

OPTIMAL DESIGN OF SUBSEA HIPPS FORTIFIED SECTION LENGTH CONSIDERING OIL VISCOSITY-THERMO CHARACTERISTICS

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Received September 2025; revised January 2026

ABSTRACT. *With the continuous expansion of subsea oil and gas development in both scale and depth, the High Integrity Pressure Protection System (HIPPS) has been widely deployed in subsea production system as a critical safeguard against abnormal high-pressure events, effectively preventing rupture of subsea oil and gas gathering and transportation pipelines and mitigating environmental risks to the surrounding seawater. Under abnormal operating conditions, such as uncontrolled choke valve opening, pipeline blockage, or emergency shutdown valve (ESDV) activation, the internal pipeline pressure can rise rapidly. In such cases, HIPPS protects the system by isolating the overpressure through a properly defined fortified section. However, existing fortified section designs are predominantly based on isothermal flow models that assume constant oil viscosity. This simplification often results in overly conservative designs with excessive redundancy in fortified section length, thereby increasing the construction and deployment cost of HIPPS. To address this limitation, this study investigates the optimization of fortified section length for subsea HIPPS by explicitly incorporating the effects of temperature on oil viscosity. A dynamic pressure-flow-temperature distributed parameter model is first established, accounting for the viscosity-thermo characteristics of crude oil. By coupling the oil flow governing equations with boundary conditions associated with throttling elements and rockshaft formation, the model enables prediction of pressure field distributions under various operating scenarios. The method of characteristics (MOC) is then employed to transform the distributed parameter model into ordinary differential equations along characteristic lines. This treatment effectively avoids numerical instability and solver divergence that may arise from ill-posed partial differential equations, thereby enhancing computational robustness. Finally, based on practical engineering design parameters, a series of simulation studies are conducted to analyze pressure field distributions under different shut-in pressures and pipeline blockage locations. The results yield an optimized fortified section length design and demonstrate that pipeline blockage is the dominant factor influencing internal pressure distribution. By incorporating the viscosity-thermo characteristics of oil into the modeling framework, the proposed method provides a more physically accurate and engineering-relevant tool for subsea HIPPS fortified section design, ensuring system reliability while reducing unnecessary capital expenditure.*

Keywords: Subsea production system, HIPPS, Viscosity-thermo characteristics, Pressure field distribution, MOC, Optimal design

1. Introduction. To support the sustained production growth of subsea oil and gas resources, global exploration activities are continuously advancing into deep-water and

ultra-deep-water regions. In recent years, deep-water high-temperature and high-pressure (HPHT) reservoirs have increasingly become a dominant focus in global oil and gas exploration and development [1]. Under abnormal operating conditions – such as pipeline blockage or equipment failure – the risk of local overpressure in crude oil leads to pipeline rupture and equipment damage, posing significant challenges to the safe and stable operation of subsea system. To mitigate such risks, conventional design approaches typically require full-length and full-rated pressure specifications for subsea pipelines, which significantly escalates the cost of subsea oil and gas development [2,3]. For the purpose of reducing the required length of pipelines designed for full pressure containment, HIPPS has been widely implemented in the international subsea oil and gas fields [4,5].

The HIPPS module is installed downstream of the X-tree or manifold, and its core components include the HIPPS valve, pressure sensor, logic controller, and the fortified section. Under normal operating conditions, the HIPPS remains in a monitoring state and does not participate in process control. Once the system pressure reaches a predefined overpressure threshold, however, the logic controller immediately actuates the shutdown mechanism to close the valve. This action rapidly isolates the upstream high pressure, thereby preventing overpressure and potential leakage in the downstream pipeline and ensuring the safety of downstream process equipment and personnel [6-10]. Due to inherent response delays during the closure of the HIPPS valve, the pressure in the downstream pipeline may continue to increase during the shut-off period [11]. If the fortified section is designed too short, overpressure and leakage may occur in the unfortified downstream section. This risk is particularly significant under severe disturbances, such as hydrate blockages or ESDV activation, which can induce pronounced pressure fluctuations [12]. Conversely, adopting an overly conservative design, such as a fortified section with double-length redundancy [13], leads to excessive pipeline configuration, substantially increasing capital expenditure and reducing economic efficiency. Therefore, minimizing the length of the HIPPS fortified section while maintaining system safety has become a critical issue in subsea oil and gas engineering design.

Most existing methods for optimizing the length of the HIPPS fortified section are based on empirical approaches or isothermal flow models [14], which often neglect subsea temperature variations and the temperature-dependent viscosity characteristics of the transported fluid. However, with increasing water depth, the ambient temperature progressively decreases – i.e., the temperature gradient is negative in the direction of increasing depth [15]. At the same time, the temperature of subsea oil and gas wells remains relatively high, resulting in continuous heat exchange within the oil transportation pipeline [16]. As a result, the crude oil viscosity varies with temperature, further influencing both pressure and flow rate distributions [17]. To ensure operational safety, published fortified section design methods adopt a conservative double redundancy approach to accommodate potential pressure fluctuations and unexpected overpressure scenarios. However, such redundancy significantly increases system cost. Therefore, it is essential to thoroughly assess the impact of temperature uncertainty on fortified section design and develop a pressure field distribution model that incorporates the thermo-viscous characteristics of crude oil. By optimizing the redundancy design coefficient under these considerations, it becomes possible to reduce the fortified section length safely and reliably, thereby cutting overall system cost without compromising safety.

To establish an accurate dynamic model of pressure or flow rate within HIPPS pipelines, it is essential to account for boundary conditions such as throttling components and wellbores, as well as the flow behavior of crude oil with temperature-dependent viscosity. Researchers have extensively studied crude oil flow in pipelines, particularly under unsteady-state conditions. Various models, including 1D incompressible flow models and

fluid-structure interaction (FSI) models, have been developed and solved using numerical methods such as the method of characteristics and finite difference methods [18]. Kandil et al. proposed an unsteady fluid dynamic model and employed the method of characteristics to numerically simulate pressure wave phenomena occurring during transient pipeline flow, validating the accuracy of their model through comparison with experimental data [19]. Ismaier and Schlücker developed a physical model comprising a tank, centrifugal pump and valves, and established the corresponding fluid flow mathematical model, which was subsequently validated against observed data [20]. Tijsseling et al. used the Skalak theory, and further analyzed FSI in liquid-filled pipelines by incorporating a “four-equation FSI model” [21]. Nikpour et al. presented a multi-physics coupling approach that integrates experiments and numerical simulations. Two experimental setups – with and without pressure-isolating tubes – were designed, and the results demonstrated good agreement with simulations, confirming the method’s accuracy in transient flow analysis [22]. Kandil et al. also used the method of characteristics to investigate the influence of pipeline materials on fluid dynamics. Their findings indicated that materials with lower elastic moduli can effectively attenuate pressure surges during fluid transients, thereby reducing mechanical stress on the pipeline system [23]. However, these studies primarily focus on onshore or shallow-water environments and do not incorporate the thermo-viscous characteristics of crude oil. As a result, there remains a lack of high-fidelity dynamic modeling methods capable of accurately capturing the transient response of subsea HIPPS pipelines under abnormal operating conditions, which limits their applicability in the optimized design of fortified section length for deep-water engineering applications.

This study develops a dynamic modeling approach for pressure in subsea HIPPS pipeline by integrating knowledge from onshore HIPPS system with the unique operational characteristics of subsea environment, aiming to support the optimization of fortified section length. Given that crude oil flows relatively slowly in the pipeline and can be treated as laminar flow [24], the flow is assumed to be 1D and unsteady, with negligible transverse and radial variations. The fluid is modeled as a weakly compressible medium. The coupled pressure-flow rate-temperature model constitutes a system of nonlinear partial differential equations (PDEs) with distributed parameters [25,26]. To solve these equations, numerical methods such as the finite element method (FEM) and MOC are commonly used [27]. FEM is highly versatile in handling complex geometries and boundary conditions, and is capable of solving multidimensional and nonlinear problems. However, it requires discretization of the pipeline into a large number of elements, resulting in high computational cost and memory demands [28]. This limitation becomes especially significant when dealing with transient flow problems, where FEM tends to exhibit lower computational efficiency compared to MOC. In contrast, the method of characteristics transforms the PDEs into a set of ordinary differential equations (ODEs) along characteristic lines, allowing for efficient handling of transient flow phenomena without solving the entire flow field. This significantly reduces computational burden and is particularly well-suited for solving 1D fluid flow models [29]. Therefore, in this study, the MOC is adopted to solve the dynamic pressure and flow velocity model for HIPPS pipelines under subsea conditions.

This study comprehensively considers the influence of temperature field variations in oil pipelines on crude oil viscosity and derives a pressure field distribution model within the pipeline. Using the method of characteristics, the pressure distribution along the pipeline is solved under three abnormal operating conditions, thereby determining the fortified section length of the subsea HIPPS. The findings provide a theoretical basis

for the optimized design of the subsea HIPPS fortified section length and contribute to reducing overall system cost. The structure of this paper is arranged as follows:

1) Section 2 describes the two operating modes of the HIPPS system and presents the corresponding assumptions.

2) Based on the assumptions proposed in Section 2, Section 3 formulates the crude oil flow equations inside the transmission pipeline while accounting for the viscosity-thermo characteristics of crude oil, including the momentum conservation equation, the continuity equation, and the associated boundary conditions.

