are shown below:

$$\frac{\partial}{\partial \tau}(\rho A) + \frac{\partial}{\partial z}(\rho VA) = 0 \quad (1)$$

$$\frac{\partial V}{\partial \tau} + V \frac{\partial V}{\partial z} = -g \sin \alpha - \frac{1}{\rho} \frac{\partial p}{\partial z} - \frac{f}{D} \frac{V^2}{2} \quad (2)$$

$$\frac{\partial}{\partial \tau} \left[(\rho A) \left(u + \frac{V^2}{2} + gs \right) \right] + \frac{\partial}{\partial z} \left[(\rho VA) \left(h + \frac{V^2}{2} + gs \right) \right] = -\pi D q \quad (3)$$

$$C_p \frac{d\psi}{d\tau} - \frac{\psi}{\rho} \beta \frac{dp}{d\tau} - \frac{fV^3}{2D} + \frac{4q}{\rho D} = 0 \quad (4)$$

where A is the cross sectional area of pipe flow, m^2 ; ρ is the density of crude oil, kg/m^3 ; V is the mean flow velocity, m/s ; τ is the time, s ; z is the axial position of pipe, m ; s is the elevation, m ; p is the pressure of oil flow section, Pa ; D is the pipe diameter, m ; g is the acceleration of gravity, m/s^2 ; u is the specific internal energy of crude oil, J/kg ; h is the specific enthalpy of crude oil, J/kg ; C_p is the specific heat capacity of crude oil at constant

pressure, $J/(kg \cdot ^\circ C)$; β is the coefficient of thermal expansion of crude oil, $^\circ C^{-1}$; ψ is the crude oil temperature, $^\circ C$; f is the Darcy friction coefficient; q is the heat transfer of crude oil per unit time and per unit wall area, W/m^2 ; and α is the angle between the axial and horizontal directions of the pipe.

In addition, the thermal conductive process of the normal transportation process involves thermal conductivity between wax layers, tube walls, and antiserial layers and heat conduction of the tube wall and the surrounding soil. The corresponding thermal equations are as follows:

$$\rho_i C_i \frac{\partial T_i}{\partial \tau} = \frac{1}{r} \frac{\partial}{\partial r} \left(\lambda_i r \frac{\partial T_i}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial \theta} \left(\lambda_i \frac{\partial T_i}{\partial \theta} \right) \quad i = 1, 2, 3 \quad (5)$$

$$\rho_s C_s \frac{\partial T_s}{\partial \tau} = \frac{\partial}{\partial x} \left(\lambda_s \frac{\partial T_s}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda_s \frac{\partial T_s}{\partial y} \right) \quad (6)$$

where $i = 1, 2, 3$ represents the wax layer, pipe wall, and anticorrosion layer of the pipeline; λ_i is the coefficient of thermal conductivity of the layer i ; T_i is the temperature of the layer i ; ρ_i is the density of layer i ; C_i is the specific heat capacity of the layer i ; r and θ represent the two directions of polar coordinates; ρ_s is the soil density, kg/m^3 ; C_s is the specific heat capacity of soil, $J/(kg \cdot ^\circ C)$; T_s is the soil temperature, $^\circ C$; x is the horizontal position perpendicular to the axial direction of the pipe, m ; and y is the buried depth of pipeline, m .

In order to accurately solve the above equations, this study sets the following conditions:

$$-\lambda_1 \frac{\partial T}{\partial r} \Big|_{r=D/2} = \alpha_0 (\psi - T_1) \quad (7)$$

$$\lambda_4 \frac{\partial T}{\partial x} = 0 \quad x = 0, -(H_0 - R_1) \leq y \leq 0 \quad (8)$$

$$\lambda_4 \frac{\partial T}{\partial x} = 0 \quad x = 0, -H \leq y \leq -(H_0 + R_1) \quad (9)$$

$$\lambda_4 \frac{\partial T}{\partial y} = \alpha_a (T_a - T_4) \quad y = 0 \quad (10)$$

$$\frac{\partial T}{\partial x} = 0 \quad x = L \quad (11)$$

$$T = T_n \quad y = -H \quad (12)$$

where α_0 is the heat release coefficient of crude oil to the inner wall of the pipe, $W/(m^2 \cdot ^\circ C)$; H_0 is the buried depth of pipe center, m ; R_1 is the outermost radius of pipe, m ; α_a is the heat transfer coefficient between the surface and the atmosphere, $W/(m^2 \cdot ^\circ C)$; T_a is the atmospheric temperature, $^\circ C$; and T_n is the soil thermostatic layer temperature, $^\circ C$.