3) Section 4 solves the proposed model using the method of characteristics.

4) Section 5 conducts simulation studies for single-well and multi-well production operations under three abnormal operating conditions. The results demonstrate that incorporating the viscosity-thermo characteristics of crude oil reduces the redundancy coefficient of the fortified section in the constant-temperature model, thereby effectively decreasing the actual fortified section length and lowering construction cost.

5) Section 6 concludes the paper with key findings and future directions.

2. Problem Description and Assumptions.

2.1. Problem description. Due to variations in subsea reservoir characteristics, the number of production wells differs across fields. As a result, HIPPS operates under two primary modes, including single-well subsea X-tree and multi-well subsea manifolds.

For single-well production operations, the process flow involving HIPPS is illustrated in Figure 1. In this mode, the HIPPS module is typically installed on the oil transportation pipeline between the X-tree and the platform. When overpressure occurs in the pipeline, the pressure sensor first detects the abnormal signal, and the logic controller immediately sends a shutoff command to the HIPPS valve, enabling rapid isolation from the high-pressure source [30]. Three primary scenarios may trigger HIPPS valve closure due to overpressure, including failure of the choke valve on the X-tree, resulting in a fully open valve; hydrate blockage in the downstream pipeline; and an ESDV event on the platform, causing the downstream ESDV to close abruptly [31]. Since HIPPS valve closure requires a finite amount of time [32], the pipeline pressure downstream of the valve must remain below the pipe's allowable pressure before complete shutoff is achieved. Therefore, it is essential to comprehensively consider the above three abnormal operating conditions when optimizing the fortified section length. This ensures that the downstream pressure remains within safe limits during the valve closure process, thereby preventing structural failure of the pipeline.

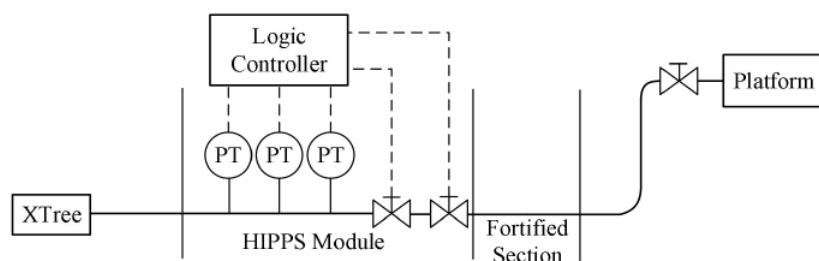
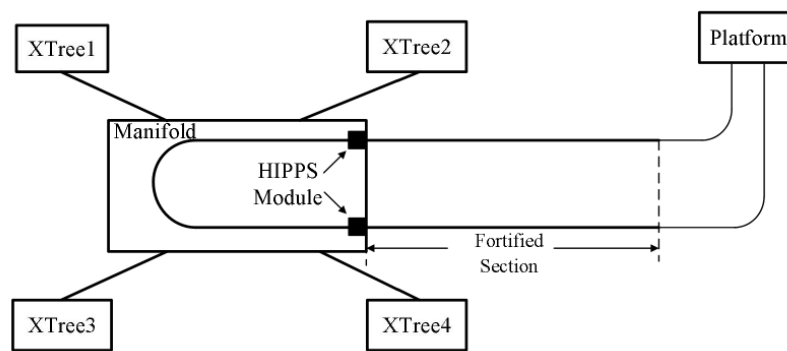


FIGURE 1. HIPPS crude oil production process of single-well

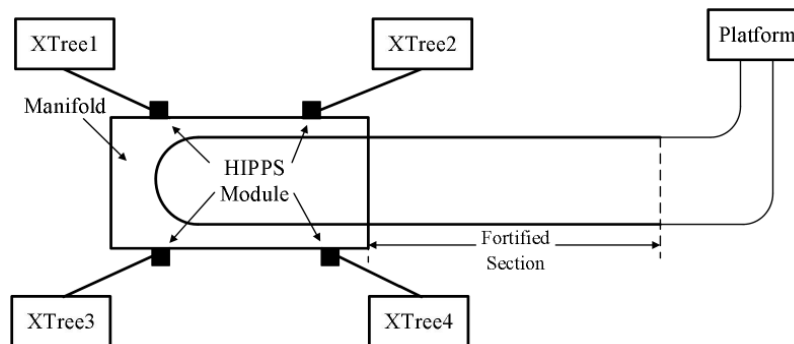
First, under the operating condition of a malfunction-induced full opening of the X-tree choke valve, both the flow rate and pressure within the tree rise sharply in a short period of time, causing a rapid increase in pressure downstream of the oil export pipeline. Once the HIPPS valve is closed, the resulting pressure surge is quickly contained upstream of

the valve, and the downstream pressure ceases to rise. Second, in the event of pipeline blockage or an ESDV closure, pressure accumulates at the blockage location or upstream of the ESDV, leading to a continuous pressure increase within the pipeline. In addition, variations in the pipeline's friction coefficient may induce water hammer effects, further intensifying transient pressure fluctuations. After the HIPPS valve closes, the downstream pipeline becomes isolated from the pressure source, pressure stops increasing, and the system gradually returns to normal operating conditions.

When subsea production system conducts multi-well oil recovery operations through a manifold, two primary installation configurations are available for HIPPS: pipeline HIPPS installation and simple HIPPS installation, with the corresponding process flows illustrated in Figure 2. The structural configuration of the HIPPS module is identical to that employed in single-well oil recovery operations [33-35].



(a) Pipeline HIPPS installation



(b) Simple HIPPS installation

FIGURE 2. Oil production process of manifold HIPPS

In multi-well production scenarios, the first HIPPS installation configuration places the system downstream of the manifold, commonly referred to as the pipeline HIPPS installation. This approach requires fewer HIPPS units, which helps reduce equipment cost; however, both the fortified section and the remaining downstream components must be designed to withstand higher pressure ratings. The second configuration installs the HIPPS module inside each X-tree, by converting one of the tree's wing valves into a dedicated HIPPS valve. This method requires a separate HIPPS unit for each well, resulting in a higher total number of HIPPS devices compared to the pipeline HIPPS installation configuration. However, it allows the rest of the system – especially the fortified section and downstream equipment – to be designed with lower pressure ratings, potentially reducing structural requirements and cost in those areas.

For the pipeline HIPPS installation, the abnormal operating conditions are similar to those encountered in single-well production, including pipeline blockage, choke valve failure leading to full opening, and ESDV closure on the FPSO. In contrast, for the simple HIPPS installation, inter-well interference must also be considered, as pressure fluctuations caused by flow dynamics between wells may impact the stability and response of the system.

2.2. Fundamental assumptions. The dynamic pressure-flow-temperature model for subsea HIPPS pipelines proposed in this study is developed based on the following fundamental assumptions.

- 1) Pressure losses due to collisions between the pipeline and throttling components are neglected.
- 2) Radial velocities induced by the thermal expansion or contraction of crude oil are minimal; thus, convective acceleration terms are omitted.
- 3) During transient flow, the energy loss at a given velocity is assumed to be equivalent to that of steady-state flow at the same velocity.
- 4) The ambient subsea temperature is assumed to remain constant and unaffected by the pipeline temperature.
- 5) The specific heat capacity of crude oil is considered constant, as its variation with temperature is negligible.

3. Model Development.

3.1. Crude oil flow equation. The momentum conservation equation and the continuity equation for crude oil flow within the oil pipeline are established as the basis of the model.

Assuming 1D flow of crude oil within an elastic-walled pipeline, as illustrated in Figure 3, two adjacent cross-sections are selected as an infinitesimal control volume of length δx . Under the influence of resultant forces, the fluid undergoes axial motion along the x -axis within the pipeline.

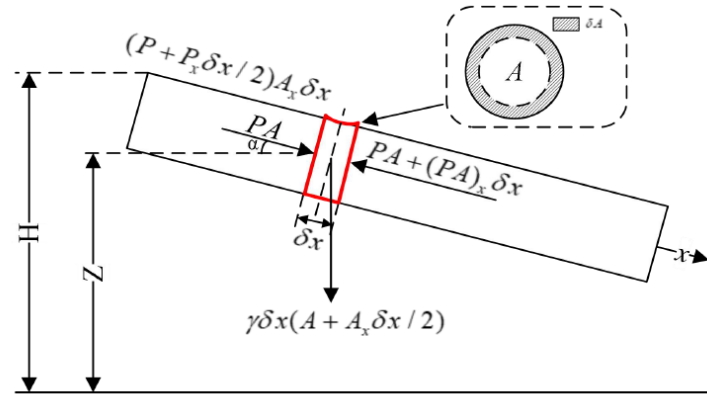


FIGURE 3. Force analysis of oil microelements

The forces acting on the infinitesimal control volume include the pressure PA on the upstream cross-section, the pressure $PA + \frac{\partial(PA)}{\partial x} \delta x$ on the downstream cross-section, the average axial pressure $(P + \frac{\partial P}{\partial x} \frac{\delta x}{2}) \frac{\partial A}{\partial x} \delta x$ induced by pipeline cross-sectional variation, the gravitational force component $(A + \frac{\partial A}{\partial x} \frac{\delta x}{2}) \delta x \gamma \sin \alpha$ along the x -axis, and the wall frictional force $\pi D \delta x \tau_0$ that resists crude oil flow. The direction of the frictional force is opposite to the direction of fluid motion.

According to Newton's Second Law, the resulting equation is expressed as Equation (1).

$$\begin{aligned} \left(A + \frac{\partial A}{\partial x} \frac{\delta x}{2}\right) \delta x \rho \frac{dV}{dt} = PA - \left[PA + \frac{\partial(PA)}{\partial x} \delta x\right] + \left(P + \frac{\partial P}{\partial x} \frac{\delta x}{2}\right) \frac{\partial A}{\partial x} \delta x \\ + \left(A + \frac{\partial A}{\partial x} \frac{\delta x}{2}\right) \delta x \gamma \sin \alpha - \pi D \delta x \tau_0 \end{aligned} \quad (1)$$

where, A is the cross-sectional area of the pipeline, D is the pipe diameter, P is the internal pressure at the cross-section, ρ is the crude oil density, τ_0 represents the wall shear stress, and V is the crude oil flow velocity.

By neglecting higher-order infinitesimal terms, Equation (1) can be simplified to Equation (2).

$$A \delta x \rho \frac{dV}{dt} = -\frac{\partial P}{\partial x} A \delta x + \frac{\partial A}{\partial x} P \delta x + A \delta x \gamma \sin \alpha - \pi D \delta x \tau_0 \quad (2)$$

By dividing all terms in Equation (2) by the mass of the infinitesimal control volume $A \delta x \rho$, and rearranging, Equation (3) is obtained.

$$\frac{1}{\rho} \frac{\partial P}{\partial x} - g \sin \alpha + \frac{4\tau_0}{\rho D} + \frac{dV}{dt} = 0 \quad (3)$$

Given that $\frac{\partial \rho}{\partial t} \ll H$ and $\frac{\partial \rho}{\partial x} \ll H$, ρ is assumed to be a constant, and the pressure is expressed by Equation (4).

$$\begin{aligned} P &= \rho g(H - Z) \\ \frac{\partial P}{\partial x} &= \rho g \left(\frac{\partial H}{\partial x} - \frac{\partial Z}{\partial x} \right) = \rho g \left(\frac{\partial H}{\partial x} + \sin \alpha \right) \end{aligned} \quad (4)$$

By substituting Equation (4) into Equation (3), Equation (5) is obtained.

$$g \frac{\partial H}{\partial x} + \frac{4\tau_0}{\rho D} + \frac{dV}{dt} = 0 \quad (5)$$

According to Assumption 3), the wall friction force is considered equal to the frictional resistance experienced by crude oil under steady-state flow conditions. Based on fundamental principles of fluid mechanics, the shear stress is influenced by factors such as the velocity profile of the crude oil, the internal diameter of the pipeline, and the surface roughness of the pipe wall. Taking account of the interaction between crude oil viscosity and the pipe wall, the frictional loss is described using the Darcy-Weisbach equation, as shown in Equation (6).

$$\tau_0 = \frac{\rho f V^2}{8} \quad (6)$$

In this equation, f represents the pipe friction factor, which is related to the pipe roughness ε , as expressed in Equation (7) [17].

$$\frac{1}{\sqrt{f}} = -2 \log \left\{ \frac{\varepsilon}{3.71D} - \frac{1.975}{Re} \left[\ln \left(\left(\frac{\varepsilon}{3.93D} \right)^{1.092} \right) + \left(\frac{7.627}{Re + 395.9} \right) \right] \right\} \quad (7)$$

where, Re denotes the Reynolds number of the crude oil, which is inversely proportional to its kinematic viscosity ν , as shown in Equation (8).

$$Re = \frac{VD}{\nu} \quad (8)$$

where, the kinematic viscosity ν is an intrinsic property of crude oil and is temperature-dependent, as expressed in Equation (9) [36].

$$\ln(\ln(v)) = 0.07547 + \frac{5.76588}{\ln(API)} - 0.00101(1.8T + 32) \times \ln(1.8T + 32) \quad (9)$$

By combining kinematic analysis and considering the velocity distribution and stress transmission of crude oil within the pipeline, Equation (6) is substituted into Equation (5), yielding a one-dimensional flow equation applicable to straight or conical pipes made of any material, as shown in Equation (10).

$$g \frac{\partial H}{\partial x} + \frac{dV}{dt} + \frac{fV}{2D}|V| = 0 \quad (10)$$

This equation characterizes the relationship between the momentum variation of crude oil within the pipeline and the geometrical features of the pipe as well as the mechanical properties of the fluid. Since the flow velocity V is a function of both the spatial coordinate x and time t , it satisfies Equation (11).

$$\frac{dV}{dt} = \frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} \quad (11)$$

By substituting Equation (11) into Equation (10), the equation can be rewritten in a general differential form, as shown in Equation (12).

$$g \frac{\partial H}{\partial x} + \frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} + \frac{fV}{2D}|V| = 0 \quad (12)$$

Since the convective acceleration term $V \frac{\partial V}{\partial x}$ is relatively small compared to the other terms, it can be neglected, yielding Equation (13).

$$g \frac{\partial H}{\partial x} + \frac{\partial V}{\partial t} + \frac{fV}{2D}|V| = 0 \quad (13)$$

This equation represents the momentum equation for crude oil, which describes the influence of varying flow velocities and frictional forces on pressure changes within the pipeline.

According to the law of mass conservation, the static mass of crude oil entering the control volume per unit time is equal to the incremental mass change within the moving control volume. This leads to the continuity equation, expressed as Equation (14).

$$\rho A(V - u) - \left[\rho A(V - u) + \frac{\partial(\rho A(V - u))}{\partial x} \delta x \right] = \frac{d}{dt}(\rho A \delta x) \quad (14)$$

where, u denotes the velocity relative to the crude oil.

The total differential of the moving infinitesimal control volume is expressed in Equation (15).

$$\frac{d}{dt} = \frac{\partial}{\partial t} + u \frac{\partial}{\partial x} \quad (15)$$

This indicates that changes in the control volume can be decomposed into variations along the temporal and spatial dimensions. By substituting Equation (15) into the continuity equation and performing expansion and simplification, Equation (16) is obtained.

$$\frac{\partial V}{\partial x} + \frac{V}{A} \frac{\partial A}{\partial x} + \frac{V}{\rho} \frac{\partial \rho}{\partial x} + \frac{1}{\rho} \frac{\partial \rho}{\partial t} + \frac{1}{A} \frac{\partial A}{\partial t} = 0 \quad (16)$$

Next, substituting the total differentials of ρ and A along the direction of fluid motion into Equation (16) and simplifying yields Equation (17).

$$\frac{d\rho/dt}{\rho} + \frac{dA/dt}{A} + V_x = 0 \quad (17)$$

where, the first term represents the compressibility of the fluid, the second term reflects the elasticity of the pipe wall material, and the last term denotes the difference between the inflow and outflow within the control volume at any given time.

The bulk modulus of elasticity of crude oil is expressed in total differential form as Equation (18).

$$K = \frac{dP}{d\rho/\rho} \quad (18)$$

For the deformation behavior of crude oil within the pipeline, given that $\frac{\partial \rho}{\partial x} \approx 0$ and $\frac{\partial A}{\partial x} \approx 0$, the effect of axial deformation can be neglected, leading to Equation (19).

$$\frac{dA/dt}{A} = \frac{1}{\pi D^2/A} \pi D \varepsilon_T \frac{D}{2} = 2\varepsilon_T = \frac{2}{E} \sigma_T \quad (19)$$

where, ε_T denotes the circumferential strain, $\varepsilon_T \frac{D}{2}$ is the increment in radius, and $\pi D \varepsilon_T \frac{D}{2}$ represents the increment in cross-sectional area. By substituting Equation (18) and Equation (19) into Equation (17) and simplifying, Equation (20) is obtained.

$$\frac{\partial V}{\partial x} + \frac{1}{K} \frac{dP}{dt} + \frac{2}{E} \sigma_T = 0 \quad (20)$$

To further characterize the changes in crude oil under variations in pressure and density, the stress expression for frictional resistance from fluid dynamics $\sigma_T = \frac{dP}{dt} \frac{D}{2e}$ is introduced and substituted into the equation, resulting in Equation (21).

$$\frac{\partial V}{\partial x} + \frac{1}{K} \left(1 + \frac{KD}{Ee} \right) \frac{dP}{dt} = 0 \quad (21)$$

For analytical convenience, a wave speed $a = \frac{\sqrt{K/\rho}}{\sqrt{1 + \frac{KD}{Ee}}}$ is defined to represent the propagation velocity of pressure disturbances in crude oil. Substituting this definition into Equation (21) yields Equation (22).

$$\frac{\partial V}{\partial x} + \frac{1}{\rho a^2} \frac{dP}{dt} = 0 \quad (22)$$

By substituting Equation (4) into Equation (22), Equation (23) is obtained.

$$\frac{a^2}{g} \frac{\partial V}{\partial x} + V \left(\frac{\partial H}{\partial x} + \sin \alpha \right) + \frac{\partial H}{\partial t} = 0 \quad (23)$$

In Equation (23), the term $V \left(\frac{\partial H}{\partial x} + \sin \alpha \right)$ is a higher-order infinitesimal compared to $\frac{a^2}{g} \frac{\partial V}{\partial x}$, and thus can be neglected. Therefore, Equation (23) can be simplified to Equation (24).

$$\frac{a^2}{g} \frac{\partial V}{\partial x} + \frac{\partial H}{\partial t} = 0 \quad (24)$$

This equation represents the continuity equation, which reflects the principle of mass conservation during the 1D unsteady flow of crude oil and describes the distribution of crude oil mass with respect to both time and spatial location.