3.2. Shutdown Process of Waxy Crude Pipelines. The temperature rules of crude oil after shutdown are the basis for calculating the pressure of pipeline restart. The temperature drop of the shutdown process in buried crude pipelines is an unstable heat transfer problem, accompanied by the phase change process, the natural convection process, and the movement of the boundary.

According to the heat transfer method after shutdown, the heat transfer of crude oil includes three stages: natural conversion, heat conduction and natural convective co-control, and pure heat conduction process. In order to simplify the calculation, most of the natural convection problems are treated

with an "equivalent thermal coefficient λ_e " as heat conduction problems, and the equivalent thermal coefficient λ_e can be determined by the following formula:

$$\lambda_e = \frac{-\alpha_0 (T - T_w)}{\left. \frac{\delta T}{\delta r} \right|_w} \quad (13)$$

where T_w is the temperature at the junction between liquid crude oil and condensate, $^\circ C$, and $\left. \frac{\delta T}{\delta r} \right|_w$ is the temperature gradient at the junction between liquid crude oil and condensate.

In order to distinguish the natural convection zone and thermally conductive zone inside the pipeline, this study introduces the lag flow point,²⁸ that is, the heat transfer method of crude oil is the natural convection method in the region where the temperature is higher than the lag flow point. Conversely, it is a thermally conductive method. Therefore, during the entire pipeline shutdown, the thermally conductive equation of crude oil in the pipeline can be represented by eq 14:

$$\rho C_p \frac{\partial \psi}{\partial \tau} = \frac{1}{r} \frac{\partial}{\partial r} \left(\lambda_e r \frac{\partial \psi}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial \theta} \left(\lambda_e \frac{\partial \psi}{\partial \theta} \right) \quad (14)$$

The heat conduction equation of the wall and the surrounding soil is the same as described in the normal transportation process.

3.3. Restart Process of Waxy Crude Pipelines. The restart process of the buried crude pipeline is a hydraulic and thermal non-stable process. When crude oil does not exhibit thixotropy, its control equation is the same as the normal transportation process. When the shutdown time is long, crude oil shows thixotropy, and the momentum equation of the oil flow can be represented by eq 15:

$$\frac{\partial V}{\partial \tau} + V \frac{\partial V}{\partial z} + \frac{1}{\rho} \frac{\partial P}{\partial z} + g \sin \alpha + \frac{4\sigma_w}{\rho D} = 0 \quad (15)$$

where σ_w is the shear stress of pipe wall.

In this study, the thixotropy of crude oil was described by the Houska model, as follows:

$$\sigma = \sigma_{y0} + \beta \sigma_{y1} + (K + \beta \Delta K) \dot{\gamma}^n \quad (16)$$

$$\frac{d\beta}{d\tau} = a(1 - \beta) + b\beta \dot{\gamma}^m \quad (17)$$

where σ is the shear stress, Pa ; σ_{y0} is the yield stress when the structure is fully cracked, Pa ; σ_{y1} is the yield stress when the structure is fully established, Pa ; $\dot{\gamma}$ is the shear rate, s^{-1} ; ΔK is the thixotropic consistency coefficient, $Pa \cdot s^n$; K is the consistency coefficient, $Pa \cdot s^n$; n is the flow characteristic index; β is the structural parameters; and a , b , and m are the structure constants.

For the discrete and solving methods of the mathematical model involved in the above process, as well as the verification of correctness of the specific solving process and program, please refer to the literature.^{29,30}

4. RESULTS AND DISCUSSION

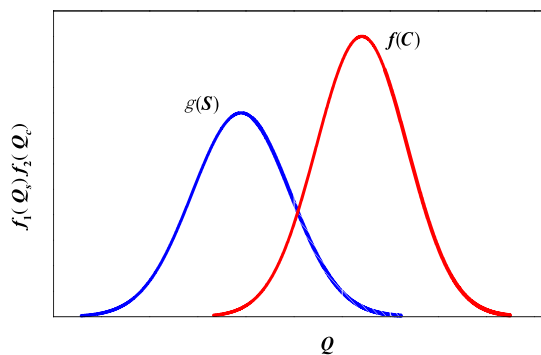
In the restart process based on constant flow mode, the outlet flow of the pipeline is given first, and the starting pressure required at this time needs to be calculated. In this case, the reliability-based pipeline restart evaluation process mainly includes the following aspects: the parameter uncertainty