According to Equation (7)-Equation (9), fluid viscosity is influenced by temperature. In the marine environment, as water depth increases, the ambient seawater temperature gradually decreases. The variation of seawater temperature with depth is described by Equation (25) [15].

$$T_h = \begin{cases} \frac{T_s(200 - h)}{200}, & 0 \leq h < 200 \\ a_2 + \frac{(a_1 - a_2)}{1 + e^{(h-a_0)/a_3}}, & h \geq 200 \end{cases} \quad (25)$$

In this equation, a_0 , a_1 , a_2 , and a_3 are empirically determined constants, T_s is the sea surface temperature, and h is the water depth. Consequently, the viscosity of crude oil within the pipeline is position-dependent.

Considering the heat transfer process in the 1D flow of crude oil, the heat introduced per unit volume – due to work done by viscous forces and thermal conduction – is equal to the increase in internal energy per unit volume. This relationship is described by Equation (26).

$$\rho \frac{\partial U}{\partial t} + V \frac{\partial U}{\partial x} = \frac{1}{gh} H_{xx} \frac{\partial V}{\partial x} + \frac{\partial}{\partial x} \left(k_1 \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_2 \frac{\partial T}{\partial y} \right) \quad (26)$$

In this equation, the first term represents the rate of change of internal kinetic energy, the second term represents the rate of internal energy change, the third term is the work done by surface deformation forces, and the last two terms are heat conduction terms. The coefficients k_1 and k_2 denote the thermal conductivities of crude oil and the pipe wall, respectively. U represents the heat content of the fluid element. The relationship between the internal heat content and temperature is given by Equation (27):

$$U = CMT \quad (27)$$

where, C is the specific heat capacity of crude oil, and M is the mass of crude oil passing through the fluid element per unit time, as expressed in Equation (28):

$$M = \rho VA \quad (28)$$

By substituting Equation (27) and Equation (28) into Equation (26), Equation (29) can be obtained:

$$C\rho A \frac{\partial(VT)}{\partial t} + CVA \frac{\partial(VT)}{\partial x} = \frac{1}{gh} H_{xx} \frac{\partial V}{\partial x} + \frac{\partial}{\partial x} \left(k_1 \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_2 \frac{\partial T}{\partial y} \right) \quad (29)$$

When temperature field variations are not considered, the temperature T in Equation (29) is treated as a constant. Accordingly, the kinematic viscosity ν in Equation (9) becomes constant, and therefore, the friction factor f in Equation (7) is also constant. As a result, the established model simplifies to the standard flow equation shown in Equation (13).

3.2. Boundary condition. The boundary conditions for HIPPS encompass key components such as the upstream wellbore, X-tree choke valve, HIPPS valve, potential pipeline blockage locations, ESDV, and the downstream host platform. Since the X-tree choke valve, HIPPS valve, pipeline blockage, and ESDV can all be regarded as throttling elements, the HIPPS boundary conditions can be equivalently represented by the upstream wellbore, throttling components, and the downstream host facility. These boundary conditions collectively determine the operating state and dynamic response characteristics of the system, influencing pressure wave propagation and the design of the fortified section. Under different operating scenarios, variations in boundary conditions directly alter the flow dynamics of crude oil within the export pipeline, thereby affecting the effectiveness of HIPPS protection and the optimization of fortified section length.

3.2.1. Wellbore and host platform. As shown in Figure 4, the oil-water mixture in the wellbore flows sequentially through the X-tree choke valve and then enters the oil export pipeline. Therefore, the boundary condition at the wellbore is established first.

The total energy of the flowing crude oil within the wellbore includes both kinetic energy and potential energy. The kinetic energy is represented by the square of the crude oil velocity, while the potential energy is closely related to the pressure intensity of the

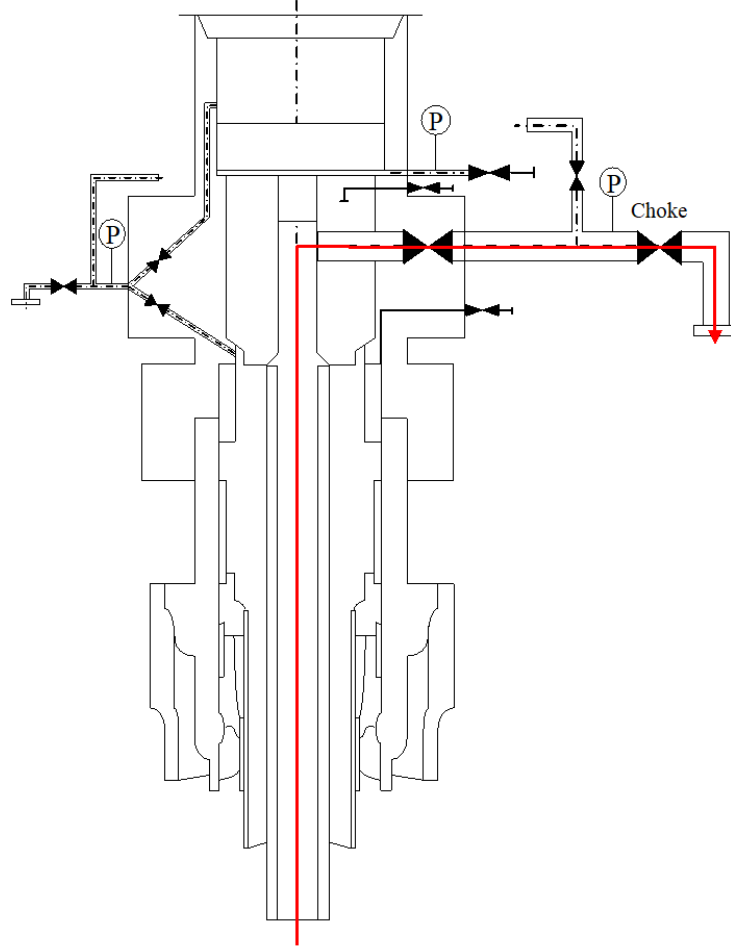


FIGURE 4. Oil flow process in X-Tree

fluid. Accordingly, the pressure distribution within the wellbore can be expressed as shown in Equation (30):

$$H_{i,1} = H_{re} - \frac{Q_{i,1}^2}{2gA^2} - k \frac{Q_{i,1}^2}{2gA^2} \quad (30)$$

where, H_{re} is the shut-in pressure within the wellbore, the second term represents the kinetic energy of the crude oil in the wellbore, the third term accounts for the pressure loss at the wellbore inlet, with k being the inlet loss coefficient. Similarly, the boundary condition at the host platform follows the same form as Equation (30) under analogous assumptions.

3.2.2. Throttling units. The shutoff process of a throttling unit is modeled as a local dynamic reduction in pipeline diameter, as illustrated in Figure 5.

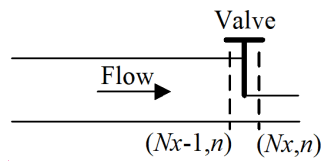


FIGURE 5. Boundary conditions for throttling units

Assuming the throttling unit has an opening degree of τ , the effective diameter of the equivalent pipeline section is given by Equation (31).

$$D_2 = D_1 \times \tau \quad (31)$$

Neglecting pressure losses at the connection interfaces, the flow dynamics at the throttling unit satisfy Equation (13) and Equation (24).

3.2.3. Multi-well manifold. In multi-well oil production operations, the manifold is composed of multiple wellbore branches and a main pipeline. Its overall flow topology can be further abstracted and simplified into an equivalent network model consisting of a series of branching junctions connected in sequence, as shown in Figure 6.

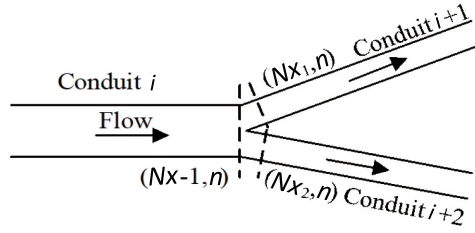


FIGURE 6. Boundary conditions for multi-well manifold

Each branching junction represents a location where fluid streams merge or split and is required to satisfy the fundamental governing equations, including mass conservation and momentum conservation. The continuity condition at each junction can be expressed by Equation (32), which describes the conservation of flow rates among the connected branches at the junction.

$$Q_{Nx-1,n} = Q_{Nx1,n} + Q_{Nx2,n} \quad (32)$$

When the local head losses at the junction and the differences in velocity head among the connected pipelines are neglected, the energy conservation relationship at the junction is given by Equation (33), which further constrains the pressure and energy distribution characteristics at the confluence point.

$$H_{Nx-1,n} = H_{Nx1,n} + H_{Nx2,n} \quad (33)$$

Through the above equivalent treatment, the complex manifold structure can be decomposed into the coupled responses of multiple local branching junctions, enabling quantitative characterization of inter-well interference within a rigorous governing-equation framework. Based on this structured modeling approach, the flow distribution, pressure-wave propagation behavior, and their impacts on the HIPPS fortified section length under transient or abnormal operating conditions can be obtained through the sequential solution of the branching-junction equations. This approach establishes a unified and physically consistent mathematical framework for subsequent derivation of branching-junction boundary conditions and solution using the method of characteristics.