Table 1. Uncertain Parameters Considered in the Safety Assessment of Pipeline Restart

classification	uncertainty parameter
operating parameters	throughput, outbound temperature
oil physical parameters	freezing point, viscosity, thixotropic parameter
environmental parameters	soil temperature, soil thermal conductivity
pipeline parameters	pipe diameter, pipe wall thickness, yield limit

Table 2. Statistics Results of Uncertain Parameters Distribution Type

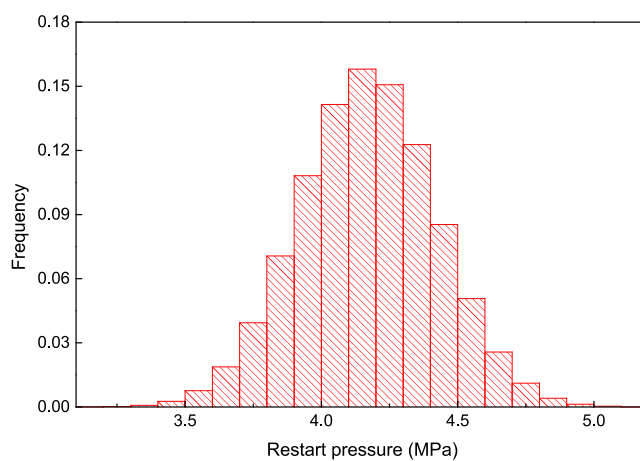
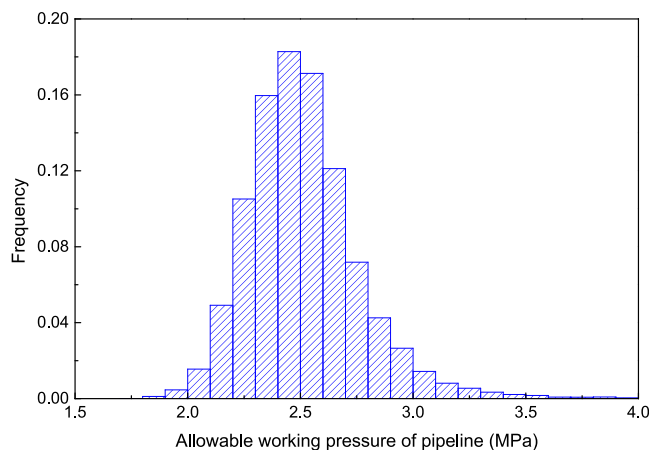
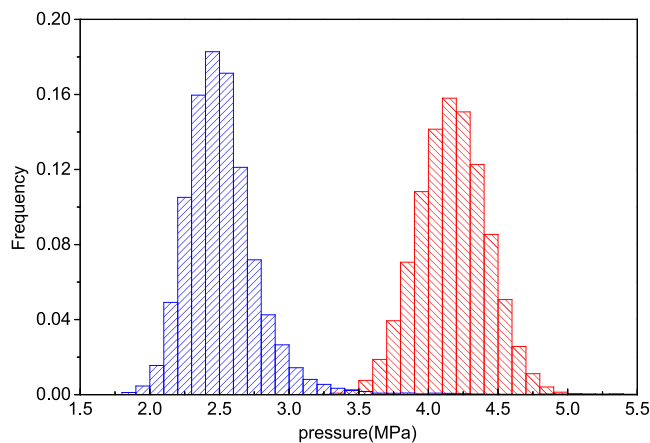
uncertainty parameter	distribution type
throughput	normal distribution
outbound temperature	normal distribution
soil temperature	normal distribution
soil thermal conductivity	normal distribution
freezing point	normal distribution
viscosity	normal distribution
thixotropic parameter	normal distribution
pipe diameter	normal distribution
pipe wall thickness	normal distribution
yield limit	normal distribution