4. Model Solution.

4.1. Method of characteristics. The flow process of crude oil in subsea HIPPS pipelines is modeled as a 1D unsteady distributed-parameter system, whose mathematical representation consists of a set of coupled partial differential equations. To efficiently and accurately capture the transient pressure response, MOC is adopted in this study to solve the model.

Considering the relationship between flow velocity and flow rate: $Q = VA$, the velocity terms in the momentum equation (13) and the continuity equation (24) are replaced with flow rate expressions, resulting in Equation (34) and Equation (35).

$$gA \frac{\partial H}{\partial x} + \frac{\partial Q}{\partial t} + \frac{fQ}{2DA} |Q| = 0 \quad (34)$$

$$\frac{a^2}{gA} \frac{\partial Q}{\partial x} + \frac{\partial H}{\partial t} = 0 \quad (35)$$

By introducing the characteristic equation (36), the above partial differential equations are transformed into ordinary differential equations.

$$\frac{d}{dx} = \frac{\partial}{\partial t} + \frac{dx}{dt} \frac{\partial}{\partial x} \quad (36)$$

Since the propagation speed along the characteristic direction is the wave speed $\frac{dx}{dt} = \pm a$, Equation (36) can be further rewritten as

$$\frac{d}{dx} = \frac{\partial}{\partial t} \pm a \frac{\partial}{\partial x} \quad (37)$$

Equation (37) indicates that along the characteristic lines propagating forward or backward at wave speed a , variations in crude oil follow the direction of the characteristics. Substituting Equation (37) into Equation (35), and then into Equation (36), results in Equation (38) and Equation (39), which describe the variation laws of flow rate and pressure along the upstream characteristics.

$$\frac{dQ}{dt} \mp a \frac{\partial Q}{\partial x} + gA \frac{\partial H}{\partial x} + \frac{fQ}{2DA} |Q| = 0 \quad (38)$$

$$a^2 \frac{\partial Q}{\partial x} + gA \left(\frac{dH}{dt} \mp a \frac{\partial H}{\partial x} \right) = 0 \quad (39)$$

For clarity of expression, Equation (38) is multiplied by $\pm a$ and then combined with Equation (39) to derive the unified characteristic equations for pressure and flow rate propagation along the positive and negative characteristic directions. These are represented as Equation (40) and Equation (41), which are the governing characteristic equations of the model.

$$C^+ : \frac{dQ}{dt} + C_a \frac{dH}{dt} + RQ|Q| = 0 \quad \frac{dx}{dt} = a \quad (40)$$

$$C^- : \frac{dQ}{dt} - C_a \frac{dH}{dt} + RQ|Q| = 0 \quad \frac{dx}{dt} = -a \quad (41)$$

where, $C_a = \frac{gA}{a}$ is the wave impedance coefficient, $R = \frac{f}{2DA}$ is the friction term coefficient. Equation (40) and Equation (41) form the mathematical foundation for analyzing the pressure-flow rate distribution in the system. As the core expression of the method of characteristics, these equations effectively describe the dynamic variations in flow rate and pressure along the characteristic lines.

To facilitate the application of the method of characteristics for solving unsteady flow problems, the model's characteristic equations must be integrated along the characteristic lines. A grid-based discretization approach is adopted, in which the pipeline is divided into segments of length Δx , as illustrated in Figure 7. Within each time step Δt , integration is performed along the characteristic lines, and the known variables are solved accordingly. This yields integral expressions along both the positive and negative characteristic lines.

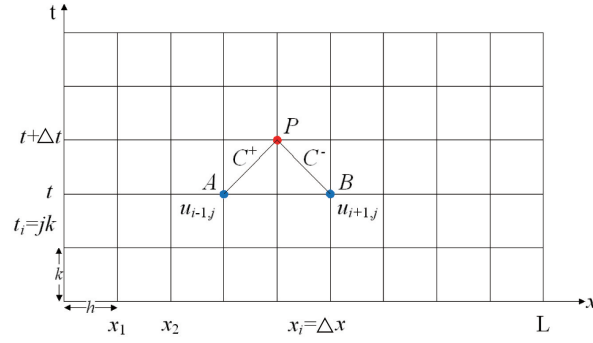


FIGURE 7. Schematic diagram of characteristic lines

By integrating along the C^+ characteristic direction and applying Equation (37), Equation (42) is obtained.

$$C^+ : \int_t^{t+\Delta t} \left(\frac{dQ}{dt} + C_a \frac{dH}{dt} + RQ|Q| \right) dt = Q_P - Q_A + C_a(H_P - H_A) + RQ_A|Q_A|\Delta t = 0 \quad (42)$$

Simplifying and rearranging the results of the integration yields Equation (43).

$$\begin{aligned} C^+ : Q_P &= C_P - C_a H_P \\ C_P &= Q_A + C_a H_A - RQ_A|Q_A|\Delta t \end{aligned} \quad (43)$$

Similarly, by integrating along the C^- direction, Equation (44) is obtained.

$$\begin{aligned} C^- : Q_P &= C_n + C_a H_P \\ C_n &= Q_B - C_a H_B - RQ_B|Q_B|\Delta t \end{aligned} \quad (44)$$

Equation (43) and Equation (44) are used to compute the pressure and flow rate distribution within the pipeline.

4.2. Solution of boundary conditions.

4.2.1. *Solution of throttling units.* To solve for the HIPPS boundary condition, substituting Equation (34) into Equation (20) yields Equation (45).

$$k_1 Q_{i,1}^2 + Q_{i,1} - (C_n + C_a H_{re}) = 0, \quad k_1 = \frac{C_a(1+k)}{2gA^2} \quad (45)$$

Solving this quadratic equation yields

$$Q_{i,1} = \frac{-1 + \sqrt{1 + 4k_1(C_n + C_a H_{re})}}{2k_1} \quad (46)$$

Based on Equation (43) and Equation (44), the pressure-flow characteristics across the throttling unit can then be determined, as expressed in Equation (47).

$$H_{Nx,n} = \frac{C_{P(Nx-1)} - C_{nNx}}{C_{a(Nx-1)} + C_{aNx}} \quad (47)$$

Based on the pressure at the valve throat, the corresponding characteristic equations can be used to solve for the crude oil flow rates on both sides of the throat in Figure 5. However, in Equation (47), when the valve opening approaches zero, the coefficient R tends toward infinity. Therefore, the boundary condition expressed in Equation (47) is only applicable to cases where the throttling unit is not fully closed. When the throttling

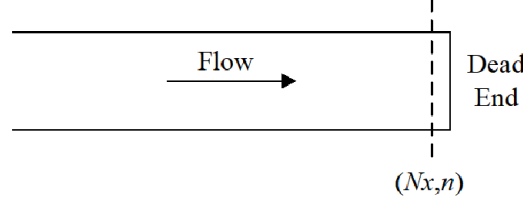


FIGURE 8. Dead zone boundary condition of throttling units

unit is nearly fully shut, the dead-end boundary condition illustrated in Figure 8 should be considered.

When the throttling unit is fully closed, no crude oil flows through it, meaning the corresponding flow rate is zero, i.e., $Q_{Nx,n} = 0$. According to the characteristic equation (43), the pressure at this moment is given by Equation (48).

$$H_{P_{Nx,n}} = \frac{C_{P_{Nx}}}{C_{a_{Nx}}} \quad (48)$$

4.2.2. *Solution of multi-well manifold.* For the branching junction shown in Figure 6, the transient flow behavior can be described by deriving the characteristic equations of each connected branch along the positive and negative characteristic lines. The characteristic equations for the three pipelines at the junction can be expressed as Equation (49).

$$\begin{cases} Q_{Nx-1,n} = C_{P_{Nx}} - C_{a_{Nx}} H_{Nx-1,n} \\ Q_{Nx1,n} = C_{n_{Nx1}} + C_{a_{Nx1}} H_{Nx1,n} \\ Q_{Nx2,n} = C_{n_{Nx2}} + C_{a_{Nx2}} H_{Nx2,n} \end{cases} \quad (49)$$

By combining these equations with the continuity condition presented in Section 3.2.3, the flow-rate expression at the endpoint of the main pipeline can be obtained as Equation (50).

$$Q_{Nx-1,n} = \frac{C_{P_{Nx}} - C_{n_{Nx1}} - C_{n_{Nx2}}}{C_{a_{Nx}} + C_{a_{Nx1}} + C_{a_{Nx2}}} \quad (50)$$

5. Simulation Experiments.

5.1. Single-well production operation.

5.1.1. *Experimental parameter settings for single-well production.* To determine the optimal fortified section length for HIPPS in the single-well configuration, this study designs a series of transient flow simulation experiments for three typical abnormal operating conditions, and analyzes the transient pressure response throughout the entire pipeline.

Based on actual engineering data, the experimental setup includes the wellbore, throttling unit, and simulation parameters of the host platform. It is assumed that the sea surface temperature is 25°C, while the wellbore temperature remains constant at 80°C [15]. The oil export pipeline has a total length of 1.8×10^3 m, with an inner diameter of 4 in., an outer diameter of 4.6 in., and a pipe roughness $\varepsilon = 5 \times 10^{-2}$ mm. The crude oil density is 800 kg/m³, and the pressure wave propagation velocity in the pipeline is 1.2×10^3 m/s. The API gravity of the crude oil is 13.8°API.

The shut-in pressure of the wellbore is set to 40 MPa, while the injection pressure from the host platform is set to 15 MPa. Under normal conditions, the HIPPS valve takes up to 8 seconds to fully close, and its trigger pressure is set to 30 MPa. The maximum allowable pressure in the non-protected pipeline segment is 35 MPa [12,37].

5.1.2. *Abnormal fully-open choke valve condition.* The normal choke valve opening is set to 0.3. At 13.3 seconds, the choke valve abnormally shifts to the fully open position, causing a sharp pressure increase within the oil export pipeline. When the pressure sensor detects that the pipeline pressure exceeds the threshold value of 30 MPa, the HIPPS valve begins to close. Simulation results considering both temperature variation and no temperature variation are shown in Figure 9.

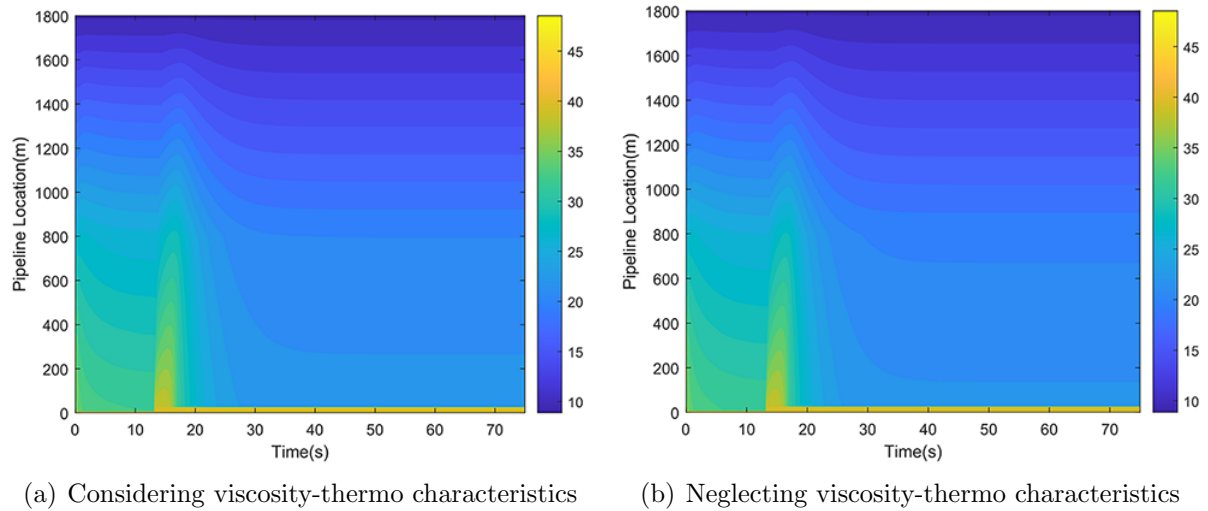


FIGURE 9. HIPPS pressure distribution cloud map for single-well oil production with abnormally open choke valve

As shown in the analysis of Figure 9, under abnormal operating conditions, the pressure within the pipeline downstream of the HIPPS valve in both models exhibits a negative correlation with pipeline position, and ultimately stabilizes at the static pressure level of the platform. When temperature variation is considered, the pressure peak in the pipeline occurs at 15.72 s; when temperature variation is not considered, the peak appears at 15.67 s. The corresponding pressure-position curves for the downstream pipeline under both modeling conditions are shown in Figure 10.

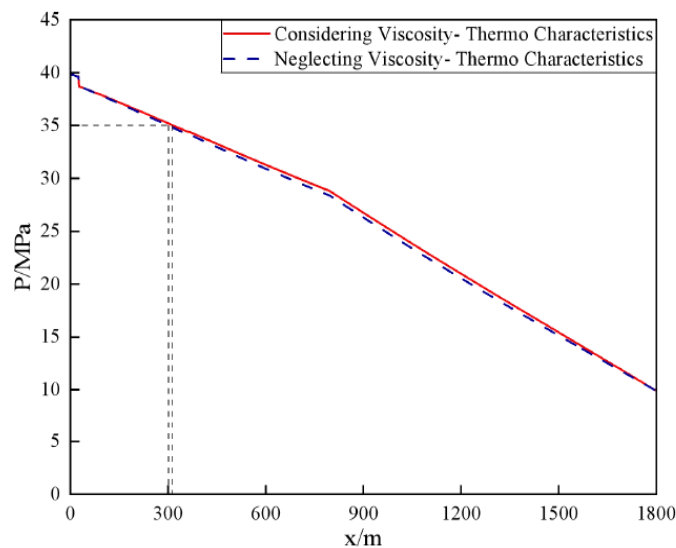


FIGURE 10. Pressure-position curve of pipeline behind HIPPS valve

For the model that considers the viscosity-thermo characteristics, the pressure in the section of the oil export pipeline within 285.5 m downstream of the HIPPS valve exceeds the maximum allowable pressure of 35 MPa for the non-protected pipeline segment. In contrast, for the model that neglects viscosity-thermo effects, the pressure exceeds 35 MPa within a distance of 269.5 m downstream of the HIPPS valve.

5.1.3. Pipeline blockage scenario. The choke valve opening is set to a normal value of 0.3. At 13.3 seconds, blockage begins to occur in the pipeline. Considering different blockage location distributions, the simulation results are shown in Figure 11.

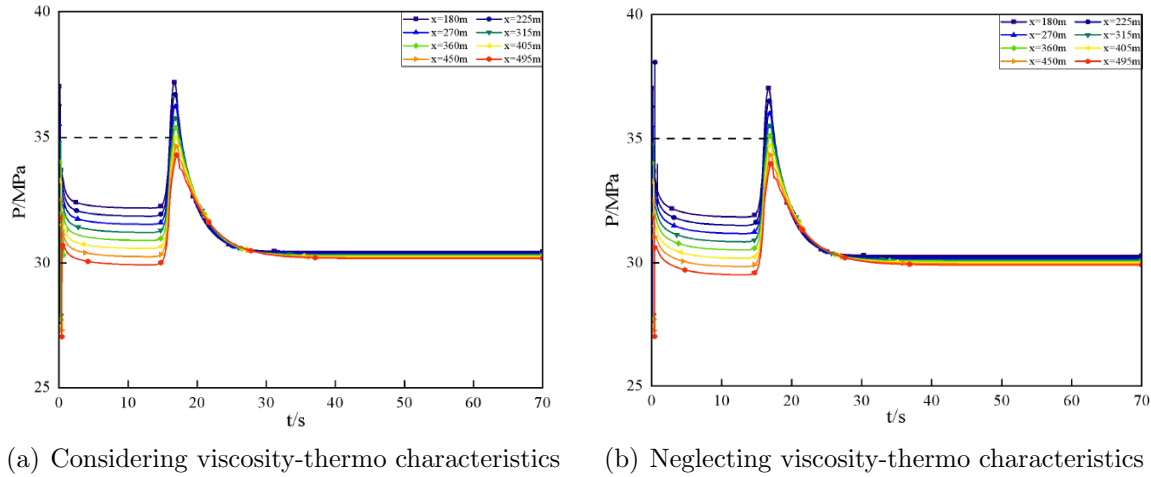


FIGURE 11. Dynamic changes in oil production pressure of HIPPS single-well at different blockages

When viscosity-thermo characteristics are considered, a fortified section length greater than 375.8 m is required to ensure that the pressure in the downstream non-reinforced pipeline remains within the allowable limit. In contrast, when viscosity-thermo effects are neglected, a fortified section length greater than 342 m is sufficient to meet the same pressure requirement.

The HIPPS valve shut-off time is set to 10 seconds, and the influence of different fortified section lengths on pipeline pressure variations is analyzed. The simulation results are presented in Figure 12.

With the increase in fortified section length, pressure fluctuations within the pipeline are progressively suppressed, significantly reducing the amplitude of pressure waves and thereby effectively preventing the occurrence of overpressure.

5.1.4. Emergency shutdown valve closure scenario. The choke valve opening is set to a normal value of 0.3. The ESDV is installed at the end of the pipeline, located a distance of 1.7685×10^3 meters from the choke valve. At 13.3 seconds, the ESDV is suddenly closed, and the simulation results are presented in Figure 13.

Under the emergency shutdown condition of the ESDV, the internal pipeline pressure remains consistently below the preset threshold. Therefore, no dedicated fortified section design is required for this condition. The rapid response of the ESDV effectively suppresses pressure fluctuations within the pipeline, prevents overpressure, and ensures system safety.