**Figure 2.** Sketch map of the interference model.**Table 3. Values of the Uncertain Parameters**

uncertain parameters	distribution type	mean value	standard deviation
throughput/(m ³ /h)	normal distribution	1864	112
outbound temperature/(°C)	normal distribution	41.7	1
soil temperature/(°C)	normal distribution	-5.2	0.5
soil thermal conductivity/(W/(m·°C))	normal distribution	1.1	0.1
freezing point/(°C)	normal distribution	33	3
pipe diameter/(mm)	normal distribution	720	1.33
pipe wall thickness/(mm)	normal distribution	8	0.37
yield limit/(MPa)	normal distribution	310	11.7

analysis, establishment of the limit state function, and solution of the limit state function.

4.1. Parametric Uncertainty Analysis. In order to make the reliability analysis reliable and efficient, it is necessary to first identify the uncertainty variables, which have important influence on the limit state function. Second, the probability

**Figure 3.** Probability distribution histogram of the pipeline allowable working pressure.**Figure 4.** Probability distribution histogram of the pipeline restart pressure.**Figure 5.** Interference histogram of the pipeline restart pressure and allowable working pressure.

distribution of each variable should be determined. Finally, a reasonable and efficient random sampling method is selected to sample each random variable.

4.1.1. Uncertainty Parameter Classification. In this study, the uncertainty parameters related to the restart safety of the waxy crude pipeline are mainly divided into the following categories: operating parameters, oil physical parameters,

Table 4. Calculation Conditions of Different Pipeline Stations after Shutdown in Winter

station	throughput/(m ³ /h)	outbound temperature/(°C)	station spacing/(km)	soil temperature/(°C)	soil thermal conductivity/(W/(m·°C))
A–B	1864	41.7	49.65	−5.2	1.10
B–C	2081	43.0	67.65	−5.0	0.95
C–D	2366	41.5	65.60	−3.7	1.10
D–E	2366	41.5	59.50	−3.0	1.05
E–F	2326	43.0	65.70	−2.5	1.15
F–G	1928	44.0	68.50	−2.5	1.00
G–H	1928	45.0	69.30	−2.5	1.00
H–I	1928	45.5	80.00	−1.6	1.15

Table 5. Restart Failure Probabilities of Different Pipeline Stations after Shutdown in Winter

	A–B	B–C	C–D	D–E	E–F	F–G	G–H	H–I
failure probability	3.03×10^{-4}	4.74×10^{-4}	7.27×10^{-3}	4.97×10^{-3}	6.34×10^{-3}	1.18×10^{-5}	9.84×10^{-5}	1.79×10^{-5}

environmental parameters, and pipeline parameters, as shown in Table 1.

The uncertainty of the above parameters mainly comes from the parameter fluctuation, adjustment of working conditions, and the measurement or processing error. For example, fluctuations in the physical properties of crude oil are not only related to the nature of crude oil but also related to the thermal history and shear history of crude oil. For another example, the uncertainty of pipe diameter is affected by the insufficiency of the manufacturing process and measurement errors on the one hand; on the other hand, due to the pipeline construction process, small deformations of the pipeline may be caused, which affects the roundness of the pipeline.

4.1.2. Determination of the Probability Distribution of Uncertainty Parameters. The uncertainty analysis of parameters is to use statistical methods to determine its probability distribution, that is, the distribution model of parameters and corresponding model parameters, on the premise of clarifying the source of the parameter's uncertainty. For parameters with a sufficiently large sample size, the determination of parameter probability distribution includes the selection of distribution type, the estimation of distribution parameters, and the test of fitting effect. For specific treatment methods, please refer to our previously published literature.³¹

In the actual statistical process, it is found that the sample size of some parameters is too small to use the methods in the above-mentioned literature to analyze the uncertainty, but the uncertainty of these parameters has a significant impact on the process of pipeline restart. For these parameters with small sample size, this study adopts the following processing methods:

- (1) The selection of distribution type of such variables can be based on the experience of dealing with similar problems and physical models.
- (2) A statistical histogram is used to visually represent the distribution of parameters.

According to the above methods, combined with the statistical results of relevant uncertain parameters of the Western crude oil pipeline³² and Zhongluo Line,³³ the statistical results of probability distribution of uncertain parameters related to the restart process are shown in Table 2.

4.2. Establishment and Solution of Limit State Function. When the pipeline is started with the mode of constant flow, the safety of the restart process is defined by whether the starting pressure is higher than the maximum allowable working pressure of the pipeline. When the starting pressure exceeds the maximum allowable working pressure, the

restart process is considered to have failed. Therefore, according to the reliability theory, the limit state equation of pipeline restart is:

$$z(x) = C - S \quad (18)$$

where x is the random parameter vector related to the pipeline restart process; C is the allowable working pressure of the pipeline; and S is the pressure required to restart the pipeline. When $z(x) \leq 0$, that is, the maximum allowable working pressure of the pipeline is lower than the pressure required for restart, then the pipeline fails to restart.

(1) Determination of the allowable working pressure of pipeline C : The allowable working pressure of pipeline C is determined by multiplying the ultimate pressure of the pipeline by the design factor. In general, the ultimate pressure is calculated according to the deterministic method, that is, the average value of each parameter under the ultimate pressure is calculated. In fact, restricted by various objective conditions, the values of each parameter are somewhat dispersed. When the dispersion is large, the allowable working pressure determined by the design coefficient tends to be unsafe. On the contrary, the calculation results are conservative when the parameter dispersion is small. In this study, the uncertainty of parameters related to the allowable working pressure of the pipeline is described by a reliability-based method, so as to obtain the allowable working pressure of the pipeline accurately.

(a) When there is no defect in the pipeline, the allowable working pressure of pipeline can be calculated according to the following equation:

$$C = \frac{2KE\delta}{D} \quad (19)$$

where δ is the pipeline wall thickness, mm; E is the yield strength of pipeline, MPa; D is the outer diameter of pipeline, mm; and K is the design coefficient.

It can be seen from eq 19 that the distribution function of the allowable working pressure is related to the distribution function of the wall thickness, yield strength, and outer diameter of the pipeline. Using the Taylor series expansion method, the mean value and standard deviation of the allowable working pressure of pipeline are

$$\mu_C = \frac{2K\mu_E\mu_\delta}{\mu_D} \quad (20)$$

$$\begin{aligned}\sigma_C &= \sqrt{\left(\frac{\partial P_p}{\partial E}\right)^2 \sigma_E^2 + \left(\frac{\partial P_p}{\partial \delta}\right)^2 \sigma_\delta^2 + \left(\frac{\partial P_p}{\partial D}\right)^2 \sigma_D^2} \\ &= \sqrt{\left(\frac{2K\delta}{D}\right)^2 \sigma_E^2 + \left(\frac{2KE}{D}\right)^2 \sigma_\delta^2 + \left(-\frac{2KE\delta}{D^2}\right)^2 \sigma_D^2}\end{aligned}\quad (21)$$

where μ_E , μ_δ , and μ_D are the average values of the pipeline yield strength E , pipeline wall thickness δ , and pipeline outer diameter D , respectively. σ_E , σ_δ , and σ_D are the standard deviations of the pipeline yield strength E , pipeline wall thickness δ , and pipeline outer diameter D , respectively.

Therefore, the distribution types and parameter values of each variable can be obtained through statistical analysis of the measurement results of each variable and combined with relevant testing standards, so as to obtain the distribution function of the allowable working pressure of the pipeline.

(b) When there is a defect in the pipeline, the calculation method of the allowable working pressure of the pipeline has the corresponding calculation method in different specifications, for example, ASME B31G and PCORRC in the United States, DNV RP F101 in the United Kingdom and Norway, and CVDA-1984 in China. In this study, the PCORRC method was used to calculate the allowable working pressure of the pipeline for high-strength steels (X65–X80), as shown below:

$$C = \sigma_b \frac{2\delta}{D} \left(1 - \frac{d}{\delta} \left(1 - \exp\left(-0.157 \frac{L}{\sqrt{R(\delta - d)}}\right) \right) \right) \quad (22)$$

where σ_b is the tensile strength, MPa; D is the defect depth, mm; R is the pipeline radius, mm; and L is the length of defect, mm.