When accounting for the temperature-dependent viscosity of crude oil, the final fortified section length is determined to be 375.8 m, representing a 9.88% increase compared to the model that does not consider viscosity-thermo characteristics. Neglecting the influence of temperature gradients on crude oil viscosity leads to an overly conservative

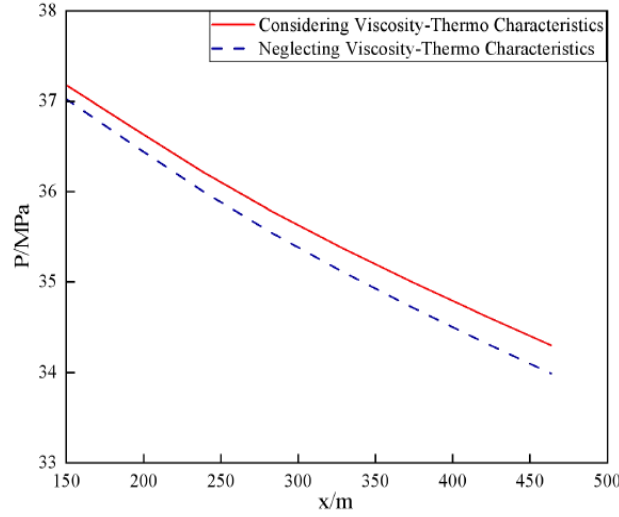


FIGURE 12. Comparison of the production fortified section length of single-well with shutdown time of 10 s

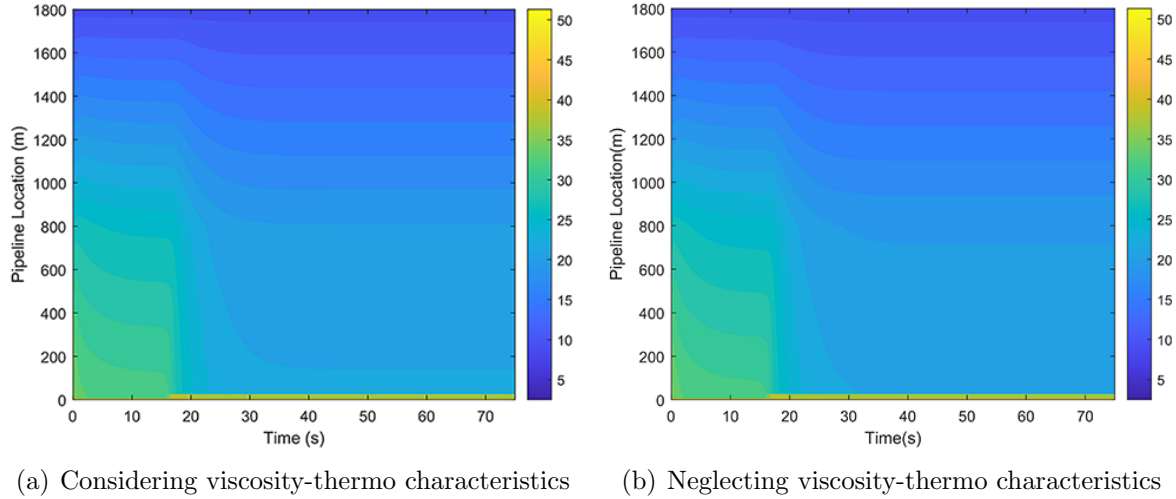


FIGURE 13. HIPPS pressure distribution cloud map for single-well oil production with ESDV shutdown

system design, introducing unnecessary safety margin and increasing construction cost. Therefore, incorporating the dynamic variation of the temperature field is a necessary condition for the rational design of the fortified section length. This approach enables a more accurate representation of real flow characteristics, optimizes system design, and avoids the economic losses associated with redundant overdesign.

5.2. Multi-well production operation.

5.2.1. Simulation parameter settings for multi-well production. To determine the optimal fortified section length for multi-well HIPPS system, a series of transient flow simulations were conducted for three typical abnormal operating conditions, and the pressure dynamics along the entire pipeline were analyzed.

Based on actual engineering data, the simulation setup includes key components such as throttling elements, pipelines, the upstream reservoir, and the downstream platform. The pipe roughness is set to $\varepsilon = 0.05$. The sea surface temperature is assumed to be 25°C , and the wellbore temperature is maintained at a constant 80°C . The oil export pipeline

has a total length of 3600 m, with an inner diameter of 4 in. and an outer diameter of 4.6 in. The crude oil density is 800 kg/m^3 , and the pressure wave velocity in the pipeline is 1200 m/s . The API gravity of the crude oil is 13.8°API . The shut-in pressures for the four wellbores are set to 39 MPa, 38 MPa, 35 MPa, and 36 MPa, respectively, with the corresponding pipeline segment lengths being 120 m, 140 m, 160 m, and 180 m. The injection pressure from the downstream host platform is 10 MPa. Under normal operating conditions, the HIPPS valve closure time is 8 seconds, and the trigger pressure is set to 30 MPa. The maximum allowable pressure for the non-protected pipeline section is 35 MPa.

Based on the pipeline parameters above, simulation parameters for the method of characteristics were configured. The pipeline length was divided into 900 spatial segments, and the simulation time was divided into 4×10^4 time steps. As a result, the spatial step size is 4 m and the temporal step size is 3.3×10^{-3} seconds.

5.2.2. Abnormal full-open choke valve condition in multi-well production. In the multi-well production scenario, the boundary conditions at both ends of the main oil export pipeline are set to the host platform. Four branch pipelines are added at intermediate positions along the main pipeline, with the wellbores serving as the boundary conditions at the downstream ends of these branches. Each branch pipeline includes HIPPS valve boundary conditions and choke valve boundary conditions, while the main pipeline includes a pipeline blockage boundary condition, and an ESDV boundary condition is placed upstream of the platform.

The normal choke valve opening is set to 0.3. At 23.1 seconds, the choke valve of the second wellbore abnormally shifts to the fully open position, resulting in a sharp pressure increase in the oil export pipeline. Pressure sensors in all four wellbores detect that the internal pipeline pressure has exceeded the critical threshold of 30 MPa, triggering the closure of all HIPPS valves across the wellbores. The simulation results are shown in Figure 14.

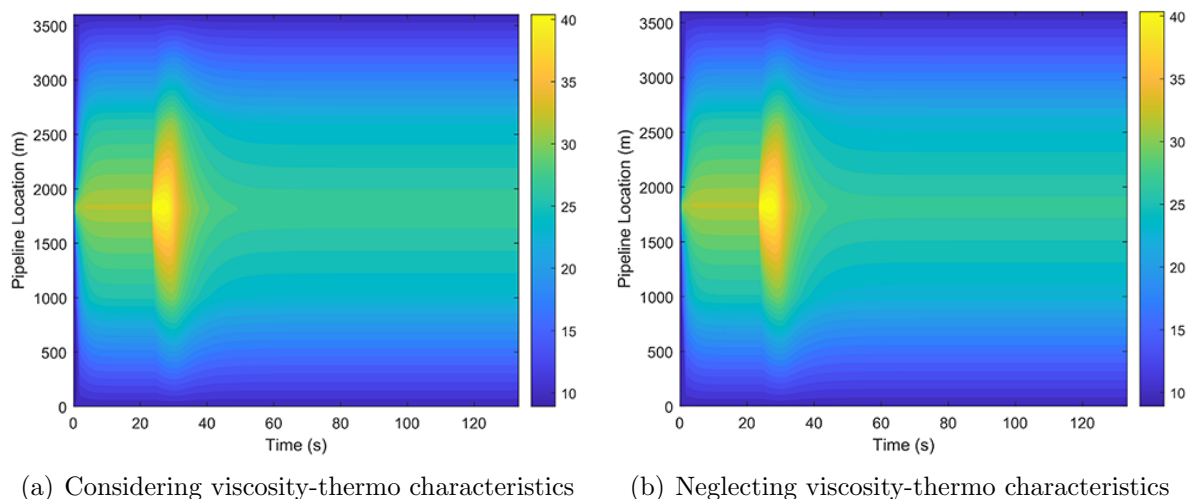


FIGURE 14. HIPPS pressure distribution cloud map for multi-well oil production with abnormally open choke valve

Under abnormal operating conditions, the pressure within the pipeline downstream of the HIPPS valve in both models exhibits a negative correlation with pipeline position, and ultimately stabilizes at the static pressure level of the downstream host platform. In both models, the pressure peak occurs at 28.25 seconds when temperature effects are

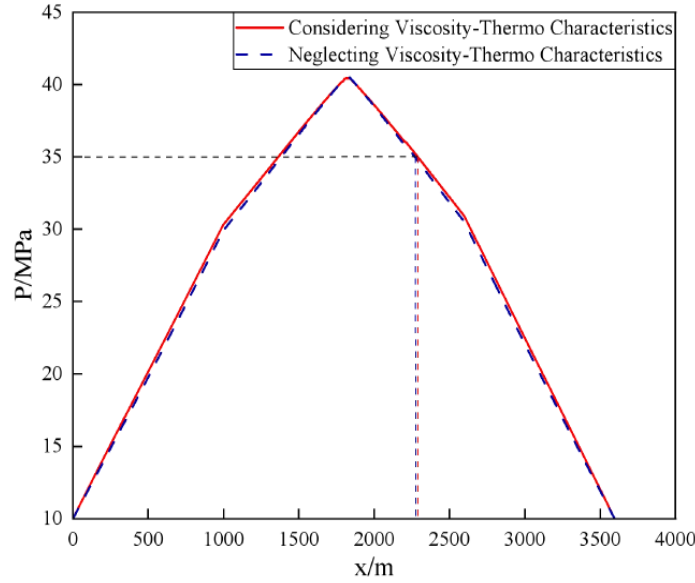


FIGURE 15. Pressure-position curve of pipeline behind HIPPS valve

considered, and at 28.16 seconds when temperature is not considered. The corresponding pressure-position curves for the downstream pipeline are shown in Figure 15.

When the viscosity-thermo characteristics of crude oil are considered, the pressure in the section of the oil export pipeline within 598 m downstream of the HIPPS valve exceeds the maximum allowable pressure of 35 MPa for the non-protected pipeline segment. In contrast, when these characteristics are not considered, the pressure exceeds 35 MPa within 564 m downstream of the HIPPS valve.

5.2.3. *Pipeline blockage condition in multi-well production.* The normal choke valve opening is set to 0.3. At 25.4 seconds, blockage begins to occur in the pipeline. Considering different blockage locations, the simulation results are presented in Figure 16.

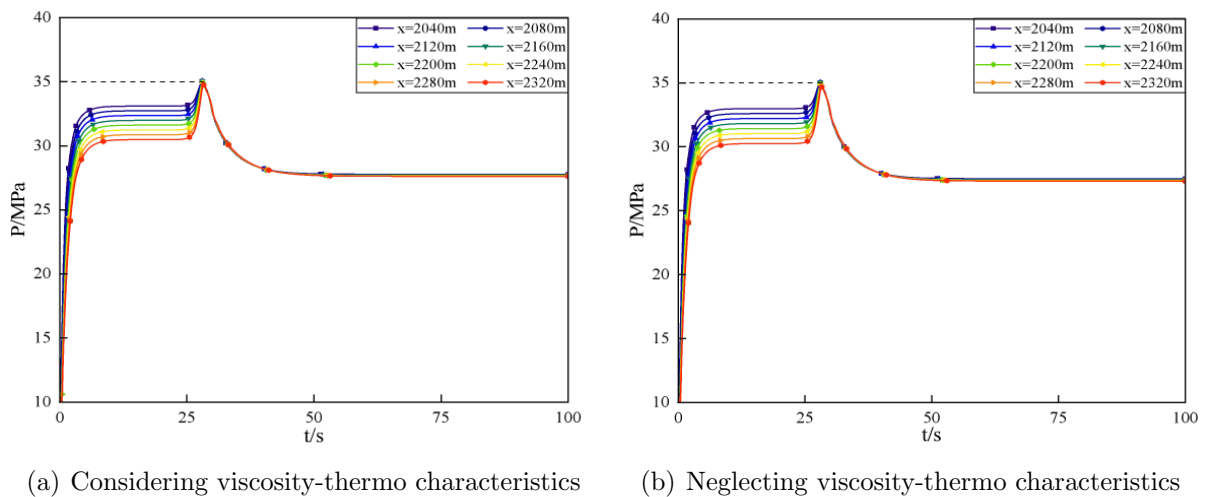


FIGURE 16. Oil production pressure of HIPPS multi-well at different blockages

When the viscosity-thermo characteristics of crude oil are considered, a fortified section length exceeding 764 m is required to ensure that the pressure in the downstream non-reinforced pipeline remains within the maximum allowable limit. Without considering

these characteristics, a fortified section length greater than 708 m is sufficient to meet the same pressure constraint.

To evaluate the impact of different fortified section lengths on pipeline pressure variation, the HIPPS valve closure time is set to 10 seconds. The corresponding simulation results are shown in Figure 17.

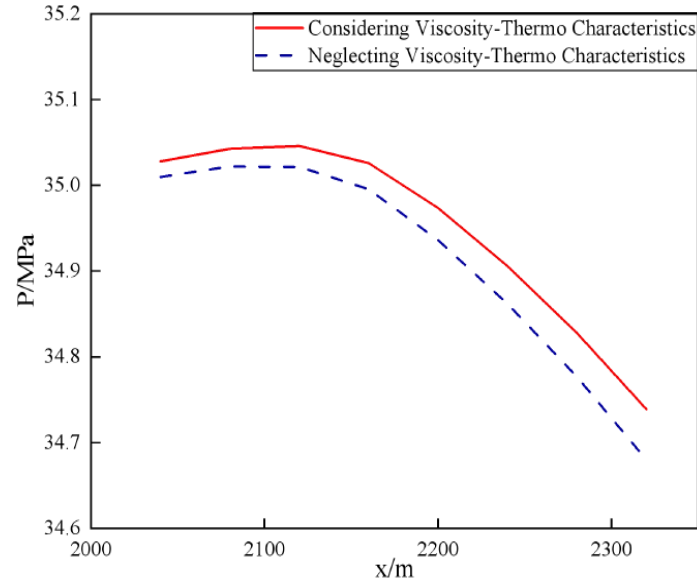


FIGURE 17. Comparison of the production fortified section length of multi-well with shutdown time of 10 s

As the fortified section length increases, pressure fluctuations within the pipeline initially increase slightly and then gradually decrease, leading to a significant reduction in pressure wave amplitude, thereby effectively preventing overpressure events.

5.2.4. Emergency shutdown valve closure scenario. The choke valve is set to a normal opening of 0.3. The ESDV is installed at the end of the pipeline, located a distance of 1.7685×10^3 meters from the choke valve. At 23.1 seconds, the pipeline is shut down in an emergency, and the simulation results are shown in Figure 18.

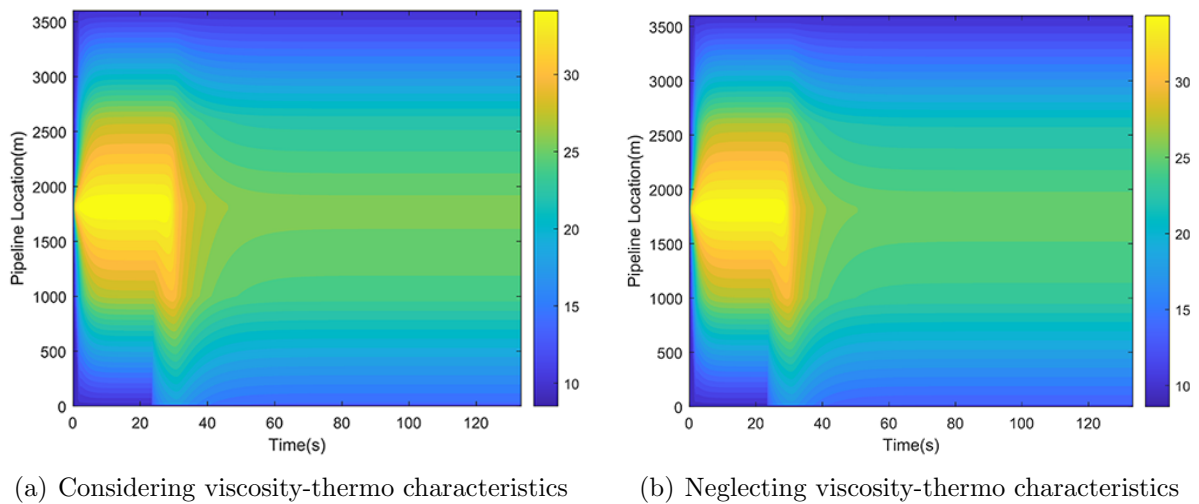


FIGURE 18. HIPPS pressure distribution cloud map for multi-well oil production with ESDV shutdown

Under the ESDV closure condition, the internal pipeline pressure consistently remains below the predefined pressure threshold, indicating that no special design of the fortified section is required for this scenario. The rapid response of the ESDV effectively suppresses pressure fluctuations within the pipeline, prevents overpressure, and ensures the safety and stability of the system.

When the viscosity-thermo characteristics of crude oil are considered, the final the fortified section length is determined to be 764 m, representing a 7.91% increase compared to the model that neglects such characteristics. This result indicates that, although the fortified section length is slightly longer, the increase is modest compared to the overly conservative design produced by the isothermal model. By incorporating the effect of temperature on crude oil viscosity, the model can more accurately capture the actual flow characteristics. This enables a rational reduction of the redundancy in the fortified section length required by isothermal models, thereby shortening the actual fortified section and reducing construction cost, all while maintaining system safety.

6. Conclusion. This paper focuses on the design and optimization of subsea HIPPS, with an emphasis on investigating the dynamic pressure field response within oil transport pipelines under various abnormal operating conditions, particularly when accounting for the viscosity-thermo characteristics of crude oil. Based on these analyses, an optimized design methodology for the fortified section length is proposed. By developing a coupled pressure-flow-temperature model for subsea HIPPS and solving it numerically using the method of characteristics, the pressure evolution under high-temperature and overpressure conditions in subsea oil pipelines is analyzed.

By constructing and analyzing a dynamic pressure field model for subsea HIPPS pipelines, this study develops a model that fully incorporates the viscosity-thermo characteristics of crude oil, enabling a more accurate description of the effects of temperature variations on flow behavior and pressure distribution. The results indicate that the impact of temperature uncertainty on the fortified section length is limited; in particular, after accounting for temperature variations, the increase in fortified section length is minor and remains controllable. On this basis, the viscosity-thermo model allows for reasonable adjustment of redundancy factors, effectively reducing the design length of the fortified section while ensuring system safety under abnormal operating conditions. This research not only provides theoretical support for minimizing redundancy in the fortified section design of subsea HIPPS but also offers an important foundation for lowering system construction cost and enhancing both economic efficiency and reliability of design.

Future work will focus on extending the proposed methodology toward system-level applications. In particular, HIPPS control strategies will be developed based on the optimized fortified section length to enable coordinated design between pressure protection logic and pipeline configuration. In addition, the modeling framework will be applied to optimizing HIPPS testing and verification intervals in accordance with pressure dynamics and operational risk levels, with the aim of reducing unnecessary testing frequency and overall operating cost while maintaining system safety and reliability. Furthermore, the incorporation of actual field data from representative subsea projects will be pursued to further validate and refine the proposed model and enhance its practical applicability.

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