Similarly, by using the Taylor series expansion method, the mean and standard deviation of the allowable working pressure of pipeline are

$$\mu_C = \mu_{\sigma_b} \frac{2\mu_\delta}{\mu_D} \left(1 - \frac{\mu_d}{\mu_\delta} \left(1 - \exp\left(-0.222 \frac{\mu_L}{\sqrt{\mu_D(\mu_\delta - \mu_d)}}\right) \right) \right) \quad (23)$$

$$\begin{aligned}\sigma_C^2 &= \left(\frac{2(\mu_\delta - \mu_d)}{\mu_D} + \frac{2\mu_d}{\mu_D} \exp\left(-\frac{0.222\mu_L}{\sqrt{\mu_D(\mu_\delta - \mu_d)}}\right) \right)^2 \sigma_{\sigma_b}^2 \\ &+ \left(\frac{0.222\mu_\delta \mu_d \mu_L (\mu_\delta - \mu_d)}{(\mu_D^5 (\mu_\delta - \mu_d)^3)^{1/2}} \right) \exp\left(-\frac{0.222\mu_L}{\sqrt{\mu_D(\mu_\delta - \mu_d)}}\right) - \frac{2\mu_{\sigma_b} \mu_\delta}{\mu_D^2} \\ &+ \frac{2\mu_{\sigma_b} \mu_d}{\mu_D^2} \left(1 - \exp\left(-\frac{0.222\mu_L}{\sqrt{\mu_D(\mu_\delta - \mu_d)}}\right) \right)^2 \sigma_D^2 \\ &+ \left(\frac{2\mu_{\sigma_b}}{\mu_D} + \frac{0.222\mu_\delta \mu_d \mu_L}{(\mu_D(\mu_\delta - \mu_d))^{3/2}} \exp\left(-\frac{0.222\mu_L}{\sqrt{\mu_D(\mu_\delta - \mu_d)}}\right) \right)^2 \sigma_\delta^2 \\ &+ \left(-\frac{2\mu_{\sigma_b}}{\mu_D} + \frac{2\mu_{\sigma_b}}{\mu_D} \exp\left(-\frac{0.222\mu_L}{\sqrt{\mu_D(\mu_\delta - \mu_d)}}\right) \right. \\ &\left. - \frac{0.222\mu_\delta \mu_d \mu_L}{(\mu_D(\mu_\delta - \mu_d))^{3/2}} \exp\left(-\frac{0.222\mu_L}{\sqrt{\mu_D(\mu_\delta - \mu_d)}}\right) \right)^2 \sigma_d^2 \\ &+ \left(-\frac{0.444\mu_\delta \mu_d}{(\mu_D^3 (\mu_\delta - \mu_d))^{1/2}} \exp\left(-\frac{0.222\mu_L}{\sqrt{\mu_D(\mu_\delta - \mu_d)}}\right) \right)^2 \sigma_L^2\end{aligned}\quad (24)$$

where μ_{σ_b} , μ_d , and μ_L are the average values of the tensile strength σ_b , defect depth D and defect length L , respectively. σ_b , σ_D , and σ_L are the standard deviations of the tensile strength σ_b , defect depth D , and defect length L , respectively.

(2) Determination of pressure required for pipeline restart: Because the uncertain parameters such as operation parameters, soil physical properties, and oil physical properties change randomly with time, using a reliability-based method to solve the pressure required for pipeline restart, it is a stochastic numerical simulation process of unsteady pipeline flow. To be specific, in the process of stochastic numerical simulation, the boundary conditions required by random sampling should be generated at first, and the unsteady heat transfer process should be solved by numerical calculation, that is, the oil temperature distribution along the pipeline during restart should be calculated according to the oil temperature distribution at the shutdown time. On the premise of comprehensively considering the probability distribution types of related variables, the POD, finite volume method, and characteristic line method were jointly used to solve the variation law of oil and soil temperature field along the pipeline.^{29,34,35} Second, according to the oil temperature distribution, the rheological properties of crude oil, and wax formation along the pipeline, the pressure required for pipeline restart is calculated.

(3) Solution of pipeline restart failure probability: It is found that the pressure required for pipeline restart and the allowable working pressure of pipeline are both statistical values and not definite values, so it is not possible to judge whether the pipeline restart process fails by simply comparing the number. In this study, the stress–strength interference theory in reliability-based design and evaluation was introduced to solve the limit state function. According to the stress–strength interference model proposed by Pugsley in 1942, if the stress subjected to the system interferes with its allowable strength, the system may fail. In the interference interval, when the system stress is greater than its allowable strength, failure accidents will occur. As shown in Figure 2, according to the stress–strength interference theory, the probability density distributions of the pressure required for pipeline restart and allowable working pressure of pipeline are $g(S)$ and $f(C)$ respectively, and then the restart failure probability is

$$P_p = (C < S) = \int_{-\infty}^{+\infty} g(S) \left[\int_{-\infty}^S f(C) dc \right] dS \quad (25)$$

4.3. Case Analysis. **4.3.1. Restart Safety between Station A and Station B.** Taking the restart process of one actual pipeline as an example, the reliability principle is used to evaluate its restart safety. The outer diameter of the pipeline is 720 mm, the wall thickness is 8 mm, the distance between station A and B is 50 km, the elevation difference between stations is 1.2 m, the average buried depth at the center of pipeline is 1.5 m, the buried depth temperature in winter is -5.2 °C, the longest allowable shutdown time is 20 h, and the thermal conductivity of pipeline is 49.8 mW/(m²·°C). In addition, the thermal conductivity of the anticorrosion layer is 0.15 W/(m²·°C), and that of the wax layer is 0.2 W/(m²·°C). The mean value and standard deviation of relevant uncertainty parameters are shown in Table 3. Moreover, the abnormal point of crude oil is 38 °C, and the relationship of viscosity–temperature is shown as follows:

$$\mu = 2.23 \times 10^5 T^{-2.40} \quad (38^\circ\text{C} \leq T \leq 70^\circ\text{C}) \quad (26)$$

$$K = 8.91 \times 10^8 e^{-0.42T} \quad (30^\circ\text{C} \leq T < 38^\circ\text{C}) \quad (27)$$

$$n = -0.86 + 0.04T \quad (30^{\circ}\text{C} \leq T < 38^{\circ}\text{C}) \quad (28)$$

Through the models and algorithms established in the early stage, the probability distribution histogram of allowable working pressure of pipeline after 50,000 times of numerical simulation is shown in Figure 3, and the probability distribution histogram of the pressure required in the pipeline restart process is shown in Figure 4.

Based on the above information, the probability of the interference histogram of the pressure required for pipeline restart and allowable working pressure is calculated (as shown in Figure 5), and the failure probability of pipeline restart between station A and B is 3.03×10^{-4} .

4.3.2. Restart Safety between All Stations after Pipeline Shutdown for 20 h in Winter. Taking the actual pipeline mentioned above as an example, the restart safety among all stations of the pipeline is evaluated by using the reliability principle adopted in this study. Table 4 shows the calculation conditions of the failure probability of restart safety between all stations after pipeline shutdown for 20 h in winter.

After calculation using the restart failure probability program, the restart failure probability of each station can be obtained, as shown in Table 5.

It can be seen that after 20 h shutdown in winter, the restart failure probability of each station is concentrated between 10^{-3} and 10^{-4} magnitude. Especially in the case of stations C–D, D–E, and E–F, the restart failure probability is the largest, mainly due to the large inter-station flow. In other words, in constant flow restart mode, the flow is the main factor to determine whether the pipeline can be restarted successfully. In addition, the restart failure probability between station A and B is higher than that between stations F–G, G–H and H–I, mainly because the soil temperature and outbound temperature between station A and B are lower. In this case, the temperature drop of crude oil during shutdown process is larger, and the stronger structure of crude oil is formed, resulting in a large probability of restart failure.

5. CONCLUSIONS

In this study, the reliability-based limit state method is applied to the restart safety evaluation of waxy crude pipelines, and the safety of the pipeline restart process under constant flow is described quantitatively in the form of probability based on the reliability principle.

- (1) Based on the analysis of the physical process of waxy crude pipeline restart, the unsteady heat transfer and flow mathematical models are established, including the heat transfer and flow issues of the pipeline's normal transportation process, shutdown process, and restart process.
- (2) Considering the uncertainty of operation parameters, oil physical property parameters, and environmental parameters, starting from the failure mechanism of pipeline restart, the limit state function based on flow recovery is established for constant flow startup mode, and the interference principle is introduced to solve it.
- (3) The failure probabilities of the restart process between stations of an actual pipeline after shutdown for 20 h in winter are calculated, and the maximum restart failure probability is 7.27×10^{-3} .

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Notes

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